Integration of Agricultural and Energy Systems

Proceedings of a conference February 12-13, 2008, in Atlanta, Georgia

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Foreword and Acknowledgements

The nation's rapid transition to a bioeconomy has significant implications for agriculture, the food system, rural communities and the global economy. The Transition to a Bioeconomy conference series is designed to inventory current knowledge, highlight lessons learned, identify future possibilities and determine future information needs. The information products generated by these conferences will provide tools to enhance the informed decision of making public and private leaders as they address the issues and challenges of the evolving economy.

The February 2008 conference, the first in the series, was a collaboration of Farm Foundation, USDA Office of Energy Policy and New Uses, and USDA Economic Research Service. Thanks are due to the Project Planning Committee: Peggy Caswell, USDA Economic Research Service; Jim Duffield, USDA Office of Energy Policy and New Uses; Vern Eidman of the University of Minnesota; Burton English of the University of Tennessee; James Fischer, Fischer & Associates; Janie Hipp and Pat Hipple, USDA Cooperative States Research Education Extension Service; Madhu Khanna, University of Illinois; Steve Klose, Texas A&M University; Suchada Langley, USDA Economic Research Service; Joe Outlaw, Texas A&M University; Laila Racevskis, University of Florida; Phil Spinelli, USDA Natural Resources Conservation Service; Wally Tyner, Purdue University; and David Zilberman, University of California-Berkeley.

Steve Halbrook
Farm Foundation

Executive Summary

Burton C. English, Jamey Menard, and Kim Jensen

High crude oil prices, concerns about the environment, and desire for increased national energy self-sufficiency have contributed to interest in alternative renewable energy sources. However, as production of liquid fuel from agricultural products increased (from 2000 to 2007, ethanol production increased from 1.63 to 6.50 billion gallons; for biodiesel, production increased from 2 million to 450 million gallons for that same timeframe), soil erosion, input use, land use, water quality, and food versus fuel resource considerations have surfaced. The potential effects of diverting land from food and feed production into energy production will not only influence retail price of food but also livestock production costs. These changes have drawn the attention of scientists, energy leaders and policymakers. In February 2008, university, private sector, and government researchers were invited to the first in a five conference series on the *Transition to a Bioeconomy* sponsored by the Farm Foundation.

The Farm Foundation's Steve Halbrook, along with Peggy Caswell, Jim Duffield, Vernon Eidman, Burton English, Jim Fischer, Janie Hipp, Steve Klose, Suchada Langley, John Miranowski, Joe Outlaw, Laila Racevskis, Felix Spinelli, Wallace Tyner, and David Zilberman were on the planning team for a series of conferences on the *Transition to a Bioeconomy*. This conference proceeding provides the written papers that were presented at the first conference in the series. Participants examined the impacts of a bioeconomy on farming systems, cropping patterns, by- and coproduct markets, and animal agriculture. Also discussed were the farming and energy systems needed to support the cellulosic industry when that technology becomes commercially viable. The conference, titled *Transition to a Bioeconomy: Integrations of Agricultural and Energy Systems*, was held on February 12-13, 2008, in Atlanta, Georgia. The conference was a collaborative effort and financially supported by the Farm Foundation, USDA's Office of Energy Policy and New Uses, and USDA's Economic Research Service.

The conference was divided into five sections including:

- An overview of the bioeconomy today and tomorrow,
- The technical and market potential for byproducts and coproducts,
- Selected paper sessions,
- Implications for animal agriculture, and
- The challenges and opportunities of the next decade.

The selected paper sessions included papers on corn fractionation, by- and coproducts, the move towards cellulosic feedstocks, and environmental and economic impacts as we move into the future.

In the opening session, Jim Fischer, USDA Research, Education & Economics, provided *An Overview of the Bioeconomy*; Wallace E. Tyner, Purdue University, presented the *Policy Options for Integrated Energy & Agricultural Markets*; and the *Possibilities for the Bioeconomy* were discussed by Hans Blaschek, Center for Advanced BioEnergy Research. Jim Fischer presented a case in which the future will be a carbohydrate-based economy that will improve national security and the U.S. trade balance, realize important environmental benefits, develop significant sustainable economic opportunities for rural America, and export the technologies developed to other countries. Wallace Tyner concluded that a "new era has arrived in which agricultural commodity prices are tied to crude oil price". Following an examination of the products and coproducts of a biorefinery, Hans Blaschek concluded that "the future is bright for the bioproduction of fuels and chemicals".

In the second session, the concept of the biorefinery was further evaluated with a discussion of its products and coproducts. Doug Tiffany, University of Minnesota, examined the *Use of Distillers Byproducts & Corn Stover as Fuels for Ethanol Plants*. *Biodiesel, Glycerin & Other Coproducts* were discussed by Joe Bozell, University of Tennessee, and Larry Russo, U.S. Department of Energy (DOE) Energy Efficiency and Renewable Energy Biomass Program, examined *The Potential of the Biorefinery* with Cynthia Bryant, Novozymes North America, Inc., discussing *The Evolution of*

Biofuels. Doug Tiffany indicated that the utilization of readily available biomass in the form of byproduct syrup and corn stover at dry-grind ethanol plants is technically feasible and financially viable, especially if low carbon fuel standards are developed. Joe Bozell indicated that oleochemicals are a key component of the biodiesel integrated biorefinery concept and could be the best initial bridge between the biorefinery and the petrochemical refinery. Integrating biodiesel production with production of chemicals provides an economically attractive process approach. Larry Russo discussed the DOE approach to the development of an economically sustainable biorefining industry and the current biorefinery investments that the United States have undertaken. Finally, Cynthia Bryant, the luncheon speaker, discussed the market impediments, the market drivers, and areas to watch. The impediments included investment speculation, feedstock prices, and production inefficiencies. Market drivers included infrastructure investment, cellulosic commercialization, and high cost of oil. Other factors to watch were consolidation, government incentives, trade policy, and E-blend tolerance.

The selected paper sessions expanded on the themes developed earlier in the conference and looked at various aspects of the bioeconomy. Since these papers are included in the book, a summary of the findings in these papers are left to the reader.

The final two sessions utilized a presentation followed by a panel discussion format. The panel in the first of the last two sessions, chaired by Charles Stenholm of Olsson, Frank & Weeda, examined the implications that the bioeconomy has had on the livestock sector. Greg Doud (beef), National Cattlemen's Beef Association, Mary Ledman (dairy), Keough-Ledman Associates, Dam Smalley (poultry), Red Hill Farms, and John Hardin (pork), Hardin Farms, discussed the implications that the ethanol industry has had on their respective livestock industries. The impacts up until now differ by industry. In the dairy industry, world demand for milk has helped offset the increase cost of feed, however, in 2008, this will likely reverse as feed costs are expected to increase 30 to 40 percents with milk prices expected to be somewhat lower. For poultry, booming ethanol production is "eating through corn supplies and forcing meat producers to pay more to feed their livestock". The impact on the U.S. poultry industry will be an increase in the costs of production of $2 billion per year and to the U.S. egg industry of $750 million per year. Average rate of per capita chicken consumption is likely to decline by one pound per year resulting in 800 farms each year not producing chickens from 2007 to 2012. For the pork industry, issues that need to be discussed, in the short term, include who will survive and how quickly will the pork industry reduce production in response to losses caused by increased demand on their feedstocks. Longer term issues include when will cellulose be a player, how high will corn yields go, and will new conversion processes provide more valuable feed coproducts to the hog industry.

The final session of the conference examined the future of the bioeconomy. Greg Krissek's, ICM, Inc., presentation was from a biofuels industry perspective. Jay Armstrong's presentation was from an agricultural perspective. These two presentations were followed by John Miranowski, Iowa State University, leading the panel discussion of *What We Know and What We Need to Know*. Greg Krissek indicated that ethanol was part of the bridge to our energy future and the industry needs:

- Continuous improvement in the grain-to-ethanol industry (food and fuel),
- Commercial cellulose ethanol, automobile and other engine optimization favoring renewable fuels at higher blends,
- Develop and deploy blender pumps that allow consumers to choose a blend,
- Continued development of flexible fueling and terminal infrastructure,
- Adoption of hybrid vehicles,
- Implementation of other sources of renewable energy such as wind and solar, and
- Nonpartisan federal based programs for advancing bioenergy.

In his discussion, John Miranowski indicated that we need to understand what it means to operate in a global economy and what biofuel expansion will mean to the global environment. A further understanding of the future of corn ethanol and how much biofuel can be extracted from residues and wastes are needed. In addition, lifecycle analyses for new facilities and feedstocks will be required. Energy policy issues, such as how the renewable fuel standard will be implemented and what role tax credits and tariffs may play, merit further investigation.

John Miranowski continued by indicating that larger economic questions exist. What are the costs involved when we attempt to fix the energy and greenhouse gas emissions problem? Will we sustain the cheap energy legacy? The government currently selects technology winners with little knowledge as their contribution to the greenhouse gas problem. What mechanisms can be used to change this? Changing consumer behavior is extremely important also. If we want an efficient solution and real progress then that change must be through markets perhaps using a carbon tax or a cap carbon and trade carbon credit set of policies. These markets may also determine how the agricultural and energy systems are integrated.

A final question John Miranowski posed focused on the environmental and amenity impacts of the growing bioeconomy. Environmental impacts on air and landscape quality plus water quantity and quality need to be addressed. The water use per gallon of biofuel needs to be determined, along with an examination of the impact this new industry will have on local water supplies (aquifers). Impacts on local and regional amenities need to be identified, including the impacts to recreation amenities that attract business and residents to a region, the contribution that the industry makes to local economic development, and the impacts of land competition, including the conversion of Conservation Reserve Program land to energy crops.

The authors and paper titles included in this book are:

- Wallace E. Tyner and Farzad Taheripour: Policy Analysis for Integrated Energy and Agricultural Markets in a Partial Equilibrium Framework;
- Hans P. Blaschek: What Are the Possibilities for the New Bioeconomy?;
- Douglas G. Tiffany, R. Vance Morey, and Matt De Kam: Use of Distillers By-Products and Corn Stover as Fuels for Ethanol Plants;
- Joseph J. Bozell: Biorefinery Product Opportunities from Glycerol;
- Phil Kenkel and Rodney Holcomb: Feasibility of On-Farm or Small Scale Oilseed Processing and Biodiesel Production;
- Bhawna Bista, Todd Hubbs, Brian T. Richert, Wallace E. Tyner, and Paul V. Preckel: Economic Value of Ethanol Byproducts in Swine Diets: Evaluating Profitability of Corn Fractionation Techniques;
- Mindy L. Baker and Bruce A. Babcock: Value Maximization from Corn Fractionation: Feed, Greenhouse Gas Reductions, and Cointegration of Ethanol and Livestock;
- Jim Larson, Burton C. English, and Lixia He: Economic Analysis of Farm-Level Supply of Biomass Feedstocks for Energy Production Under Alternative Contract Scenarios and Risk;
- Burton C. English, Daniel G. De La Torre Ugarte, R. Jamey Menard, and Tris West: Economic and Environmental Impacts of Biofuels Expansion: The Role of Cellulosic Ethanol;
- Brian J. Frosch, Roland J. Fumasi, James W. Richardson, Joe L. Outlaw, and Brian K. Herbst: Estimating and Comparing Alternative Ethanol Processes and Feedstock Choices;
- Roland J. Fumasi, Steven L. Klose, Greg H. Kaase, James W. Richardson, and Joe L. Outlaw: Viability of Cellulosic Feedstock Production from Produce to Biorefinery; and
- Francis M. Epplin: Millions of Acres for Dedicated Energy Crops: Farms, Ranches or Plantations?

Policy Analysis for Integrated Energy and Agricultural Markets in a Partial Equilibrium Framework

Wallace E. Tyner and Farzad Taheripour[1]

Background

In the past, most agricultural markets have been well integrated. Markets for different energy commodities, especially liquid energy products, also have been tightly linked. However, agricultural markets and energy markets have not been closely correlated. Table 1 contains partial correlation coefficients between pairwise prices (both levels and first differences) of corn, soybeans, crude oil, gasoline, and ethanol obtained from monthly data for the period of 1982-2007. Clearly, the energy pair correlations are quite high ranging from 0.86 to 0.98, while the energy agricultural correlations are quite low, ranging from 0.13 to 0.25. The corn-soybean pair has a correlation of 0.72.

Historically, recognizing this market separation, energy and agricultural commodities and policies have been evaluated.[2] Can this continue into the future? Until 2002 the fraction of the U.S. corn crop going to ethanol had always been less than 10 percent. As recently as 2004, it was about 11 percent. Yet in 2007, the fraction of the corn crop going to ethanol will be about 22 percent, double that three years ago – even with about a 25 percent increase in corn production in 2007. This fraction may exceed 30 percent in 2008, and it could even approach 40 percent depending on what happens to corn acreage and production.

Massive production of energy, mainly liquid fuels, from agricultural resources will link agricultural and energy markets, tightly (Schmidhuber, 2007). The new market integration is perhaps the most fundamentally important change to occur in agriculture in decades. The link between energy and agricultural markets requires an integrated environment to study these markets and design policy alternatives to guide them towards designated goals. This article develops an integrated partial equilibrium framework to analyze economic impacts of four alternative policies which can be implemented in promoting ethanol production. These policies are: a fixed subsidy per gallon of ethanol, no subsidy, a variable subsidy linked to the crude oil price, and a renewable fuel standard.

In this article, the combinations of corn-crude oil prices which maintain a representative ethanol producer at the breakeven condition (zero economic profit) with and without government supports, in terms of a fixed subsidy (51 cents) per gallon of ethanol produced are examined. Then firm profitability is linked using a partial equilibrium model to analyze the economic impacts of the alternative policies to promote ethanol production under different economic conditions.

Corn-Crude Oil Prices and Ethanol Profitability at a Firm Level

Tyner and Taheripour (2007) have examined profitability of a typical ethanol producer with and without the 51 cents ethanol subsidy for different combinations of corn-crude prices. Figure 1 depicts these combinations with two breakeven lines.

The top line in this graph gives the breakeven combinations of corn-crude oil prices with no subsidy and the second line shows the combinations with 51 cents subsidy. In both cases, ethanol is assumed to be priced on an energy equivalent basis with gasoline. Table 2 provides the breakeven corn prices from the graph for selected oil prices.[3] Several important facts can be deduced from Figure 1 and Table 2. First,

[1] Tyner is a Professor and Taheripour is a Postdoctoral Research Fellow, all respectively, in the Department of Agricultural Economics at Purdue University, West Lafayette, Indiana.

[2] Several articles have addressed the impacts of higher energy prices on the agricultural cost of production (Dvoskin and Heady, 1976; Christensen *et al*., 1981). These papers do not refer to the link between these markets from the demand side. In this paper, we focus on the link between energy and agriculture from the demand side. In the future, the demand for agricultural commodities (e.g. demand for corn) will be linked to the demand for energy, in particular, for gasoline due the massive production of biofuels from agricultural reserves.

[3] The data in Table 2 and Figure 1 assume long term equilibrium pricing relationships between crude oil and gasoline and gasoline and ethanol. In the fourth quarter of 2007, both the crude-gasoline and gasoline-ethanol market were in disequilibria for different reasons (Tyne, 2008). However, in due course we can expect then to return to more standard price relationships.

Table 1. Agricultural and Energy Historic Price Correlations Based on Data From 1982 to 2007

Data Pair	Correlation Coefficient (price levels)	Correlation Coefficient (first differences)
Crude-gasoline	0.98	0.65
Crude-ethanol	0.88	0.29
Gasoline-ethanol	0.86	0.35
Ethanol-corn	0.25	0.05
Crude-corn	0.16	-0.11
Crude-soybeans	0.13	-0.01
Corn-soybeans	0.72	0.61

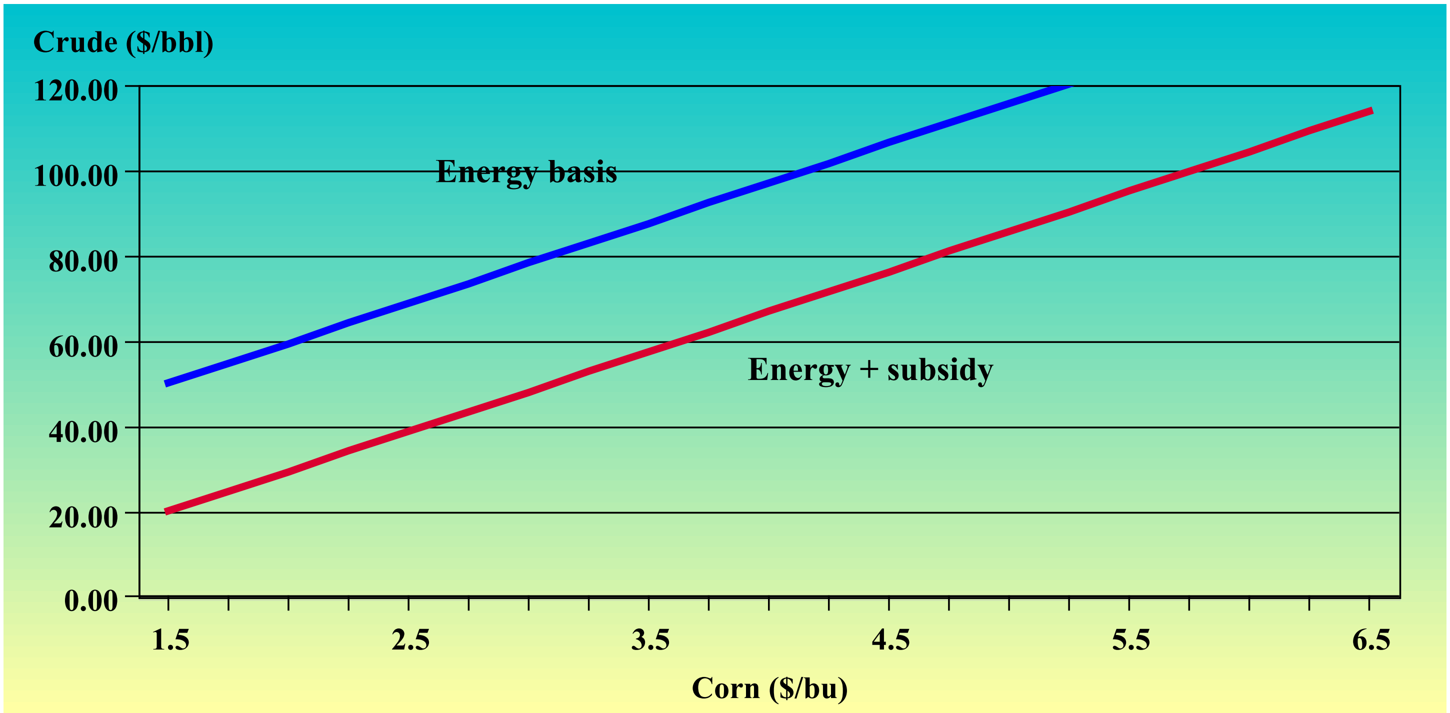

Figure 1. Firm Level Breakeven Combinations of Corn and Crude Oil Prices

Table 2. Crude Oil - Corn Price Breakeven Points for Ethanol Production (2007)

Crude Oil	Energy Basis	Energy Plus Subsidy Basis
($/bbl)	($/bu)	($/bu)
20	<0	1.50
40	0.96	2.56
60	2.01	3.62
80	3.08	4.68
100	4.14	5.74
120	5.20	6.81

the subsidy adds about $1.60/bu to the breakeven price.[4] This shows that the subsidy considerably increases the breakeven corn prices. Second, the ethanol industry would not have gotten off the ground without federal subsidies. However, with the subsidy and lower capital and operating costs that existed during that period, ethanol was profitable, but not hugely profitable. The industry grew slowly and steadily over that 20 year period (Tyner, 2008).

[4] This is higher than the pure volumetric value (about $1.40), because we assume DDGS price moves with the corn price and natural gas and gasoline (the denaturant) move with oil prices.

Third, with the subsidy and with high oil prices (once gasoline and ethanol pricing follow the long run pattern), ethanol can be very profitable, such as the ethanol boom experienced in the United States. The ethanol industry will grow so long as expected oil and corn prices and subsidies indicate profitability. At some point, the increased demand for corn bids up the corn price to the point that it chokes off any additional investment.

Finally, if oil were to fall back to $40, corn price would have to fall because many of the plants would cease production with lower oil prices and higher corn prices. That reduced demand for corn for ethanol would, in turn, lead to a drop in corn prices. Given that about a third of our corn crop will be used in the production of ethanol, this price drop could be quite large.

Clearly, a new era has arrived – one with a tight long-term connection between crude oil and corn prices. Since this tight linkage will exist between crude oil and corn, it can be expected to exist between crude oil and other agricultural commodities as well. To examine and to illustrate these linkages, a partial equilibrium model was developed incorporating the energy – agriculture linkages between crude, gasoline, ethanol, and corn.

Modeling Integrated Markets

Consider two integrated markets of corn and gasoline. The supply side of the corn market consists of identical corn producers. They produce corn using constant returns to scale Cobb-Douglas production functions and sell their product in a competitive market. Under these assumptions, an aggregated Cobb-Douglas production function for the whole market is defined. In short-run the variable input of corn producers is a composite input which covers all inputs such as seed, fertilizers, chemicals, fuel, electricity, and so on. In the short run, capital and land are fixed. The demand side of the corn market consists of three users: domestic users which use corn for feed and food purposes, foreign users, and ethanol producers. Domestic and foreign demands are represented using constant price elasticity functions. The foreign demand for corn is more elastic than the domestic demand. The demand of the ethanol industry for corn is a function of the demand for ethanol.

The gasoline market has two groups of producers: gasoline and ethanol producers. Ethanol is assumed to substitute for gasoline with no additive value. The gasoline and ethanol producers produce according to short run Cobb-Douglas production functions. The variable input of gasoline producers is crude oil and the variable input of ethanol producers is corn. Both groups of producers are price takers in product and input markets. The demand side is modeled using a constant price elasticity of demand. The constant parameter of this function can change due to changes in income and population. The gasoline industry is assumed to be well established and operates at long run equilibrium, but the ethanol industry is expanding. The new ethanol producers opt in when there are profits. No physical or technical limit on ethanol production is assumed – only economic limits. The profitability model

Table 3. Major Model Parameters

Parameter Description	Value
Own price elasticity of demand for corn for domestic use[a]	-0.1
Own price elasticity for corn for exports[a]	-0.5
Own price elasticity for corn supply[b]	0.4
Own price elasticity for gasoline demand[c]	0.08
Own price elasticity for gasoline supply[d]	0.4
Own price elasticity for ethanol supply[e]	0.1
DDGS price ($/ton) = 70.12 + 12.57 * Price of corn ($/bu)[f]	
Corn variable costs ($/bu) = 0.64 = 0.0123 * oil price ($/bbl)[g]	

[a]In this study we assign -0.1 to the domestic demand elasticity (a bit lower than normal) because we assume that DDGS is a perfect substitute for corn and it covers a portion of the domestic demand for corn. We assigned -0.5 to the elasticity of foreign demand for corn according to the Database for Trade Liberalization Studies (Sullivan *et al*., 1989).

[b]This parameter is based on Westcott (1998) and White and Shideed (1991).

[c]This parameter is taken from Hughes, Knittel, and Sperling (2006).

[d]This parameter is taken from Parry and Small (2002).

[e]Several papers have reported or used very inelastic supply functions for ethanol (examples are Miranowski (2007) and Rask (1998)). We also assigned a small value to the short run price elasticity of ethanol supply.

[f]This equation is taken from Tyner and Taheripour (2007).

[g]This equation is obtained from a time series for the period of 1975-2006.

is taken from Tyner and Taheripour (2007). A more detailed model description is provided in Appendix A.

The model is calibrated to 2006 data and then solved using Mathematica (Wolfram, 1999) for several scenarios. Elasticities are taken from the existing literature. These parameters are presented in Table 3. Endogenous variables are gasoline supply, demand, and price: ethanol supply, demand, and price; corn price and production; corn use for ethanol, domestic use, and exports; DDGS supply and price; land used for corn; and the price of the composite input for corn. Exogenous variables include crude oil price, corn yield, ethanol conversion rate, ethanol subsidy level and policy mechanism, and gasoline demand shock (due to non-price variables such as population and income). The model is driven and solved by market clearing conditions that corn supply equal the sum of corn demands and that ethanol production expands to the point of zero profit. The model is simulated over a range of oil prices and with and without the demand shock. The origin of the demand shock is the DOE gasoline demand projection for 2015 compared with 2006 demand. The DOE business as usual forecast has gasoline demand increasing 10% by 2015 with little change in oil prices. The no demand shock case essentially assumes the increased Corporate Average Fuel Economy (CAFE) standards such that gasoline demand around 2015-2020 is similar to 2006 demand. The simulations in this analysis use crude oil prices ranging between $40 and $120.

For each demand scenario and the entire range of oil prices, the following policy alternatives are simulated:

- Continuation of the current fixed subsidy of 51 cents per gallon of ethanol,
- No ethanol subsidy,
- A variable ethanol subsidy beginning at $70 crude oil and increasing $0.0175 for each $ crude oil falls below $70, and
- A renewable fuel standard (RFS) of 15 billion gallons per year from corn.

In addition to these policy simulations, the impact of increased corn yields and increased conversion rate for corn to ethanol are also simulated.

Simulation Results

As is often the case, there are hundreds of results when one considers all the different assumptions, parameters, oil prices, etc. Due to space limitations, results are restricted to reporting on gasoline demand, ethanol production, corn production, corn price, fraction of corn used for ethanol, exports of corn, and required subsidies – all at oil prices ranging from $40 to $120 in $20 increments.

In general, the results conform to expectations and depict well the expected strong linkage in the future between crude oil prices and corn prices and production. While there is no definitive adjustment period included in the model structure, a common target year in some of the pending legislation is the year 2020. For each of the key results, two cases are presented. The base case has no demand shift; hence, the higher CAFE standards are assumed to leave gasoline consumption at roughly $60 oil (our 2006 base) essentially unchanged unless there is a change in oil price. Hence, the higher CAFE standards would essentially offset demand growth due to higher incomes and population. The second case assumes gasoline demand growth of 10% at roughly constant oil prices. This case assumes, implicitly, that crude oil supply does not continue to keep up with growth in gasoline demand as it has in the past two decades.

Gasoline Demand

Gasoline demand elasticity in this model is -0.08 (Hughes, Knittel, and Sperling, 2006). Even with this low demand elasticity, for the no demand shock case, gasoline demand varies from roughly 144 billion gallons (BG) per year at $40 oil to about 136 BG at $120 oil, depending on the policy simulated. For the 10% demand shock case, total gasoline demand varies from about 156 BG at $40 to 147 BG at $120. In general, there is not a lot of variation in gasoline demand among the different policy scenarios, which is to be expected.

Ethanol Production

As would be expected, ethanol production varies substantially among the different demand and policy scenarios (Table 4 and Figures 2 and 3). With no demand shock and the current fixed subsidy, ethanol production is 3.3 BG, about the level reached when oil was $40. But at higher oil prices, ethanol production grows considerably to 10 BG for $60 oil and 17.6 BG for $120 oil. With no subsidy, there is no ethanol production until oil reaches $60, which is consistent with our earlier work at the firm level. However, by the time oil reaches $120, ethanol production is 12.7 BG. With the variable subsidy, there is 3.7 BG of ethanol at $40 oil and 4 BG at $60 oil. For higher oil prices, the production levels equal the no subsidy case since there is no subsidy for oil above $70. For the no demand shock case, the RFS level of 15 BG becomes the production level, regardless of the oil price. In other words, the standard is binding at all oil prices. Therefore, there is an implicit tax at all oil prices. The implicit tax ranges from $1.05/gal at $40 oil down to $0.23/gal at $120 oil.

For the 10% demand shock and fixed subsidy case, ethanol ranges from 9.7 BG at $40 oil to 23.2 BG at $120. The demand shock increases gasoline price, which, in turn, increases ethanol profitability and production. With no subsidy, no ethanol is produced at $40 oil, but production ranges

Table 4. Ethanol and Corn Ouputs with and without Gasoline Demand Shock

	Crude Oil Price									
Scenarion and Policy Tool	40	60	80	100	120	40	60	80	100	120
No Demand Shock	Ethanol Production (billion gallons)					Corn Production (billion bushels)				
Fixed Subsidy	3.3	10.0	13.7	16.0	17.6	10.5	11.5	12.0	12.3	12.5
No Subsidy	0.0	0.5	6.5	10.2	12.7	9.9	9.8	10.6	11.2	11.5
Variable Subsidy	3.7	4.0	6.5	10.2	12.7	10.6	10.4	10.6	11.2	11.5
RFS	15.0	15.0	15.0	15.0	15.0	12.7	12.4	12.3	12.1	12.0
10% Demand Shock										
Fixed Subsidy	9.7	16.0	19.5	21.7	23.2	11.7	12.6	13.1	13.4	13.6
No Subsidy	0.0	8.0	13.4	16.7	19.0	9.9	11.1	11.9	12.4	12.8
Variable Subsidy	10.0	10.9	13.4	16.7	19.0	11.7	11.7	11.9	12.4	12.8
RFS	15.0	15.0	15.0	16.7	19.0	12.7	12.4	12.3	12.4	12.8

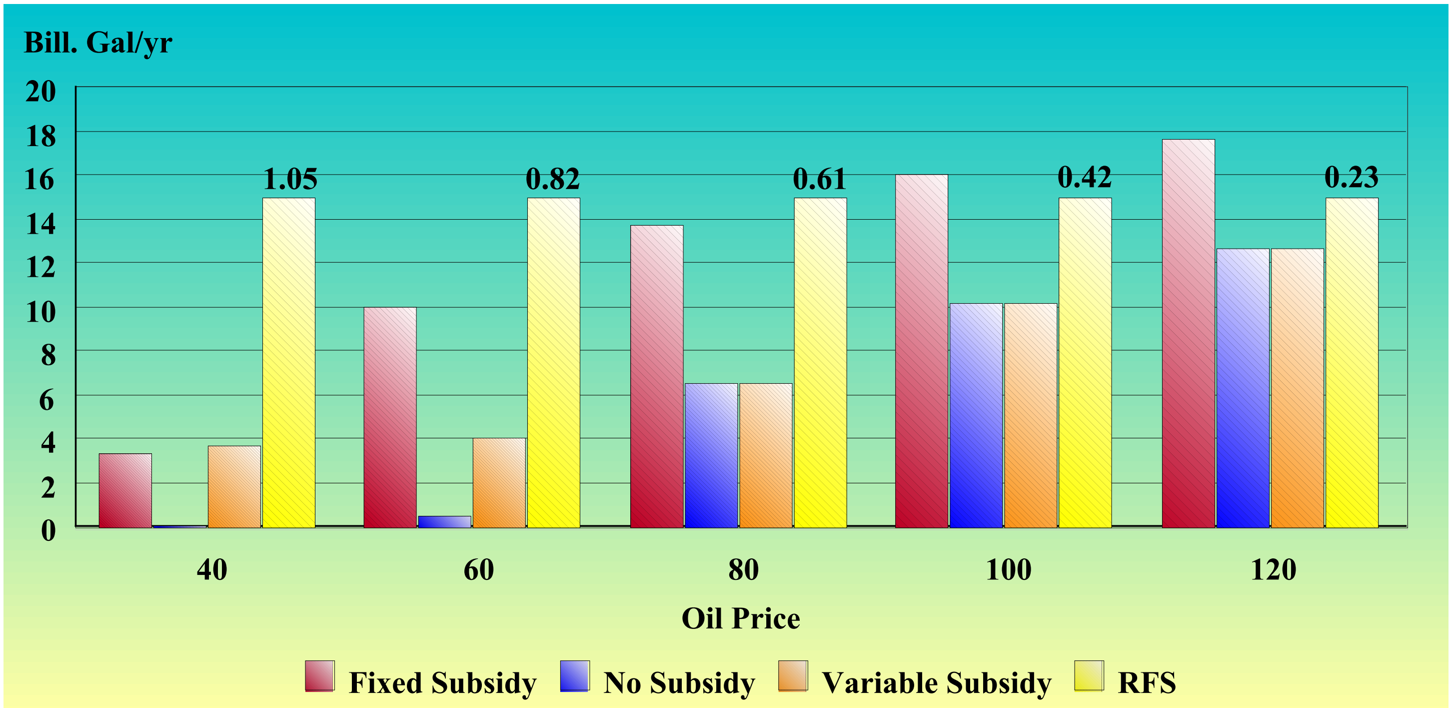

Figure 2. Ethanol Production with No Gasoline Demand Shock

from 3.9 to 19.0 BG for oil ranging from \$50 to \$120. With the variable subsidy, ethanol production ranges between 10 and 19 BG over the oil price range. For the RFS, production is at the standard of 15 BG up to \$90 oil, but reaches 19 BG with oil at \$120. The RFS reaches the same level in the no subsidy and variable subsidy cases because economically, the renewable fuel standard is another mechanism for implementing a variable incentive. Consumers pay at the pump instead of through their tax bill. The implicit tax is \$0.78 at \$40 oil and \$0.13 at \$80 oil. The implicit tax is zero at oil prices above \$80 in this case.

Corn Production

Corn production and acreage respond as might be expected from the above results. Because of space limitations, only corn production in reported in this paper (Table 4 and Figures 4 and 5). In the no demand shock case with fixed subsidy, corn production ranges between 10.51 billion bushels (BB) at \$40 oil to 12.48 BB at \$120 oil. With no subsidy, corn production is 9.93 BB at \$40 oil and 11.49 BB at \$120 oil. Similar to previous cases, with oil at \$40, corn supply is 10.57 BB, but at \$120 oil, it is the same as the no subsidy case at 11.49 BB. For the variable subsidy case, corn production is pretty flat over the entire range, with production at \$40 oil being 10.57 BB and at \$120 oil 11.49 BB. Again,

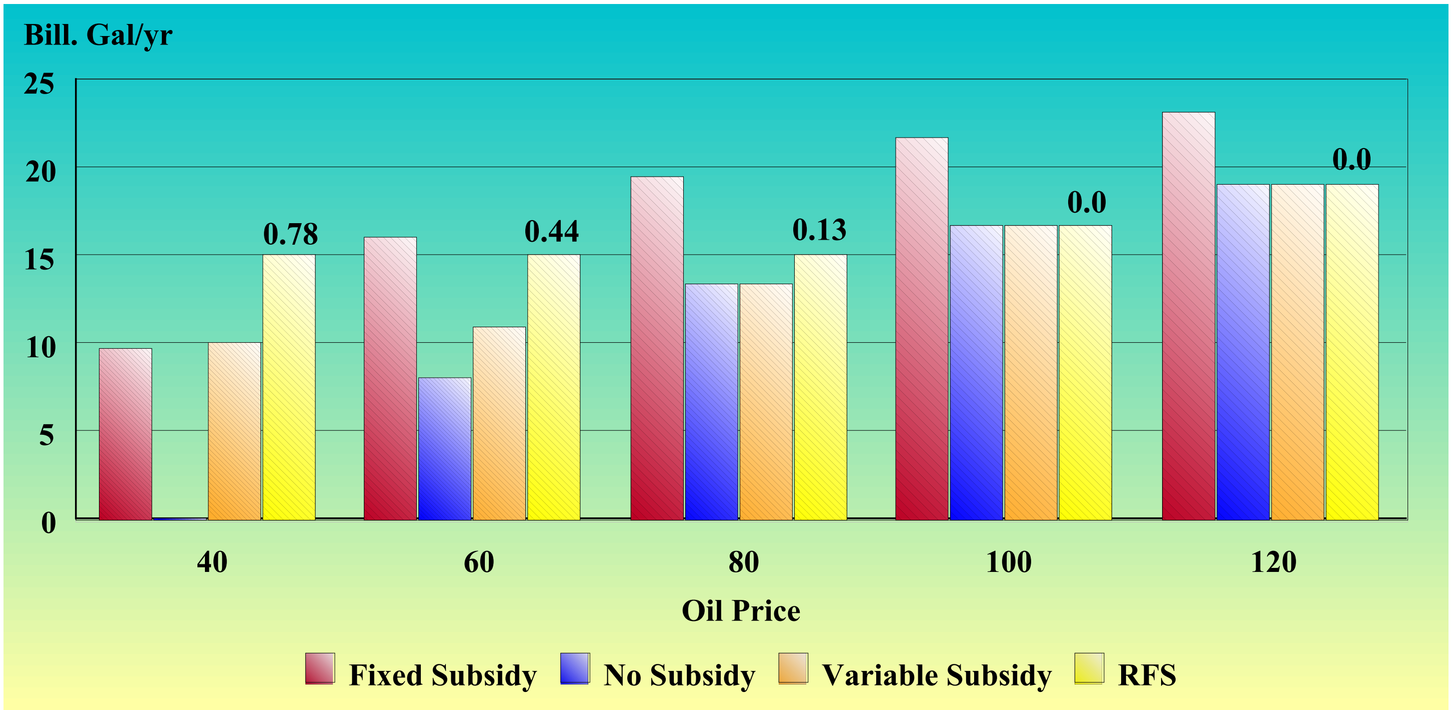

Figure 3. Ethanol Production with 10 Percent Gasoline Demand Shock

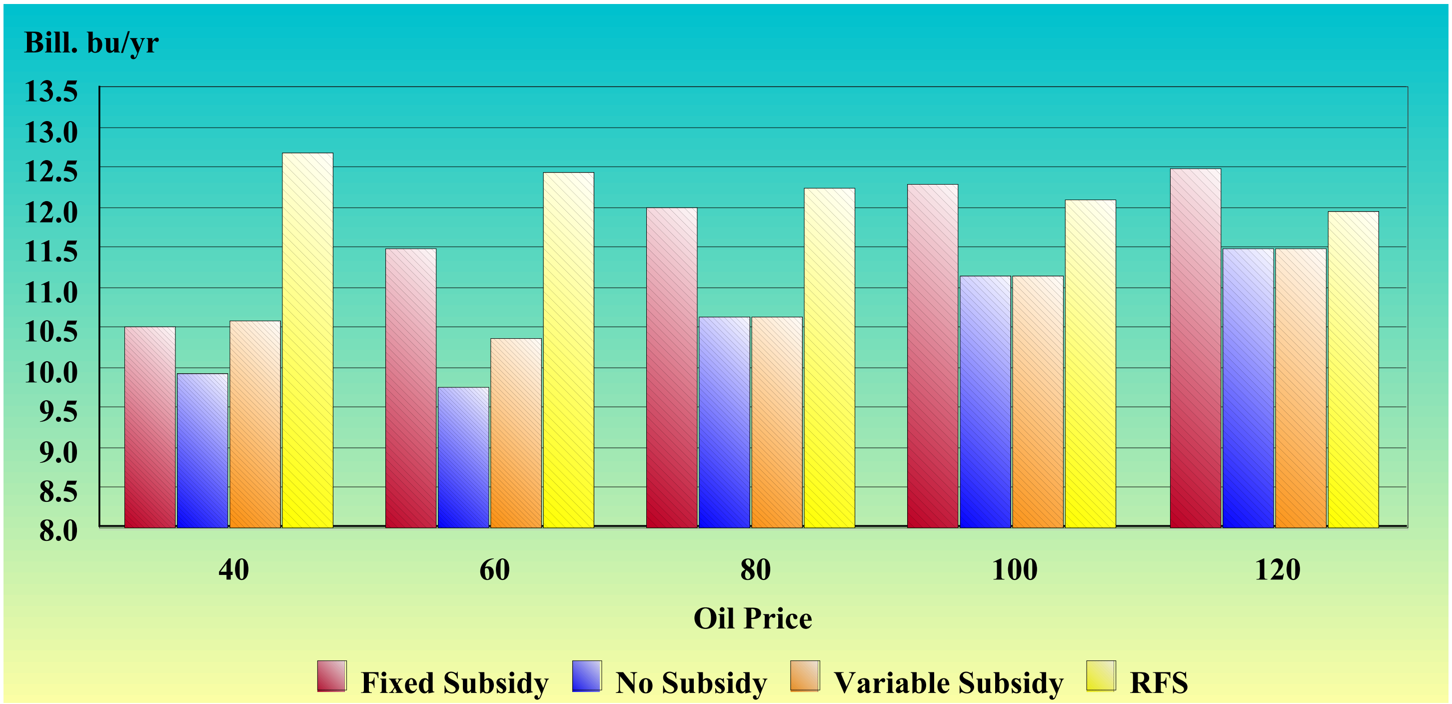

Figure 4. Corn Production with No Gasoline Demand Shock

this is to be expected, since more stability is one of the major objectives of the variable subsidy. With the renewable fuel standard, corn production is actually slightly higher at $40 oil that at $120 oil because corn cost of production increases with crude oil price. Corn production at $40 is 12.68 BB, whereas it is 11.95 BB at $120 oil.

With the 10% demand shock in place, the pattern is similar, but not the absolute numbers. With the fixed subsidy, corn production at $40 oil is 11.67 BB, and it is 13.63 BB at $120 oil. With no subsidy, corn production is 9.93 BB at $40 oil, rising to 12.75 BB at $120 oil. With the variable subsidy, $40 oil yields 11.73 BB of corn, but the upper end remains 12.75 BB. With the RFS and demand shock, corn production

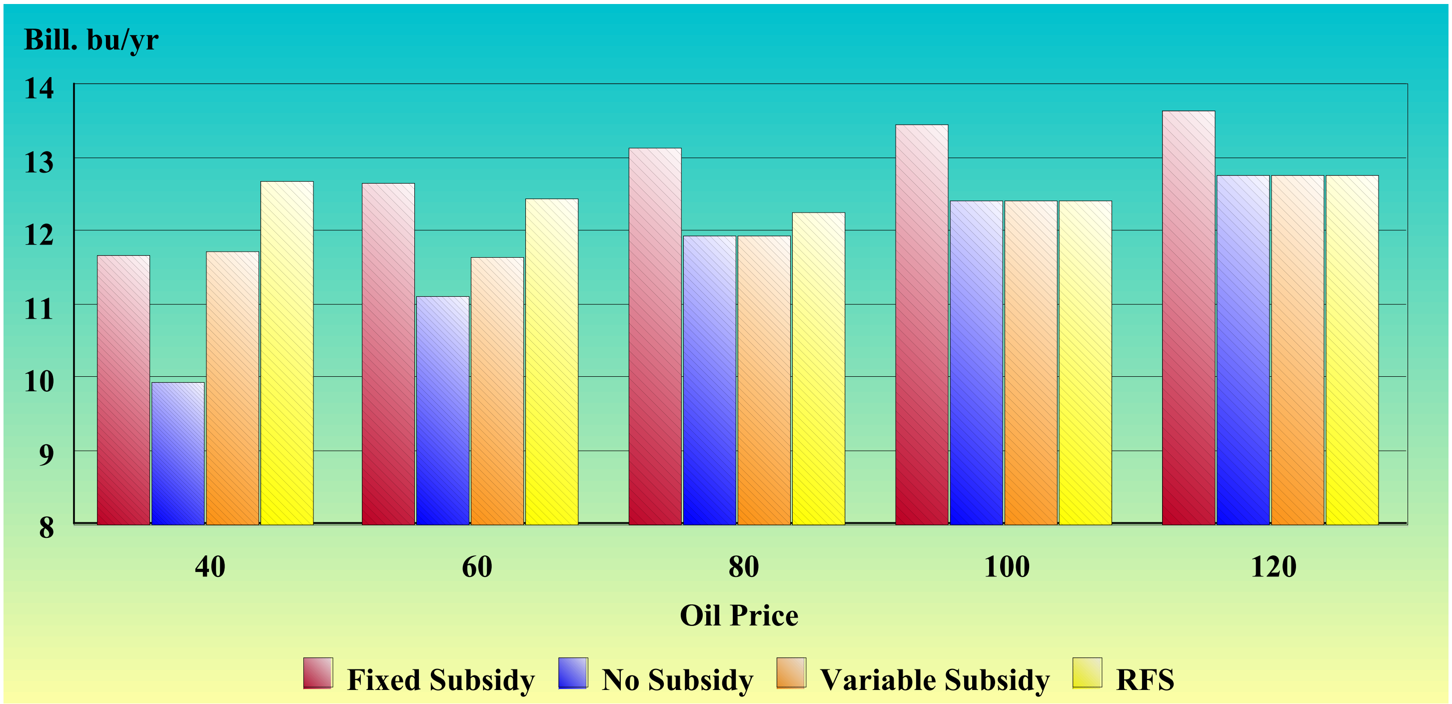

Figure 5. Corn Production with 10 Percent Gasoline Demand Shock

Table 5. Corn Price and Fraction of Corn in Ethanol with and without Gasoline Demand Shock

	Crude Oil Price									
Scenario and Policy Tool	40	60	80	100	120	40	60	80	100	120
No Demand Shock	Corn Price ($/bu)					Fraction of Corn in Ethanol (%)				
Fixed Subsidy	1.97	2.99	3.92	4.81	5.65	11.7	32.3	42.3	48.3	52.4
No Subsidy	1.71	1.99	2.90	3.77	4.60	0.0	1.9	22.6	33.9	40.9
Variable Subsidy	2.00	2.32	2.90	3.77	4.60	12.9	14.2	22.6	33.9	40.9
RFS	3.15	3.65	4.14	4.61	5.07	43.9	44.7	45.4	46.0	46.5
10% Demand Shock										
Fixed Subsidy	2.56	3.80	4.94	6.01	7.04	30.9	46.9	54.9	59.8	63.2
No Subsidy	1.71	2.75	3.87	4.94	5.96	0.0	26.8	41.5	49.8	55.1
Variable Subsidy	2.59	3.10	3.87	4.94	5.96	31.7	34.7	41.5	49.8	55.1
RFS	3.15	3.65	4.14	4.94	5.96	43.9	44.7	45.4	49.8	55.1

is remarkably stable, varying between 12.68 BB at $40 oil and 12.75 BB at $120 oil.

Corn Prices

Corn price varies dramatically depending on the oil price in either demand scenario as our hypothesis would predict (Table 5 and Figures 6 and 7). With no demand shock and the fixed subsidy in place, corn varies between $1.97/bu at $40 oil to $5.65 at $120 oil. With no subsidy, corn price varies between $1.71 at $40 oil to $4.60 at $120 oil. The subsidy clearly has a greater impact on corn price at higher oil prices. With the variable subsidy, corn price ranges between $2.00 and $4.60. The variable subsidy provides a bit more support than the fixed subsidy at the low end, but changes nothing at the high end as there is no subsidy. With the RFS in place, the corn price ranges between $3.15 at $40 oil and $5.07 at $120 oil. With no demand shock, there is an implicit subsidy at any oil price. The RFS does a far better job of supporting corn price, because the implicit subsidy at low oil prices is much higher.

With the demand shock assumption, the results are quite different. With the fixed subsidy, the corn price ranges between $2.56 for $40 oil and $7.04 for $120 oil. Because the demand shock increases the gasoline price, it also increases the ethanol price and therefore induces use of more corn for ethanol and higher corn price. With no subsidy in effect, the range is very different, being $1.71 for $40 oil and $5.96 for $120 oil. However, the point is that if crude oil supply

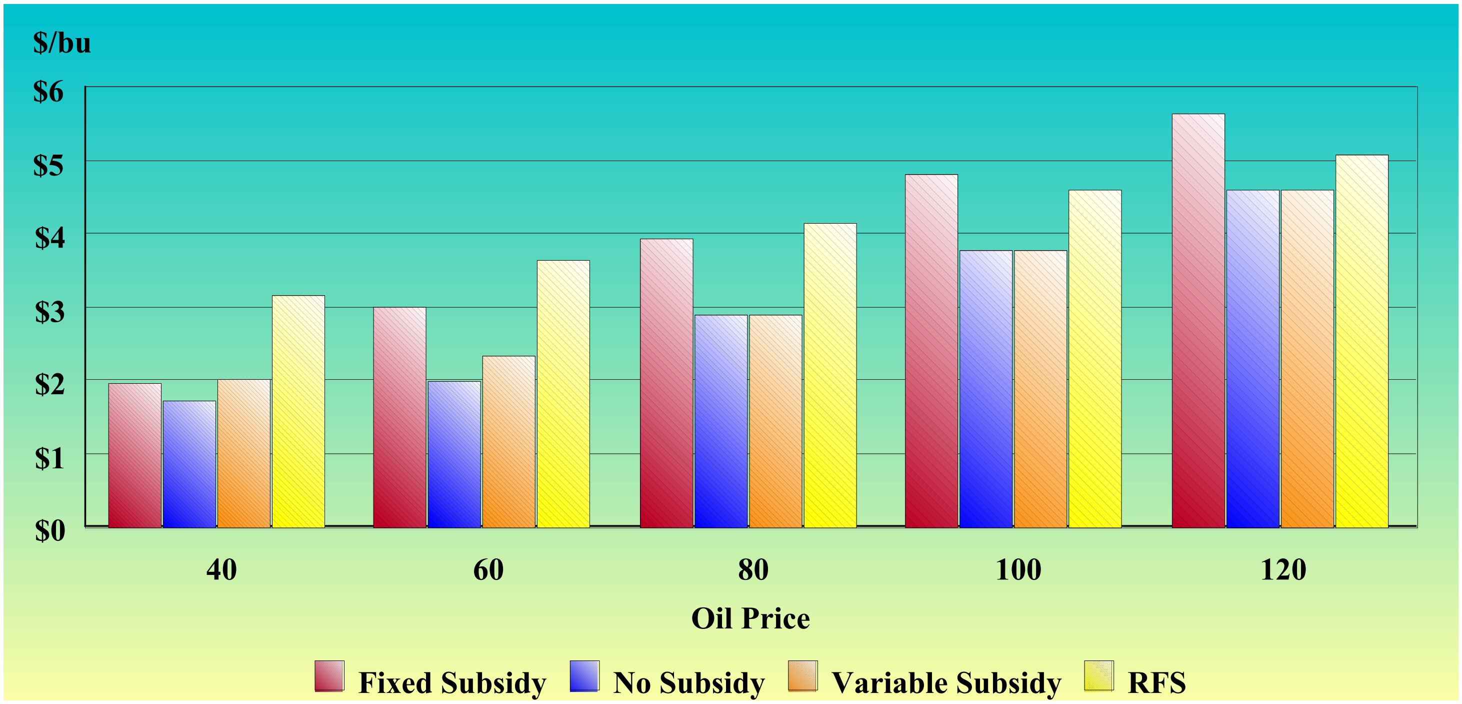

Figure 6. Corn Price with No Gasoline Demand Shock

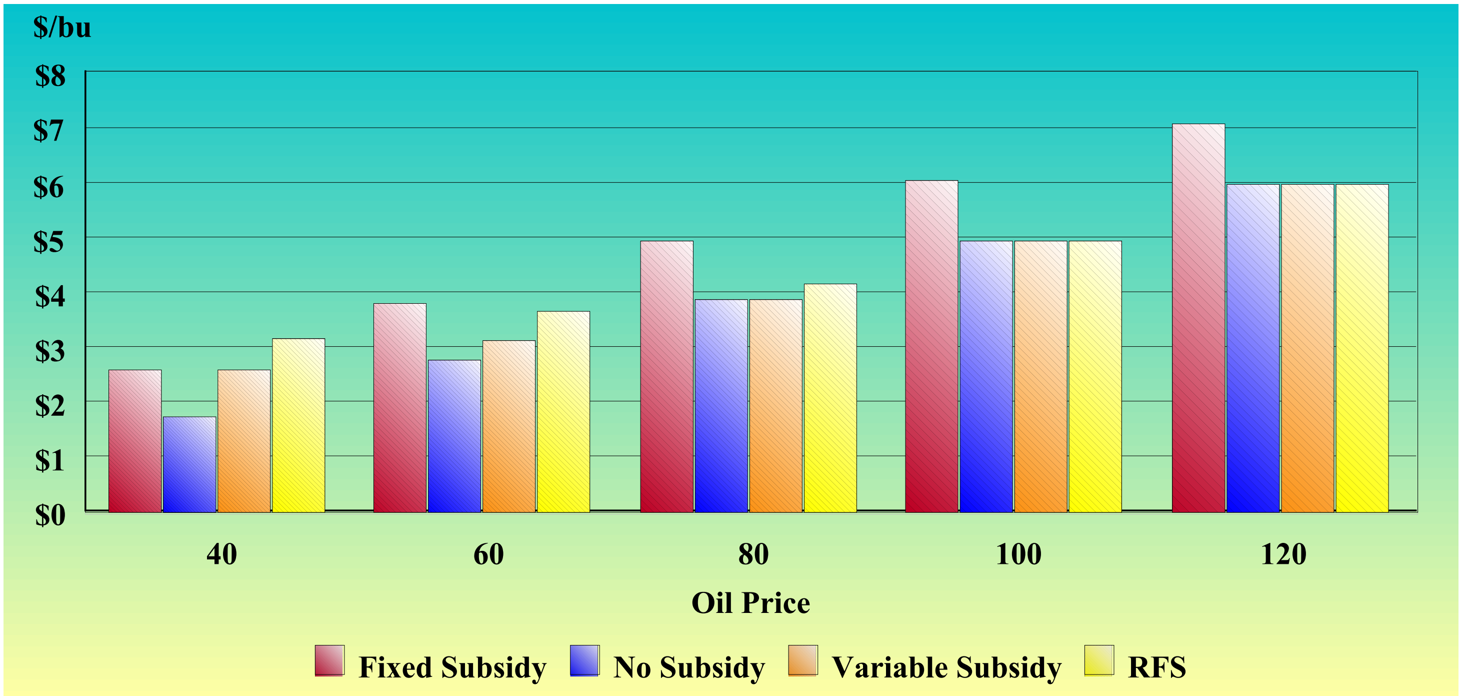

Figure 7. Corn Price with a 10 Percent Gasoline Demand Shock

response in the future is less than in the past, demand shocks could have a powerful influence on the ethanol market. With the variable subsidy in effect, the corn price ranges between $2.59 and $5.96, so there is a greater impact on the low end and no impact on the high end as would be expected. With the renewable fuel standard in effect, the corn price ranges between $3.15 for $40 oil to $5.96 for $120 oil. The lower end price is higher, because the implicit subsidy with the RFS in effect is higher than the fixed or variable subsidy. On the upper end, the implicit subsidy with the RFS is zero, so the result is the same as the no subsidy case.

Fraction of Corn Used for Ethanol

The fraction of corn used for ethanol is another important indicator of the results of the different policy alternatives (Table 5 and Figures 8 and 9). In general, as corn use

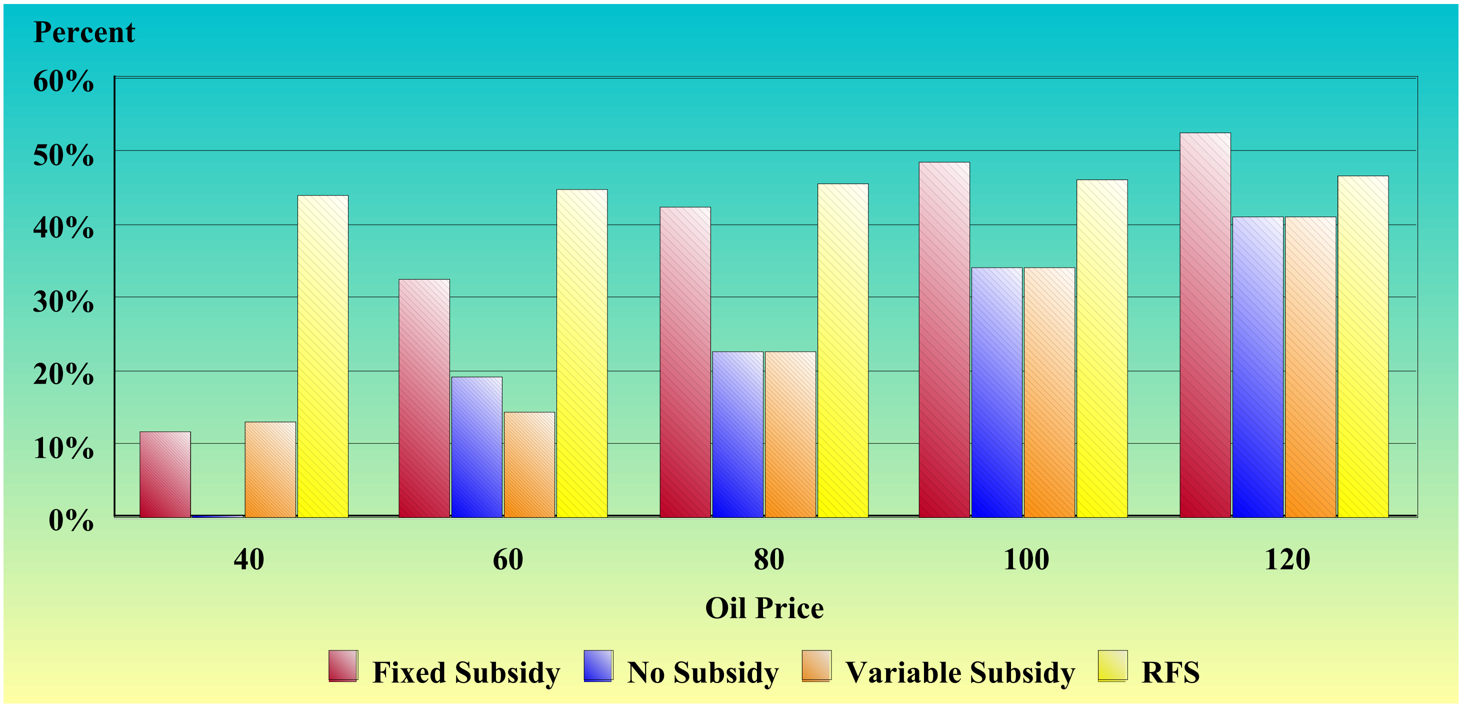

Figure 8. Fraction of Corn for Ethanol with No Gasoline Demand Shock

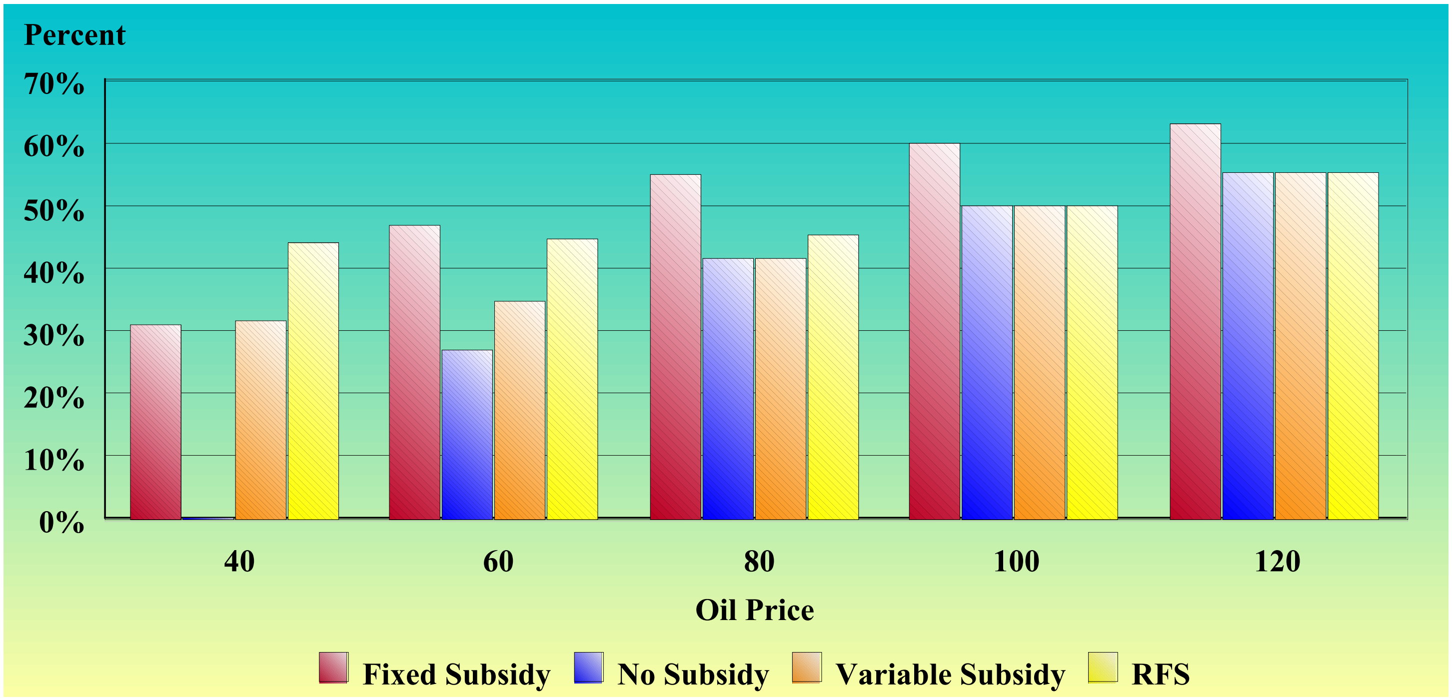

Figure 9. Fraction of Corn for Ethanol with a 10 Percent Gasoline Demand Shock

for ethanol increases, it is corn use for exports that declines. There are some declines in domestic use, but exports take the biggest hit. For the no demand shock scenario with the fixed subsidy, corn utilization for ethanol ranges between 12% and 52% as crude oil moves from $40 to $120. With no subsidy in effect, there is no ethanol at $40 oil, but the share of the crop at $120 is 41%. With the variable subsidy, the ethanol share of corn demand ranges between 13% at $40 oil and 41% at $120 oil, a bit more at the lower end and no change at the higher end. With the RFS in effect, the corn share for ethanol is remarkably stable ranging between 44 and 47% over the entire oil price range.

With the demand shock and fixed subsidy in effect, the corn share for ethanol is 31% for $40 oil and 63% for $120 oil. With no subsidy, there is again no corn used for ethanol at $40 oil but 55% used at $120 oil. With the variable sub-

Table 6. Corn Exports and Policy Costs with and without Gasoline Demand Shock

	Crude Oil Price									
Scenario and Policy Tool	40	60	80	100	120	40	60	80	100	120
No Demand Shock	Corn Exports (billion bushels)					Policy Costs ($ billions)				
Fixed Subsidy	2.46	1.99	1.74	1.57	1.45	1.69	5.10	6.98	8.17	8.99
No Subsidy	2.64	2.44	2.02	1.78	1.61	0.00	0.00	0.00	0.00	0.00
Variable Subsidy	2.44	2.26	2.02	1.78	1.61	1.93	0.69	0.00	0.00	0.00
RFS	1.94	1.80	1.69	1.60	1.53	15.77	12.31	9.18	6.25	3.49
10% Demand Shock										
Fixed Subsidy	2.15	1.77	1.55	1.41	1.30	4.96	8.16	9.93	11.06	11.84
No Subsidy	2.64	2.08	1.75	1.55	1.41	0.00	0.00	0.00	0.00	0.00
Variable Subsidy	2.14	1.96	1.75	1.55	1.41	5.27	1.91	0.00	0.00	0.00
RFS	1.94	1.80	1.69	1.55	1.41	11.70	6.63	1.96	0.00	0.00

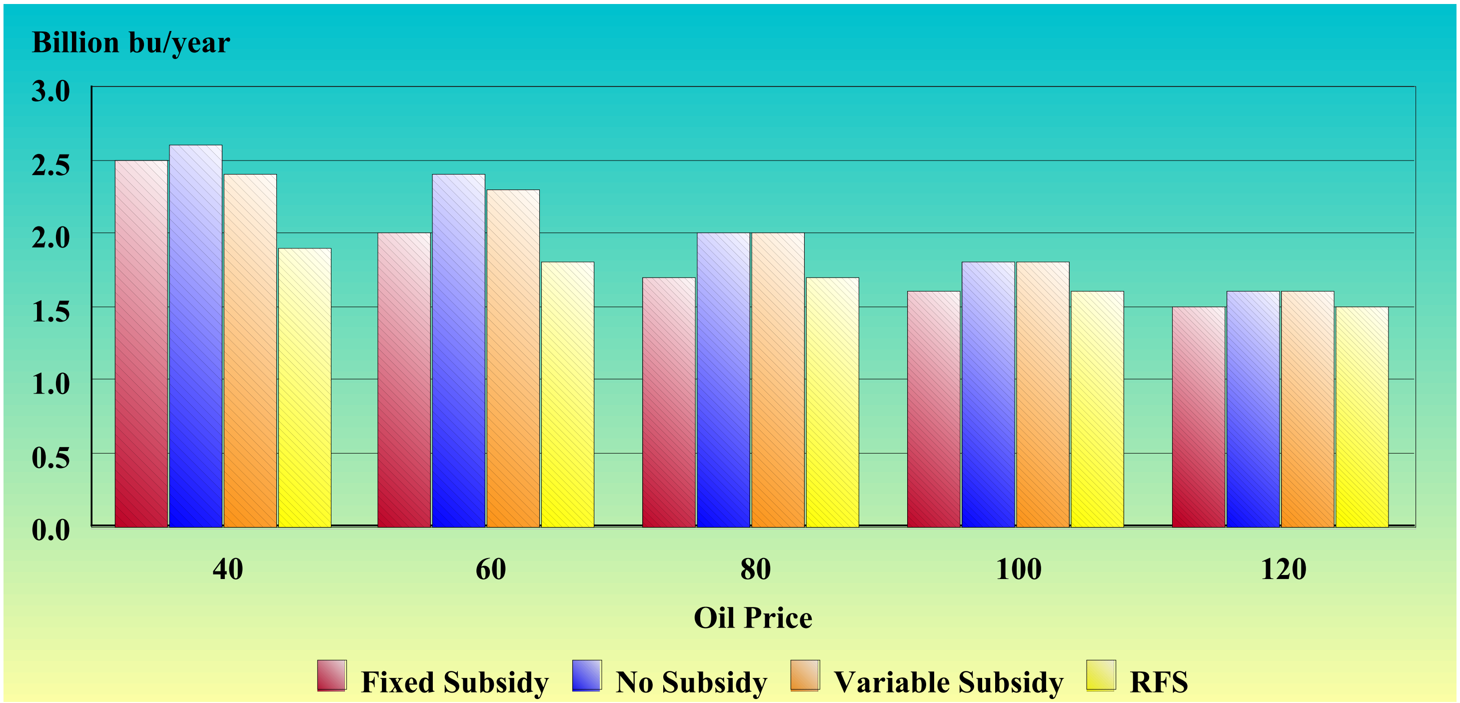

Figure 10. Corn Exports with No Gasoline Demand Shock

sidy in effect, the range is 32% to 55%. With the RFS the corn share begins at 44% for $40 oil, but the peak is 55% for $120 – the same level as the no subsidy case because there is no implicit subsidy with the RFS at $120 oil.

Corn Exports

Corn exports fall due to more production of ethanol under all policy options when the crude oil price goes up for both cases of no demand shock and 10% demand shock (Table 6 and Figures 10 and 11). In general the RFS and fixed subsidy cause more reduction in corn exports, because these policies stimulate the ethanol market more than the no subsidy and variable subsidy policies. Under the fixed subsidy, corn exports fall from 2.46 BB to 1.45 BB when the crude oil price goes up from $40 to $120 per barrel with no demand shock. Under this policy, corn exports fall from 2.15 BB to 1.3 BB for the same crude oil price change with a 10% demand shock. Under the RFS, corn exports fall from 1.94 BB to 1.53 BB when the crude oil price goes up from $40 to $120 with no demand shock. With the demand shock corn exports fall from 1.94 BB to 1.41 BB under the RFS. In this analysis, it is assumed that the price elasticity of foreign demand for corn is 0.5. If the corn export demand were more elastic, corn exports would fall more.

Policy Costs

Finally, government or consumer costs needed to implement the alternative policies are presented (Table 6 and Fig-

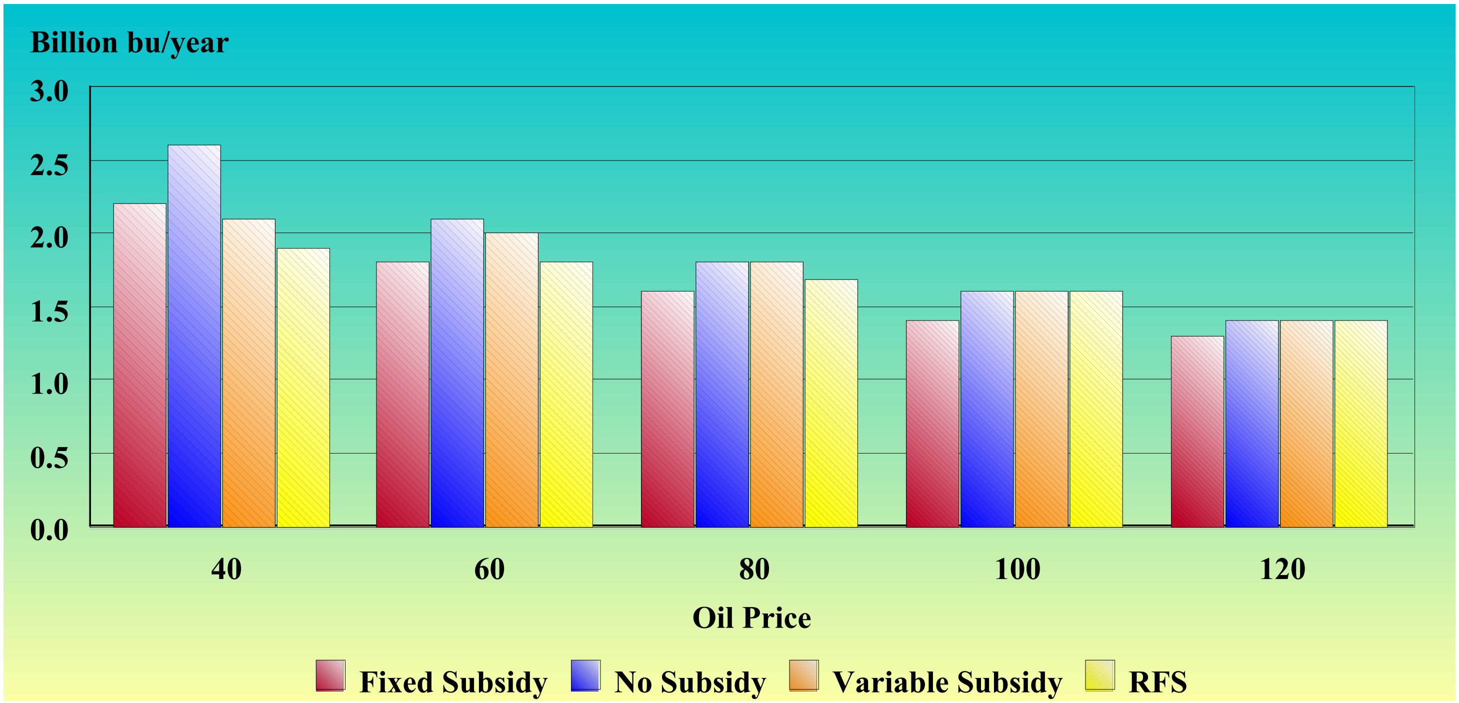

Figure 11. Corn Exports with a 10 Percent Gasoline Demand Shock

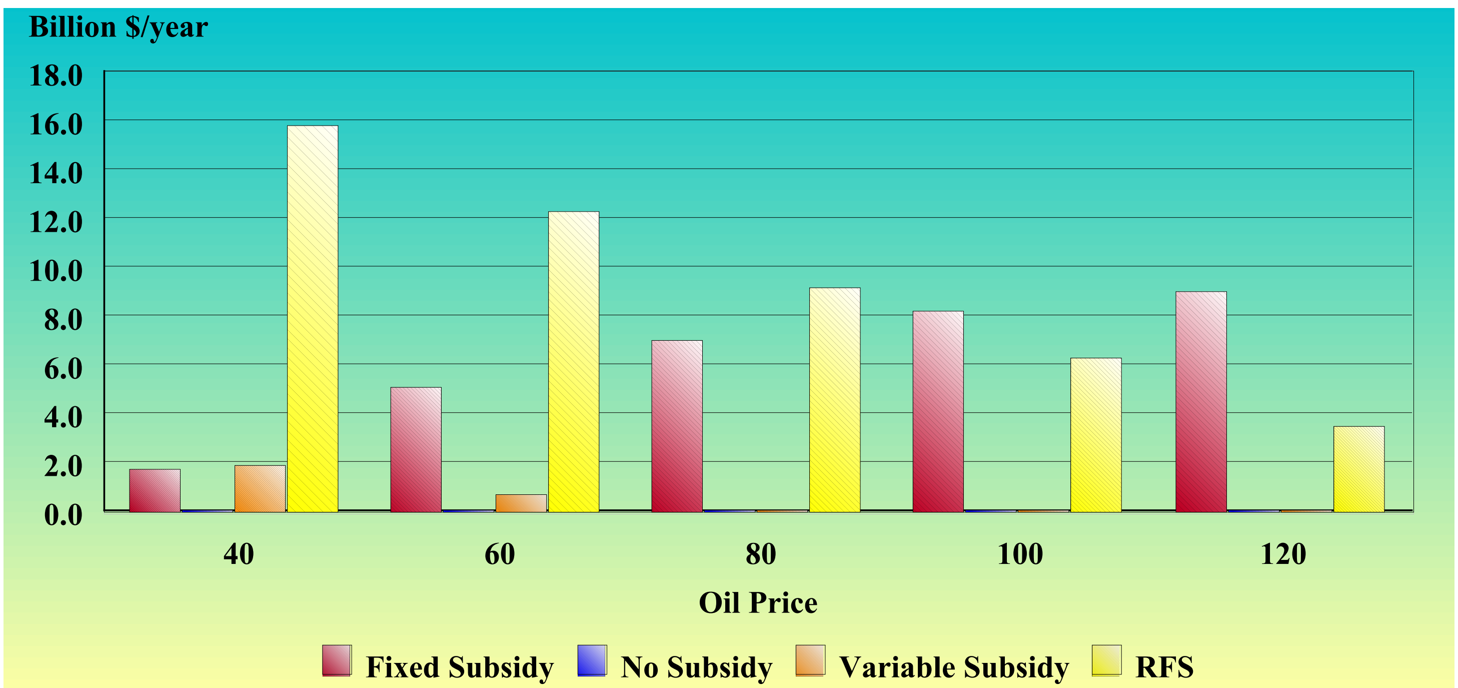

Figure 12. Policy Costs with No Gasoline Demand Shock

ures 12 and 13). Of course, the no subsidy policy has no cost either for consumers or government. The fixed subsidy has high government budget costs. With no demand shock, subsidies paid by the government go up from $1.69 to $8.99 billion when the crude oil price goes up from $40 to $120 per barrel under the fixed subsidy policy. With a 10 percent demand shock the subsidy goes up from $4.96 to $11.84 billion under this policy. The variable subsidy policy only causes financial burden for low prices of crude oil. For example, when the crude oil price is $40 per barrel, required subsidies are $1.93 and $5.27 billion with no demand shock and a 10% demand shock, respectively. The RFS policy has no financial burden for the government, but it increases the fuel cost for consumers through an implicit tax. For example, when the crude oil price is $40 per barrel, the implicit tax costs are $15.77 and $11.7 billion with no demand shock and a 10% demand shock, respectively. The implicit tax falls as oil price increases.

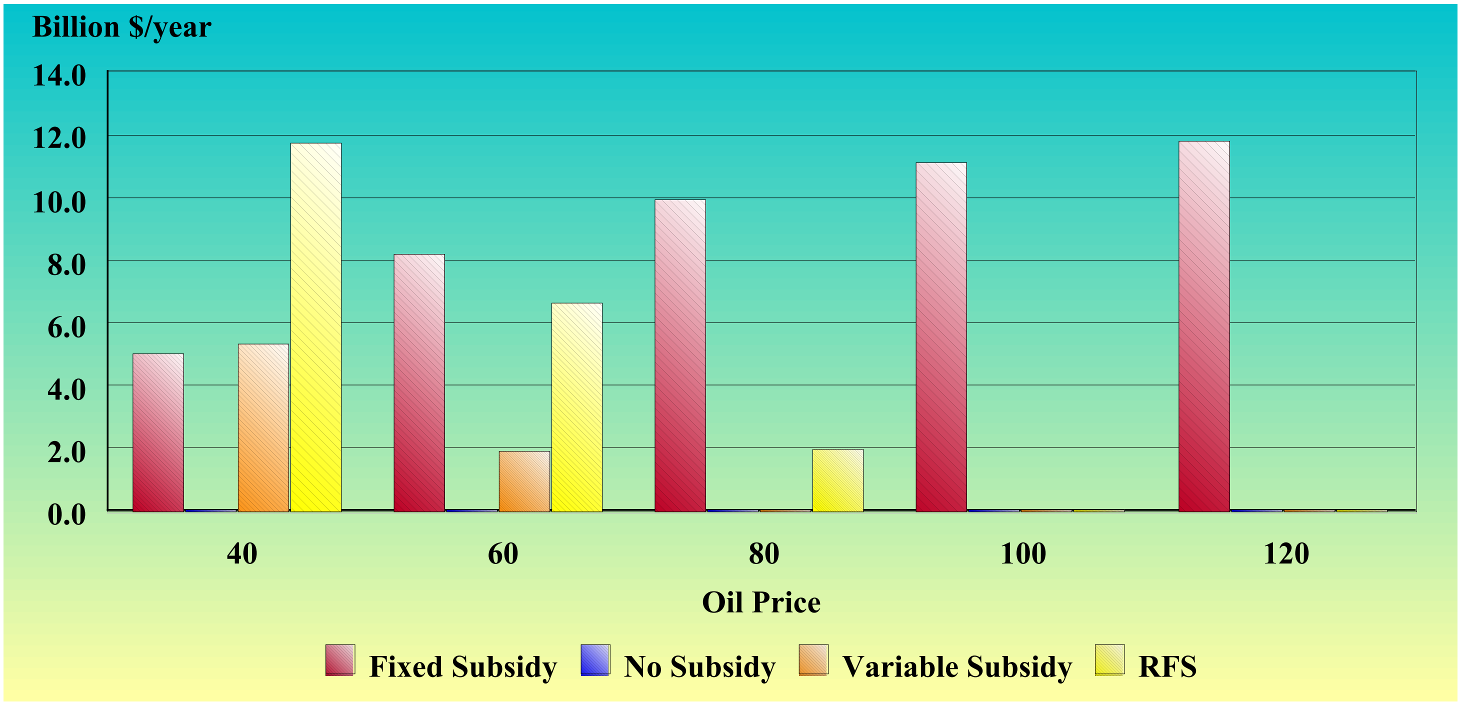

Figure 13. Policy Costs with a 10 Percent Gasoline Demand Shock

The average policy cost over all oil prices is quite sensitive to the presence or absence of a demand shock. With no demand shock, the fixed subsidy cost averages $6.2 billion, and the RFS $9.4 billion annually. However, with the demand shock, the fixed subsidy costs $9.2 billion, and the RFS $4.1 billion. Thus, the greater the demand stimulus, the greater the advantage of RFS over the fixed subsidy. The variable subsidy average cost is quite low under either demand scenario.

Sensitivity Analysis

For this paper, a sensitivity analysis is conducted for a corn yield increase of 30% (Tables 7 and 8). Results are reported for the no demand shock and 10% demand shock cases. The results conform to expectations. In all cases both ethanol production and corn production increase. At $120 oil with no demand shock, for example, with the fixed subsidy, ethanol production reaches 27.1 BG (compared to 17.6 BG in the base case), and corn production reaches 15.2 BB (compared with 12.5 BB in the base case). With the demand shock, the numbers are even larger. For the other policy options, the differences are smaller. Corn price is lower in every case in the yield shock scenario as would be expected. The share of corn going to ethanol tends to be lower for low oil prices compared to the base case and higher when oil prices are higher.

Conclusions

Large differences in costs occur among the policy alternatives. Government officials will have to weigh the trade-

Table 7. Ethanol and Corn Outputs with and without Gasoline Demand Shock with 30% Increase in Corn Yield

	Crude Oil Price									
Scenario and Policy Tool	40	60	80	100	120	40	60	80	100	120
No Demand Shock	Ethanol Production (billion gallons)					Corn Production (billion bushels)				
Fixed Subsidy	10.9	18.5	22.7	25.3	27.1	12.8	14.0	14.6	14.9	15.2
No Subsidy	0.0	6.6	13.6	17.8	20.7	10.9	11.7	12.8	13.4	13.9
Variable Subsidy	11.3	10.9	13.6	17.8	20.7	12.9	12.5	12.8	13.4	13.9
RFS	15.0	15.0	15.0	17.8	20.7	13.6	13.3	13.1	13.4	13.9
10% Demand Shock										
Fixed Subsidy	18.5	25.7	29.6	32.1	33.8	14.2	15.4	16.0	16.4	16.6
No Subsidy	3.8	15.6	21.8	25.7	28.3	11.5	13.4	14.4	15.0	15.4
Variable Subsidy	18.9	19.2	21.8	25.7	28.3	14.3	14.1	14.4	15.0	15.4
RFS	15.0	15.6	21.8	25.7	28.3	13.6	13.4	14.4	15.0	15.4

Table 8. Corn Price and Fraction of Corn in Ethanol with and without Gasoline Demand Shock with 30% Increase in Corn Yield

	Crude Oil Price									
Scenario and Policy Tool	40	60	80	100	120	40	60	80	100	120
No Demand Shock	Corn Price ($/bu)					Fraction of Corn in Ethanol (%)				
Fixed Subsidy	1.67	2.53	3.32	4.06	4.77	31.5	49.1	57.7	62.8	66.2
No Subsidy	1.11	1.64	2.39	3.12	3.81	0.00	20.9	39.3	49.3	55.5
Variable Subsidy	1.70	1.92	2.39	3.12	3.81	32.7	32.3	39.3	49.3	55.5
RFS	1.93	2.23	2.52	3.12	3.81	41.0	41.9	42.6	49.3	55.5
10% Demand Shock										
Fixed Subsidy	2.18	3.23	4.19	5.10	5.96	48.3	61.9	68.6	72.8	75.6
No Subsidy	1.29	2.28	3.22	4.11	4.97	12.1	43.2	56.2	63.4	68.1
Variable Subsidy	2.21	2.59	3.22	4.11	4.97	49.0	50.5	56.2	63.4	68.1
RFS	1.93	2.28	3.22	4.11	4.97	41.0	43.2	56.2	63.4	68.1

offs between perceived benefits and costs of each of the alternatives.

At high oil prices, the differences among the policy alternatives are smaller with the oil price playing the dominant role in influencing corn price and production as well as ethanol price and production.

The bottom line from this paper is clear – a new era has arrived in which agricultural commodity prices are tied to crude oil prices. This conclusion holds regardless of the policy option in effect (including no subsidy), but the kind of policy being followed has a substantial impact on the size of the impacts. This energy – agriculture linkage must be incorporated in our future policy analyses.

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Appendix A

Model Description

This Appendix explains the main components of the model used in this paper. First, the demand and supply sides of the corn and gasoline markets are explained. Then DDGS is introduced as a substitute for corn in the corn market. Finally, market clearing conditions are defined and other equations used in the model are introduced.

Corn Market

Demand side

The demand side consists of three major corn users:

Foreign users (corn demand for exports, q_{cxd}),

Domestic uses for food and feed (corn demand for food and feed, q_{ccd}), and

Ethanol industry (corn demand for ethanol, q_{ced}).

Foreign and domestic demands for corn are functions of the corn price, p_c, with the following functional forms:

$q_{cxd} = {}^{A}cxd/p_c^{\,cxa}$, and

$q_{cdd} = {}^{A}cdd/p_c^{\,cda}$.

Here *cxa* and *cda* are own price elasticities of the demands for exports and domestic uses for food and feed. In these demands functions, A_{cxd} and A_{cdd} are constant parameters in short run, but they can change in the long run. The demand of the ethanol industry for corn will be equal to:

$q_{ced} = y.q_{se}$.

Here y is the corn-ethanol conversion factor and q_{se} is the quantity of supply of ethanol.

Finally, the total corn demand is equal to:

$q_{cd} = q_{cxd} + q_{cdd} + q_{ced}$.

Supply side

A Cobb-Douglas production function is used for a representative corn producer to estimate the supply side of the corn market:

$q_{cs} = AK^{\theta 1}L^{\theta 2}R^{\theta 3}F^{\theta 4}$.

Here q_{cs} represents quantity of corn and A is a constant parameter. In this production function, K, L, and R stand for capital, labor, and land, respectively. Here, F is an aggregated input and represents inputs such as fertilizer, pesticides, seeds energy, and other variable inputs. Parameters θ_1, θ_2, θ_3, and θ_4 show elasticities of output with respect to changes in inputs. All inputs, except F, are constant in the short-run and that $\sum\theta_i = 1$. According to these assumptions the following short run corn production function can be defined:

$q_{cs} = M.F^{\theta 4}$,

where $M = AK^{\theta 1}L^{\theta 2}R^{\theta 3}$. This short run production function is used to define the following short run profit function:

$\pi = p_C(M.F^{\theta 4}) - p_F F$.

Here, p_F is the price of the composite input F. The corn producer determines the optimal level of F to maximize its profit. From the first order condition of the profit maximization problem, the optimal level of F would be equal to:

$p_F = (p_F/\theta_4.p_C.M)^{1/\theta 4\text{-}1}$.

The optimal level of F is substituted into the short run production function to derive the following short run supply function for corn:

$q_{cs} = A_{CS}(p_C)^{CS\beta}\,(p_F)^{-CS\beta}$.

In this supply function $A_{CS} = M(1/\theta_4.M)^{\theta 4/\theta 4\text{-}1}$ and $-\theta_4/\theta_4$-1. In this supply function, $CS\beta$ is the own price elasticity of corn with respect to its price. This elasticity is positive because $\theta_4 < 1$. Note that the parameter A_{CS} is constant in the short run but it can change due to changes in capital, labor, and land in long run.

Gasoline Market

Demand side

The following functional form for the gasoline demand is considered:

$q_{gd} = {}^{A}gd/p_g^{\,ga}$.

Here q_{gd} is the quantity of demand for gasoline, *ga* is its own price elasticity, and p_g is the price of gasoline. In this function A_{gd} is constant in the short run, but it can change in the long run. In particular, it can grow with income and population, and decline with energy efficiency improvement.

Supply side

The supply side of this market consists of gasoline producers and ethanol producers. Methods to define the supply of corn are used to define short run supply functions for gasoline and ethanol. Gasoline producers produce gasoline from crude oil. The supply of gasoline is a function of its price and the price of crude oil according to following functional form:

$q_{gos} = A_{gos}(p_g)^{gs\beta}\,(p_o)^{-gs\beta}$.

Here q_{gos} is the quantity of gasoline produced from crude oil, $gs\beta$ is the own price elasticity of supply of gasoline with respect to its price, and p_o is the crude oil price. In this supply function A_{gos} is a constant parameter in the short run, but it can change in the long run due to changes in capital, labor, and other inputs.

Ethanol producers produce ethanol from corn. The supply of ethanol is a function of its price and the price of corn according to following functional form:

$q_{es} = A_{es}(p_e)^{es\beta}\,(p_c)^{-es\beta}$.

Here q_{es} is the quantity of supply of ethanol produced from corn, $es\beta$ is the own price elasticity of supply of ethanol with respect to its price, and p_c is the corn price. In this function A_{es} is a constant parameter in the short run, but it can change in the long run. In particular, this parameter increases with new investment in ethanol industry.

Each gallon of ethanol is assumed to contain 70% energy of a gallon of gasoline. Hence total supply of gasoline is equal to:

$q_{gs} = q_{gos} + 0.7*q_{es}.$

DDGS as a Substitute for Corn

DDGS is a byproduct of ethanol industry. This byproduct plays two important roles. It is a substitute for corn in livestock industry. Therefore, to some extent, it can mitigate impacts of ethanol production on the corn market. On the other hand it enhances profitability of ethanol industry. In particular, if the price of DDGS goes up with the corn price, it helps ethanol producers to maintain their profitability when the corn price goes up. For these reasons, it is assumed DDGS is a substitute for corn and covers a portion of corn demand. The production of DDGS is determined according to the following relationship:

$$q_{DDGS} = \gamma . q_{ced} .$$

Here q_{DDGS} is the quantity of produced DDGS and γ is the corn-DDGS conversion factor.

Market Clearing Conditions

The market clearing conditions are defined by the following relationships:

$$q_{cs} = q_{cxd} + (q_{cdd} - q_{DDGS}) + q_{ced} \text{, and}$$

$$q_{gs} = q_{gd} .$$

The first relationship represents the corn market clearing condition. In this relationship it is assume that DDGS is perfect substitute for the domestic use of corn. The second relationship represents the gasoline market clearing condition. In the second equation it is assumed that gasoline and ethanol (adjusted for the energy content) are perfect substitute.

Expansion of Ethanol Industry

The ethanol industry is currently experiencing a gold rush period. Expansion is assumed to continue until a zero profit condition is reached. Profits per gallon of ethanol are estimated according to the following relationship:

$$\pi = (0.7p_g.q_{es} + p_{DDGS}.q_{DDGS} - p_c.q_{ced} - oc.q_{es})/q_{es} .$$

All variables in the above equation are defined earlier except *oc*. This variable represents non-corn costs per gallon of ethanol. In the base year *oc* is et equal to = *$0.99* according to Tyner and Taheripour (2007) and that *oc* increases slightly with the crude oil price. In addition, it is assumed that the ethanol industry will expand to reach $\pi=0$ in long run.

Other Equations

The operating costs of producing corn are assigned to variable F and p_F is defined as the costs of producing corn per bushel of corn. p_F is function of crude oil price and a linear relationship is established between these two variables according to the following equation:

$$p_F = a + bp_o$$

The parameters of this equation are estimated according to annual time series from 1975 to 2006. The estimated equation is:

$$p_F = 0.64 + 0.0123p_o \qquad R^2 = 0.45$$

$$\downarrow \qquad \downarrow$$

$$t = 10.11 \qquad t = 4.95$$

Here, p_F is measured in \$/bushel and the price of crude oil is measures in \$/barrel. The price of DDGS is determined with the following linear equation according to Tyner and Taheripour (2007):

$$p_{DDGS}(\$/ton) = 70.12 + 12.57p_c(\$/bushel).$$

What Are the Possibilities for the New Bioeconomy?

Hans P. Blaschek[1]

This paper discusses the state of current bioenergy platforms, the impact of the new biology of genomics on biomass conversion, and the biorefinery of the future. A biorefinery is herein defined as a facility that integrates biomass conversion processes and equipment to produce fuels, power, and chemicals from biomass. The biorefinery concept is analogous to today's petroleum refineries, which produce multiple fuels and products from petroleum.

In order to discuss what the future may hold when it comes to the bioeconomy, it is important to examine where we are today with respect to the current bioenergy platforms. Both dry and wet mill ethanol production from corn starch (U.S.) and ethanol production from sugarcane (Brazil) are regarded as essentially mature technologies for producing bio-ethanol. Currently, dry-grind ethanol plants produce the majority of fuel ethanol (ca. 60%) in the U.S. Given concerns regarding net energy balance and the food versus fuel debate, ethanol production from corn is expected to level off (von Braun, 2007). However, some incremental increases in energy efficiency of these processes can be expected as coproduct utilization (e.g. distiller's grains and bagasse) is incorporated into next generation plants. Currently, distiller's grains from corn ethanol production are used as animal feed, while most of the bagasse from sugar cane production is burned for power generation.

More than eight million metric tonnes of distillers grains (DDGS) are expected to be produced in the U.S. by the end of this year. Some experts are predicting that DDGS production in the U.S. will reach up to 15 million metric tonnes in a few years (University of Minnesota, 2008; Archibeque, Freetly, and Ferrell, 2008). In addition to starch, distiller's grain contains fiber, which is composed of cellulose, xylan and arabinan. If these coproducts were further hydrolyzed and converted into liquid fuels or other bioproducts, the efficiency and profitability of these plants would be expected to improve even further. In order to accomplish this, technologies have to be developed for de-construction and enzyme treatment of the fiber component present in DDGS. Members of The Midwest Consortium for Biobased Products recently completed a comprehensive study on the utilization of DDGS that will be published in a special edition of Bioresource Technology. As part of this study, the fermentation of DDGS hydrolysates to biobutanol by the solvent-producing *clostridia* was examined (Ezeji and Blaschek, 2008).

An outline of the potential steps for pre-treatment and conversion of DDGS to simple 5 and 6 carbon sugars and fermentation to value added products such as acetone, butanol and ethanol can be seen in Figure 1.

Ethanol production from corn is reaching maximal production levels, and it is anticipated that cellulosic ethanol will play a bigger role in order to supply a target of 30% of U.S. gasoline demand by 2030. While ethanol from corn is suggested by most investigators to have a slight positive net energy balance, ethanol production from cellulose allows for an improved net energy balance along with a significant reduction in greenhouse gas emissions. Work carried out at Argonne National Labs by May Wu and colleagues suggests that the production of higher alcohols such as bio-butanol from biomass will help to improve the overall picture for greenhouse gas avoidance (Figure 2; Wu *et al*., 2007).

Butanol as a second generation liquid fuel offers significant advantages over ethanol. The advantages are higher energy content than ethanol, can be stored under humid conditions (lack of solubility with water), can be used in internal combustion and diesel engines (less corrosive), can be shipped through existing pipelines, and it is a replacement for gasoline or as a chemical. An overview of recent developments in the genetics and downstream processing of biobutanol was recently reported (Ezeji, Qureshi, and Blaschek, 2007a). The development of an integrated system for biobutanol production and removal may have a significant impact on commercialization of this process using the solvent producing *clostridia*.

[1] Blaschek is a Professor and Director of the Center for Advanced Bioenergy Research at the University of Illinois, Urbana-Champaign, Illinois.

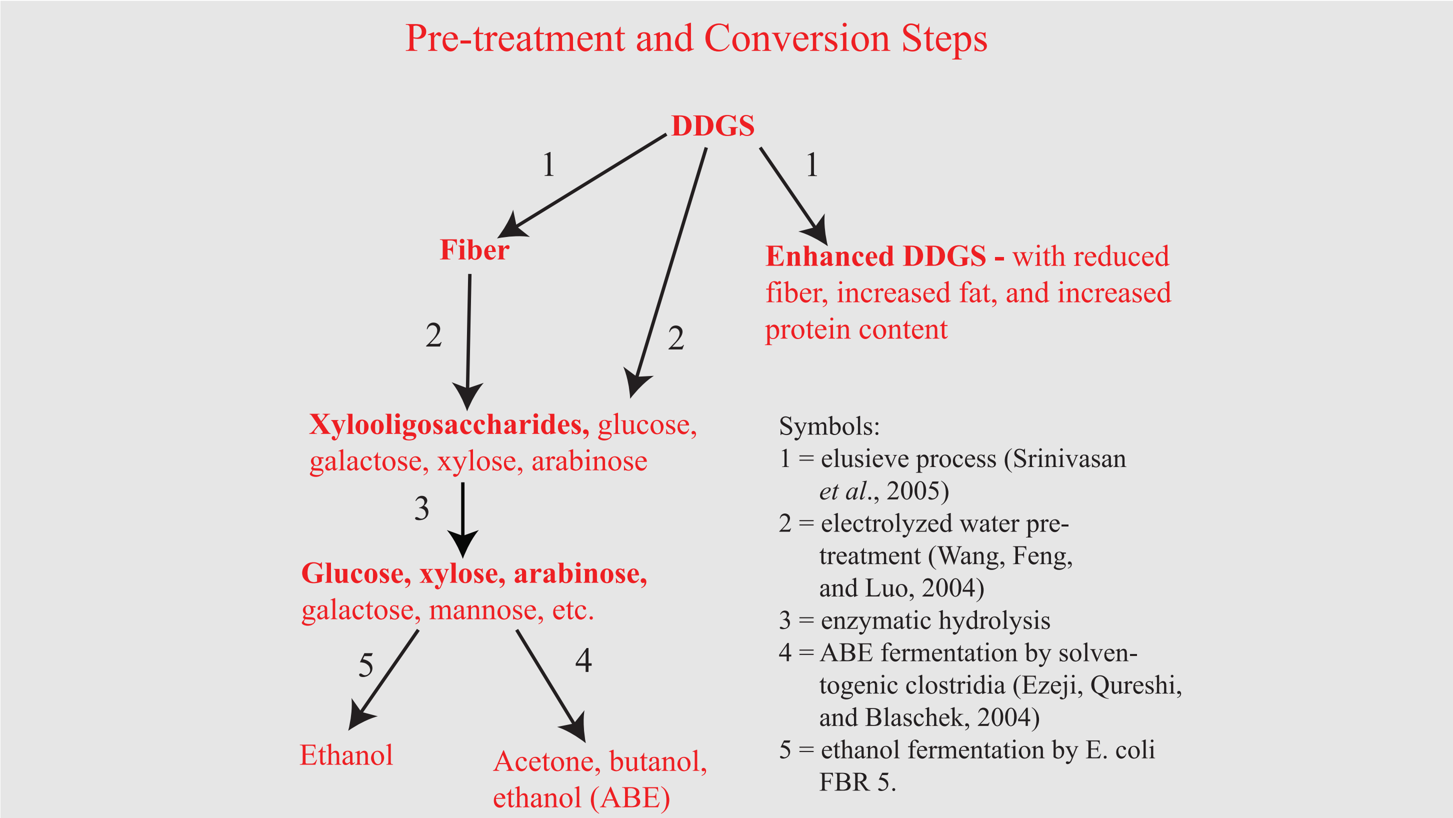

Figure 1. Pre-treatment and Conversion of DDGS to Value Added Products

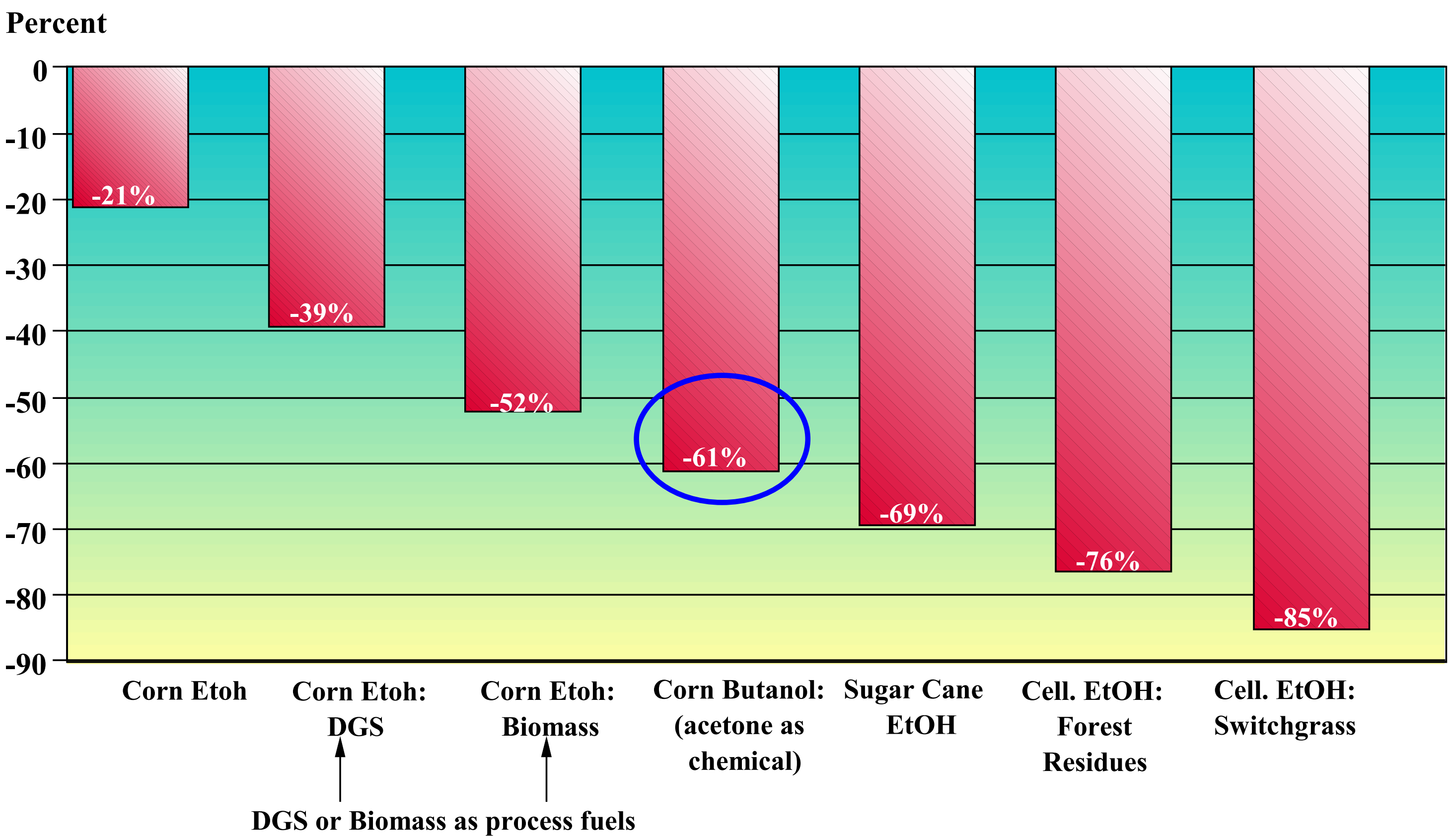

Figure 2. Greenhouse Gas Avoidance by Utilization of Various Feedstocks and Producution of different Biofuels (Wu *et al.*, 2007)

The challenge on the sugar platform side of the conceptual biorefinery will be to scale up technologies for cell wall deconstruction to the point where they become practical on a commercial scale. While it is feasible to produce sugars from lignocellulosic biomass, the concern relates mostly to the production of inhibitors of fermentation (e.g. furfurals, acetic acid, coumaric acid, etc.) that are produced during the pretreatment process (Ezeji, Qureshi, and Blaschek, 2007b).

It appears that in addition to economics, and specifically the price of petroleum, sustainable environmental aspects are driving the push to the use of alternative feedstocks such as corn stover, switchgrass, miscanthus and tropical maize or sweet sorghum. The economics of perennials are particularly favorable given that miscanthus is expected to yield 15 tons of biomass/acre as compared to corn which has a yield of 160 bushels per acre. At a level of 50% removal, corn stover alone is expected to provide 90M tons of fermentable sugars for conversion to fuels and chemicals without negatively impacting soil fertility. While some modifications may have to be made to current harvesting equipment, corn stover is readily available, is largely unused, and therefore, requires little additional investment or resources to produce it.

Today, biomass provides about 3-4% of the energy in the U.S. (Perlack *et al*., 2005). It is anticipated that biomass could satisfy between 25 – 50% of the world's demand for energy by the middle of the 21st Century. An examination of the bioenergy value chain from sunlight to bioproducts, suggests that a multidisciplinary approach is required in order to overcome limitations to making crop based resources become a viable alternative to petrochemical based systems for chemicals and energy (Figure 3). Because of the interdisciplinary nature of this field, efforts are underway to develop new bioenergy courses and curricula to respond to demand in this area (Blaschek *et al*., 2008).

The current limitations and bottlenecks in the production of second generation biofuels based on lignocellulosics include improvements in the efficiency of bioconversion of plant fibers to value added products and the efficient recovery of these high value products (Figure 4). Biological conversion involves utilization of both 5 and 6 carbon sugars by various microbes such as yeast and bacteria. *Saccharomyces cerevisae* is currently being engineered to ferment arabinose, *Zymomonas mobilis* to ferment xylose and arabinose and the solventogenic *clostridia* to simultaneously saccharify and ferment.

Because of the need for multi-disciplinary expertise, the utilization of plant and microbial genomic-based approaches leading to translational bioengineering and process scale up has been described by some as an "Apollo Project". The "New Biology of Genomics" allows for the application and integration of systems biology and metabolic engineering of fermentation pathways to overcome technical barriers in the production of biofuels from lignocellulosic substrates.

An approach for the development of new plant biomass sources involves examination of maize germplasm collections for particular cell wall characteristics and compositions. One way to do this is to screen germplasm collections for cell wall characteristics such as lignin content. Given its recalcitrance, the selection of maize lines with low lignin content would be expected to allow for improved fermentation processes. In addition to examination of lignocellulose as a potential feedstock, topical maize or "sugar corn" offers a potential short term feedstock solution. According to work recently carried out at the University of Illinois, sugar corn requires low nitrogen input, can be grown in temperate climates and contains high concentrations of sucrose, glucose and fructose. Just like sugarcane, the sugars in tropical maize can be directly fermented in the absence of pre-treatment and enzyme treatment, making this feedstock potentially very interesting as a near term alternative for production of fuels and chemicals (bioenergy.uiuc.edu).

The "New Biology" of genomics also allows for examination of gene function and expression. This will allow for the development of road maps for construction of new plant and microbial strains with characteristics that are tailor-made for production of a particular biorefinery-based product. This technology will result in improved economics and efficiencies and allow for direct competition of bioproducts for feedstock chemicals currently produced by the petrochemical industry.

Some current examples of biorefinery activities include the investigation by Dupont and BP of bio-butanol, an advanced 4-carbon biofuel, the production of 1,3 propanediol as a polymer platform, the construction of a commercial scale biorefinery to produce polylactide polymers, the announcement by ADM of pilot scale testing of corn fiber as a substrate for bioproducts and the commercial scale production of ethanol from wheat straw by Iogen. This is only the beginning of the possibilities for the biorefinery of the future. It is anticipated that there will be both a sugar-based and a syngas-based platform that will allow for conversion of various feedstocks (including plant materials and waste products) to numerous chemicals and fuels. The biorefinery of the future is expected to be similar in magnitude and be able produce a variety of products quite similar to today's mature and vertically-integrated petrochemical refinery (Figure 5).

The future is bright for the bio-production of fuels and chemicals. An overview of the biofuels production cycle can be seen in Figure 6.

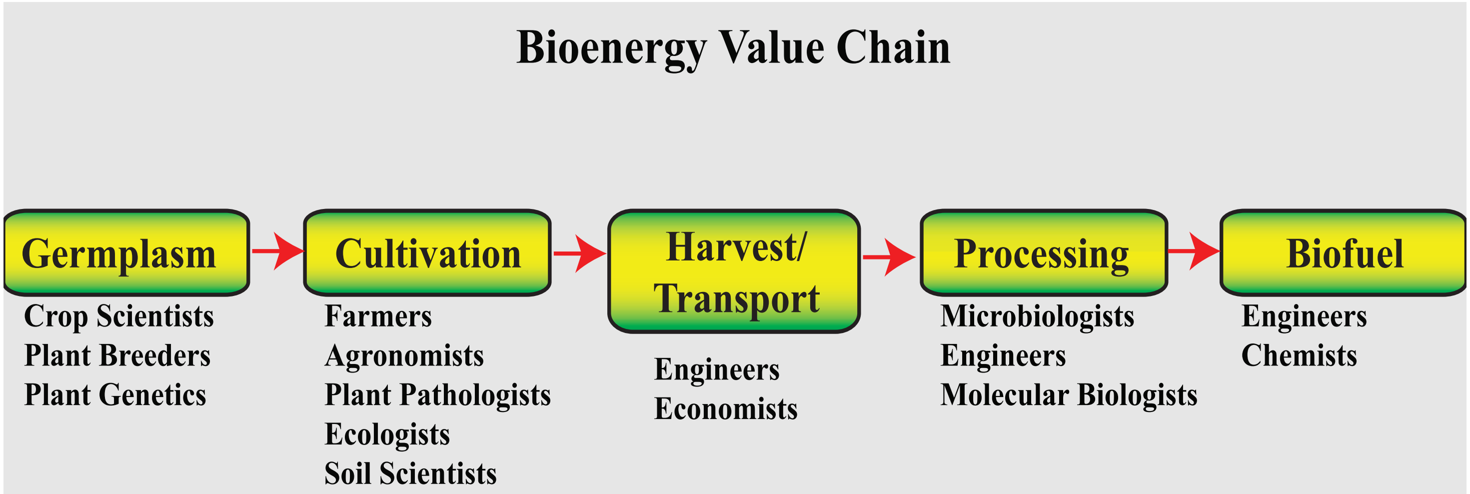

Figure 3. The Bioenergy Value Chain and Associated Expertise Needs

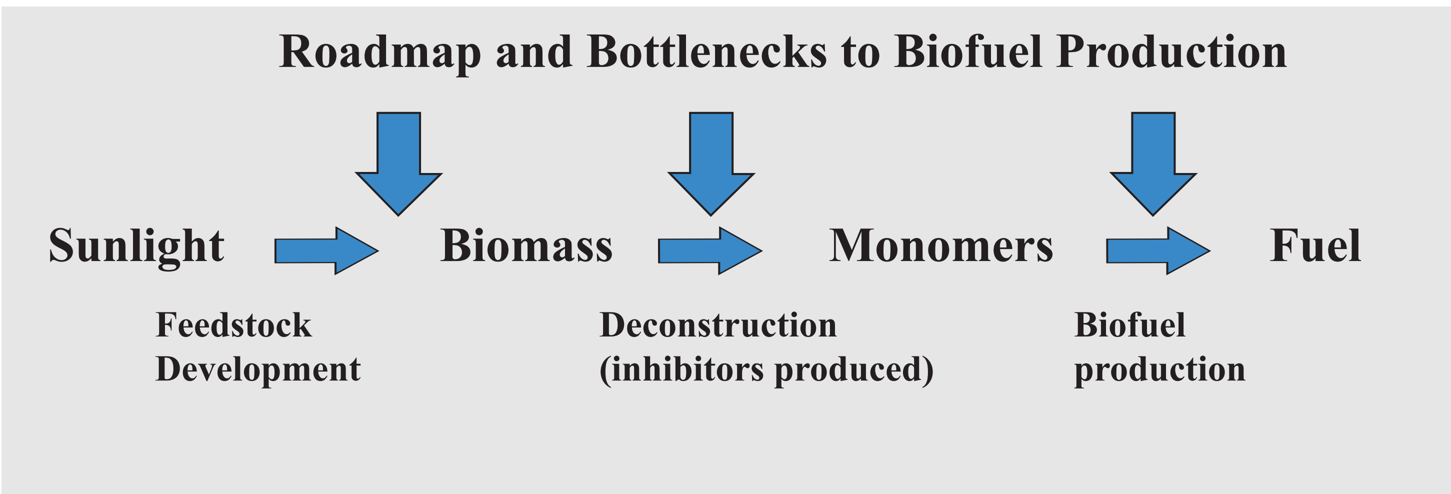

Figure 4. Roadmap and Bottlenecks to Biofuel Production

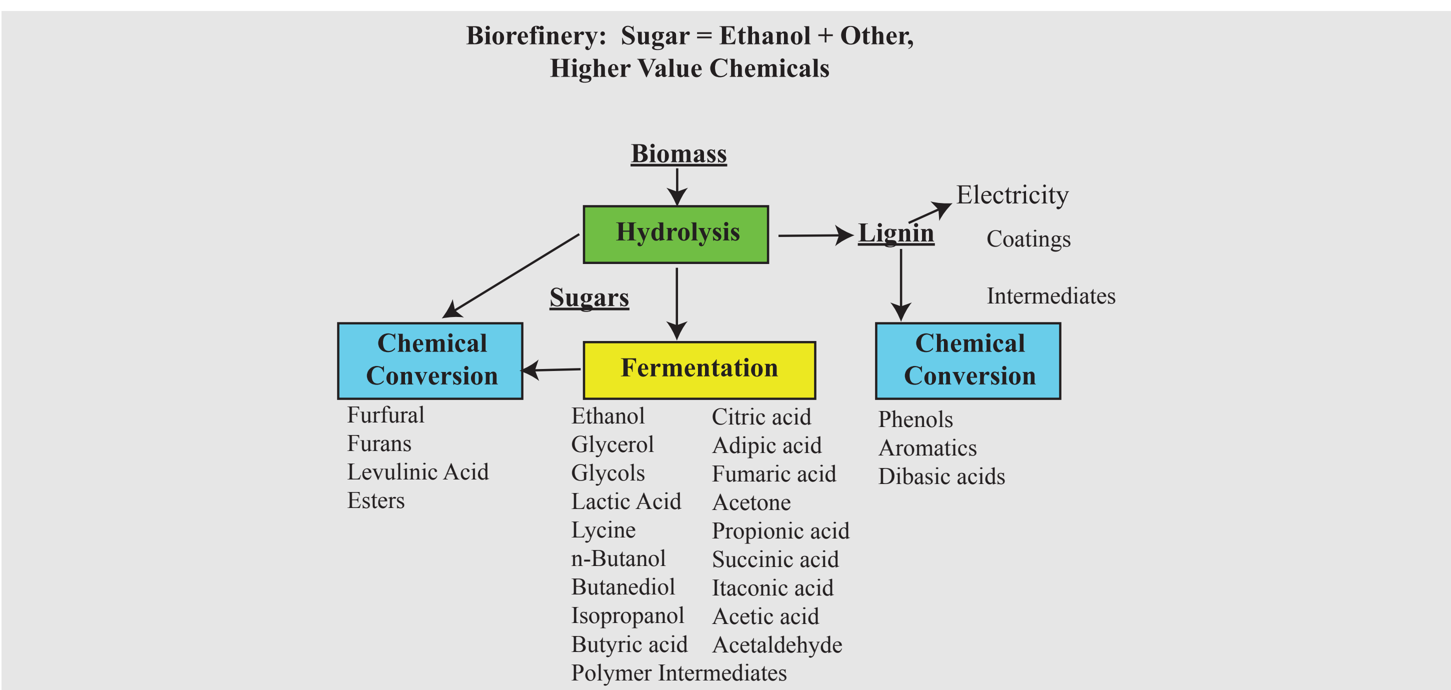

Figure 5. The Biorefinery of the Future

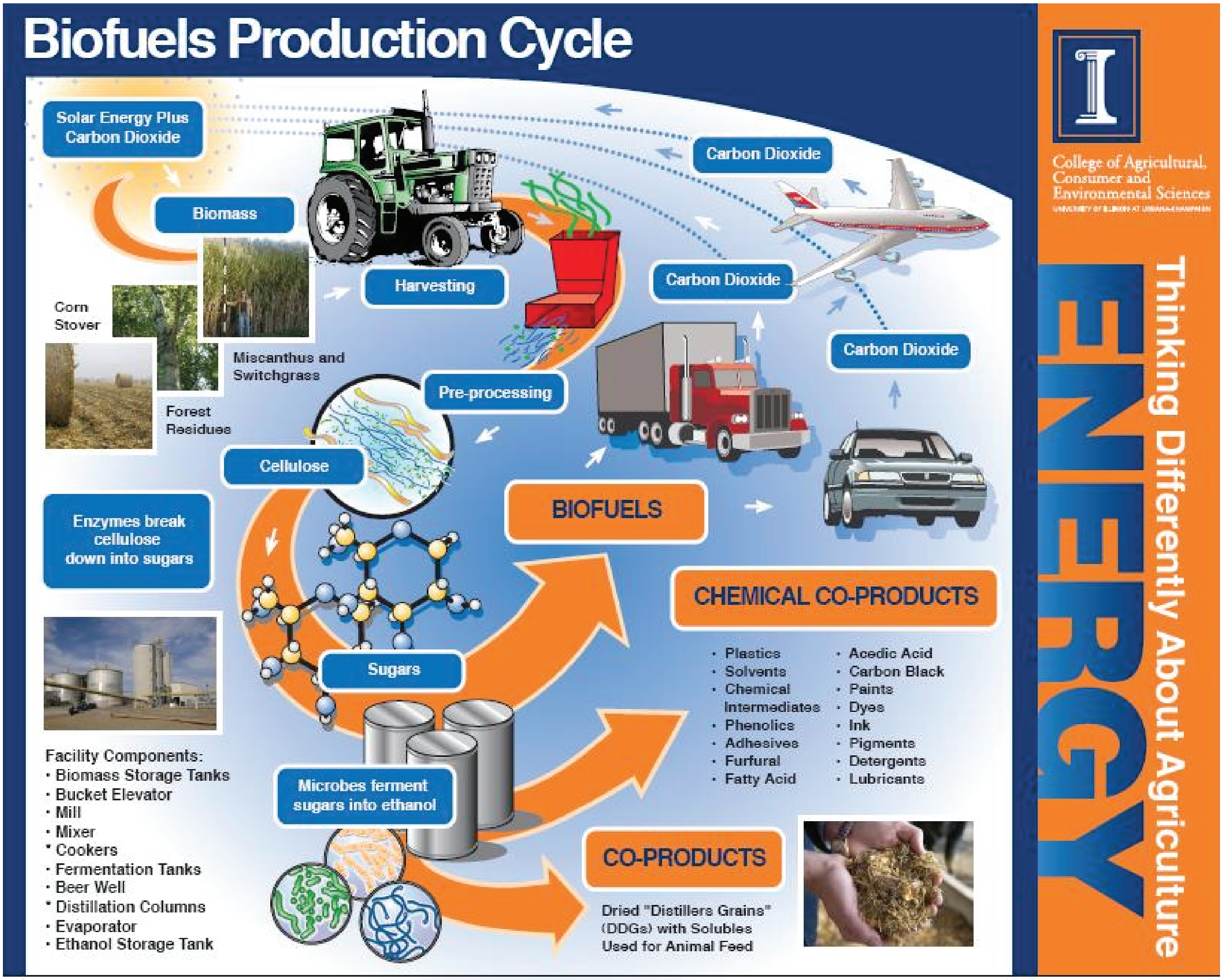

Figure 6. Biofuels Production Cycle

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Use of Distillers By-Products and Corn Stover as Fuels for Ethanol Plants*

Douglas G. Tiffany, R. Vance Morey, and Matt De Kam[1]

Introduction

Production of fuel ethanol by the dry-grind process is expanding rapidly in the U.S. and annual production capacity is expected to exceed 12 Billion gallons per year by the end of 2008 (Renewable Fuels Association, 2007). The energy required to produce ethanol continues to be an important topic in the biofuel industry, because process energy in the form of heat and electricity is the largest energy input into the ethanol production process (Shapouri, Duffield, and Wang, 2002). Natural gas has been the fuel typically used to produce process heat at these plants, while coal has sometimes been used for fuel, especially in plants greater than 100 million gallons per year of capacity. Biomass is an alternative, renewable source of energy for ethanol plants. Dry-grind corn ethanol plants produce biomass coproducts which contain a significant amount of energy when used as a fuel. Ethanol plants also are typically located near corn producing areas which have a large amount of corn stover available for use as a fuel. Biomass powered dry-grind ethanol plants could generate the electricity they need for processing as well as surplus electricity to sell to the grid. Using biomass as a fuel replaces a large fossil fuel input with a renewable fuel input which will significantly improve the renewable energy balance of dry-grind corn ethanol (Morey, Tiffany, and Hatfield, 2006). Dry-grind ethanol plants typically yield 2.75 gallons of anhydrous ethanol per bushel (56 pounds) of corn and 18 pounds of Dried Distillers Grains with Solubles (DDGS). Drying of DDGS requires approximately one-third of the natural gas used by the plant. Consideration of the coproduct DDGS as a biomass fuel reveals that there is sufficient energy to supply all needed process heat and electricity for the facility with additional energy available for electrical power generation for sale to the grid.

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[1] Tiffany is a Research Fellow, Department of Applied Economics; Morey is a Professor; and De Kam is a MS candidate, both in the Department of Bioproducts and Biosystems Engineering, all respectively, at the University of Minnesota, Twin Cities, Minnesota.

Focus of Study

The leading methods of thermal conversion of ethanol coproducts or field residues that would be technically feasible and financially prudent under a range of economic conditions were identified by De Kam, Morey, and Tiffany (2007) and include a fluidized bed and gasification as the main thermal conversion options. Technical data related to characteristics of DDGS, syrup, and corn stover were collected so that conversion of energy derived from these biomass fuels could be modified (Morey *et al*., 2006). Combustion and gasification performance of the technologies were modeled in order to predict emissions of NOx and SOx from the biomass fuels. In addition, issues of ash fusion caused by the alkali metals in the biomass were studied to help identify combustion/gasification strategies that will have operational reliability.

Objectives

The main objectives of this paper are to identify opportunities to significantly improve the carbon footprint of ethanol produced from corn starch with processes and methods that are available today. This is achieved through technical integration of several biomass energy conversion systems into the dry-grind corn ethanol process, requiring system designs capable of providing necessary process heat while meeting prevailing air emissions standards. Next, the economic performance of biomass-powered ethanol plants are compared with conventional plants that utilize purchased natural gas and electricity.

1. Technical Integration

Methods

The technical analysis for integrating biomass energy into the dry-grind ethanol process is described in detail in De Kam, Morey, and Tiffany (2007). The analysis was performed primarily using Aspen Plus process simulation software. An Aspen Plus model of the dry-grind ethanol process was obtained from the USDA Agricultural Research Service (McAloon *et al*., 2000; McAloon, Taylor, and Yee, 2004; Kwiatowski *et al*., 2006), and was altered to accommodate the energy conversion systems. Biomass systems with a rated annual capacity of 50 million gallons of denatured ethanol were modeled. The primary components of the process such as fermentation, distillation, and evaporation were not changed. Only those components impacted by using biomass fuel were modified. They included steam generation (biomass combustion or gasification), thermal oxidation, coproduct drying, and emissions control. Process data from several ethanol plants participating in the project were also taken into account in the modeling process. Finally, analysis was performed on several economic variables to highlight the sensitivity of the findings.

Three biomass fuels were included in the analysis – DDGS, corn stover, and a mixture of corn stover and "syrup" (the solubles portion of DDGS). Three levels of technology were analyzed for providing energy at dry-grind plants. They included: 1) process heat only, 2) process heat and electricity for the plant – combined heat and power (CHP), and 3) CHP plus additional electricity for the grid. The limit for the third case was defined in terms of the maximum energy available if all of the DDGS were used to provide process heat and electricity. A conventional ethanol plant using natural gas and electricity was also modeled to provide comparison information for the economic analysis.

Fluidized bed combustion was used for corn stover and the mixture of corn stover and syrup. Fluidized bed gasification was used for DDGS to overcome problems with low ash fusion temperatures. Appropriate drying modifications were made to accommodate each fuel/conversion configuration. The necessary emissions control technologies, primarily for oxides of nitrogen (NOx) and oxides of sulfur (SOx), were also modeled for each configuration. In order to determine the extent of potential emissions issues, the properties of the biomass were analyzed.

Biomass Property Data

A typical dry-grind corn ethanol plant produces DDGS as a coproduct. DDGS is a mixture of two process streams called distiller's wet grains (DWG) and concentrated distiller's solubles (also known as "syrup"). The DWG and syrup are mixed and dried together to become DDGS. Property data for these process streams and corn stover were needed in order to build an accurate model. Morey *et al*. (2006) provided an analysis of the fuel properties of these streams based on data taken from five dry-grind ethanol plants, as well as a fuel characterization of corn stover. Table 1 provides a summary of some of the important biomass property data.

Emissions Estimates

An engineering consulting firm, RMT, Inc., assisted in generating the predictive emissions estimates from the various thermal conversion technologies and fuel combinations. Computational fluid dynamics modeling was performed for several scenarios with the results focusing mainly on emissions of oxides of nitrogen (NOx) and oxides of sulfur (SOx). An equilibrium model (minimization of the Gibbs function) was used to simulate the combustion reaction in Aspen Plus. The computational fluid dynamics emissions estimates were used to adjust the emissions output of the Aspen Plus models.

Definition of Technology Combinations

Defining technology combinations was an iterative process of gathering industry data from vendors, ethanol plants, literature, and engineering firms, then modeling certain scenarios to determine their feasibility. Engineering consulting firms, AMEC and RMT Inc., assisted in the development of suitable technology combinations.

Thermal Conversion

Fluidized bed combustion and gasification were the main thermal conversion options evaluated in the analysis. Fluidized bed combustion was a good candidate because of its capacity to utilize high moisture fuels with the option of adding limestone as a bed material to control SOx emissions. Fluidized bed gasification has the added benefit of lower operating temperatures which was important because of the low ash fusion temperatures of DDGS. Gasification also permits greater control of the conversion process through the option of producer gas cleanup before subsequent combustion.

Drying and Thermal Oxidation

Conventional dry-grind ethanol plants generally use natural gas direct fired dryers (rotary, or ring type) to dry the DDGS. In a plant powered by solid fuel, a common option is to use steam tube (indirect heat) rotary dryers. In this setup steam from the boiler provides heat to the wet material and air in the dryer through a series of tubes arranged inside the rotating dryer cylinder.

When gasification is used as the thermal conversion process the option exists to modify a natural gas fired dryer to utilize producer gas as a fuel. This method requires some producer gas cleanup processes.

In the analysis, steam tube dryers had their dryer exhaust routed to the combustion unit where thermal oxidation occurred. The assumption made for modeling purposes in terms of thermal oxidation was that the combustion reactor average temperature had to be greater than 816° C (1500° F) (Lewan-

Table 1. Selected Biomass Property Data [a]				
Fuel	Moisture Content	HHV	Nitrogen	Sulfur
	(% wet basis)	(MJ/kg dry matter)	(% dry matter)	(% dry matter)
Corn Stover	13	17.9	0.7	0.04
Syrup	67	19.7	2.6	1.0
DDGS	10	21.8	4.8	0.8
DWG	64	22.0	5.4	0.7

[a]Morey *et al*. (2006).

dowski, 2000). Future analyses may include several alternative dryer options.

Emissions Control

The emission estimates and technology specifications were made using data from the literature on emissions control technology and suggestions from the partner engineering firms. Combustion modeling results from RMT and our own calculations indicated that for the chosen system sizes most cases would need to be classified as a major source due to the emissions of NO_x and/or SO_x (U.S. EPA, 2006).

For the purposes of this paper SO_x emission potential was calculated based on the amount of sulfur in the fuel. Destruction efficiencies for each control technology were estimated and used to calculate the resulting air emissions data. Fluidized bed combustors allow for the use of limestone as a bed material, which helps to reduce SO_x emissions. In the DDGS gasification cases, flue gas desulfurization semi-dry scrubbers were used to reduce SO_x emissions. Emissions of NO_x were controlled using selective non-catalytic reduction (SNCR) via injection of ammonia into the boiler.

There are indications that chlorine emissions from the fuels will need to be controlled by installation of scrubbers. Although costs for treatment of chlorine have not been included, they are expected to be minor. Emissions of particulate matter were not simulated in the analysis although the necessary particulate removal equipment was specified in each case. The particulate removal equipment (cyclones, baghouse, etc.) was specified using estimates from similar processes.

Steam Cycle and Electricity Production

Several variations of steam turbine power cycles were used to generate electricity in this analysis. Each fuel combination and technology scenario was analyzed on three levels of electricity production.

At the first level, the system simply provides the process heat needed to produce ethanol and dry the coproduct. No electricity is generated. The second level system generates steam at an elevated temperature and pressure and uses a backpressure turbine to produce electricity.

The limiting factor for electricity production in this case is that all the outlet steam from the turbine needs to be used for ethanol production and coproduct drying. Under these constraints the actual amount of electricity produced is very close to meeting the ethanol plant requirements. Because of this, the second level of electricity production will be referred to as CHP (Combined Heat and Power). At the third level a surplus of steam is generated at high temperature and pressure and is used to drive extraction type turbines.

Technical Integration Power Scenarios

Three combinations of fuel and thermal conversion technology were analyzed, each at the three different levels of electricity generation. For each case, system performance results are presented.

Corn Stover Combustion

The first option analyzed was the direct combustion of corn stover in a fluidized bed. The corn stover was assumed to be densified at an off-site facility. Figure 1 shows a simplified process flow diagram of this case. At the heart of the process is the bubbling fluidized bed boiler. The dryer exhaust stream is routed through the combustor to accomplish thermal oxidation of the volatile organic compounds it contains. Oxides of nitrogen are controlled using SNCR at the boiler. Particulate matter is removed from the flue gas by cyclones and a baghouse. At the first level, no electricity is generated.

At the second level, electricity is generated using a backpressure turbine. Steam is produced at 6.3 MPa (900 psig) and 482°C (900°F), then expanded through a backpressure turbine to 1.1 MPa (150 psig) (see Figure 2). Some de-superheating is then necessary to provide saturated steam to the ethanol process and the coproduct dryer.

The third level of electricity production uses an extraction turbine. A surplus of steam is generated in the boiler at 6.3 MPa (900 psig) and 482°C (900°F). Process steam is extracted from the turbine at 1.1 MPa (150 psig) (see Figure 3). The remaining steam continues through the low pressure stage of the turbine and is condensed.

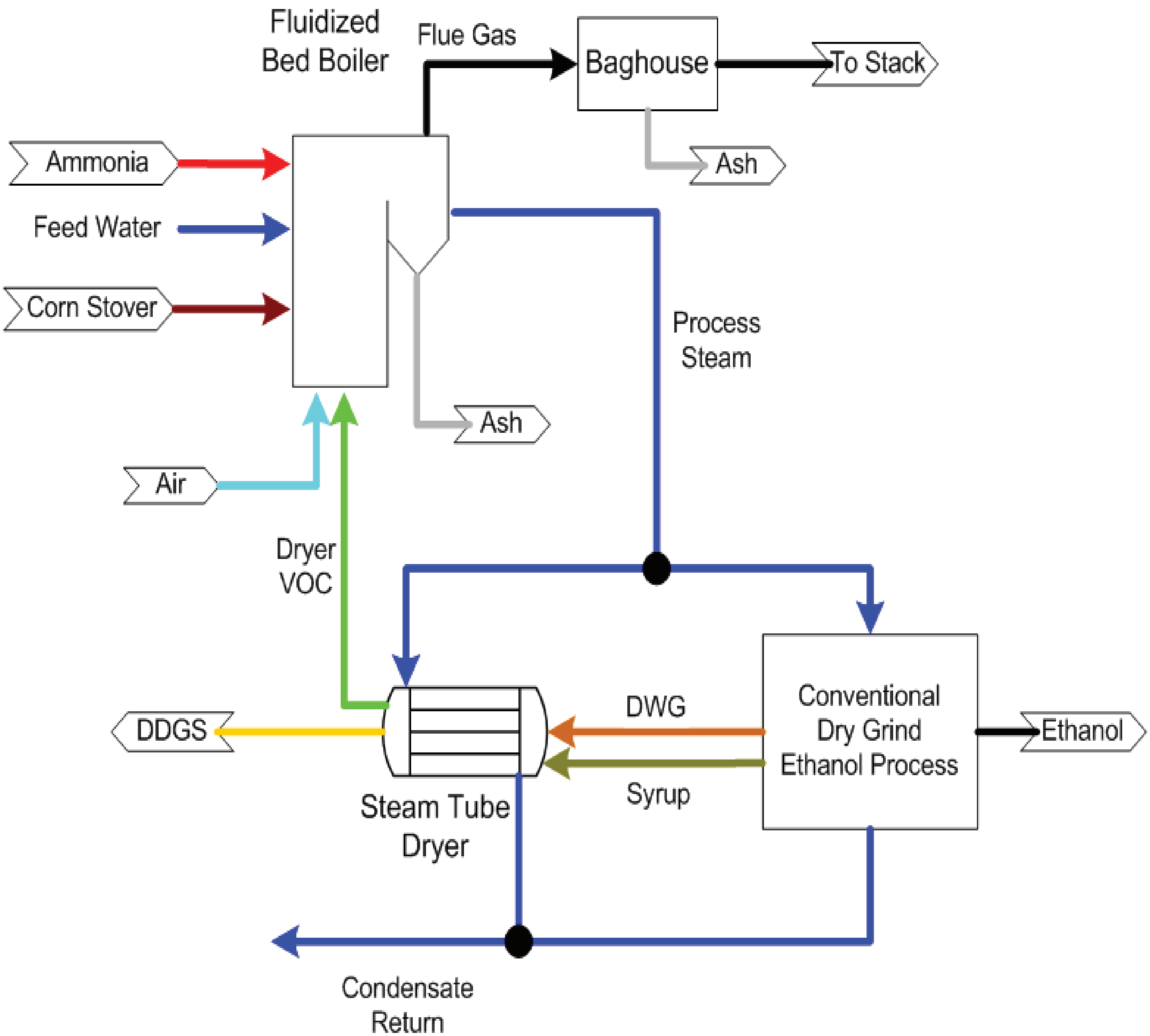

Figure 1. Corn Stover Combustions, Level 1: Process Heat Only

Syrup and Corn Stover Combustion

The second option analyzed was combustion of the syrup coproduct supplemented with corn stover. The process flow diagrams for this system are essentially the same as the corn stover combustion case except that the syrup coproduct is not dried, but rather combusted in the fluidized bed boiler along with corn stover. Limestone is used as the bed material in the combustor to reduce emissions of SO_x. The drying operation in this case is much smaller because only the DWG co-product must be dried. This makes the overall process steam load smaller as well.

Figure 4 shows fuel energy input from syrup and corn stover for each level. The amount of fuel used is shown in Figure 5. The average moisture contents of the fuel mixture for the process heat, CHP, and CHP + grid scenarios were 56%, 53%, and 44% respectively.

DDGS Gasification

The final option analyzed was the gasification of DDGS. Once again the three options reflecting greater intensity of biomass usage reflect the process models of Figures 1, 2, and 3. The system chosen uses an air-blown fluidized bed gasifier to convert the DDGS into producer gas. Particulates are removed from the gas stream in high-temperature

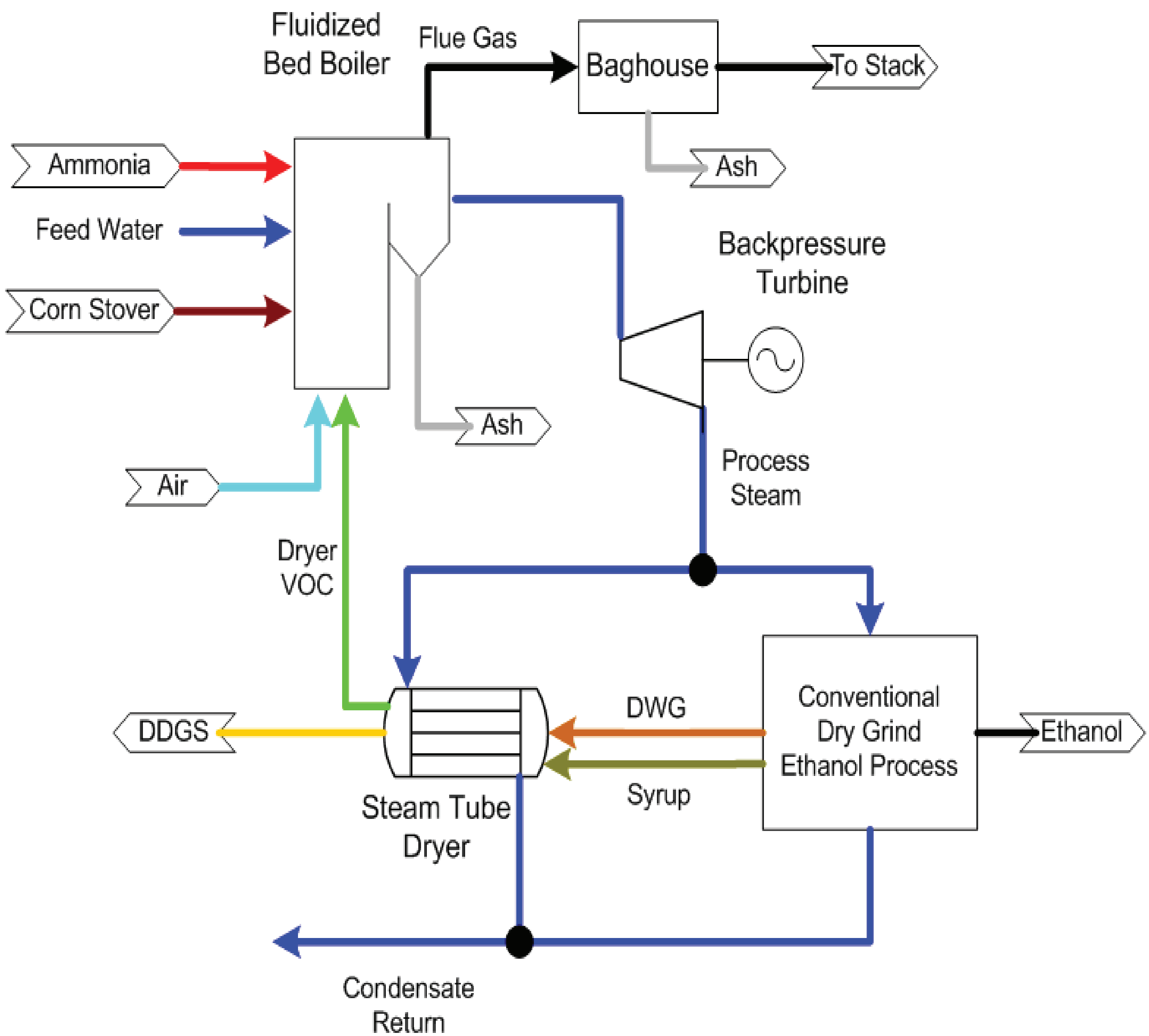

Figure 2. Corn Stover Combustions, Level 2: CHP

cyclones. The producer gas is not allowed to cool significantly in order to avoid condensation of tars. A staged combustion reactor is used to combust the producer gas. Ambient air and exhaust from the DDGS dryer are added at separate stages. This combustion reactor acts as a thermal oxidizer for the dryer exhaust stream and eliminates that capital expense. Immediately following the combustor is a heat recovery steam generator (HRSG) where steam is produced for the ethanol process, coproduct drying, and electricity production depending on the specific case. Emissions of NO_x are controlled using SNCR ammonia injection during combustion. A semi-dry scrubber using a lime slurry is then utilized to reduce the emissions of SO_x.

Technical Integration Results

System Performance Comparison

Figure 4 shows fuel energy input from syrup and corn stover for each level. The amount of fuel used is shown in Figure 5. The average moisture content of the fuel mixtures for the process heat, CHP, and CHP + grid scenarios were 56 percent, 53 percent, and 44 percent respectively.

Table 2 presents some of the performance data of interest from each case. In general the combustion of corn stover makes most efficient use of the fuel energy input due to its simplicity and relatively low fuel moisture content.

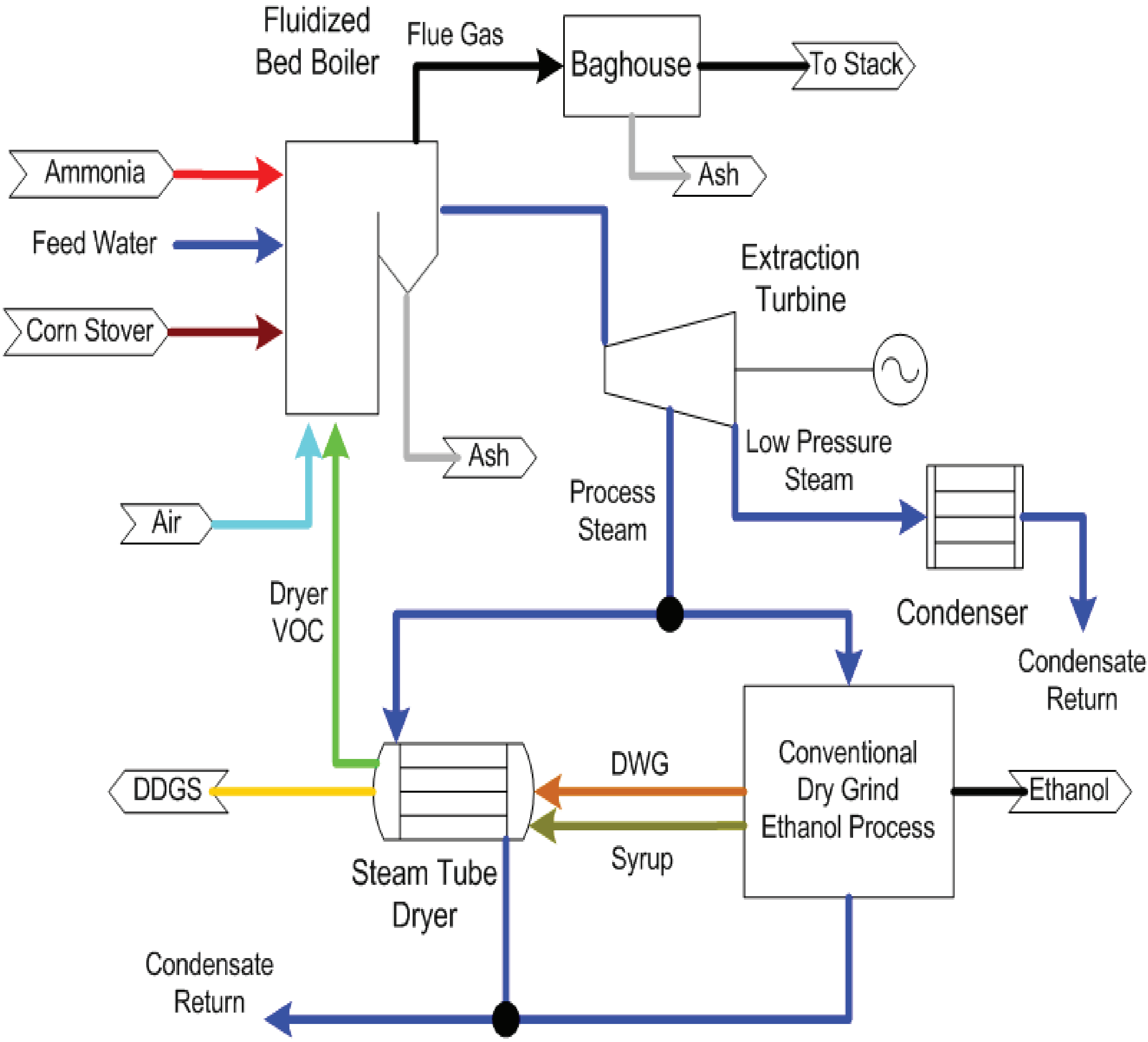

Figure 3. Corn Stover Combustions, Level 3: CHP and Electricity to the Grid

However, in the syrup and corn stover combustion cases the energy for drying the syrup coproduct is effectively hidden in the lower system thermal efficiency. This is because the syrup moisture is vaporized in the combustor where it decreases the boiler efficiency rather than being evaporated in the dryer via process steam where the energy would be counted as a useful output of the system. This dynamic also explains why less electricity is generated in level 2 of the syrup and corn stover combustion cases. Less process steam is required for drying the coproduct since only DWG is being dried. This limits the amount of steam flowing through the backpressure turbine, since all of the output steam must be used to meet process needs.

The renewable energy ratio for each case was calculated following the assumptions presented in a previous study (Morey, Tiffany, and Hatfield, 2006). The renewable energy ratio is defined as follows:

(Energy in Ethanol + Coproduct Energy + Electricity to Grid Energy) ÷ Fossil Energy Input

The energy use and credit assumptions made by Morey, Tiffany, and Hatfield (2006) use data from Shapouri, Duffield, and Wang (2002) as a basis for these calculations. Some slight changes have been made to the electricity use assumptions for the purposes of this report. An updated value of 0.2 kWh/L of ethanol produced (0.75 kWh/gal) was

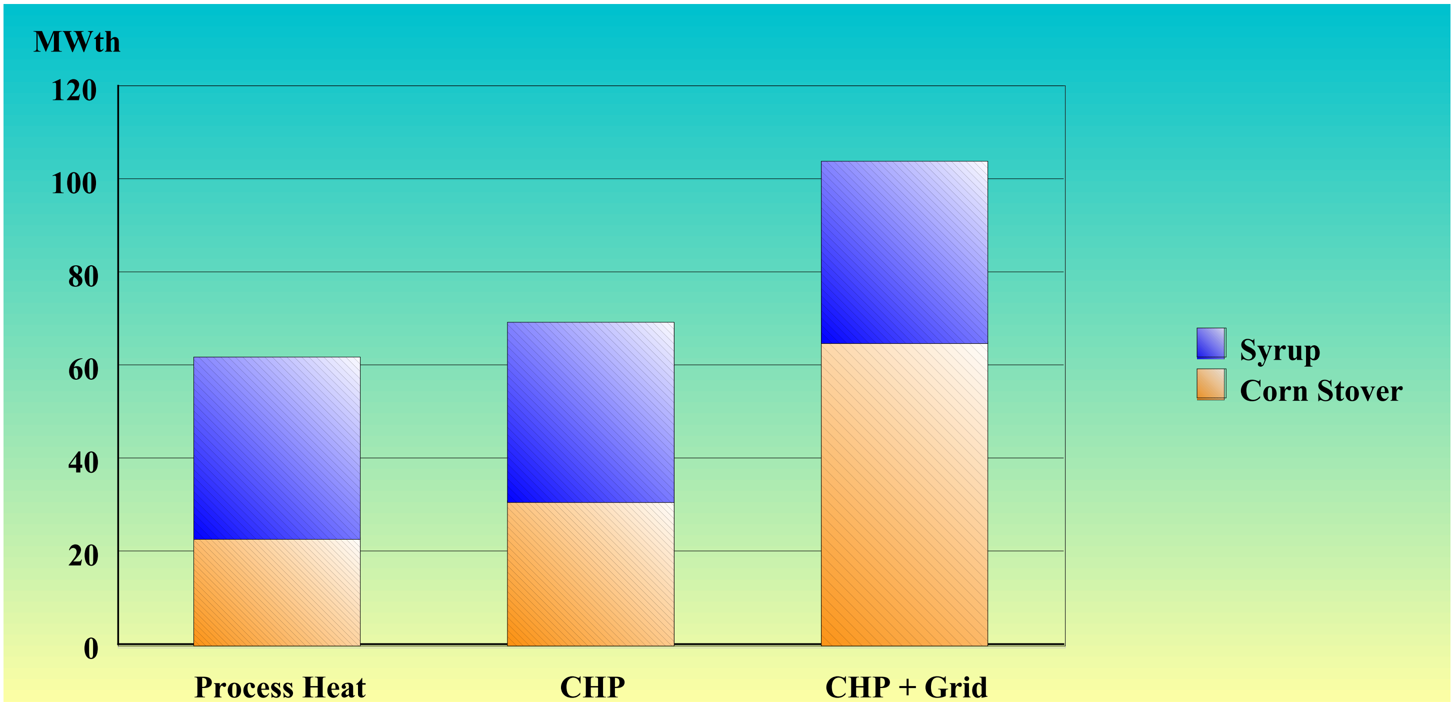

Figure 4. Syrup and Corn Stover Combustion: Fuel Energy Input Rate Contribution (HHV)

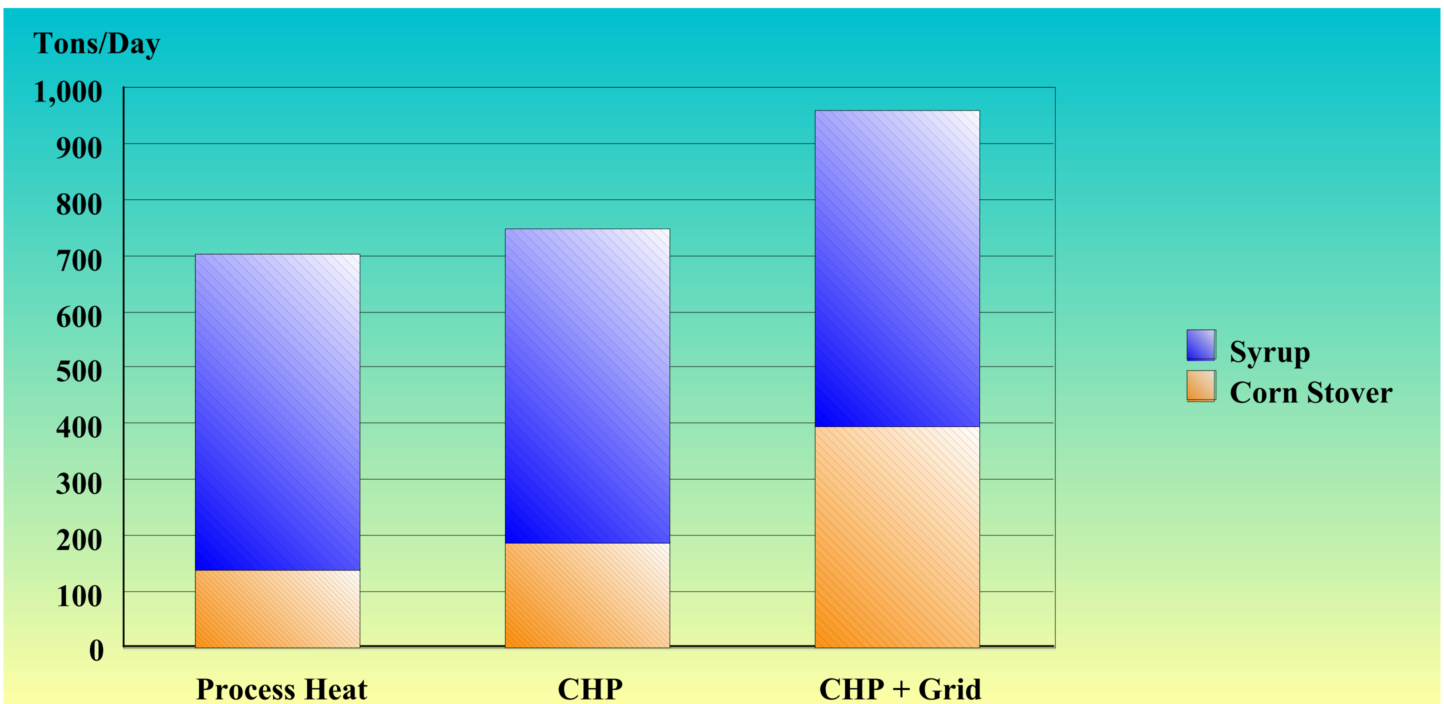

Figure 5. Syrup and Corn Stover Combustion: Fuel Use

used for the electricity demand in the conventional natural gas ethanol plant calculations. We estimated the electricity demand of the biomass fueled ethanol facilities to be higher at 0.25 kWh/L (0.95 kWh/gal) due to added equipment. Also, some of the equipment contributing to the parasitic electric load was modeled. These loads were subtracted from the gross electricity production for each case.

Figure 6 shows the comparison of renewable energy ratio between the modeled cases and a conventional dry-grind corn ethanol plant. It can be seen that using biomass as a fuel can greatly increase the renewable energy balance of ethanol production.

Table 2. System Performance Results for a 50 Million Gallon Per Year Dry-Grind Ethanol Plant[a]

	Biomass Fuel Use[b] (Wet Basis)	Fuel Energy Input Rate	Power Generated (Gross)	Power to Grid (Net)[c]	Power Generation Efficiency	System Thermal Efficiency[d]
	(T/day)	(MW_{th})	(MW_e)	(MW_e)		
Corn Stover Combustion						
Level 1: Process Heat Only	400	66	0	-6.0	--	80.5%
Level 2: CHP	458	75	6.6	0.4	8.8%	78.9%
Level 3: CHP & Elec. to Grid	634	104	13.0	6.8	12.5%	63.1%
Syrup & Corn Stover Combustion						
Level 1: Process Heat Only	702	62	0	-6.2	--	70.1%
Level 2: CHP	749	70	5.4	-0.7	7.8%	69.7%
Level 3: CHP & Elec. to Grid	959	104	12.9	6.7	12.4%	53.8%
DDGS Gasification						
Level 1: Process Heat Only	350	72	0	-6.2	--	73.3%
Level 2: CHP	402	83	7.0	0.8	8.5%	72.2%
Level 3: CHP & Elec. to Grid	506	104	11.5	5.2	11.1%	61.6%

[a]All energy and power values in this table are based on fuel Higher Heating Value (HHV).

[b]Moisture contents: Corn stover - 13%; Syrup & corn stover - 56%, 53%, and 44% for levels 1, 2, and 3 respectively; DDGS - 10%

[c]Negative values refer to power purchased from the grid by the ethanol facility

[d]Efficiency of converting fuel energy into other useful forms of energy (process heat and electricity)

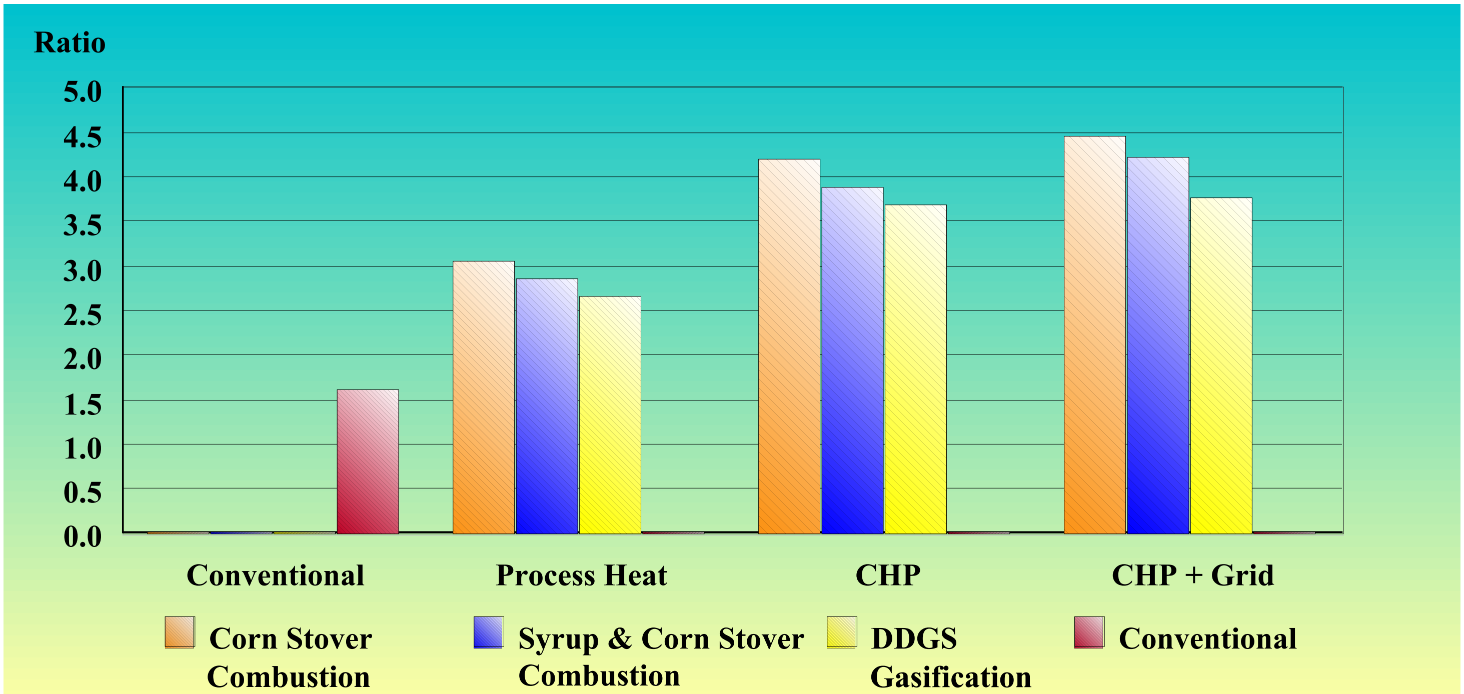

Figure 6. Renewable Energy Ratio (LHV)

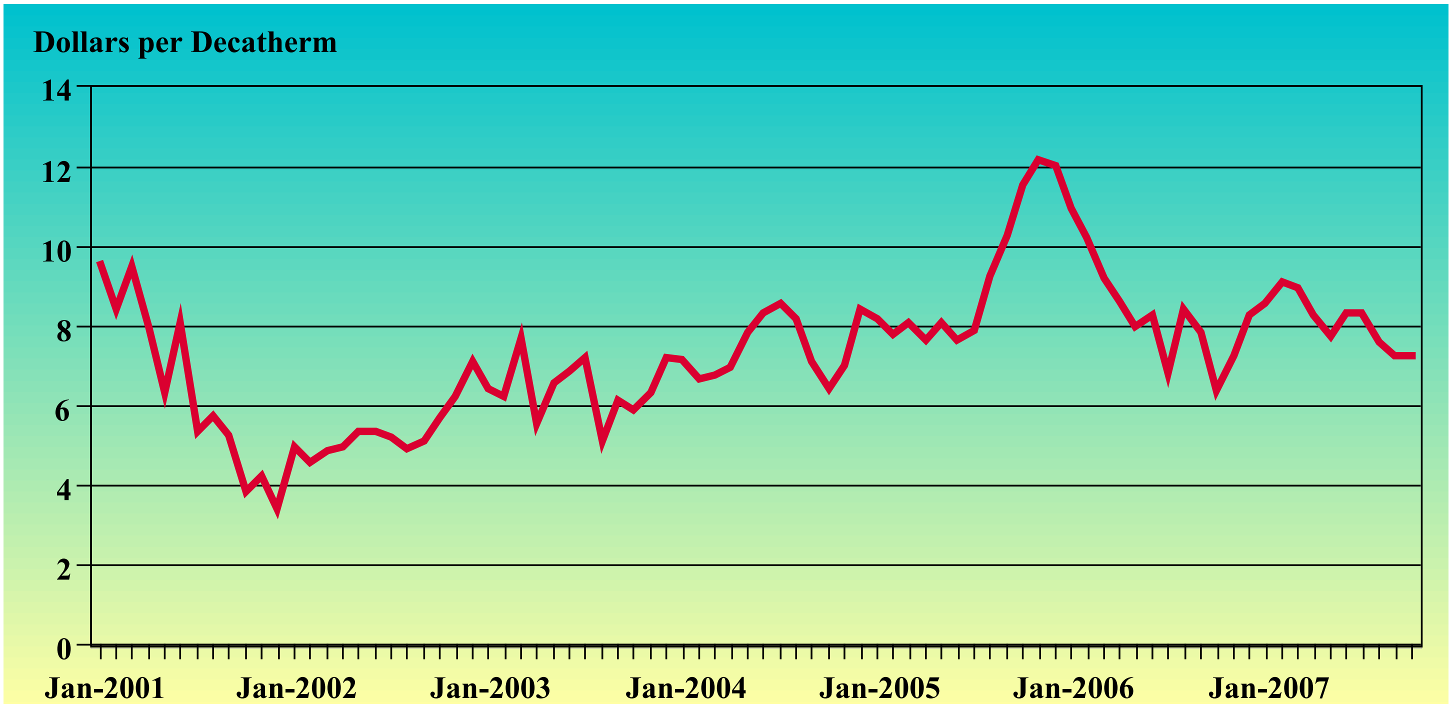

Figure 7. Industrial Natural Gas Prices in Iowa from 2001-Ocotober, 2007 (U.S. Department of Energy, Energy Information Agency, 2007)

2. Economic Analysis

Key Economic Drivers for Adopting Biomass

Natural gas costs are the second largest operating cost for dry-grind ethanol plants, following only the cost of the corn as an operating expense. At this time of expansion of dry-grind ethanol production in the U.S. Corn Belt, demands for natural gas are also expanding rapidly, which exacerbates supply issues on natural gas lines of limited capacity in certain rural areas. Figure 7 shows the history of natural gas prices in Iowa, the heart of the U.S. Corn Belt, with the effects of damage to natural gas infrastructure caused by Hurricane Katrina becoming evident in August of 2005.

Electricity costs are not as important to ethanol plant economics in magnitude, but plants have a self-interest in producing enough power on-site in order to maintain uninterrupted operation of computers, process controls, and other vital systems. In some areas, local power providers would welcome the ability of newly established ethanol plants to provide their own power in order to avoid heavy investments to upgrade distribution capacity. In addition, there are improving incentives available to ethanol plants and other facilities to produce power for the grid from biomass as individual states establish goals that increase the renewable percentage of the power used within their borders.

In the years before 2006, revenues from sales of distillers dried grains and solubles (DDGS) often represented 20% of the total revenue stream of dry-grind plants; however, since that time the percent of total revenues from this by-product has fallen to about half of that amount. Given the rapid expansion of ethanol capacity that is underway in the U.S., it will be improbable for U.S. livestock populations to consume the burgeoning production of this by-product. One of the reasons why U.S. livestock can't consume the increased production of DDGS stems from the maximum potential inclusion rates for this mid-level protein feed when fed to certain classes of livestock. DDGS contain nutritional energy, but contain a form of fat that some species of animals can't tolerate at high intake rates while achieving favorable performance. Dairy cows experience milkfat depression when fed diets too high in the fats found in DDGS. Swine and poultry have lower abilities to utilize DDGS in their diets due to adverse effects of the dietary fat on carcass quality and due to the poor balance of amino acids, respectively.

As a feedstuff, DDGS have been hampered by issues of variability due to differences in corn quality (year to year) as well as ethanol plant operational issues involving the amount of concentrated solubles (syrup) dried with the dry portions of the stillage. The control and management of the DDGS dryers can cause a problem in feed quality when syrup balls are formed in DDGS. The composition of solubles in the DDGS and the manner in which they are dried or handled can also affect issues such as caking when the DDGS are shipped. Figure 8 shows a history of DDGS prices, which have historically been highly correlated with and about equal to corn prices on a per ton basis. Table 3 demonstrates the challenge of feeding the production of

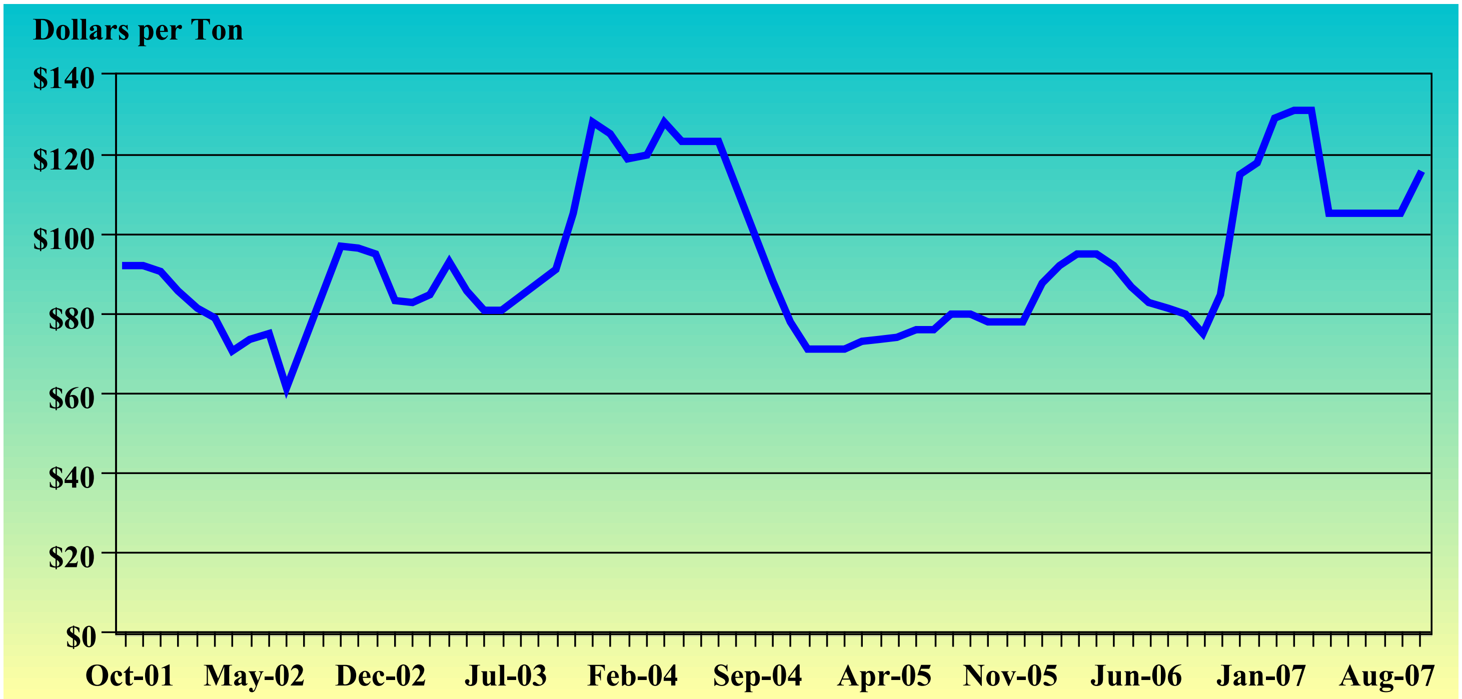

Figure 8. Historical Prices of Distillers Dried Grains at Lawrenceburg, Indiana (USDA, ERS Feed Grains Database)

Table 3. Consumption of Available DDGS (28 Million Metric Tons) by Percent of Market Penetration Based on Annual Ethanol Production of 10 Billion Gallons

Species	Millions of Grain-Consuming Animal Units	Maximum Rate of Inclusion	Millions of Metric tons Market Penetration Percent 50%	75%	100%
Dairy	10.2	20%	1.9	2.8	3.8
Beef	24.8	40%	9.2	13.8	18.4
Pork	23.8	20%	4.3	6.5	8.7
Poultry	31.1	10%	2.9	4.3	5.8
Total	89.9		18.3	27.4	36.6

Source: Geoff Cooper, National Corn Growers, in Distillers Grains Quarterly, 1st Qtr., 2006.

U.S. DDGS projected to be produced by 2009 at maximum dietary inclusion rates to the 2006 U.S. livestock population. Based on this table, it will require maximum dietary inclusion rates fed to 75% of the livestock populations to approach consumption of the amount of DDGS produced in 2009.

Use of by-products of the ethanol plant (DDGS, DDG, or syrup) or use of corn stover as a fuel to operate the plant can improve the net energy balance of the whole process of making fuel ethanol from corn. This occurs because fossil sources of energy are replaced by renewable sources. Morey, Tiffany, and Hatfield (2006) estimated net renewable energy values for corn ethanol with biomass to operate the plant comparable to estimates for cellulosic ethanol based on biochemical processes.

Low Carbon Fuels Standards

The efforts of California and growing interests on the national level to reduce the carbon footprint of the fuel supply should establish higher prices for ethanol produced by methods that result in lower emissions of greenhouse gases. California's goal is to reduce greenhouse gases from the transportation sector by 10% by 2020. As California's AB-32 Legislation is implemented, firms selling fuels in that state should be willing to pay more for ethanol produced with a low-carbon footprint whether due to the feedstock used, the source of the imbedded energy in the fertilizer used or other factors affecting imbedded energy usage.

Well to wheels studies by Wang, Wu, and Huo (2007) of Argonne National Laboratory reveal that use of biomass as a source of process heat and power in ethanol plants results in nearly a three-fold reduction in greenhouse gas emis-

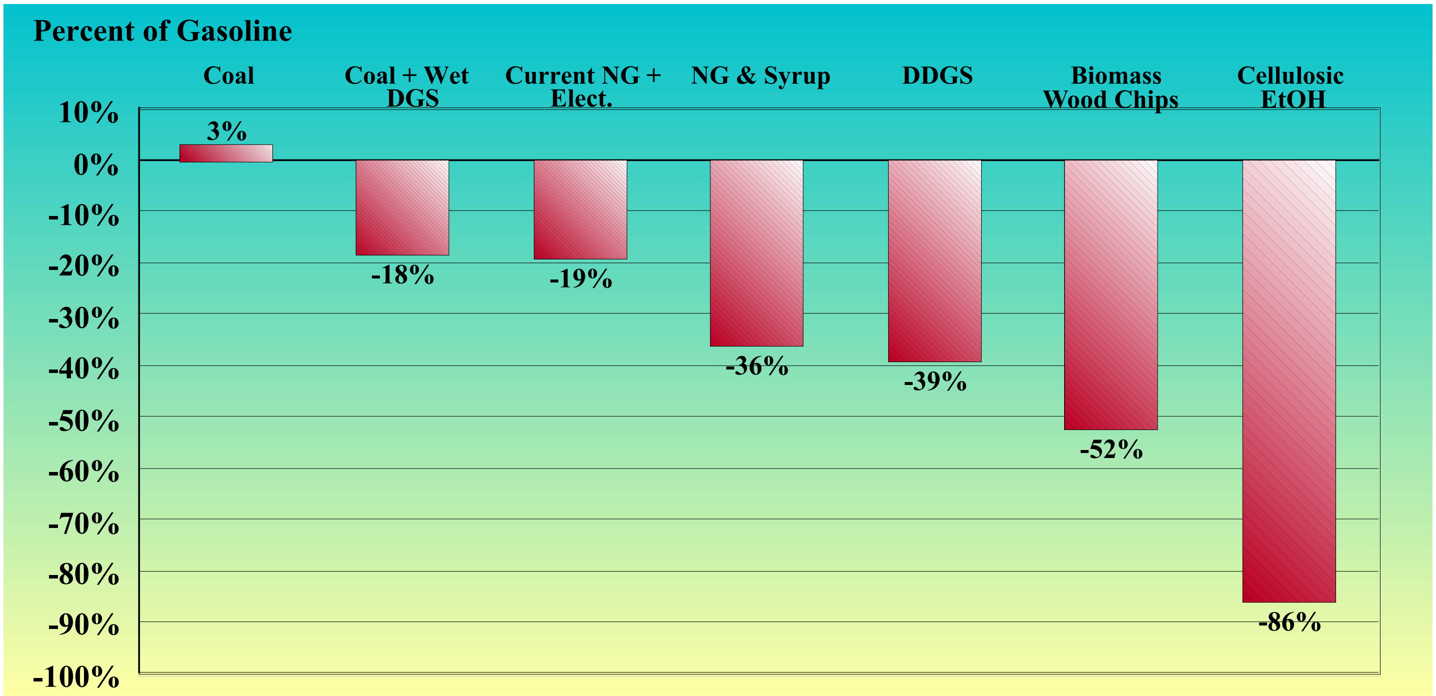

Figure 9. Wells to Wheels Greenhouse Gas Emissions Changes from Fuel Ethanol Produced Using Various Fuels and Conversion Assumptions at the Plant Relative to Gasoline (Wang, Wu, and Huo, 2007)

sions compared to using the current fuel of natural gas and purchased electricity (Figure 9). This data implies that a California fuel supplier would need to purchase and transport one-third as much ethanol to blend in order to achieve equivalent GHG reductions if the ethanol were produced at a plant using biomass for process heat and electricity. Ethanol produced at plants using biomass fuels, with a lower carbon footprint than ethanol produced at plants using natural gas and purchased electricity, should command a price premium in the market related to savings in freight required to move ethanol from the Corn Belt to California.

Methods

Estimating Capital Costs

The Aspen Plus model estimated important material and energy flows which allowed us to specify the capacities of the required capital equipment. Using these capacities, an engineering firm was consulted to specify equipment to meet these requirements. The consulting engineering firm then estimated equipment costs using data from previous projects and by soliciting bids from potential vendors for some items. Cost estimates are categorized according to new equipment and the equipment that would be replaced (avoided cost) compared to a conventional dry-grind plant. The analysis evaluated the net change in equipment cost required to construct a dry grind ethanol plant to use biomass rather than natural gas and purchased electricity as energy sources.

In the biomass scenarios, we assumed that a package natural gas boiler would be included for backup and also perhaps to phase in biomass as a fuel source over time, so the cost of that equipment was not deducted from the conventional base case of a natural gas powered plant. However, we were able to eliminate the capital costs of the thermal oxidizer that would be required in the natural gas-fired conventional plants.

Equipment costs for new items were first estimated, and then other costs associated with the project were added. Among these were installation, building, electrical, contractor costs and fees, engineering, contingency, and escalation to arrive at the total project cost for new items (Tiffany, Morey, and De Kam, 2007). Total project costs prevailing in 2007 (including operating capital) for conventional (natural gas) dry-grind plants obtained from design-build firms and bankers (Eidman, 2007) are shown in Table 4. Net (new – avoided) project costs for biomass systems are added to the cost of conventional plants to obtain total capital cost estimates for 50 million gallon per year biomass fueled plants.

Cost estimates for the 100 million gallon per year plants are developed based on the ratio of the plant sizes (100/50 = 2). The cost estimating factor for the 100 million gallon plant is $(2)^{0.7}$ or 1.62. Thus, the cost for 100 million gallon plant is estimated to be 1.62 times the cost for a 50 million gallon plant for a similar fuel and level. This technique of adjusting costs for scale is commonly used in many chemical and industrial processes. Based on responses from design/builders of ethanol plants, efforts to optimize and de-

Table 4. Nameplate Installed Costs for Conventional and Biomass-Fueled Dry-Grind Ethanol Plants

	50 Million Gallon Plants		100 Million Gallon Plants	
Type	Capital Cost	Nameplate Cost ($/gal)	Capital Cost	Nameplate Cost ($/gal)
Conventional	$112,500,000	$2.25	$182,756,789	$1.83
Corn Stover				
Process Heat	$147,120,000	$2.94	$238,997,145	$2.39
CHP	$162,938,000	$3.26	$264,693,562	$2.65
CHP + Grid	$180,590,000	$3.61	$293,369,321	$2.93
Corn Stover + Syrup				
Process Heat	$136,522,000	$2.73	$221,780,643	$2.22
CHP	$150,769,000	$3.02	$244,924,963	$2.45
CHP + Grid	$168,372,000	$3.37	$273,521,121	$2.74
DDGS				
Process Heat	$142,465,000	$2.85	$231,435,075	$2.31
CHP	$156,279,000	$3.13	$253,875,985	$2.54
CHP + Heat	$171,637,000	$3.43	$278,825,129	$2.79

bottleneck plants can raise capacity 6% in the case of coal or biomass plants and 20% or more in the case of conventional plants (Nicola, 2005). Nameplate installed costs are summarized for the nine fuel/technology combinations in Table 4.

Estimating Operating Costs and Other Baseline Assumptions

Table 5 contains the key baseline assumptions that affect profitability of the dry-grind ethanol plants being evaluated. It includes assumptions about the levels of debt and equity in the plant as well as the overall interest rate charged on the debt. A hurdle rate of return (ROR) on equity can be established, and the number of years assumed for depreciation can be established.

Baseline ethanol price is established at $1.80/gallon received at the ethanol plant. Corn price is assumed to be $3.50/bushel (for the next ten years) based on the 2007 Baseline Report of the U.S. Department of Agriculture (2007). Natural gas is established at $8 per decatherm (1.06 million kJ or 1 million BTUs). Electricity is assumed to be priced at $0.06 per kWh under baseline conditions, whether the plant is buying or selling.

DDGS are established at the price of $100/ton. In the scenarios when the syrup is combusted, the resulting by-product is DDG, which we assume has a market value 120% of conventional DDGS. We base this on presumed attributes of greater consistency and the higher inclusion rates that DDG should offer to producers. Corn stover is assumed to be priced at $80/ton when it is delivered in a dry, densified form at the plant gate (Sokhansanj and Turhollow, 2004; Petrolia, 2006). The value of ash is assumed to be $200/ton based on reported values for the ash collected at Corn Plus Ethanol, in Winnebago, MN.

The low-carbon premium is established at 20¢/gallon for each unit of ethanol produced using biomass, based upon the savings in transportation costs that accrue when California ethanol buyers are able to purchase ethanol having a carbon imprint 1/3 that of ethanol produced at conventional dry-grind plants using natural gas and purchased electricity. In biomass cases that produce only process heat, it is assumed that 90% of the maximum credit is captured when biomass substitutes for process heat. The Federal Renewable Energy Electricity Credit of $.019/kWh is assumed to be received by the ethanol plant (even though it may be necessary for a private or corporate entity with sufficient passive income and tax liability to own the electrical generation equipment). There are additional minor assumptions including the Renewable Fuel Standard tradable credit of 10¢/gallon that approximates the average transportation and storage cost for the average unit of ethanol that gets produced and used in the U.S.

Certain expense items can be considered scale-neutral and are applied equally in 50 million gallon and 100 million gallon plants. These include per gallon expenses for enzymes, yeasts, process chemicals & antibiotics, boiler & cooling tower chemicals, water and denaturants. We assume $.04 per gallon of enzyme expense, $.004 per gallon of yeast expense, processing chemicals & antibiotics of $.02 per gallon (Shapouri and Gallagher, 2005). We also assume boiler and cooling tower chemical costs of $.005 and water of $.003 per gallon of denatured ethanol produced. We assume $120,000 of real estate taxes, $840,000 of licenses, fees & insurance, as well as $240,000 in miscellaneous

Table 5. Common Assumptions for all Systems

Category	Baseline Values
Debt-Equity Assumptions	
Factor of Equity	40%
Factor of Debt	60%
Interest Rate Charged on Debt	8%
Depreciation Period	15 years
Output Market Prices	
Ethanol Price	$1.80/gallon
DDGS Price	$100/ton
Electricity Sale Price	$0.06/kWh
Sale Price of Ash	$200/ton
CO2 Price Per Liquid Unit	$8/ton
Low-Carbon Premium	20¢/gallon
Government Subsidies	
Federal Small Producer Credit	$0.10
RFS Ethanol Tradable Credit	$0.10
Federal Renewable Electricity Credit	$0.019/kWh
Feedstock Delivered Price Paid by Processor	
Corn Price	$3.50/bushel
Energy Prices	
Natural Gas	$8/decatherm
Stover Delivered to Plant	$80/ton
Electricity Price	$0.06/kWh
Propane Price	$1.10/gallon
Operating Costs -- Input Prices	
Denaturant Price Per Gallon	$1.80/gallon
Denaturant Rate (Volume Units Per 100 of Anhydrous)	5
Ethanol Yield (Anhydrous)	2.75 gallon/bushel

expenses per year in the 50 million gallon plants, whether powered by natural gas or biomass, with these figures doubled in the case of 100 million gallon nameplate plants. We apply the assumption that management and quality control costs represent one third of labor costs for large and small plants (Nicola, 2005).

Maintenance expenses of biomass plants were established by starting with the costs per gallon of ethanol produced in a natural gas-fired plant (Shapouri and Gallagher, 2005) and then determining maintenance costs of the biomass technology bundles in proportion to the capital costs of each biomass bundle. To establish maintenance costs for the 100 million gallon conventional and biomass plants, we applied the scale-up factor for capital costs of 2.0 raised to the .7 exponent (1.62) and multiplied it by the maintenance costs of the corresponding 50 million gallon plant.

Labor expenses of biomass plants were established by starting with the costs per gallon of ethanol produced in a natural gas-fired plant (Shapouri and Gallagher, 2005) and then adding the estimates of additional labor needed in the biomass technology bundles. A 50 million gallon per year nameplate biomass-powered plant producing process heat can be expected to have $184,000 more in labor expense than its natural gas-fired counterpart (Nicola, 2005). We assumed an additional $184,000 increase in labor expense for the 50 million gallon biomass bundles that generate electricity. In the case of labor costs for 100 million gallon plants, we applied the conclusion that the larger plants spend 75% as much per gallon produced as the smaller plants (Kotrba, 2006). Thus, a 100 million gallon natural gas-fired plant can be expected to spend $4,500,000 per year in labor versus $3,000,000 in a 50 million gallon plant. A 100 million gallon per year nameplate biomass plant producing process heat is expected to have $368,000 greater labor expense than its natural gas-fired counterpart (Nicola, 2005). We assumed an additional $368,000 in labor costs for plants that generate electricity at the 100 million gallon scale are needed.

Economic Model

Biomass fuel/technology combinations along with a conventional natural gas plant are compared in a workbook, with each assigned a specific worksheet. Pro forma budgets are constructed for each combination and a common menu page is established to orchestrate various economic conditions to determine the economic viability of various options. The format of the pro forma budgets used to analyze ethanol plant economic sensitivity was originally developed by Tiffany and Eidman (2003).

The nine biomass fuel technology combinations and the conventional plant are compared on the basis of rates of return using the baseline assumptions for 50 million gallon and 100 million gallon per year capacities. Sensitivities of rates of return to changes in some of the key variables are then evaluated.

Results

Baseline Cases

Rates of return on investment for 50 million gallon per year capacities are shown in Figure 10. At baseline conditions rates of return of biomass plants producing process heat exceed the natural gas-fired plant only in the cases of stover and syrup + stover. Syrup and stover utilization in plants producing CHP also provide a higher rate of return than the natural gas-fired plant. Under baseline assumptions, natural gas-fired plants have higher rates of return than any of the three biomass plants producing CHP plus sales of electricity to the grid. Similar comparisons are shown for the 100 million gallon per year plants in Figure 11.

Sensitivity to Changes in Key Variables

Sensitivities of rates of return to changes in key variables are compared in Tables 6 and 7 for 50 million gallon and 100 million gallon per year plants, respectively. Shaded values indicate higher rates of return for biomass alternatives than for the corresponding conventional plant. Rates of return are higher in magnitude for the larger plants; however, the cases which favor biomass alternatives over conventional plants are the same for both plant sizes in relative terms.

An exogenous rise in natural gas prices from $8 to $12 per decatherm affect conventional ethanol plants with no effects shown on the biomass plants when all plants are at baseline conditions. Shifts to higher natural gas prices from the baseline level, drastically cut the ROR of the conventional plant powered by natural gas, giving all the biomass options higher RORs than the conventional plants at $12 per decatherm and even at $10 per decatherm for both sizes of plants. The natural gas price issue is very sensitive to currently constructed ethanol plants, and despite the higher capital costs to implement the biomass options, higher rates

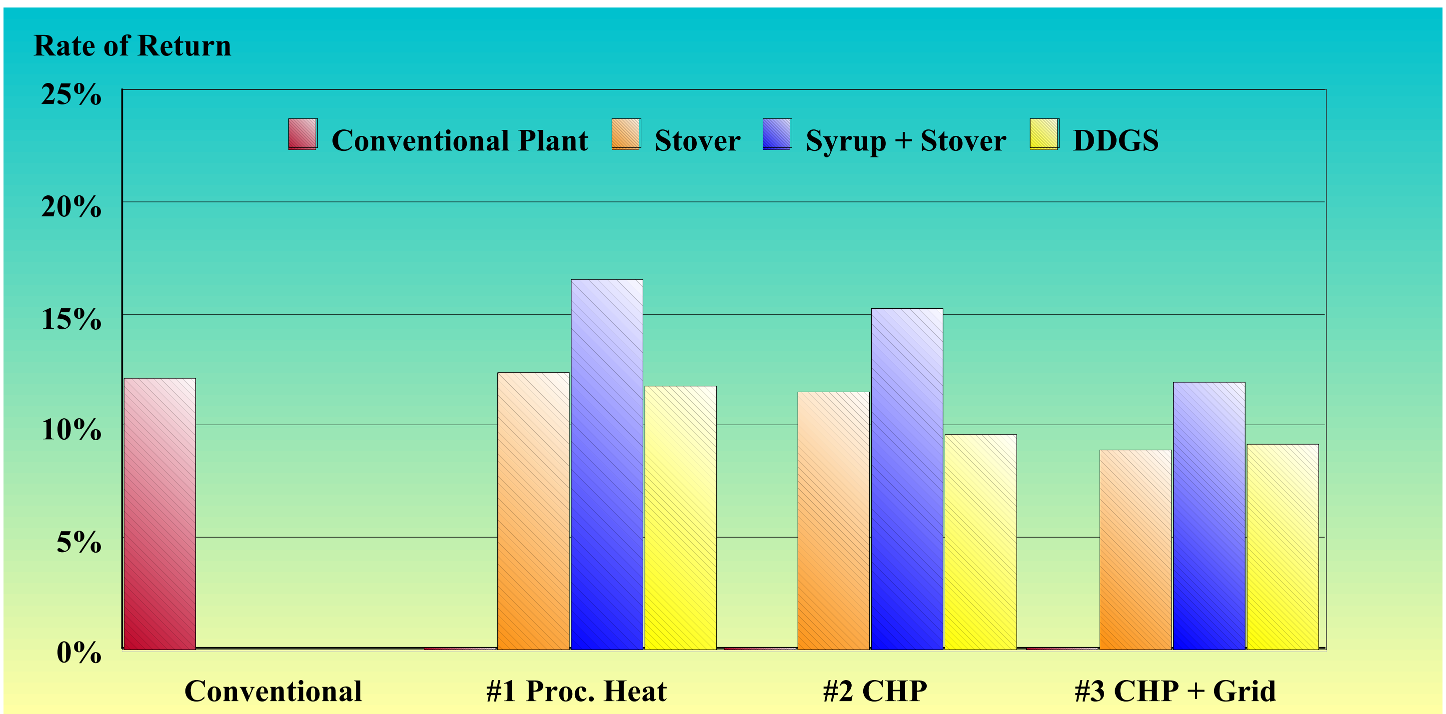

Figure 10. Baseline Rates of Return for 50 Million Gallon Per Year Capacities for the Nine Biomass Fuel/Technology Combinations and the Conventional Plant

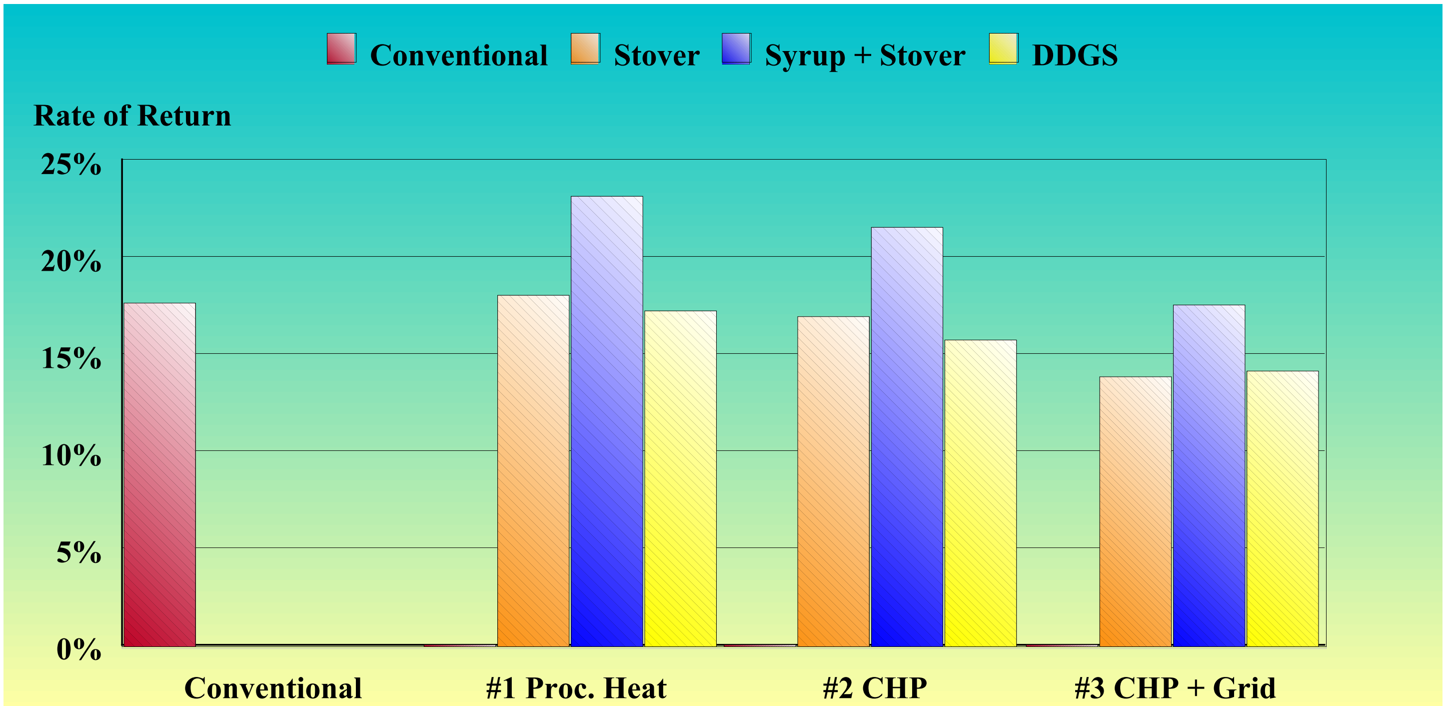

Figure 11. Baseline Rates of Return for 100 Million Gallon Per Year Capacities for the Nine Biomass Fuel/Technology Combinations and the Conventional Plant

of return will be captured by plants utilizing biomass under baseline conditions.

Declines in DDGS prices from $100 to $70 per ton have a more pronounced effect on the conventional plant using natural gas. Plants using stover as fuel have substantial declines as well, for they are producing as much DDGS as the conventional plant. The plants using syrup and stover are less affected and have less DDGS to sell in all cases because the syrup represents 40% of the dry matter in DDGS. The plants combusting DDGS have the least effect with the drop in DDGS price; and in the case of level #3 (CHP plus sales of electricity to the grid), no effect is noted because all of the DDGS are combusted.

Higher ethanol prices would remove much of the economic attraction for designing and building ethanol plants capable of using biomass. Higher ethanol prices experienced when moving from the price of $1.80/gallon at baseline to $2.00/gallon result in a favorable rate of return on investment in the case of the conventional plant. The shift to lower ethanol prices is similar to conditions experienced by plants in the second half of 2007, with ethanol prices dropping from the baseline level of $1.80/gallon to $1.60/gallon. With this exogenous shift, the biomass-powered plants' rates of returns were trimmed much less than the conventional plants' rate of return.

Changes in the premium price for ethanol produced with a low carbon footprint can have substantial impact on the rates of return of the biomass-powered plants. If the price premium increases from $.20 to $.40 per gallon, the biomass-powered plants at all fuel/technology combinations are favored over conventional ethanol plants. If the price premium is zero instead of the $.20 per gallon assumed in the baseline, the RORs of the biomass-powered plants are trimmed and are less than those of the conventional plants, which are unaffected.

In instances where electricity can be sold at a favorable price of 10¢/kWh versus 6¢/kWh, the CHP plus grid cases experience higher rates of return. This would reflect a situation of a utility making a strong response to a state mandate for renewable energy. Such a shift, with other levels at baseline, results in a higher rate of return for the CHP + Grid option for the Stover + Syrup bundle versus the conventional natural gas-fired plant.

A rise in corn price from the $3.50/bushel baseline to $4.00/bushel reduces the rates of return of all the plants. However, it is interesting to note that the biomass-powered plants possess a degree of economic resiliency due to their control of the second highest operating cost of natural gas and the premiums they would receive for producing low carbon fuel versus the conventional plant in this shift from baseline levels. Despite higher capital costs than the conventional plants, biomass plants offer greater stability in their RORs and may be positioned to achieve more success in the face of corn prices substantially above the baseline of $3.50 per bushel.

Table 6. Sensitivity on the Rates of Return to Changes in Key Economic Parameters for 50 Million Gallons Per Year Plants[a]

Case Number and Description of Sensitivity Analysis	Convention-al Plant	Biomass Process Heat: Corn Stover	Stover & Syrup	DDGS
1. Baseline Case	12.1%	12.4%	16.6%	11.8%
2. Natural Gas: $8 to $12/decatherm	5.0%	12.4%	16.6%	11.8%
3. DDGS: $100 to $70/ton	7.1%	9.0%	14.0%	10.7%
4. DDGS: $100 to $130/ton	17.1%	15.8%	19.1%	12.8%
5. Ethanol: $1.80 to $2.00/gallon	22.8%	19.6%	24.3%	19.2%
6. Ethanol: $1.80 to $1.60/gallon	1.5%	5.2%	8.8%	4.4%
7. Low carbon premium: 20¢ to 40¢/gallon	12.1%	18.6%	23.2%	18.2%
8. Low carbon premium: 20¢ to 0¢/gallon	12.1%	6.2%	9.9%	5.4%
9. Electricity sale price: 6¢ to 10¢/kWh	12.1%	12.4%	16.6%	11.8%
10. Corn price: $3.50 to $4.00/bu	2.9%	6.2%	9.8%	5.3%
11. Corn stover price: $80 to $100/ton	12.1%	10.5%	15.8%	11.8%
12. Corn stover price: $80 to $60/ton	12.1%	14.3%	17.3%	11.8%
13. Natural gas: $8 to $12/dekatherm and DDGS: $100 to $70/ton	0%	9.0%	14.0%	10.7%
		Biomass CHP		
1. Baseline Case	12.1%	11.5%	15.2%	9.6%
2. Natural Gas: $8 to $12/decatherm	5.0%	11.5%	15.2%	9.6%
3. DDGS: $100 to $70/ton	7.1%	8.5%	12.9%	9.0%
4. DDGS: $100 to $130/ton	17.1%	14.6%	17.6%	10.3%
5. Ethanol: $1.80 to $2.00/gallon	22.8%	18.0%	22.3%	16.4%
6. Ethanol: $1.80 to $1.60/gallon	1.5%	5.0%	8.2%	2.8%
7. Low carbon premium: 20¢ to 40¢/gallon	12.1%	17.7%	21.9%	16.1%
8. Low carbon premium: 20¢ to 0¢/gallon	12.1%	5.3%	8.5%	3.1%
9. Electricity sale price: 6¢ to 10¢/kWh	12.1%	11.6%	15.2%	9.8%
10. Corn price: $3.50 to $4.00/bu	2.9%	5.9%	9.1%	3.7%
11. Corn stover price: $80 to $100/ton	12.1%	9.6%	14.3%	9.6%
12. Corn stover price: $80 to $60/ton	12.1%	13.5%	16.1%	9.6%
13. Natural gas: $8 to $12/dekatherm and DDGS: $100 to $70/ton	0%	8.5%	12.9%	9.0%
		Biomass CHP + Grid		
1. Baseline Case	12.1%	8.9%	12.0%	9.2%
2. Natural Gas: $8 to $12/decatherm	5.0%	8.9%	12.0%	9.2%
3. DDGS: $100 to $70/ton	7.1%	6.2%	9.9%	9.2%
4. DDGS: $100 to $130/ton	17.1%	11.7%	14.0%	9.2%
5. Ethanol: $1.80 to $2.00/gallon	22.8%	14.8%	18.3%	15.4%
6. Ethanol: $1.80 to $1.60/gallon	1.5%	3.1%	5.7%	3.0%
7. Low carbon premium: 20¢ to 40¢/gallon	12.1%	14.5%	18.0%	15.1%
8. Low carbon premium: 20¢ to 0¢/gallon	12.1%	3.3%	5.9%	3.3%
9. Electricity sale price: 6¢ to 10¢/kWh	12.1%	10.1%	13.2%	10.4%
10. Corn price: $3.50 to $4.00/bu	2.9%	3.8%	6.5%	3.8%
11. Corn stover price: $80 to $100/ton	12.1%	6.5%	10.3%	9.2%
12. Corn stover price: $80 to $60/ton	12.1%	11.4%	13.6%	9.2%
13. Natural gas: $8 to $12/dekatherm and DDGS: $100 to $70/ton	0%	6.2%	9.9%	9.2%

[a] Darker shaded values indicate higher rates of return for biomass alternative than for corresponding conventional plan

Table 7. Sensitivity of Rates of Return to Changes in Key Economic Parameters for 100 Million Gallons Per Year Plants[a]

Economic Parameters	Conventional Plant	Biomass Process Heat: Corn Stover	Stover & Syrup	DDGS
1. Baseline Case	17.6%	18.0%	23.1%	17.2%
2. Natural Gas: $8 to $12/decatherm	8.8%	18.0%	23.1%	17.2%
3. DDGS: $100 to $70/ton	11.4%	13.9%	19.9%	15.9%
4. DDGS: $100 to $130/ton	23.7%	22.2%	26.3%	18.5%
5. Ethanol: $1.80 to $2.00/gallon	30.7%	26.9%	32.7%	26.4%
6. Ethanol: $1.80 to $1.60/gallon	4.4%	9.1%	13.5%	8.1%
7. Low carbon premium: 20¢ to 40¢/gallon	17.6%	25.6%	31.3%	25.1%
8. Low carbon premium: 20¢ to 0¢/gallon	17.6%	10.4%	14.9%	9.4%
9. Electricity sale price: 6¢ to 10¢/kWh	17.6%	18.0%	23.1%	17.2%
10. Corn price: $3.50 to $4.00/bu	6.2%	10.3%	14.8%	9.3%
11. Corn stover price: $80 to $100/ton	17.6%	15.7%	22.2%	17.2%
12. Corn stover price: $80 to $60/ton	17.6%	20.4%	24.0%	17.2%
13. Natural gas: $8 to $12/dekatherm and DDGS: $100 to $70/ton	2.6%	13.9%	19.9%	15.9%
		Biomass CHP		
1. Baseline Case	17.6%	16.9%	21.5%	15.7%
2. Natural Gas: $8 to $12/decatherm	8.8%	16.9%	21.5%	15.7%
3. DDGS: $100 to $70/ton	11.4%	13.2%	18.6%	14.9%
4. DDGS: $100 to $130/ton	23.7%	20.7%	24.4%	16.4%
5. Ethanol: $1.80 to $2.00/gallon	30.7%	25.0%	30.1%	24.0%
6. Ethanol: $1.80 to $1.60/gallon	4.4%	8.9%	12.8%	7.3%
7. Low carbon premium: 20¢ to 40¢/gallon	17.6%	24.6%	29.7%	23.6%
8. Low carbon premium: 20¢ to 0¢/gallon	17.6%	9.3%	13.2%	7.7%
9. Electricity sale price: 6¢ to 10¢/kWh	17.6%	17.1%	21.5%	15.9%
10. Corn price: $3.50 to $4.00/bu	6.2%	10.0%	14.0%	8.4%
11. Corn stover price: $80 to $100/ton	17.6%	14.5%	20.4%	15.7%
12. Corn stover price: $80 to $60/ton	17.6%	19.4%	22.6%	15.7%
13. Natural gas: $8 to $12/dekatherm and DDGS: $100 to $70/ton	2.6%	13.2%	18.6%	14.9%
		Biomass CHP + Grid		
1. Baseline Case	17.6%	13.8%	17.5%	14.1%
2. Natural Gas: $8 to $12/decatherm	8.8%	13.8%	17.5%	14.1%
3. DDGS: $100 to $70/ton	11.4%	10.4%	14.9%	14.1%
4. DDGS: $100 to $130/ton	23.7%	17.2%	20.1%	14.1%
5. Ethanol: $1.80 to $2.00/gallon	30.7%	21.0%	25.3%	21.7%
6. Ethanol: $1.80 to $1.60/gallon	4.4%	6.6%	9.7%	6.5%
7. Low carbon premium: 20¢ to 40¢/gallon	17.6%	20.7%	24.9%	21.4%
8. Low carbon premium: 20¢ to 0¢/gallon	17.6%	6.9%	10.1%	6.8%
9. Electricity sale price: 6¢ to 10¢/kWh	17.6%	15.3%	19.1%	15.6%
10. Corn price: $3.50 to $4.00/bu	6.2%	7.5%	10.8%	7.5%
11. Corn stover price: $80 to $100/ton	17.6%	10.8%	15.5%	14.1%
12. Corn stover price: $80 to $60/ton	17.6%	16.8%	19.5%	14.1%
13. Natural gas: $8 to $12/dekatherm and DDGS: $100 to $70/ton	2.6%	10.4%	14.9%	14.1%

[a]Darker shaded values indicate higher rates of return for biomass alternative than for corresponding conventional plan

A shift to higher stover prices from $80 to $100 per ton results in minor shifts in the RORs of the options that use stover and no effect on the plants that use DDGS as a fuel. In any case, process heat and CHP applications still maintain higher rates of return than the conventional plant in the case of the syrup plus corn stover fuel. These results offer some assurance that additional expenses that may be required to densify and process corn stover can be economically justified by plants using corn stover. However, if corn stover is available as cheap as $60 per ton, then three additional biomass options exceed the natural gas fired plant, including the stover + syrup option producing CHP and electricity for the grid.

Case 13 in Tables 6 and 7 shows the effects of two exogenous factors on RORs of the competing technology bundles. If the price of DDGS drops from baseline of $100 to $70 per ton and natural gas rises from baseline at $8 to $12 per decatherm, the ROR of a conventional plant is reduced to zero for the 50 million gallon per year case, while all the plants using biomass would be producing reasonably favorable rates of return. Although, all rates of return are higher for the larger plants, biomass alternatives produce much higher RORs than the natural gas-fired plant under these assumptions.

Conclusions

Various technology bundles of equipment, fuels and operating activities were modeled and found capable of supplying energy and satisfying emissions requirements for dry-grind ethanol plants of 50 and 100 million gallons per year capacity using corn stover, distillers dried grains and solubles (DDGS), or a mixture of corn stover and "syrup" (the solubles portion of DDGS). From these specifications, capital and operating costs for plants using biomass fuels were estimated. Although plants using biomass have higher capital costs, they offer increased economic resiliency to changes in some of the key operating variables. Results show favorable rates of return for biomass alternatives compared to conventional plants using natural gas and purchased electricity over a range of conditions. The mixture of corn stover and syrup provided the highest rates of return in general. Factors favoring biomass-fired plants include higher premiums for low carbon footprint ethanol, higher natural gas prices, lower DDGS prices, lower ethanol prices, and higher corn prices. The ramifications of Low Carbon Fuel Standards and policies to encourage electricity generated from biomass will have strong influences on the decisions of ethanol plants to utilize the biomass that is readily available at or near ethanol plants. This analysis identifies the potential to greatly improve the carbon footprint of ethanol produced from corn starch with processes and methods that are available today. In addition, dry-grind ethanol plants can produce substantial amounts of reliable, renewable electricity in excess of their needs while utilizing locally available biomass to reduce the carbon footprint of the fuel they produce.

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Biorefinery Product Opportunities from Glycerol

Joseph J. Bozell[1]

Introduction

Plant triglycerides from oil crops give the integrated biorefinery a hydrocarbon-based source of renewable carbon for the production of fuels and chemicals. Biodiesel is formed when triglycerides (or a wide variety of other naturally occurring hydrocarbons) are subjected to transesterification with methanol using a strongly basic catalyst such as sodium or potassium hydroxide. The reaction forms a mixture of fatty acid methyl esters (biodiesel), and aqueous glycerol (glycerine)[2] as a coproduct in a 90/10 wt% ratio (Claude, 1999).[3] The ease of this reaction, coupled with a \$1.00/gallon tax credit for biodiesel blenders, has stimulated significant recent growth for the industry. About 580 million gallons of biodiesel were produced in 2007, as compared with 100 million gallons as recently as 2005 (National Biodiesel Board, 2007). Biodiesel is fully compatible with existing diesel engines, and offers several environmental and performance benefits (Fukuda, Kondo, and Noda, 2001; Lotero *et al*, 2005; and Hill *et al*, 2006). In the context of the integrated biorefinery, biodiesel becomes one member of a family of compounds manufactured by an oleochemical operating unit also producing fatty acids, glycerol, meal and protein (Figure 1).

Recent research has focused on converting the glycerol coproduct into fuels and high value chemicals as a means to offset the production cost of biodiesel, which is significantly higher than nonrenewable diesel. In the biorefinery model, glycerol coproducts have a positive, synergistic effect on biodiesel production. Tyson *et al* have reported that inclusion of coproducts in biodiesel production could potentially lower the effective biodiesel cost from \$2.50/gal to slightly over \$1.00/gal (Tyson, *et al*, 2004). Conversely, failure to find new uses for glycerol may serve to limit the growth of the biodiesel industry as surplus glycerol accumulates.

A number of promising new technologies have started to emerge from current research as potential candidates for conversion of inexpensive glycerol into both fuel and chemicals (Pagliaro *et al*, 2007; Johnson and Taconi, 2007; and Behr *et al*, 2008).[4] This paper briefly overviews several new opportunities.

Glycerol in Fuel Applications

The nation's fuel supply is potentially an immense sink for consuming surplus glycerol. Glycerol's high polarity and water solubility preclude its direct addition to fuel supplies, but gasification and steam reforming have been examined as means to produce syngas (CO/H_2) or hydrogen from glycerol via equations 1 and 2 (Soares, Simonetti, and Dumesic, 2006).

$$C_3H_8O_3\ (\text{glycerol}) + H_2O \rightarrow 3\,CO + 4\,H_2 \qquad [1]$$

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad [2]$$

These processes are great equalizers of biomass feedstocks, as conditions can generally be found to deconstruct a huge number of different organic materials into hydrogen for fuel applications or syngas for well-known Fischer-Tropsch processes. The primary challenge to these processes is their cost relative to producing the same materials from coal or natural gas.

Syngas and hydrogen formation can be coupled with downstream conversions expanding gasification to include chemical and power production (Simonetti *et al*, 2007). By incorporating several fundamental process steps (reforming, catalytic upgrading, Fischer-Tropsch synthesis, combustion, etc.) with syngas production, glycerol can also be positioned as a primary biorefinery feedstock for chemicals, fuels and

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[2] Although the terms are frequently interchanged, this paper will use the term *glycerol* to describe the pure compound, 1,2,3-trihydroxypropane, and *glycerine* to describe an aqueous solution containing glycerol as the primary component.

[3] Note that other sources indicate up to 14 wt% of glycerol (Garcia, Besson, and Gallezot, 1997).

[4] The number of citations in Web of Science for the term "biodiesel" has increased from 46 in 2000 to 494 in 2007. The subset of those papers describing relevant research on glycerol has increased from three papers in 2000 to 68 in 2007.

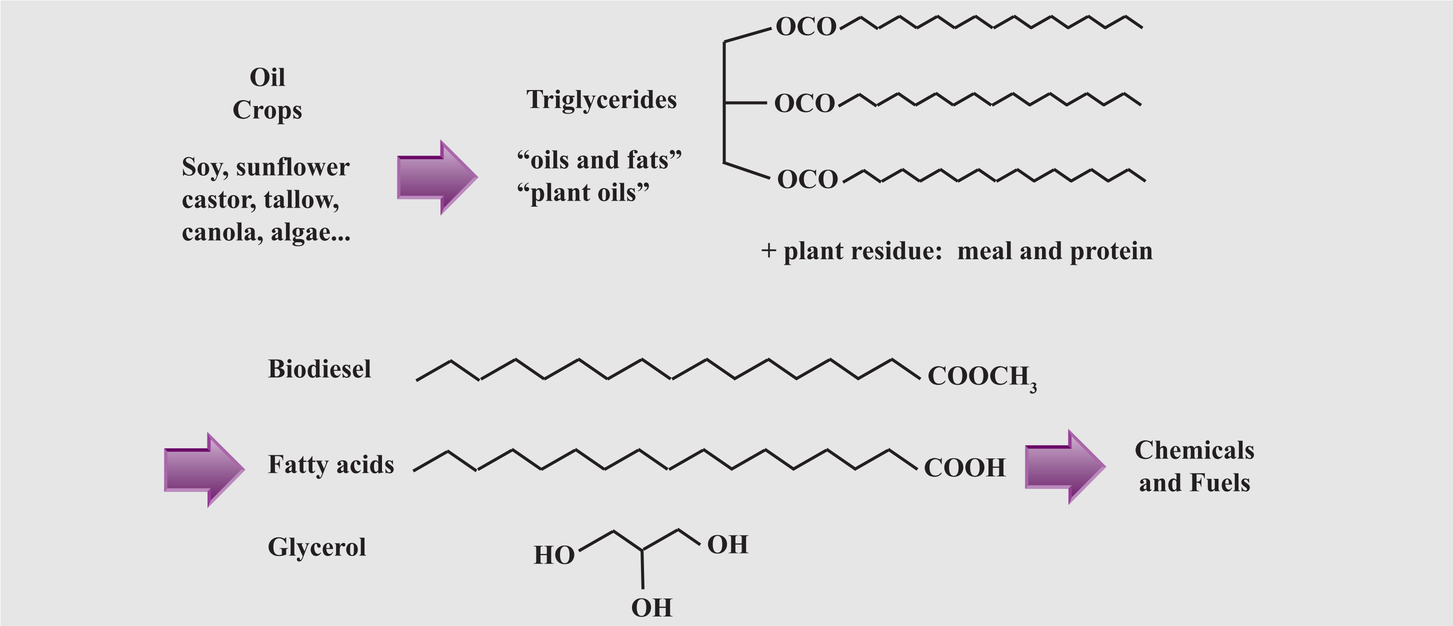

Figure 1. The Oleochemical Operating Unit of the Integrated Biorefinery

power, depending on the conversion technology employed. Glycerol can also be used as a starting material for production of fuel additives. Fuel oxygenates also address a large market opportunity for surplus glycerol. t-Butyl ethers and glycerol acetate esters are recognized as diesel (or gasoline) oxygenates because of their high octane value and ability to improve cold flow properties (Wessendorf, 1995; Klepacova, Mravec, and Bajus, 2005; and Karinen and Krause, 2006). Processes suitable for scaleup to pilot levels have been described (Behr and Obendorf, 2003, Melero *et al*, 2007).

Glycerol as a Primary Chemical Building Block for the Biorefinery

An effective consumption of glycerol will result from its use as a chemical building block. The historically high price of glycerol ($0.50 – 0.90/lb) has limited the economic viability of processes requiring chemical modification of its structure. Accordingly, glycerol has normally been used "as-is" after isolation and purification. As the price of glycerol drops and its availability rises, glycerol ceases to become a simple additive for a fragmented list of small volume products, and assumes a position as the starting point for the production of large volume materials. The polyfunctional structure of glycerol suggests a number of processes that can be carried out.

a. Reduction Processes

Catalytic hydrogenolysis converts glycerol into a family of derivatives currently produced by the chemical industry, including ethylene glycol, propylene glycol, acetol and lactic acid (Maris *et al*, 2007) (Figure 2). Of particular interest is Suppes' report of a selective, high yield hydrogenolysis of glycerol leading to propylene glycol (Dasari *et al*, 2005). Over 1 billion pounds of propylene glycol is produced annually, and serves as a replacement for ethylene glycol in antifreeze, as a polymer component and a number of smaller volume applications. The process also offers product control. By altering the conditions, acetol can be made as the primary product in >90% selectivity (Chiu *et al*, 2006). This process is currently being examined as a new commercial route for propylene glycol production.

b. Oxidation Processes

Catalytic oxidation converts glycerol into several structurally interesting materials, often in high yield (Figure 3) (Gallezot, 1997; Garcia, Besson, and Gallezot, 1995; Kimura *et al*, 1993; Kimura, 1993; Carrettin *et al*, 2002; Ketchie, Murayama, and Davis, 2007; and Ciriminna and Pagliaro, 2004). The product composition of these conversions is controlled through choice of catalyst, oxidant, and reaction pH. In contrast to glycerol reduction, the compounds most easily prepared by oxidation do not currently address large volume chemical markets. But as the cost of glycerol drops, products resulting from oxidation will experience a parallel drop in production cost, making the available structures of greater interest to industry. For example, Gallezot has described heterogeneously catalyzed aerobic processes that lead to glycerol derivatives of increasing oxidation state. More recent work has examined selective oxidation as a route to convert glycerol into acrylic acid, which would provide a link between a renewable starting material and another recognized high volume industrial chemical.[5]

[5] J. Dubois, French Patent FR 2897059 to Arkema, 2007.

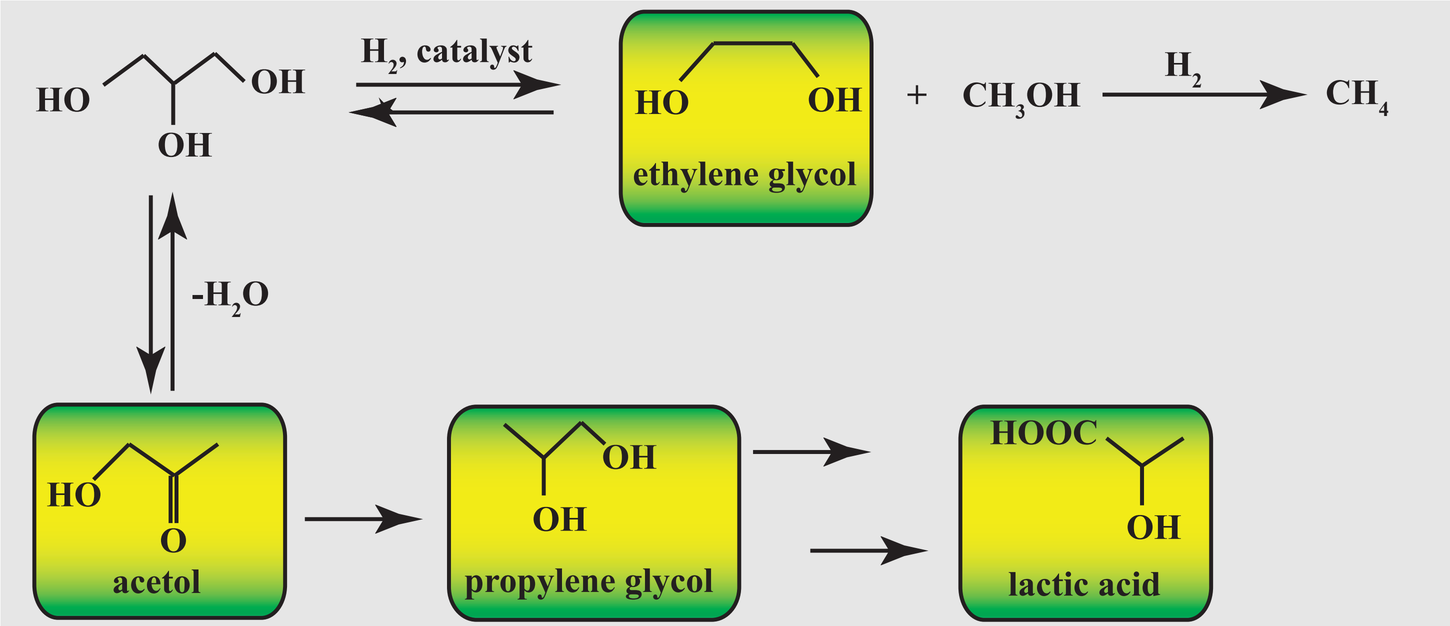

Figure 2. Glycerol Reduction Products

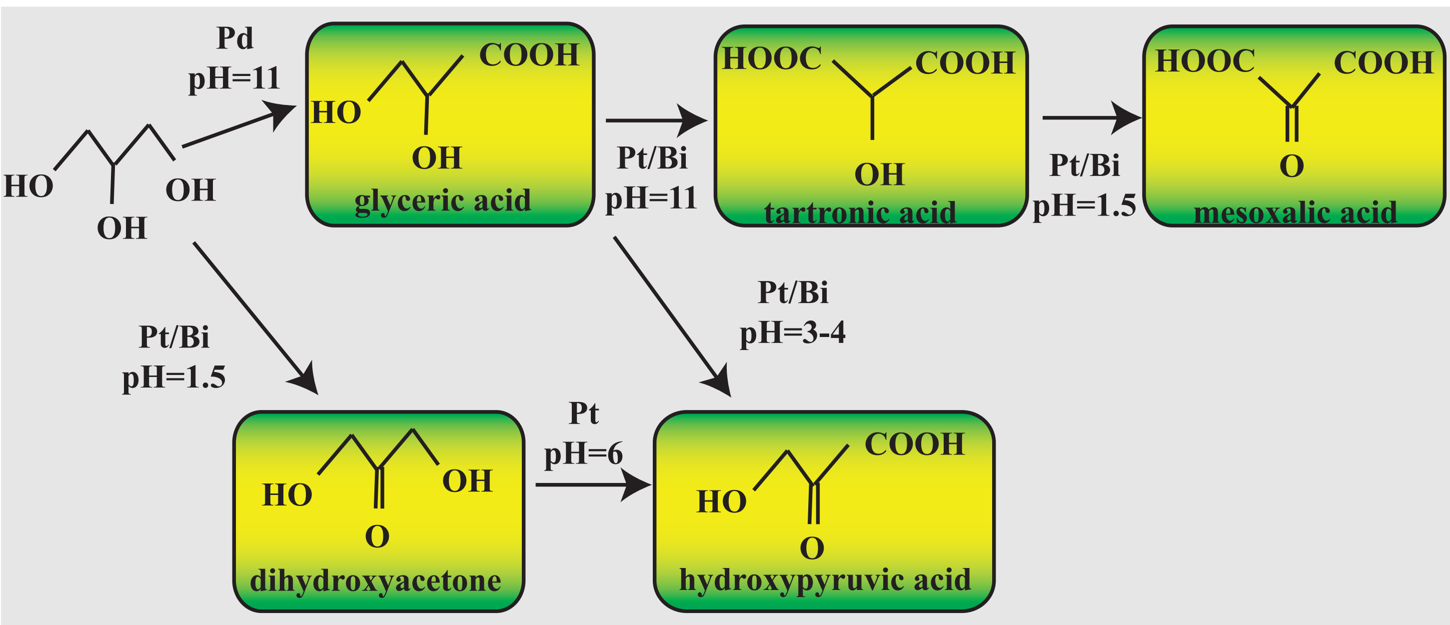

Figure 3. Glycerol Oxidation Processes

c. Dehydration Processes

Catalytic and thermal dehydration of glycerol is used to produce a third family of chemical derivatives (Figure 4), and links to several large volume products. Within this family of compounds, acrolein has received the most recent attention, primarily because of its possible use as a precursor to acrylic acid, a high volume chemical with an annual production of 2.6 x 10^9 lb. Several processes have been reported for this conversion (Watanabe *et al*, 2007; Ott, Bicker, and Vogel, 2006; Chai *et al*, 2007; and Tsukuda *et al*, 2007).

d. Polymerization Processes

Glycerol has traditionally played a role in the production of several types of commercial polymers. Selective etherification reactions convert glycerol into polyglycerol esters, which have been used as biodegradable surfactants and lubricants (Clacens, Pouilloux, and Barault, 2002; Kunieda *et al*, 2002)[6] and as replacements for conventional poly (oxoethylene) nonionic surfactants. Polyglycerol and polyglycerol methacrylates are used as treatments for wood to improve its stability (Morlat *et al*, 2001).

[6] A. Behler and B. Fabry, Eur Pat EP 1106675, 2001.

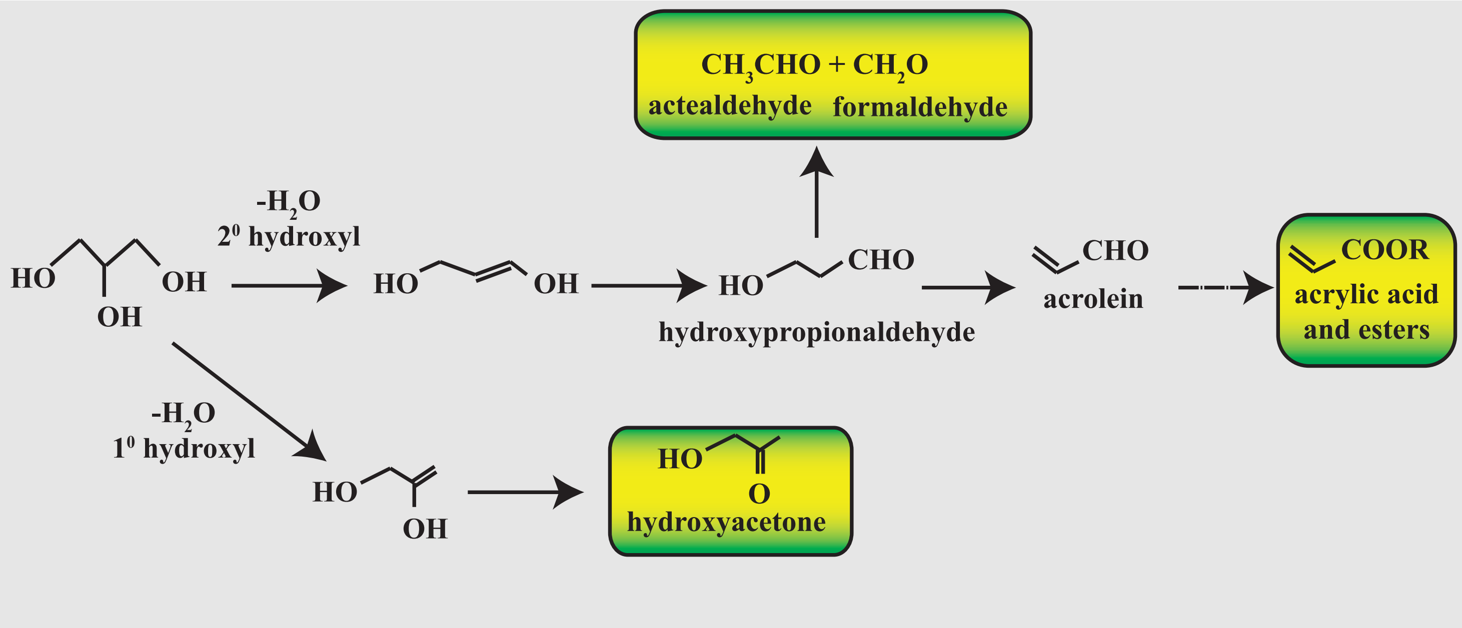

Figure 4. Dehydration Processes for Glycerol

More recently, glycerol's multifunctional structure has been used to prepare highly branched polymers (Arvanitoyannis *et al*, 1995). Branched polymers exhibit a wide range of new properties that could be exploited in useful marketplace products. Many of these could be high value applications, such as use in sensors, personal care products, or organic conductors. However, the volume of such materials will be fairly low, thus, while they might help the profitability of the oleochemical operating unit, they would not be able to offer a significant consumption of large amounts of glycerol. Other applications in large volume markets have been suggested, and branched polymers could find utility as polyester polyols, surfactants, coatings and alkyd resins, new solvents, and polyurethanes (Table 1).

Table 1. Size of Various Market Segments Related to the Use of Branched Polymers

Market Segment	Market Size	Year
	(10^6 lb)	
Polyether polyols	7600	2001
Polyester polyols	460	2001
Surfactants	1700[a]	2000
Alkyd resins & coatings	1700	2000
Polyurethane foam	3400	2001
Polyurethane elastomers	430	1997

[a]detergents only

e. Biochemical Processes

Glycerol is a feedstock in biochemical transformations, with the majority of current research focused on its conversion to 1,3-propanediol (1,3-PDO). 1,3-PDO is one of the components of DuPont's Sorona (1,3 PDO and terephthalic acid), a polymer being investigated for use in textiles and carpeting, and the basis of a commercial production facility in Loudon, TN. The current biochemical production of 1,3-PDO, developed by Genencor and DuPont[7], ferments corn-derived glucose using transgenic *E. coli*. However, glycerol can also be biochemically converted into 1,3-PDO (Cameron *et al*, 1998). Glucose-based processes give high 1,3-PDO concentrations (>125 g/L), but their yield (g 1,3-PDO/g glucose) is relatively low (30-40%). In contrast, the theoretical yield from glycerol is 67%. Fermentation of glycerol is being investigated with several organisms, including transgenic *Clostridium acetobutylicum* (Ganzalez-Pajuelo *et al*, 2006), *Klebsiella pneumoniae* (Mu *et al*, 2006)), and *Clostridium butyricum*. The latter is suggested to be an economical source of 1,3-PDO at a glycerol cost of $0.14/lb (Gonzalez-Pajuelo, Andrade, and Vasconcelos, 2004). Cameron has described engineering *E. coli* for a biochemical production of the structurally similar propylene glycol (1,2-PDO) from glycerol (Altaras and Cameron, 1999). This process proceeds through dihydroxyacetone as a metabolic intermediate, implying that proper choice of organism could lead to either 1,2- or 1,3-PDO from glycerol, since one of the first intermediates in 1,3-PDO production is also dihydroxyacetone (Cameron *et al*, 1998).

Several organisms ferment glycerol to 3-hydroxypropionaldehyde (3-HPA) (Doleyres, *et al*, 2005). Although research on 3-HPA is still exploratory, it is an interesting chemical intermediate as the proposed central component of a network of several high volume biorefinery products, including 1,3-PDO (Figure 5). HPA exhibits considerable product inhibition because of its toxicity (Zheng *et al*, 2006).

[7] L. Laffend, V. Nagarajan, and C. Nakamura, US Patent 5,686,276, 1997.

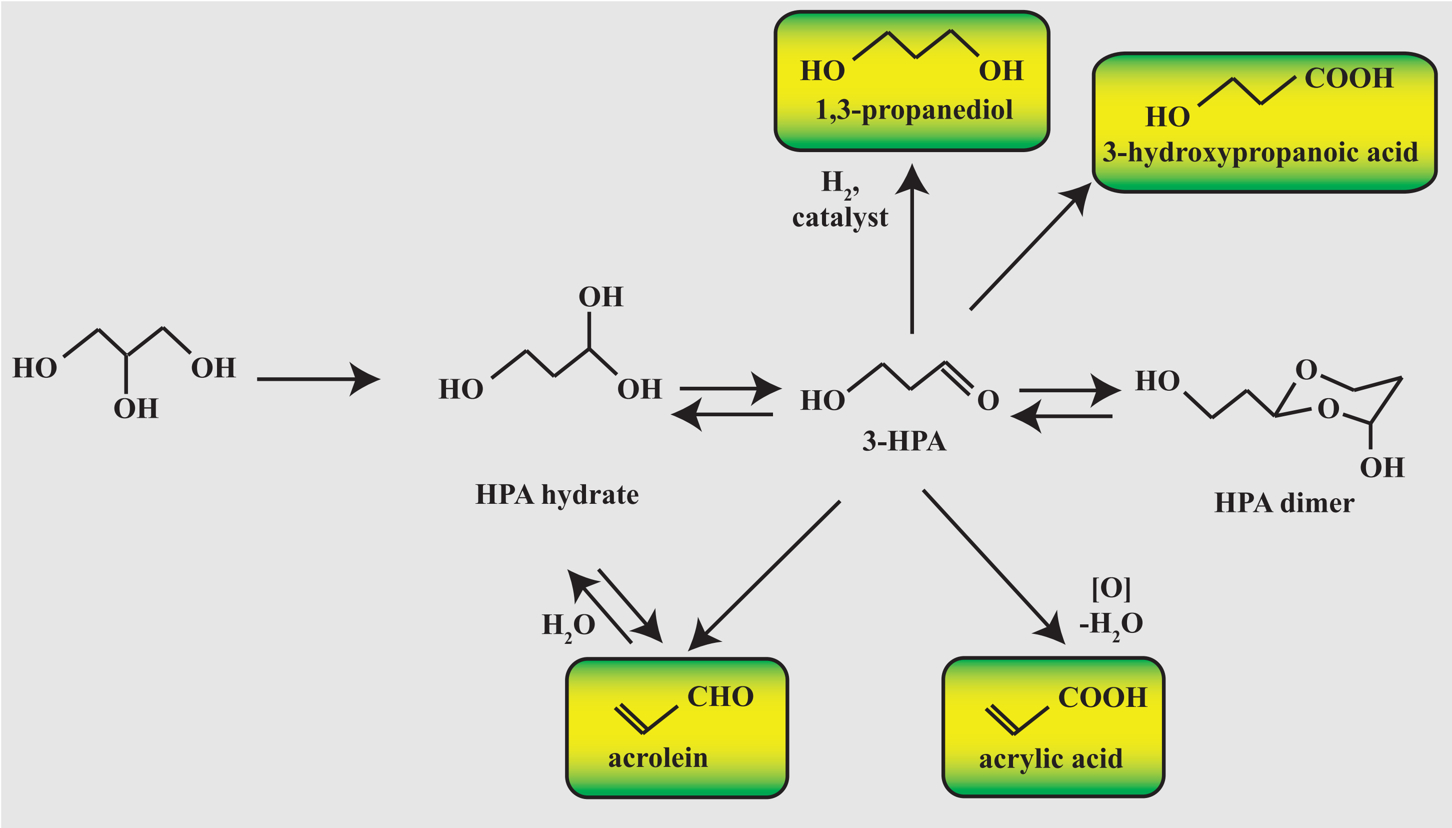

Figure 5. Conversion of Glycerol to 3-HPA and Related Derivatives

However, interest in 3-HPA as a chemical intermediate has led to processes that mediate its toxic effects, including product removal during fermentation (Ruetti *et al*, 2007), or fermentation with different organisms (Vancauwenberge, Slininger, and Bothast, 1990). In aqueous solution, *Lactobaccilus reuteri* exhibits significantly higher tolerance toward 3-HPA than other organisms and converts glycerol to reuterin, a natural antimicrobial that is an equilibrium mixture of 3-HPA, 3-HPA hydrate, and the 3-HPA dimer. The antimicrobial properties of reuterin have been extensively exploited in the food industry, for example, by inhibiting growth of *Listeria* or *E. coli* in meat and dairy products.

Inexpensive glycerol could allow 3-HPA to serve as a precursor to several important industrial chemicals. A potential large-scale use of 3-HPA is in the production of 1,3-PDO by combining the high yield of 3-HPA from *L. reuteri* or other processes with conventional catalytic hydrogenation (Besson *et al*, 2003).[8] A direct, one-pot approach is possible, as 3-HPA hydrogenations in aqueous solution have been reported.[9] The eventual choice between glycerol and glucose-based processes for PDO production will be made based on the relative economic performance.

Alternatively, 3-HPA is a precursor to acrolein and acrylic acid. Heating of aqueous 3-HPA solutions leads to the formation of acrolein, and conversely, acrolein hydration forms HPA hydrate. 3-HP is also a precursor to 3-hydroxypropanoic acid, which has been observed in low concentrations from a number of biosynthetic and enzymatic conversions of glycerol (van Maris *et al*, 2004).[10] Catalytic dehydrations of 3-hydroxypropionic acid can be used to form acrylic acid and acrylate esters.[11] However, no commercial processes based on this technology have been developed (Vollenweider, 2004).

f. Other Glycerol Derivatives

Glycerol carbonate. Glycerol carbonate (Figure 6) is a relatively new material in the chemical industry, but one that could offer some interesting opportunities, as it can be prepared directly and in high yield from glycerol.

Glycerol carbonate has been investigated as a novel component of gas separation membranes, polyurethane foams[12]

[8] G. Komplin and J. Smegal, PCT Patent WO 2007121219 to Shell International, 2007; N. Matsuoka and T. Kadota, Patent JP 2004182622 to Asahi, 2004.

[9] G. Komplin, J. Powell, and P. Weider, US Patent Application 20050414, 2005.

[10] M. Mukoyama and T. Toratani, Japan Patent JP 2007082476 to Nippon Shokubai Company, 2007; D. Cameron, World Patent WO 2000US23878 to Wisconsin Alumni Research Foundation, 2001.

[11] A. Zacher, J. Holladay, M. Lilga, J. White, D. Muzatko, R. Orth, P. Tsobanakis, X. Meng, and T. Abraham, PCT WO 2007106100 to Battelle Memorial Institute, 2007.

[12] D. Randall and R. De Vos, Eur Pat. EP 419114 to Imperial Chemical Industries PLC, UK 1991.

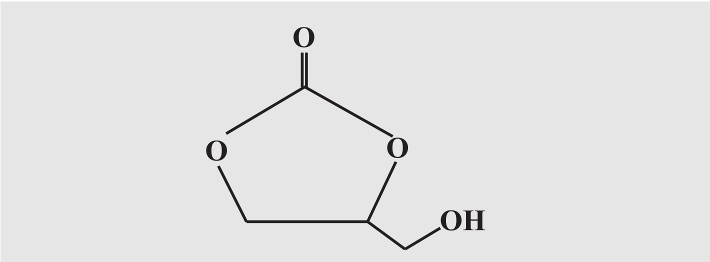

Figure 6. Structure of Glycerol Carbonate

as a surfactant component[13] as a new solvent for several types of materials, as a component in coatings, as a potential component of the paint industry, acting as a nonvolatile reactive solvent, as a source of new hyperbranched polymers (Rokicki *et al*, 2005), and as a component of detergents. Dimethyl carbonate is being positioned as a green replacement for phosgene in the production of polycarbonates and polyurethanes. Inexpensive glycerol carbonate could serve as a source of new polymeric materials for this industry.

Glycerol carbonate can be prepared by simple processes, such as the direct reaction of glycerol with urea at 120° in diethylene glycol for 24h[14] or the treatment of glycerol with ethylene or propylene carbonate.[15] Direct production of glycerol carbonate from glycerol and carbon dioxide under supercritical conditions or in the presence of tin or cerium catalysts has also been reported (Vieville, *et al*, 1999; Aresta *et al*, 2006).[16] Recently, glycerol carbonate has been synthesized in very high yield by the reaction of glycerol and dimethyl carbonate in the presence of an immobilized lipase from *Candida antarctica* (Kim *et al*, 2007).

Epichlorohydrin. Recent work has examined the use of glycerol as a starting material for the production of epichlorohydrin, a high value chemical intermediate with production levels of nearly 1 billion lb/yr. Traditional routes to epichlorohydrin start by hydroxychlorination of propylene, and proceed through 1,3-dichloro-2-propanol as an intermediate (Figure 7) (Weissermel and Arpe, 2003). However, this process also forms the 1,2-dichloro isomer, which is considerably less reactive. Glycerol, in contrast, selectively forms the 1,3-isomer, and thus, low cost glycerol could be a viable alternative for the production of epichlorohydrin. Recent work has examined the kinetics and mechanism of this reaction (Tesser *et al*, 2007).

Conclusions

The growth of today's biodiesel industry has resulted in the development of a parallel glut of glycerol. While glycerol is potentially a structurally well-defined three carbon chemical intermediate, its traditional high cost has resulted in a lack of technology for conversion into other chemical compounds. As the cost of glycerol drops, new processes incorporating additional conversion steps will become economically viable, allowing glycerol to be used as a platform for a wide variety of new biobased industrial chemicals and fuels.

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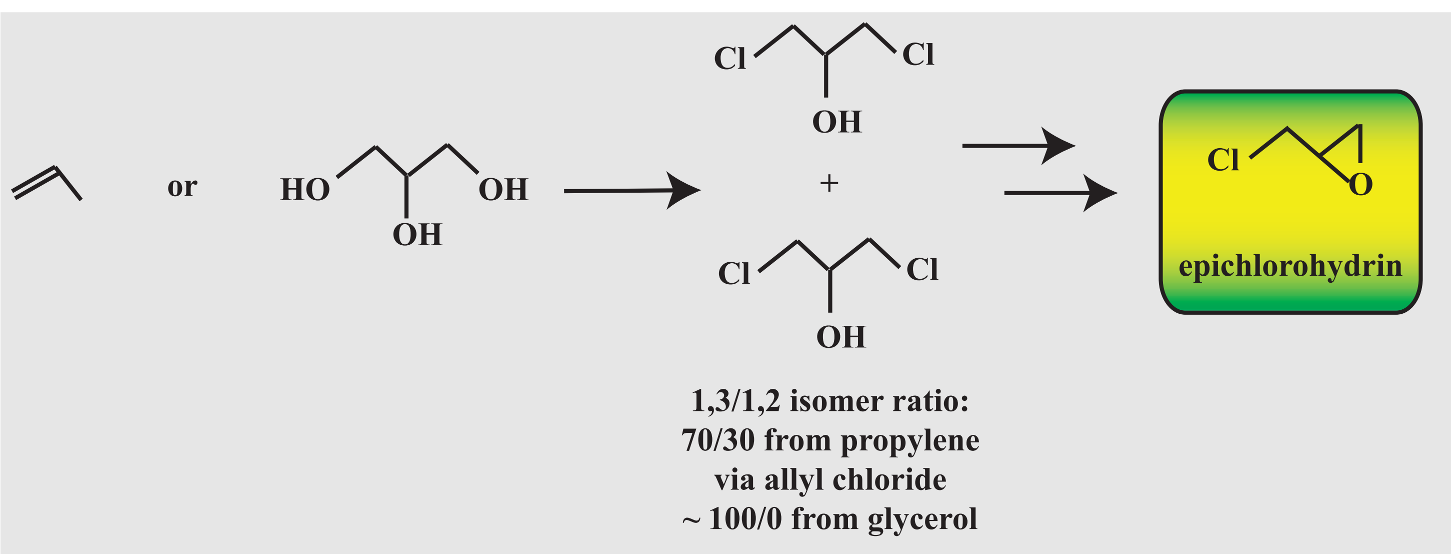

Figure 7. Conversion of 3-Carbon Building Blocks to Epichlorohydrin

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Feasibility of On-Farm or Small Scale Oilseed Processing and Biodiesel Production

Philip Kenkel and Rodney Holcomb[1]

Background

The rapid increase in biofuel production has had obvious impacts on the agricultural sector. The production of ethanol, the dominant biofuel in the U.S. has had significant impact on feed grain prices. A recent study by the Center for Agriculture and Rural Development projected that ethanol expansion is likely to continue under a long-run equilibrium corn price of $4.05/bu is achieved (Tokgoz et al., 2007). Corn producers, and owners of crop land in the grain belt region appear to be early beneficiaries from the ethanol boom. Other groups of producers, such as pork and poultry producers, are generally considered to be disadvantaged by higher feed prices. Many producers have also invested in ethanol and other biofuel projects. Not surprisingly, these investments have also been concentrated in the grain belt region. Producers in non-ethanol producing areas are often interested in benefiting from the new "biofuel economy".

The desire to participate in the perceived value-added opportunities of biofuel production has led to increased interest in small scale oilseed processing and biodiesel production. Biodiesel can be produced from a wide range of oilseed feed stocks. An oilseed based biodiesel operation is a technical possibility for producers in most regions of the U.S. The rapid increase in fuel expense has also contributed to the interest in small scale biodiesel production. Farm diesel prices have increased over 300% since the mid-1990s and have risen over 100% in the last three years (DOE-EIA, 2008). While fuel costs represent only 10% of the cost of production for most crops, they are a highly visible component. On-farm oilseed processing and biodiesel production is often considered as a possible strategy to mitigate the impact of rising fuel prices. Several states have also developed specific incentives to benefit producers who produce biofuels for their own consumption.

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The processing of extracting oil from oilseed crops and producing biodiesel and feed coproducts is not technically complex and can be conducted at a farm scale level. As in most industrial processes there are significant economies of scale to biofuel production. However there are several factors which could help to justify small scale biodiesel production. There is substantial variation in the local basis for oilseed crops. A producer's opportunity cost for diverting oilseed crops to a processing operation may therefore be substantially below the national or regional price level. A farm-scale oilseed processing/biodiesel production facility may also use farm infrastructure and/or labor which has low out-of-pocket costs. Many producers can also use the meal feed coproducts from oilseed processing in livestock operations or have opportunities to sell them in local markets. On-farm processing also eliminates transportation and retailing costs for both the fuel and the feed coproducts if used on-farm.

In light of the current interest in small scale oilseed processing/biodiesel production, there is a need to determine whether a farm-based or small scale operation could be economically feasible. This study examines the feasibility of a small scale integrated oilseed crushing and biodiesel production operation. The analysis considers alternate oilseed feed stocks and a range of biodiesel prices.

Oilseed Processing

Oil can be extracted from oilseed crops using either chemical (solvent) or mechanical systems. Solvent-based systems typically involve the use of hexane which is an environmentally sensitive and potentially explosive substance. The entry level price for a new solvent plant is over $10 million. Mechanical extraction systems include simple expellers (often called cold presses), pre-heated expellers and extruder-expeller systems. The process of heating oilseeds significantly increased the extraction efficiency. Heat pre-treatment also assists in deactivating enzymes and can improve the protein quality and texture of the meal, relative to that of a mechanical cold press.

Extruder/expellers compress the oilseed to very high pressure using friction as a source of heat to raise the temperature to approximately 135° C. The heat deactivating the enzymes and destroys micro-organisms. The compressed material then expands rapidly as it leaves the extruder. The expansion ruptures the starch cell structure, facilitating the release of the oil. After leaving the extruder the extruded oilseed is immediately processed in a screw press (Anderson, 2004). The extrusion step increases oil yield relative to a cold pressing system. In addition, the seeds have a very short dwell time at high temperature and the temperature and dwell time can be manipulated to improve the digestibility and quality of the meal. The meal from extruder/expeller system generally has a higher level of bypass protein, a desired property in dairy cattle rations.

Because of its relative simplicity and relatively high extraction efficiency, most small scale oilseed processing operations use the extruder-expeller technology. A flow chart of the process is provided in Figure 1.

Biodiesel Production

Biodiesel can be produced by chemically combining several types of natural oils or fats with an alcohol to form alkyl esters of fatty acids (Ryan, 2004). Fatty acid alkyl esters that meet stringent transportation fuel quality standards are generally known as biodiesel. Biodiesel can be used in pure form (B-100) or blended with petroleum diesel. Blends as low as 2% (B-2) have been demonstrated to be sufficient to create lubrication advantages, while blends are up 20% (B-20) can be used in most diesel engines without modification. Biodiesel has an oxygen content of approximately 11% (by weight). This oxygen in biodiesel improves combustion and therefore reduces hydrocarbon, carbon monoxide, and particulate emissions but tends to increase nitrogen oxide emissions. Biodiesel has better lubrication properties (lubricity) than current low-sulfur (500 ppm sulfur by weight) petroleum diesel. This lubricity advantage has become more important since ultra-low-sulfur petroleum diesel (15 ppm sulfur by weight) was introduced in 2006. A one or two percent volumetric blend

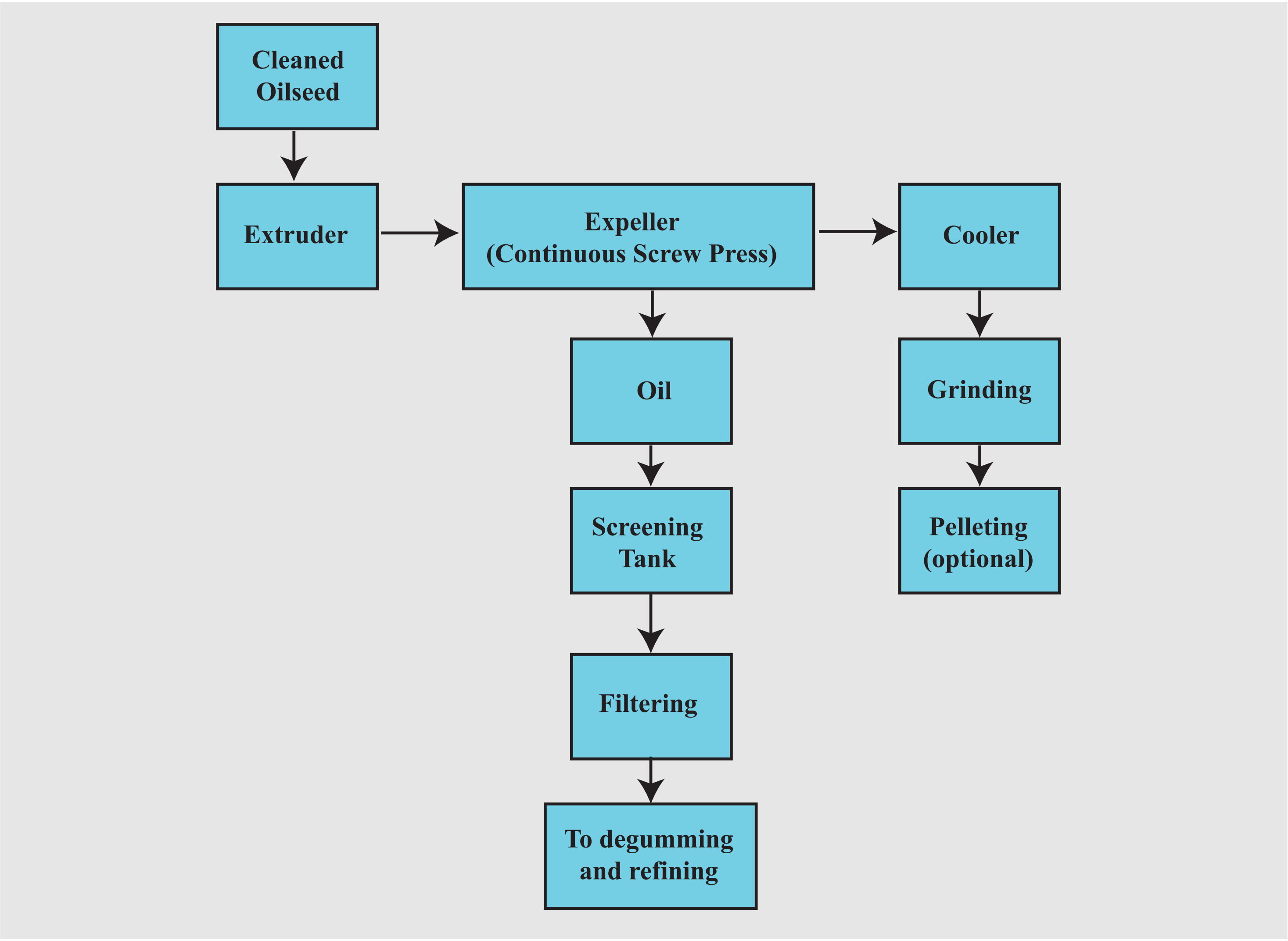

Figure 1. Extruder/Expelling Processing Flowchart

of biodiesel in low-sulfur petroleum diesel improves lubricity substantially. This lubricity advantage increased the demand for biodiesel demand as a fuel additive.

The most common production process for biodiesel is base catalyzed transesterification, a relatively simple process which has a conversion yield of around 98%. Crude vegetable oil contains triglycerides which are glycerine molecules three long chain fatty acids attached. (Vegetable oils vary in the nature of the fatty acids which can in turn affect the characteristics of the biodiesel.) In the transesterification process, the triglyceride is reacted with alcohol (usually methanol or ethanol) in the presence of a catalyst which is usually a strong alkaline like potassium hydroxide or sodium hydroxide. The alcohol reacts with the fatty acids to form the mono-alkyl ester, or biodiesel and crude glycerol.

The biodiesel production process (Figure 2) begins by mixing of alcohol and catalyst which is typically sodium hydroxide (caustic soda) or potassium hydroxide (potash). The alcohol and catalyst are mixed or agitated and then transferred to a closed reaction vessel where the oil is added. The system after adding the oil from here is totally closed to the atmosphere to prevent the loss of alcohol. The reaction mix is kept just above the boiling point of the alcohol (around 160°F) to speed up the reaction and process is closed to the atmosphere to prevent the loss of alcohol.

The reaction produces two basic products: glycerin and biodiesel. Each has a substantial amount of the excess methanol that was used in the reaction. Glycerin has a higher density than biodiesel and can be gravity separated by simply drawing off the bottom of the settling vessel. A centrifuge can be used to separate the glycerin and biodiesel more rapidly. The biodiesel is purified by washing gently with warm water to remove residual catalyst or soaps, dried, and sent to storage. Prior to use as a commercial fuel, the finished biodiesel must be analyzed using sophisticated analytical equipment to ensure it meets any required specifications.

The glycerin separation contains unused catalyst and soaps. Mineral acids are used to neutralize the glycerin before it is routed to the evaporator where water and alcohol are removed. These steps yield an 80-88% pure glycerin that can be sold as crude glycerin. The glycerin can also be distilled to 99% or higher purity and sold into the cosmetic and pharmaceutical markets.

Baseline Scenario

Equipment lists and cost quotations for "bare bones" systems for oilseed crushing and biodiesel production were estimated by the food equipment engineer at the Food and Agricultural Products Center at Oklahoma State University. The oilseed processing system had a capacity of approximately 1 ton per hour or around 2,000 tons/year if operated on an 8 hour day basis. The biodiesel equipment had an annual capacity of approximately 250,000 gallons/year which was a fairly close match to the protected oil yield from the crush operation using a high oil content oilseed such as canola. This production level would likely exceed the needs of most producers but could be a practical size for a small group of producers or cooperative. Operating costs for the biodiesel and crushing systems were based on the chemical inputs required for each gallon of throughput and from the electrical costs of the systems.

Results and Implications

The equipment compliment including a extruder-expeller with a 10 HP electric motor, associated conveying systems, two 500 gallon biodiesel reaction/settling tanks, methanol tank and various transfer and metering pumps was estimated to cost $341,369. No costs were included for a building or installation. The processing operation was assumed to be 50% debt financed at a 7.5% (Lawrence, 2008) interest rate. Electricity costs were estimated at $.08/KW (Sperry, 2008) and no expenses for operator labor were included. The meal feed coproduct was assigned a value of $300/ton (University of Missouri, 2008) which, at current price levels, represents the high end of the retail price for a 35-40% protein supplement. The biodiesel produced was assigned a value of $3.00/gallon and no subsidies were considered. While obviously optimistic, this price might be appropriate for producers in states with specific subsidies for on-farm production of biodiesel. An opportunity cost value of $.11/lb (Neuens, 2008) was assigned to the canola seed processed. The scenarios considering sunflower and soybeans used values of $.15/lb and $8.00/bu (Neuens, 2008) respectively.

At the (admittedly optimistic) baseline assumptions the canola processing/biodiesel operation had an internal rate of return of 5.71%. It should be emphasized that this analysis assumed use of existing land and buildings and placed on value on the farm operator labor. At this level of returns even a producer with excess labor availability would be better served by paying down existing farm loans rather than investing in the processing operation. The sensitivity of the returns to the implicit value of the biodiesel and meal feed coproduct are provided in Tables 1 and 2. The analysis indicates that on-farm processing might be attractive at biodiesel values above $3.10/gallon and/or meal values above $320/ton.

Canola seed has an oil content of approximately 40%. The analysis of sunflower seed which has an oil content of 44% and a slightly higher farm value (opportunity cost) yielded similar profitability levels. However the on-farm processing of soybeans (which have an oil content of approximately 20%) was not projected to be profitable at biodiesel prices below $3.50. Because the extracted oil and biodiesel is the more valuable on a per pound basis relative to the meal feed

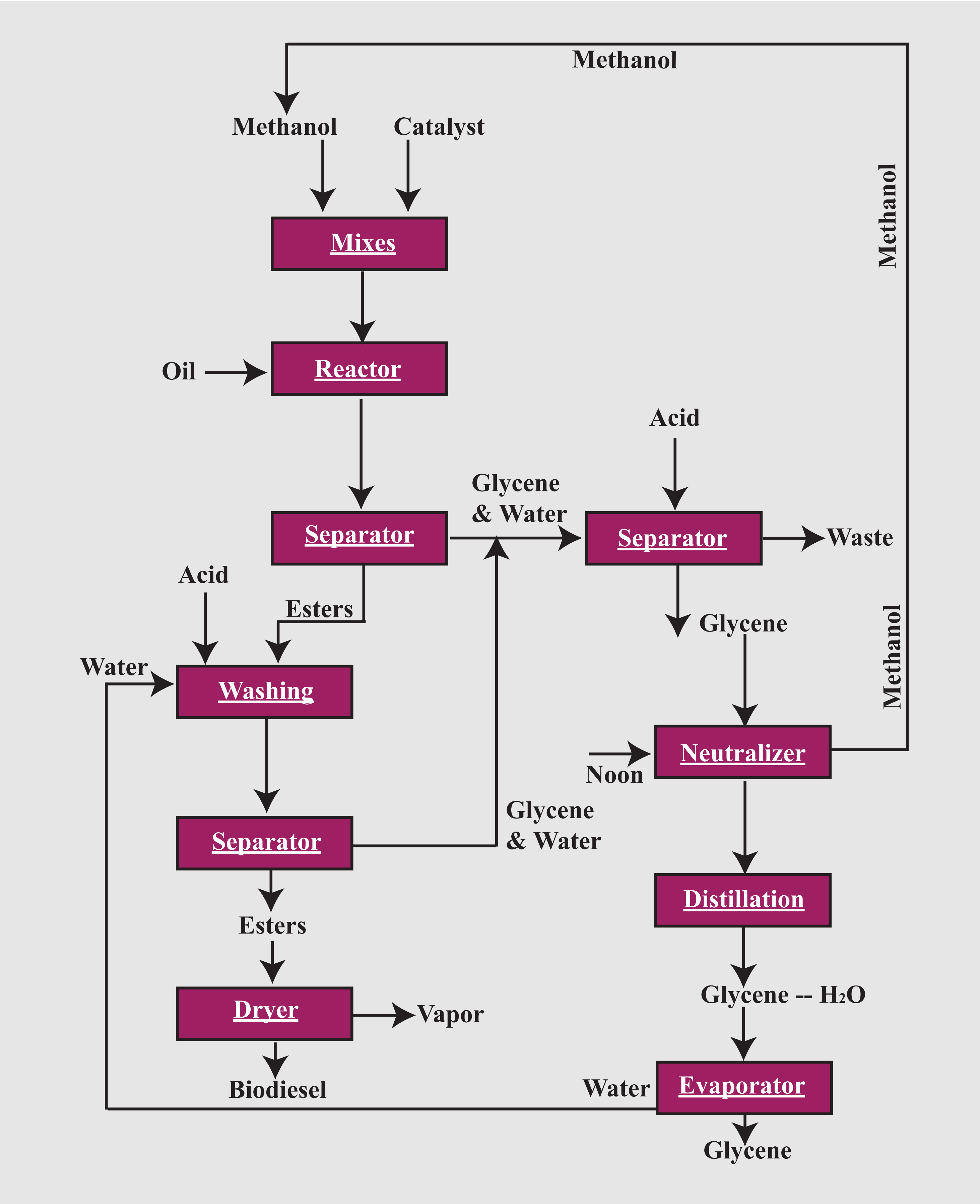

Figure 2. Biodiesel Production Process

Table 1. Sensitivity of Canola Processing Return to Biodiesel Value

Economic Variable	Biodiesel Price					
	$2.90	$3.00	$3.10	$3.20	$3.30	$3.40
Internal Rate of Return	Neg	5.7%	15.7%	24.2%	40.2%	47.9%
Return on Assets	-3.3%	4.4%	12.1%	19.7%	27.4%	35.0%
Return on Equity	-6.4%	8.8%	24.2%	39.5%	54.8%	70.0%

Table 2. Sensitivity of Canola Processing Return to Meal Value

Economic Variable	Meal Price					
	$280	$290	$300	$310	$320	$330
Internal Rate of Return	Neg	0.3$	5.7%	10.7%	15.3%	19.6%
Return on Assets	-3.1%	0.7%	4.4%	8.1%	11.9%	15.7%
Return on Equity	-6.2%	1.3%	8.8%	16.3%	23.8%	31.3%

Table 3. Breakeven Oilseed Crop Values at Various Biodiesel Prices

Economic Variable	Biodiesel Price				
	$2.50	$2.75	$3.00	$3.25	$3.50
Breakeven Canola Price $/lb	0.082	0.097	0.113	0.130	0.146
Breakeven Sunflower Price $/lb	0.074	0.091	0.108	0.125	0.143
Breakeven Soybean Price $/bu	5.30	6.00	6.70	7.40	8.10

coproduct, the profitability decreases as the oil content of the feed stock crop decreases.

Grain market prices, which represent the opportunity cost of processing oilseed into biodiesel are obviously one of the key factors in determining the feasibility of an on-farm crushing and biodiesel production operation. Current (spring 2008) oilseed prices are at historic highs. Processing $12/bu soybeans or $.21/lb canola or sunflowers into biodiesel would require a biodiesel value of over $4.75/gallon to breakeven. The breakeven oilseed crop price for various biodiesel price levels is provided in Table 3.

Conclusion

Interest in on-farm or small scale processing of oilseed crops into biodiesel is likely to cycle with fuel prices. The results of this study indicate that an on-farm canola processing/biodiesel operation is not profitable at current biodiesel and meal feed prices. However the returns are sensitive to the value of biodiesel and to a lesser extent the value of the meal feed. Producers who placed a high value on the biodiesel produced either because of its value in replacing purchased fuel or through state-specific incentives might find on-farm processing of a high oil content crop such as canola or sunflowers profitable. On-farm processing of soybeans (the predominant oilseed crop in the U.S.) is much more difficult to justify. Because of the lower oil content, a soybean based processing operation is unlikely to cover even the direct production costs at reasonable biodiesel values.

The results summarized in this report were developed using the "On-Farm Oilseed Processing Feasibility Template" developed by Oklahoma State University. The template which is incorporated into a Microsoft Excel spreadsheet allows the user to customize the analysis to meet their particular situation and to consider a wide range of sensitivity analysis. A full report of the feasibility study and the feasibility template are available free of charge by contacting Phil Kenkel, Department of Agricultural Economics, Oklahoma State University, phil.kenkel@okstate.edu.

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Economic Value of Ethanol Byproducts in Swine Diets: Evaluating Profitability of Corn Fractionation Techniques

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Introduction

According to the National Corn Grower's Association (NCGA, 2007), the U.S. ethanol industry will be generating approximately 16 million tons of distiller's grains in 2012, or more than twice the amount produced in 2004. In addition to DDGS, new dry-milling processes have resulted in new feedstuffs such as germ and bran as a protein and energy supplement. Technology for corn-to-ethanol conversion continues to improve. The dramatic increase in fuel ethanol production, with a concurrent increase in feed products from the same plants, warrants a thorough nutritional assessment of these new byproducts in order to determine their economically optimal utilization in the livestock feeding sectors. In addition, there is an urgent need to determine the profitability of new techniques employed in ethanol production and understand how these new techniques affect the nutritional value of the resulting byproducts.

Among many technological improvements that have been made to the conventional ethanol processing methods to improve yield and reduce operating costs, corn fractionation, which has been used for some time in wet milling, is arguably the most cost-effective technology. Although there are many variants, the basic process of corn fractionation involves fractionating or separating the corn kernel into three fractions: fiber, germ and endosperm. The technique helps increase starch availability for ethanol production, as well as increase protein concentration of the resulting byproducts. It is also claimed to increase profitability of ethanol plants through higher ethanol yields and reductions in plant emissions and energy costs. A number of companies, including Renessen LLC (Jakel, 2006), Poet LLC and FWS Technologies, have developed and improved the fractionation technique to increase ethanol yields and produce high value byproducts. As of October 2007, Poet Ethanol, the largest dry-mill ethanol producer in the United States, has three ethanol plants using the new and improved bio-refining technology for advanced corn fractionation, marketed as the "BFrac" technique. The technology produces Dakota Gold HP, Dakota Bran and Dakota Gold Corn Germ Dehydrated (see Figure 1).

DDGS, with its high fiber content, is fed primarily to ruminants. However, with new fractionation techniques that reduce fiber content, DDGS could be used effectively for non-ruminants such as swine and poultry. Feed costs typically represent more than 60% of total costs of production for livestock producers. Protein and energy are the nutrients with the largest impact on feed cost. Even with the introduction of new value-added products from improved technologies, little research has been done to compare the economic value of different types of DDGS and new feed byproducts in the market.

Given the importance of feed costs and the effect of fractionation techniques on the nutritional value of the feed byproducts, the first objective of this study is to estimate and compare the economic value of feed byproducts as ingredients for swine diets from traditional ethanol plants and from plants that employ fractionation techniques. Processing techniques have a major impact on the nutritional profile of the resulting byproducts. Therefore, the second objective of this study is to determine if the changes in investment and operating costs associated with the new corn fractionation technology can be justified economically given the projected changes in the value of byproducts. For this purpose, shadow prices and yield data are used to calculate the revenue from conventional and fractionation techniques of ethanol production in order to determine the possibility of offsetting processing costs of the new technology.

Background

Economic viability of the entire grain-based fuel ethanol industry is heavily dependent on the market value of the distiller's grains byproduct that is sold as feed to the livestock industry. Economic Research Service of the United States Department of Agriculture (USDA-ERS) estimates that 75

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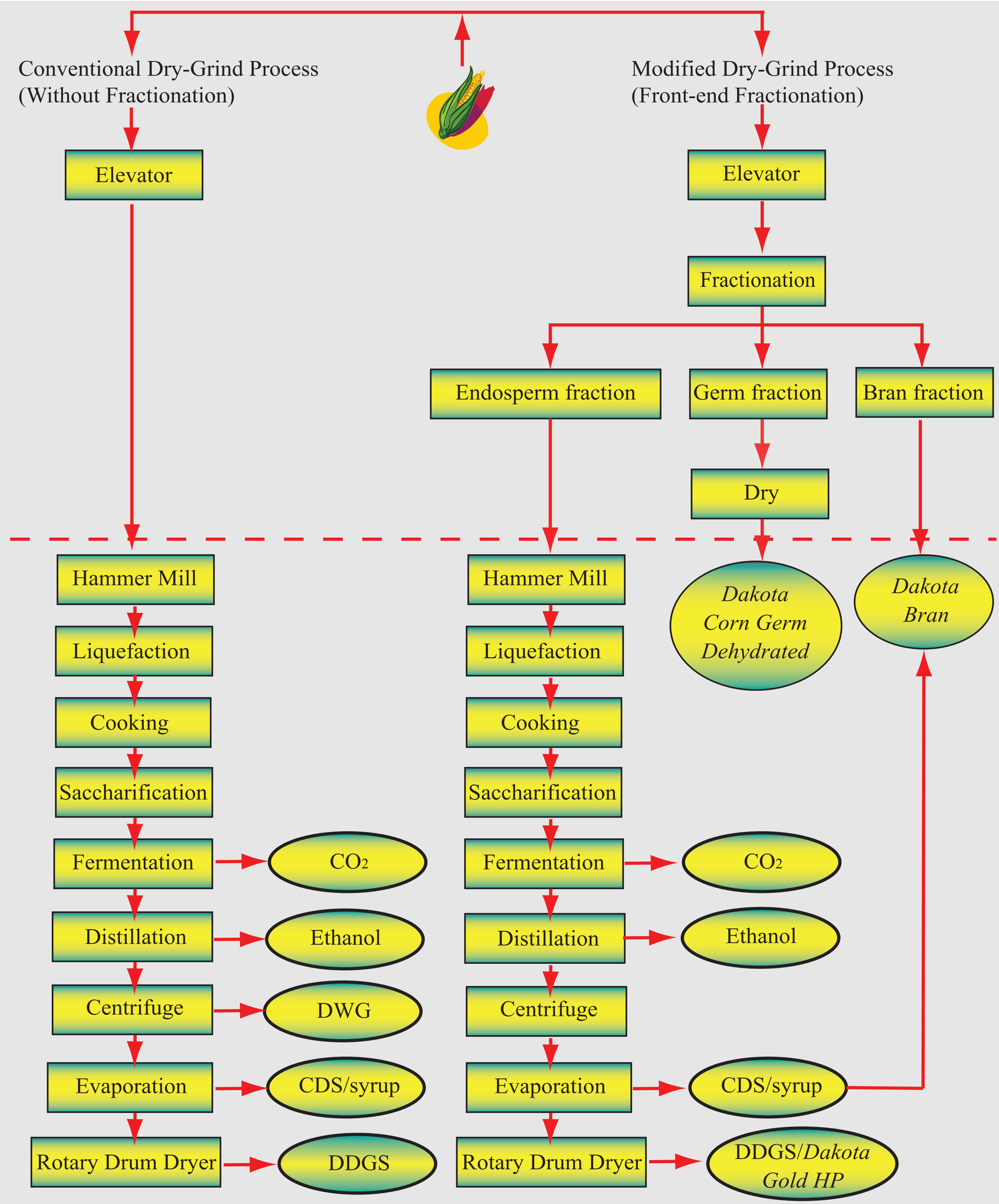

Figure 1. Ethanol Production, With and Without Fractionation Technology

percent of distiller's grains produced are fed to livestock in the U.S., 10 percent is exported and 15 percent goes to other non-feed domestic uses. Of the 75 percent within the livestock portion, 80 percent is assumed to go to beef cattle, 10 percent to dairy cattle, and 5 percent each to hogs and poultry (USDA-ERS, 2007). Animal nutrition studies estimate that distiller's grains on a dry matter basis are assumed to replace corn in rations of 1 pound distiller's grains for 0.85 pound corn for hog rations (Shurson *et al*., 2003; Vander Pol *et al*., 2006).

The germ fraction of the corn kernel, produced from fractionation, can be used as a protein and energy supplement to replace concentrates (corn and SBM) in feedlot and dairy diets (Kleinhans, Pritchard, and Holt, 2005). The bran fraction of the corn kernel is added to the corn condensed distiller's solubles (CDS) or syrup to produce a high fiber byproduct. This study calculated the economic value of fractionated DDGS and the germ fraction for use in swine diets.

Data and Methodology

In a typical feed ration model, a ration is formulated to minimize cost while providing sufficient nutrients to meet the needs of the animal type being fed. In order to value the byproducts (DDGS and Germ) as a feed ingredient, it is necessary to determine the nutrient requirements for various production phases of swine. These requirements will include the minimum and maximum levels of protein, amino acids, and other nutrients necessary for healthy hog growth at different stages of development. Second, the nutritional profile of the feed byproducts to be used by producers and other main feed ingredients are required. The levels available to hogs will provide the economic valuation necessary to determine inclusion levels in a nutritious diet. Thirdly, the various prices for all the feed ingredients need to be found to provide the proper valuation and minimal cost for a diet containing DDGS and Germ. Finally, these factors need to be brought together to determine the ability DDGS or Germ has to complement corn and soybean meal in a viable swine diet.

An evaluation of DDGS inclusion levels in swine diets requires a study of hog response at various growth stages. Optimal swine diet is based on digestible lysine levels with the other prominent amino acids as a percentage of digestible lysine. The prices for major feed ingredients were taken from Feed Ingredient Weekly, October 2007 (Informa Economics, 2007), while synthetic amino acid prices were obtained from Akey's Feed Company (Richert, 2007).

Nutrient data on conventional DDGS (without fractionation technique) was obtained from Big River Resources Ethanol plant at West Burlington, Iowa (Richert, 2007). The Iowa plant uses state-of-the-art technology to produce high quality DDGS using conventional dry milling technique. Data on the nutrient profile of fractionated byproducts for swine diets i.e. fractionated DDGS and Germ (from BFrac technology) was obtained from the Poet LLC website (2006) (Table 1). Data show that fractionated DDGS is higher in digestible lysine than either Iowa DDGS or Germ. Low digestibility of lysine in DDGS is a result of heat damage due to excessive heating during the drying process (Stein, 2006). The Germ fraction has lower digestible lysine content than the fractionated DDGS because Germ is produced by further drying the germ fraction of the corn kernel.

Diets of grow-finish pigs weighing 45-95 lbs (Grower1), 95-155 lbs (Grower2), 155-205 lbs (Finisher1), 205-260 lbs (Finisher2) and 300-500 lbs (Gestating Sow) were formulated to contain the same level of apparent digestible lysine within each of the dietary phases. These experimental diets were formulated assuming perfect knowledge of unit prices of feedstuffs, nutrient requirements, and nutrient composition of feedstuffs. Two diets are formed at the Finisher2 production

Table 1. Nutrient Composition Comparison (as Fed Basis) between Byproducts

	Units	Iowa DDGS	Fractionated DDGS	Germ
Metabolizable Energy	kcal/lb	1775	1687	1828
Crude Protein	%	29.1	41.0	15.7
App. Dig. Lysine	%	0.51	0.70	0.47
App. Dig. Meth+Cys	%	0.85	1.72	0.46
App. Dig. Threonine	%	0.73	1.16	0.30
App. Dig. Tryptophan	%	0.15	0.27	0.13
App. Dig. Isoleucine	%	0.75	1.16	0.23
App. Dig. Valine	%	0.98	1.57	0.43
Calcium	%	0.03	0.01	0.02
Phosphorous	%	0.81	0.35	1.28
Digestible Phosphorous	%	0.49	0.28	0.77
Crude Fiber	%	6.20	6.67	5.10

phase -- one with Paylean-9®, and one without Paylean-9®. Paylean® (ractopamine hydrochloride by Elanco) is a feed additive that can increase the rate and efficiency of muscle tissue growth in pigs that helps produce lean and quality pork (Schinckel, Richert, and Kendall, 2001). Paylean-9® refers to Paylean® at 9 grams per ton mixed into the feeds for the finishing production phase only. According to Elanco, Paylean® can be fed at levels of 4.5 to 9 grams per ton for the last 45-90 lbs live weight prior to market. The 9 grams per ton level results in substantial reduction in carcass fat gain especially at the time of the maximal Paylean® response.

Linear Programming Model for Diet Cost

A feed ration model, in the form of a constrained cost minimization linear program (LP), was used to impute the value of the Iowa DDGS, fractionated DDGS and Germ. The model minimizes feed cost subject to upper and lower bounds on nutrients specific to the growth stage of the pig. The model chooses a cost minimizing mix of the feedstuffs that sum to a full diet complement equal to one so that the reported inclusion rates for each item are in percentage terms. The value of the byproduct was observed as the shadow price on the byproduct inclusion constraint. The maximum and minimum nutrient inclusion rates in the diet was obtained from Tri-State Swine Nutrition Guide, Bulletin 869-98 (1998) and the National Research Council (NRC) guidelines for swine (NRC, 1998). The shadow value, at the maximum inclusion levels, serves as a proxy for the market value of the DDGS and Germ as a feed ingredient incorporated at the specified levels conditional upon the prices of other feed ingredients and the specified nutrient limits.

Excel Spreadsheet Model for Ethanol Plant

The second objective of this paper was to determine the plant revenue from the byproducts from the two technologies under study, with and without fractionation. For this purpose, a model of a 50 million gallon per year (MGY) ethanol plant was constructed in Excel. Data on capital cost, operating cost, amount of corn required and yield information for the model plant employing fractionation technology was obtained from FWS Technologies (2006), a division of the FWS Group of Companies based in Winnepeg, Canada. The spreadsheet uses this information along with prices of corn (input) and outputs (ethanol and byproducts) to calculate revenue and cost of ethanol production.

The minimum across the different rations of the shadow values from the LP model for Iowa DDGS, fractionated DDGS and Germ, at their maximum inclusion level were used as proxies for the market values of the byproducts. Shadow prices represent the maximum a firm would be willing to pay. What they actually pay is different for a wide range of reasons on both the supply and demand sides. To account for that difference, the market price for DDGS divided by the shadow value of the Iowa DDGS to serve as the ratio of DDGS market and shadow values for fractionated DDGS and Germ is used. This is an approximation, but it is the best value that can be obtained within the scope of the analysis and given the paucity of market data on the other products. Earnings, before interest, taxes, depreciation and amortization (EBITDA), was used to evaluate a plant's profitability and operating performance.

Financial assumptions for the ethanol plant were made as 40% proportion of equity paid on the debt capital, 60% proportion of debt paid on the debt capital, a debt interest rate of 8% and the rate of return on equity capital as 12% (Tyner and Taheripour, 2007). Therefore, the weighted average return percent required by investors on new debt and equity capital is 9.6%. This value is used as the discount rate for the investment decisions on the new technology. Using the discount rate and the life of the plant as 20 years, the present value of the increased annual revenue is calculated. This value also represents the maximum ethanol producers could pay in increased capital cost for the fractionation plant.

Results and Discussion

The first objective of this study was to estimate and compare the economic value of the Iowa DDGS and the fractionated byproducts. Diet formulations will depend on the nutritional profile of the byproducts included in the diet and the nutrient requirements of the pig's phase of growth. The data show large differences in nutrient concentrations of the byproducts for the two processing methods (see Table 1). It is important to remember that in this paper, swine diets are balanced on digestible lysine levels with the other prominent amino acids as a percentage of digestible lysine (see Tables 2 and 3). Tables 4, 5 and 6 present the least cost diet and nutrient composition for each of the feeding phases with maximum inclusion levels of Iowa DDGS, fractionated DDGS and Germ respectively.

Comparing the diets for the various distiller's products to the corn-soybean meal based diets formulated by the same model as "control" diets (see Table 7), there are varying rates of replacement for corn and soybean meal in the diet. The Iowa DDGS product replaces both corn and soybean meal at a ratio of 75-77% corn and 23-25% SBM. However, the fractionated DDGS replaces a much greater amount of SBM on a ratio basis, 47-52% SBM and 48-56% Corn. The germ product is more similar to the conventional DDGS with a 81-85% Corn: 13-19% SBM dietary replacement ratio.

Results presented in Table 8 show that the diet containing fractionated DDGS has about half or less of the inclusion rates of the Iowa DDGS in all the grow-finish phases. Due to the rich amino acid profile of the fractionated DDGS, a lower inclusion rate is necessary to meet the amino acid constraints while maintaining proper metabolizable energy levels. At

Table 2. Nutrient Composition per lb of Feed Ingredient[a]

	Corn	SBM	Limestone	DiCalPhos	Vitpremix
Metabolizable Energy	1551	1533	0	0	0
Crude Protein	8.30%	47.50%	0.00%	0.00%	0.00%
App. Dig. Lysine	0.17%	2.57%	0.00%	0.00%	0.00%
App. Dig. Meth+Cys	0.30%	1.16%	0.00%	0.00%	0.00%
App. Dig. Threonine	0.20%	1.44%	0.00%	0.00%	0.00%
App. Dig. Tryptophan	0.04%	0.53%	0.00%	0.00%	0.00%
App. Dig. Isoleucine	0.31%	1.81%	0.00%	0.00%	0.00%
App. Dig. Valine	0.22%	1.84%	0.00%	0.00%	0.00%
Calcium	0.03%	0.34%	38.50%	21.50%	0.00%
Phosphorous	0.28%	0.69%	0.02%	18.50%	0.00%
Digestible Phosphorous	0.04%	0.16%	0.02%	18.50%	0.00%
Crude Fiber	2.30%	3.40%	0.00%	0.00%	0.00%
Vit. Premix	0.00%	0.00%	0.00%	0.00%	100.00%

[a] Ingredient composition for these feedstuffs are from the Swine NRC, 1998.

Table 2 (Cont.). Nutrient Composition per lb of Feed Ingredient[a]

	Lysine HCL	DL Meth	Grease	Lthreo	Ltryp
Metabolizable Energy	0	0	3615	0	0
Crude Protein	78.00%	98.00%	0.00%	98.00%	98.00%
App. Dig. Lysine	78.00%	0.00%	0.00%	0.00%	0.00%
App. Dig. Meth+Cys	0.00%	98.00%	0.00%	0.00%	0.00%
App. Dig. Threonine	0.00%	0.00%	0.00%	98.00%	0.00%
App. Dig. Tryptophan	0.00%	0.00%	0.00%	0.00%	98.00%
App. Dig. Isoleucine	0.00%	0.00%	0.00%	0.00%	0.00%
App. Dig. Valine	0.00%	0.00%	0.00%	0.00%	0.00%
Calcium	0.00%	0.00%	0.00%	0.00%	0.00%
Phosphorous	0.00%	0.00%	0.00%	0.00%	0.00%
Digestible Phosphorous	0.00%	0.00%	0.00%	0.00%	0.00%
Crude Fiber	0.00%	0.00%	0.00%	0.00%	0.00%
Vit. Premix	0.00%	0.00%	0.00%	0.00%	0.00%

[a] Ingredient composition for these feedstuffs are from the Swine NRC, 1998.

the maximum inclusion levels, the nutrient composition of the diet hits the maximum allowable for digestible sulphur amino acid (methionine + cystine). At low inclusion levels, it replaces less of corn and phosphorus in the diet. However, if the sulphur amino acids constraint is relaxed, higher maximum inclusion levels of the fractionated DDGS are possible. At higher inclusion levels, it not only replaces more corn but also more soybean meal (SBM) in the diet.

A higher inclusion level of Iowa DDGS is possible due to its low levels of digestible lysine, relative to the amino acid and lysine requirements of swine (37% lower than fractionated DDGS). The DDGS inclusion levels of Iowa DDGS matches the approximate maximum inclusions that would be recommended by swine nutritionists (30% early and 20% max. late finishing). Many nutritionists are recommending 0-10% DDGS in the finisher 2 diets due to the risk of producing pork with soft bellies because of the high levels of corn oil in the DDGS products. Germ, being low in protein but rich in energy source, allowed for high optimal inclusion levels in grower and gestating sow diets.

While the maximum inclusion level of Iowa DDGS in the Finisher2 diet without Paylean-9® is 19.23%, it can be increased to 26.62% with the addition of Paylean-9® which can aid in building up muscle tissue growth in finishing pigs.

Table 3. Maximum and Minimum Nutrient Inclusion Rates in Swine Diets (in lb per lb of diet)

	Grower 1 (45-95 lbs)		Grower 2 (95-155 lbs)		Finisher 1 (155-205 lbs)	
	Min	Max	Min	Max	Min	Max
Metabolizable Energy	1500	100000	1500	1000000	1500	100000
Crude Protein	0.18	100000	0.15	1000000	0.14	100000
App. Dig. Lysine	0.0095	0.00951	0.0085	0.00851	0.00725	0.00726
App. Dig. Meth+Cys	0.00551	0.0065	0.0051	0.0061	0.004423	0.0054
App. Dig. Threonine	0.0057	0.0067	0.00527	0.0062	0.004568	0.0055
App. Dig. Tryptophan	0.001615	0.00261	0.001445	0.0024	0.001233	0.0022
App. Dig. Isoleucine	0.005225	100000	0.004675	100000	0.003988	100000
App. Dig. Valine	0.006365	100000	0.005695	100000	0.004858	100000
Calcium	0.0072	0.0082	0.0072	0.0082	0.0058	0.0068
Phosphorous	0.000001	0.0072	0.0000001	0.0072	0.000001	0.0058
Digestible Phosphorous	0.003	100000	0.0024	100000	0.0021	100000
Crude Fiber	0.000001	0.035	0.0000001	0.035	0.000001	0.035
Vit. Premix	0.0015	0.0015	0.0015	0.0015	0.0013	0.0013
Paylean9	--	--	--	--	--	--

Table 3 (Cont.). Maximum and Minimum Nutrient Inclusion Rates in Swine Diets (in lb per lb of diet)

	Finisher 2 (205-260 lbs)		Finisher 2 with Paylean9		Gestating Sow (300-500 lbs)	
	Min	Max	Min	Max	Min	Max
Metabolizable Energy	1500	100000	1500	100000	1480	100000
Crude Protein	0.12	100000	0.16	100000	0.12	100000
App. Dig. Lysine	0.006	0.00601	0.0095	0.0095	0.004	0.00401
App. Dig. Meth+Cys	0.00372	0.0047	0.00589	0.0068	0.0028	0.0038
App. Dig. Threonine	0.00384	0.0048	0.00608	0.007	0.0032	0.0042
App. Dig. Tryptophan	0.00102	0.002	0.001615	0.0026	0.00072	0.0017
App. Dig. Isoleucine	0.0033	100000	0.005225	100000	0.0024	100000
App. Dig. Valine	0.00402	100000	0.006365	100000	0.00272	100000
Calcium	0.0050	0.0060	0.0058	0.0068	0.0075	0.01
Phosphorous	0.000001	0.0050	0.0000001	0.0058	0.000001	0.0075
Digestible Phosphorous	0.0019	100000	0.0021	100000	0.0042	0.005
Crude Fiber	0.000001	0.035	0.000001	0.035	0.000001	0.035
Vit. Premix	0.00125	0.00125	0.0013	0.0013	0.005	0.005
Paylean9	--	--	0.00025	0.0003	--	--

The digestible lysine level in Germ is around 9% lower than that of Iowa DDGS. Although a poor protein and digestible lysine source, Germ has a higher metabolizable energy (ME) value than either Iowa DDGS or fractionated DDGS. These factors explain the high maximum inclusion levels of Germ in grower and gestating sow diets. One issue not evaluated in this model was the effect of the additional corn oil in the DDGS and germ products would have on pork quality. These elevated levels of corn oil could limit the ethanol industry byproducts inclusion rates in swine finishing diets.

The shadow value of the DDGS provides an upper bound on its market value at various levels of inclusion. According to Shurson, the ME content, amino acid level and digestibility, and digestible phosphorus levels of feed ingredients are the primary factors that influence the suitability and value of DDGS in swine diets (Shurson, 2006). Nutrient data shows

Table 4. Swine Diet Composition with Maximum Inclusion Level of Iowa DDGS[b]

Feed Ingredient	Grower 1 (45-95 lbs)	Grower 2 (95-155 lbs)	Finisher 1 (155-205 lbs)	Finisher 2 (205-260 lbs)	Finisher 2 with Paylean9	Gestating Sow (300-500 lbs)
DDGS	26.95%	27.92%	28.65%	19.23%	26.62%	9.66%
Corn	51.38%	54.26%	58.59%	70.23%	52.22%	81.92%
SBM	19.04%	15.32%	10.76%	8.63%	19.08%	4.87%
Limestone	1.55%	1.76%	1.58%	1.19%	1.46%	1.49%
DiCalPhosphate	0.62%	0.30%	0.04%	0.39%	0.14%	1.78%
Vit. Premix	0.15%	0.15%	0.13%	0.13%	0.13%	0.15%
Lysine HCL	0.30%	0.28%	0.26%	0.21%	0.30%	0.11%
DL-Methionine	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Grease	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
L-threonine	0.00%	0.00%	0.00%	0.00%	0.03%	0.02%
L-tryptophan	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Paylean®	--	--	--	--	0.02%	--
Total	100%	100%	100%	100%	100%	100%
Nutrient Composition						
Metabolizable Energy	1567	1572	1582	1563	1575	1517
Crude Protein	21.39%	20.13%	18.51%	15.68%	21.41%	12.03%
App. Dig. Lysine	0.95%	0.85%	0.73%	0.60%	0.95%	0.40%
App. Dig. Meth+Cys	0.60%	0.57%	0.54%	0.47%	0.60%	0.38%
App. Dig. Threonine	0.57%	0.53%	0.48%	0.41%	0.61%	0.32%
App. Dig. Tryptophan	0.16%	0.14%	0.12%	0.10%	0.16%	0.07%
App. Dig. Isoleucine	0.71%	0.65%	0.59%	0.52%	0.71%	0.41%
App. Dig. Valine	0.73%	0.68%	0.61%	0.50%	0.73%	0.37%
Calcium	0.82%	0.82%	0.68%	0.60%	0.68%	1.00%
Phosphorous	0.61%	0.54%	0.48%	0.48%	0.52%	0.67%
Dig Phosphorous	0.30%	0.24%	0.19%	0.21%	0.21%	0.42%
Crude Fiber	3.50%	3.50%	3.49%	3.10%	3.50%	2.65%
Paylean9®	--	--	--	--	0.02%	--

[b] Based on prices ($.lb) from Feed Ingredient Weekly, October 2007: DDGS = $0.06, Corn = $0.06, SBM = $0.13, Limestone = $0.05, DiCalcium Phosphate = $0.28, Vit. Premix = $0.85, Lysine HCL = $0.99, DL-Methionine = $1.30, Grease = $0.24, L-threonine = $1.20, L-tryptophan = $22.50, and Paylean® = $26.00

that the crude fiber content of fractionated DDGS is slightly higher than either Iowa DDGS or Germ (see Table 1). Intuitively, the high crude fiber content in the diet with fractionated DDGS should cause its shadow value to be lower in comparison to the diet containing Iowa DDGS or Germ. But in the grower and finisher dietary phases, the nutrient limiting constraint for sulfur amino acids, Apparent Digestible Methionine + Cystine, is binding for diets with fractionated DDGS and non-binding for grower diets with Iowa DDGS. The counterintuitive results for this diet phase could be explained by this fact.

The results show that the total cost of diets containing Iowa DDGS is lower than the diets containing fractionated DDGS in all the diet phases. The lower diet cost is explained by the levels of digestible phosphorus in the diet, which is the third most expensive ingredient in swine diet after amino acids. Iowa DDGS has around 43% higher digestible phosphorus than fractionated DDGS (see Table 1). This means that the diet with Iowa DDGS will be lower due to a reduced need for inorganic phosphorus as supplement which is priced at 0.28 $/lb. The same argument applies to the reason why the diet containing Germ has lower cost than those containing Iowa DDGS or fractionated DDGS. Germ has around 57% higher digestible phosphorus levels than Iowa DDGS. Hence, the diet containing Germ has a lower cost than the diet with Iowa DDGS as well as diets with fractionated DDGS. With the addition of Paylean-9® to the Finisher2 diets, the diets become more expense even though

Table 5. Swine Diet Composition with Maximum Inclusion Level of Fractionated DDGS[b]

Feed Ingredient	Grower 1 (45-95 lbs)	Grower 2 (95-155 lbs)	Finisher 1 (155-205 lbs)	Finisher 2 (205-260 lbs)	Finisher 2 with Paylean9	Gestating Sow (300-500 lbs)
DDGS	14.08%	13.08%	9.79%	6.57%	16.92%	0.90%
Corn	64.27%	68.41%	75.05%	81.29%	63.35%	86.20%
SBM	18.77%	15.75%	12.91%	10.07%	17.38%	9.31%
Limestone	1.30%	1.48%	1.26%	0.98%	1.23%	1.34%
DiCalPhosphate	1.10%	0.81%	0.60%	0.76%	0.58%	1.98%
Vit. Premix	0.15%	0.15%	0.13%	0.13%	0.13%	0.15%
Lysine HCL	0.33%	0.30%	0.25%	0.20%	0.35%	0.01%
DL-Methionine	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Grease	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
L-threonine	0.01%	0.01%	0.01%	0.00%	0.03%	0.00%
L-tryptophan	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Paylean®	--	--	--	--	0.02%	--
Total	100%	100%	100%	100%	100%	100%
Nutrient Composition						
Metabolizable Energy	1522	1523	1527	1526	1534	1497
Crude Protein	20.29%	18.77%	16.58%	14.38%	20.76%	12.00%
App. Dig. Lysine	0.95%	0.85%	0.73%	0.60%	0.95%	0.40%
App. Dig. Meth+Cys	0.65%	0.61%	0.54%	0.47%	0.68%	0.38%
App. Dig. Threonine	0.57%	0.53%	0.46%	0.38%	0.61%	0.32%
App. Dig. Tryptophan	0.16%	0.14%	0.12%	0.10%	0.16%	0.08%
App. Dig. Isoleucine	0.70%	0.65%	0.58%	0.51%	0.71%	0.45%
App. Dig. Valine	0.71%	0.65%	0.56%	0.47%	0.73%	0.38%
Calcium	0.82%	0.82%	0.68%	0.60%	0.68%	1.00%
Phosphorous	0.56%	0.50%	0.44%	0.46%	0.46%	0.68%
Dig Phosphorous	0.30%	0.24%	0.19%	0.21%	0.21%	0.42%
Crude Fiber	3.06%	2.98%	2.82%	2.65%	3.18%	2.37%
Paylean9®	--	--	--	--	0.02%	--

[b] Based on prices ($.lb) from Feed Ingredient Weekly, October 2007: DDGS = $0.06, Corn = $0.06, SBM = $0.13, Limestone = $0.05, DiCalcium Phosphate = $0.28, Vit. Premix = $0.85, Lysine HCL = $0.99, DL-Methionine = $1.30, Grease = $0.24, L-threonine = $1.20, L-tryptophan = $22.50, and Paylean® = $26.00

the maximum inclusion levels are similar to or lower than the other phases.

For the 50 MGY ethanol plant model, the minimum shadow price of the byproducts across the different rations from the LP model, adjusted to reflect marketing costs, were 118 $/ton for Iowa DDGS, 107.78 $/ton for the fractionated DDGS and 101.30 $/ton for Germ. Results presented in Table 9 show that greater revenue is generated from high value byproducts from the ethanol plant employing the fractionation technique based on the ingredient shadow prices. The ethanol plant operating without fractionation technology produces fifty million gallons of ethanol and $28,367,857 in EBITDA. The ethanol plant operating with fractionation technology produces fifty five million gallons of ethanol (a 10% increase) and $32,818,123 in EBITDA, which is $12,489,364 greater revenue than the traditional plant.

Production costs for the plant include the cost of corn and operating cost. The ethanol plant employing the fractionation technique requires about 15% more corn than a conventional plant not employing the fractionation technique. Hence, the cost of corn is higher for the plant employing the fractionation technique by $9,389,098. Fractionation techniques employed by both Poet ethanol plants as well as FWS Companies boast of fewer processing steps which translate to lower operating costs. Hence, the operating cost of the ethanol plant employing the fractionation technique is lower than that without the fractionation technique by $1,350,000. Production costs for the plant employing

Table 6. Swine Diet Composition with Maximum Inclusion Level of Germ[b]

Feed Ingredient	Grower 1 (45-95 lbs)	Grower 2 (95-155 lbs)	Finisher 1 (155-205 lbs)	Finisher 2 (205-260 lbs)	Finisher 2 with Paylean9	Gestating Sow (300-500 lbs)
DDGS	35.86%	37.66%	25.03%	8.27%	21.01%	32.25%
Corn	40.43%	42.96%	59.57%	78.16%	53.71%	60.89%
SBM	21.37%	17.00%	13.40%	11.63%	23.24%	3.76%
Limestone	1.89%	1.93%	1.59%	1.10%	1.51%	2.08%
DiCalPhosphate	0.00%	0.00%	0.00%	0.51%	0.00%	0.76%
Vit. Premix	0.15%	0.15%	0.13%	0.13%	0.13%	0.15%
Lysine HCL	0.21%	0.21%	0.21%	0.16%	0.21%	0.06%
DL-Methionine	0.02%	0.01%	0.00%	0.00%	0.06%	0.00%
Grease	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
L-threonine	0.07%	0.08%	0.07%	0.04%	0.10%	0.05%
L-tryptophan	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Paylean®	--	--	--	--	0.02%	--
Total	100%	100%	100%	100%	100%	100%
Nutrient Composition						
Metabolizable Energy	1610	1615	1587	1542	1573	1592
Crude Protein	19.39%	17.81%	15.47%	13.47%	19.13%	12.00%
App. Dig. Lysine	0.95%	0.85%	0.72%	0.60%	0.95%	0.40%
App. Dig. Meth+Cys	0.55%	0.51%	0.45%	0.40%	0.59%	0.37%
App. Dig. Threonine	0.57%	0.53%	0.46%	0.38%	0.61%	0.32%
App. Dig. Tryptophan	0.17%	0.15%	0.13%	0.10%	0.17%	0.09%
App. Dig. Isoleucine	0.59%	0.53%	0.48%	0.47%	0.64%	0.33%
App. Dig. Valine	0.64%	0.57%	0.49%	0.42%	0.64%	0.34%
Calcium	0.82%	0.82%	0.68%	0.60%	0.68%	1.00%
Phosphorous	0.72%	0.72%	0.58%	0.50%	0.58%	0.75%
Dig Phosphorous	0.33%	0.33%	0.24%	0.21%	0.22%	0.42%
Crude Fiber	3.49%	3.49%	3.10%	2.61%	3.10%	3.17%
Paylean9®	--	--	--	--	0.02%	--

[b] Based on prices ($.lb) from Feed Ingredient Weekly, October 2007: DDGS = $0.06, Corn = $0.06, SBM = $0.13, Limestone = $0.05, DiCalcium Phosphate = $0.28, Vit. Premix = $0.85, Lysine HCL = $0.99, DL-Methionine = $1.30, Grease = $0.24, L-threonine = $1.20, L-tryptophan = $22.50, and Paylean® = $26.00

fractionation technology, mainly as a result of higher corn cost, is higher by $8,039,098 than the plant operating without the fractionation technique. The increased revenue from the greater ethanol yield and from the increase in value of the byproducts offsets the costs, resulting in increased net income from fractionation technique of $4,450,266. Assuming a plant life of 20 years and a discount rate of 9.6 percent, the present value of the increased net income that represents the maximum amount ethanol producers could pay in increased capital cost for the fractionation plant is $38,945,481.

Conclusions

Fractionation technology results in high protein but lower fat content in DDGS, which slightly affects the byproduct's energy value for swine diets. Despite a good amino acid profile of the fractionated DDGS, much of the increase in crude protein is at the expense of phosphorus which is reduced by around 43%. Since diets were formulated on a digestible lysine basis, the amino acid profile and low digestibility of lysine in Iowa DDGS allowed for higher inclusion levels in all phases of the diet while still maintaining a low total diet cost in comparison to diets containing lower levels of fractionated DDGS.

Table 7. Control Corn-Soybean Meal Swine Diet Composition[b]

Feed Ingredient	Grower 1 (45-95 lbs)	Grower 2 (95-155 lbs)	Finisher 1 (155-205 lbs)	Finisher 2 (205-260 lbs)	Finisher 2 with Paylean9	Gestating Sow (300-500 lbs)
DDGS	0.00	0.00	0.00	0.00	0.00	0.00
Corn	71.10%	75.31%	80.24%	84.77%	71.67%	86.36%
SBM	26.07%	21.95%	17.56%	13.19%	26.00%	10.17%
Limestone	1.16%	1.36%	1.16%	0.91%	1.06%	1.33%
DiCalPhosphate	1.23%	0.93%	0.69%	0.83%	0.75%	1.98%
Vit. Premix	0.15%	0.15%	0.13%	0.13%	0.13%	0.15%
Lysine HCL	0.20%	0.02%	0.18%	0.15%	0.20%	0.00%
DL-Methionine	0.04%	0.03%	0.00%	0.00%	0.08%	0.00%
Grease	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
L-threonine	0.05%	0.06%	0.04%	0.02%	0.09%	0.02%
L-tryptophan	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Paylean®	--	--	--	--	0.02%	--
Total	100%	100%	100%	100%	100%	100%
Diet Costs, $/ton	170.22	163.11	153.80	147.23	183.99	144.96

[b] Based on prices ($.lb) from Feed Ingredient Weekly, October 2007: DDGS = $0.06, Corn = $0.06, SBM = $0.13, Limestone = $0.05, DiCalcium Phosphate = $0.28, Vit. Premix = $0.85, Lysine HCL = $0.99, DL-Methionine = $1.30, Grease = $0.24, L-threonine = $1.20, L-tryptophan = $22.50, and Paylean® = $26.00

Table 8. Total Diet Cost and Shadow Value of Byproducts (in $/ton) at Maximum Inclusion Level[b]

Pig Growth Stage	Iowa DDGS Max. %	Iowa DDGS Shadow Value	Iowa DDGS Total Diet Cost	Fractionated DDGS Max. %	Fractionated DDGS Shadow Value	Fractionated DDGS Total Diet Cost	Germ Max. %	Germ Shadow Value	Germ Total Diet Cost
Grower 1	26.95	$158.57	$156.80	14.08	$144.84	$159.42	35.86	$137.47	$157.70
Grower 2	27.92	$158.57	$149.51	13.08	$157.49	$153.22	37.66	$137.47	$151.35
Finisher 1	28.65	$158.57	$140.98	9.79	$186.92	$146.86	25.03	$136.13	$145.32
Finisher 2 w/o Paylean-9®	19.23	$158.57	$138.52	6.57	$186.92	$142.36	8.27	$157.26	$143.64
Finisher 2 w/ Paylean-9®	26.62	$164.10	$168.11	16.92	$186.92	$168.72	21.01	$137.47	$175.06
Gestating Sow	9.66	$182.31	$138.16	0.90	$209.50	$143.40	32.25	$157.87	$131.47

[b] Based on prices ($.lb) from Feed Ingredient Weekly, October 2007: DDGS = $0.06, Corn = $0.06, SBM = $0.13, Limestone = $0.05, DiCalcium Phosphate = $0.28, Vit. Premix = $0.85, Lysine HCL = $0.99, DL-Methionine = $1.30, Grease = $0.24, L-threonine = $1.20, L-tryptophan = $22.50, and Paylean® = $26.00

In assessing the validity of total diet cost results with respect to the fractionated DDGS and Iowa DDGS, fractionated DDGS shows a higher total diet cost with lower inclusion rates. Due to the higher amino acid availability in fractionated DDGS samples, a lower inclusion rate for the DDGS is necessary to meet the amino acid constraints while maintaining proper metabolizable energy levels. At a lower inclusion rate it replaces SBM in the diet. This creates a higher overall cost for a diet since currently DDGS is priced substantially lower than soybean meal. The higher inclusion rate for Iowa DDGS creates a lower overall diet cost at its optimal level, but this cost does not account for negative impacts high inclusion levels of DDGS have on carcass value in swine. If Iowa DDGS is evaluated at the same inclusion level that is optimal for fractionated DDGS, the diet cost will be higher. A producer wishing to feed greater than 20% of the diet composed of DDGS should include a discount factor in the calculations.

Despite low inclusion levels of fractionated DDGS in the swine diet, its shadow value is comparable to that of Iowa DDGS at higher inclusion levels. In addition, when sulphur amino acid constraints were relaxed, higher maximum in-

Table 9. A 50 MGY Ethanol Plant Model[c]		
	W/O Fractionation	With Fractionation
Annual Ethanol Capacity (MGY)	50,000,000	55,000,000
Corn Required (bushels)	17,857,143	20,676,692
Operating Cost ($/gallon)	$0.61	$0.53
Iowa DDGS Yield (lbs/bu)	17.4	
Fractionated DDGS Yield (lbs/bu)		12.5
Bran Yield (lbs/bu)		3.4
Germ Yield (lbs/bu)		4.4
Revenues	Plant Totals	Plant Totals
Ethanol	$100,000,000	$110,000,000
Iowa DDGS	$18,332,143	
Fractionated DDGS		$13,928,665
Bran		$2,284,750
Germ		$4,608,093
Total Revenues	$118,332,143	$130,821,507
Corn Cost	$59,464,286	$68,853,384
Operating Costs	$30,500,000	$29,150,000
Total Costs	$89,964,286	$98,003,384
EBITDA	$28,367,857	$32,818,123
Net Income	$28,367,857	$32,818,123
Increased Net Income from Fractionation Technique = $4,450,266		
Present Value (PV) of Increased Annual Revenue = $38,945,481		

[c] Based on prices: Corn =3.33 $/bushel, Ethanol = 2.00 $/gal, Iowa DDGS = 118.00 $/ton, Fractionated DDGS = 107.78 $/ton, Bran = 65.00 $/ton, and Germ = 101.30 $/ton

clusion levels of the fractionated DDGS are possible that replaced more corn and SBM in the diet. Germ has substantially higher levels of energy and digestible phosphorous than both Iowa DDGS and fractionated DDGS, but lysine and other amino acids are not increased proportionately. Its high energy content allowed for high optimal inclusion levels in both grower and gestating sow diets.

The 50 MGY ethanol plant spreadsheet model showed that fractionation technology results in greater ethanol yield and higher revenue from the feed byproducts. Despite lower inclusion levels, fractionated DDGS has higher economic value than Iowa DDGS and should increase net revenue for the ethanol plant producers. So long as the increase in capital cost is less than $38 million, the plant's overall profitability will improve.

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Value Maximization from Corn Fractionation: Feed, Greenhouse Gas Reductions, and Cointegration of Ethanol and Livestock

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Introduction

Shrinking ethanol margins have heightened the importance of maximizing the value of all outputs from ethanol refinery. To illustrate, on November 28 the cash cost of corn at an Iowa ethanol plant was approximately \$3.75 per bushel. This bushel can produce 2.8 gallons of ethanol, which had a market value of approximately \$1.80 per gallon, or \$5.04 per bushel. With an operating cost of \$1.46 per bushel (Lichts, 2006) to convert the corn to ethanol, this leaves a margin over operating costs of only -\$0.17 per bushel. However, on November 28, the value for dried distillers' grains with solubles (DDGS), a byproduct of ethanol production, was \$0.07 per pound.[2] Processing one bushel of corn produces 17 pounds of DDGS. Therefore, the byproduct value increased the plant's November 28th margin from a meager -\$0.17 per bushel to a much more robust \$1.028 per bushel (20.2% of ethanol revenue).

Feed byproducts from ethanol will generate even more value if the United States adopts policies that place a value on greenhouse gas reductions. Because distiller's grains are fed to livestock, they displace other sources of feed. Hence, the greenhouse gas emissions associated with producing the displaced feed sources reduce the net greenhouse gas emissions of an ethanol biorefinery. The magnitude of the offset can be large, potentially offsetting a significant proportion of the greenhouse gas emissions of an ethanol plant powered by natural gas.

Currently, most ethanol dry mill plants produce DDGS and then ship them to livestock feeders. Because ethanol is produced primarily in the Corn Belt and most cattle are finished in the Southern Plains, the large increase in DDGS production has meant increased shipping distances. Hogs, which are fed in the Corn Belt, cannot consume all the DDGS that are produced. Because of DDGS fat content and amino acid digestibility concerns, inclusion rates for DDGS are lower for swine than cattle. Increased shipping distance lowers the price of DDGS, as local market value reflects the cost of shipping DDGS to the farthest away market.

Dry mill ethanol plants process the entire corn kernel, even though the starch is the only part of the kernel that produces ethanol; the material left over after distillation is DDGS. An alternative method is to dry fractionate the corn kernel before it enters the mash tank, where the starch is converted to fermentable sugars. Fractionation separates the endosperm (primarily starch), the germ, and the bran. The starch can go into the mash tank, whereas the germ and bran can be processed into different products.

At least two different fractionation methods are being employed. Renessen, a joint venture of Monsanto and Cargill, uses a method that produces corn oil, high protein feed, and a different type of distillers' grain product than currently produced in dry mills. The new Renew Energy plant in Jefferson, Wisconsin, produces a high protein meal, high fat corn germ, and corn bran. The plant is the largest dry mill ethanol plant in operation with capacity to produce 130 million gallons of ethanol per year.

This study has three objectives. Objective one is to estimate the value of ethanol coproducts. This will be achieved by using the shadow values provided when solving a least cost feed ration. The second objective is to determine the potential for enhanced value if the Renew Energy fractionation method is used incorporating greenhouse gas benefits from feed replacement. Finally, the third objective is to determine whether fractionation has the potential to increase the market incorporating additional feeding to swine and poultry.

Research on the economic value of corn ethanol's byproducts is scant. Elobeid *et al.* (2007) estimated that the value of DDGS will move with the price of corn and that domestic and foreign livestock producers will find it profitable to use DDGS in their rations. Shurson (2005) notes that the value of DDGS is often limited by a lack of a consistent standard

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[2] Corn, ethanol and DDG values were taken from USDA-AMS: http://www.ams.usda.gov/mnreports/nw_gr111.txt.

for establishing the nutrient content of DDGS across plants and within plants across time. It is likely that the problem of a lack of a standardized product will only exacerbate with the new products that will come from plants that fractionate their corn.

Ladd and Martin (1976) show how to value byproducts using linear programming to obtain values for input attributes. Melton, Colette, and Willham (1994) extend Ladd and Martin's model to impute the value of input characteristics in inseparable bundles. They estimate the value to a beef producer of genetic characteristics such as birth weight, average gain per day, and slaughter weight, among other things. Yu *et al*. (2002) use a version of these techniques to value different corn quality traits such as increased protein content, increased lysine content, and increased oil content for livestock feed.

In this paper, the value of corn ethanol byproducts is estimated using these standard linear programming techniques for beef cattle and hogs. The value of the byproducts is derived from their ability to substitute for corn and soybean meal in feed rations. For given corn and soybean prices, the imputed value of DDGS and products derived from corn fractionation is estimated to determine the possible increase in feed value from fractionation. DDGS and fractionation products are then allowed to enter least-cost feed rations to determine the amount of corn and soybean meal displacement. This allows the calculation of greenhouse gas credits. Finally, by calculating the change in value of byproducts from fractionation, insight is provided into the extent to which dry mill ethanol plants can be integrated with hog finishing operations.

Valuation of DDGS

Ladd and Martin demonstrated that in a cost minimization problem, the price paid for an input equals the sum of the marginal values of the input's characteristics. This methodology is used to infer the value of traditional distiller's grains and new fractionation products in livestock rations. Although market prices can be observed for DDGS, their reliability in revealing marginal values is questionable because of the rapid supply expansion that has taken place with DDGS. Because fractionation products are so new, there are no observations available on their prices. The maximum willingness to pay for byproducts is estimated by finding the shadow values of energy, protein and lysine, from a corn and soybean meal diet and then apply these values to the energy and protein content of the byproducts. Separate shadow values for beef cattle, dairy cattle, hogs and poultry are found.

The least cost food ration solves:

$$\sum_{i=1}^{6} p_i * X_i \text{ subject to } \sum_{i=1}^{6} a_{i,j} X_i \geq b_j$$

Where **x** is a vector of possible feed ingredients (i=1 to 3 for corn and soybean meal and DDGS and/or i=4 to 6 for the fractionated products [corn germ, high protein, and high fiber] depending on the scenario), **p** is the vector of feed prices, **a** is a matrix which translates feed ingredients (i) into values of nutrients (j), and **b** is a vector which represents the minimum requirements of specified nutrients (j) per day. The Lagrangian for this problem is

$$£ = px + \lambda[\beta b - ax]$$

where λ is a vector of j Lagrange multipliers. The envelope theorem guarantees that the marginal cost saving at the optimal solution of relaxing the nutrient requirement, b_j , is equal to the Lagrange multiplier λ_j .

$$\partial C\ (x_i^*(p_i, a_i, b_j))\ /\ \partial b_j = \lambda_j$$

Upon solving the producer's cost minimization problem, the value of feed characteristics such as protein and amino acid content is determined. These λ_j, or shadow prices, of the nutrients essentially tell us the value per pound of each nutrient. From the shadow prices for each nutrient present in a feedstuff, the precise value of the feedstuff can be determined for the livestock producer. While this methodology does not provide shadow prices for every nutrient, vitamin, and mineral possible in any feedstock, shadow prices for the most essential nutrients can be recovered using the cost minimization problem.

Determining Shadow Prices

Livestock producers choose from a few main ingredients in formulating their feed rations. Corn, soybean meal, and DDGS are the most popular ingredients (Tiffany and Fruin, 2000). To estimate the shadow values of energy, protein, and lysine to livestock producers requires prices for the main feed ingredients. Because the goal is to estimate the maximum willingness to pay for byproducts, DDGS are not allowed to enter the least cost ration. Rather feed ingredients are limited to corn and soybean meal.[3] Weekly shadow prices for energy and protein for beef cattle, and energy, protein and lysine for hogs from January 2000 to June 2007 are estimated using weekly average nearby CBOT futures contracts for corn and soybean meal for p. For each set of prices in the time series, the producer's cost minimization problem is solved, and the shadow value of each nutrient recorded.

Table 1 shows the nutrient requirements and the feed conversion matrix for finish cattle in a feedlot, A_{cattle}, Jurgens (2002). NE is net energy, NE_m is net energy for maintenance,

[3] There are a wide variety of feedstocks used to formulate feed rations even without consideration of ethanol byproducts. By limiting feed rations to corn, soybean meal, and synthetic lysine only, we likely overstate the cost of actual least cost feed rations. Hence our measure of the willingness to pay for ethanol byproducts is overstated to the extent that feedstocks other than corn and soybean meal enter the feed ration.

NE_g is net energy for gain, NE_L is net energy for lactation. ME is metabolizable energy. Tables 2, 3 and 4 provide the corresponding information for dairy cattle, hogs and poultry, respectively. Protein and lysine are reported as percent per pound of feed on a dry matter basis. The nutritional requirements have been converted to requirements in pounds per day.

Table 1. Conversion Matrix ($A_{Beefcattle}$) and Requirement Vector[a]

	Corn	Soybean Meal	b
NE[b]	1.38 Mcal/lb	1.44 Mcal/lb	13.43 Mcal/day
Protein	9.1%	43.3%	1.84 lb

[a]Requirements for beef cattle, 1,200 lbs@finish – 660lb/300kg body weight, Table 8-2C (Jurgens, 2002)

[b]$NE = NE_m + NE_g$

Table 2. Conversion Matrix ($A_{Dairycattle}$) and Requirement Vector[a]

	Corn	Soybean Meal	b
NE[b]	1.38 Mcal/lb	1.44 Mcal/lb	28.2 Mcal/day
Protein	9.1%	43.3%	4.96 lb

[a]Requirements for dairy cattle, 660 kg live weight, Table 9-5 (Jurgens, 2002)

[b]$NE = NE_m + NE_L$

Table 3. Conversion Matrix (A_{Swine}) and Requirement Vector b[a]

	Corn	Soybean Meal	b
ME	1.47 Mcal	1.305 Mcal	10.03 Mcal/day
Protein	9.1%	43.3%	0.893 lb
Lysine	0.3%	2.8%	0.0407 lb

[a]Requirements for growing pigs, (80-120kg), Table 7-2B (Jurgens, 2002)

Table 4. Conversion Matrix ($A_{Poultry}$) and Requirement Vector b[a]

	Corn	Soybean Meal	b
NE[b]	1.47 Mcal	1.305 Mcal	2.37 Mcal/day
Protein	9.1%	43.3%	.1841 lb
Lysine	0.3%	2.8%	0.0092 lb

[a]Requirements of 5 week old male broilers, Table 12-4 (Jurgens, 2002)

Valuing DDGS

For each set of weekly corn and soybean meal prices[4], the value of DDGS to dairy cattle, beef cattle, pork and poultry producers is determined from the shadow value of nutrients. The prices represent what a livestock feeder should be willing to pay for corn and soybean meal in North Central Iowa and the price that would be received by the ethanol plant. The following nutrient profile of DDGS is used:[5] 1.67 Mcal/lb in $NE_m + NE_g$ to beef cattle, 1.95 Mcal/lb in $NE_m + NE_L$ to dairy cattle, 1.72 Mcal/lb in ME to swine and poultry, are 30.03% protein, and contain .91% lysine. The resulting imputed values are the maximum prices that livestock feeders would pay for DDGS. If the market price for DDGS were greater than this value then livestock producers would feed corn and soybean meal and would not include DDGS in their feed ration. If the price of DDGS were less than this value, then feeders would feed DDGS. The least cost feed rations were solved with species-specific maximum inclusion rates, which are 40% for beef cattle, 20% for dairy cattle, 20% for hogs and 15% for poultry by weight (Noll, 2005; Schingoethe, Kalscheur, and Garcia, 2002; Shurson and Spiehs, 2002; and Tjardes and Wright, 2002). Figure 1 shows the time series of corn and soybean meal prices.

Figure 2 shows the maximum willingness to pay ($/ton) for DDGS along with actual DDGS prices. As shown, dairy cattle have the greatest willingness to pay for DDGS, closely followed by beef cattle, and then by swine and poultry. All species have a willingness to pay that far exceeds reported plant prices of DDGS.

How are DDGS Priced in the Market?

The discrepancy in Figure 2 between willingness to pay and actual prices received is likely caused by a number of factors including livestock feeders' discounting the value of DDGS because of quality variability, and transportation costs. The corn and soybean meal prices used to calculate the value of DDGS represent the prices paid by livestock feeders in North Central Iowa. DDGS from Iowa are currently being shipped to livestock feeders in many parts of the country, and some are being exported. The spot price of DDGS at an ethanol plant reflects the cost of transportation to the producer who is just at the margin of deciding whether to include DDGS in rations. For example, high transportation costs to a poultry producer in the Southeast may be determining the price received for DDGS. The beneficiaries of pricing DDGS based on the marginal livestock feeder is that cattle producers located near ethanol plants will be able to pay a price that is much below their maximum willingness to pay. A detailed examination of the implications of spatial heterogeneity and transportation costs on the market price of DDGS and on consumer surplus accruing to livestock feeders is beyond the scope of this study.

Abstracting from spatial heterogeneity of livestock operations, consider the market for DDGS where all livestock and ethanol production takes place in the same location, or alternatively, when transportation is costless. Demand for DDGS would come first from the livestock that values it most highly based on its ability to substitute for corn and soybean

[4] The data are reported by USDA's Agriculture Marketing Service and archived by the Livestock Marketing Information Center.

[5] Nutrient profiles are based on samples taken by Gerald Shurson at the University of Minnesota and reported in various publication and presentations taken from http://www.ddgs.umn.edu/.

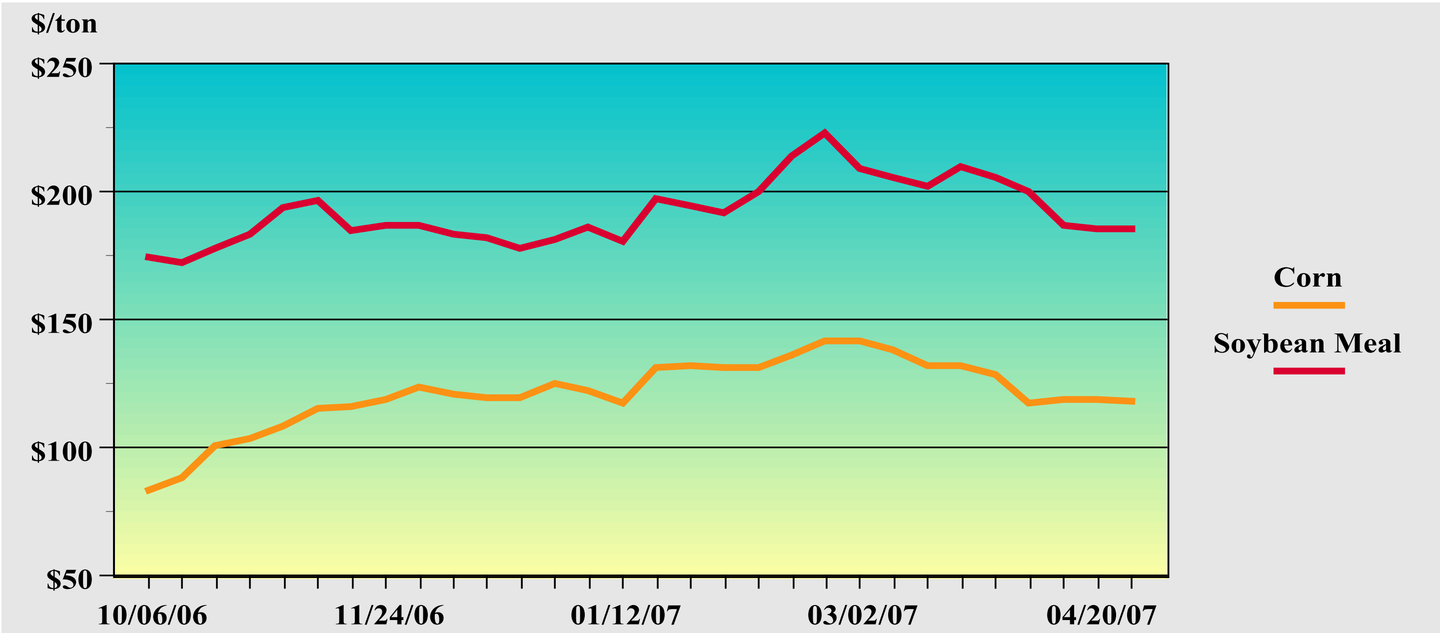

Figure 1. Corn and Soybean Meal Prices
Source: USDA-AMS corn prices for Iowa and soybean meal from the Chicago Board of Trade.

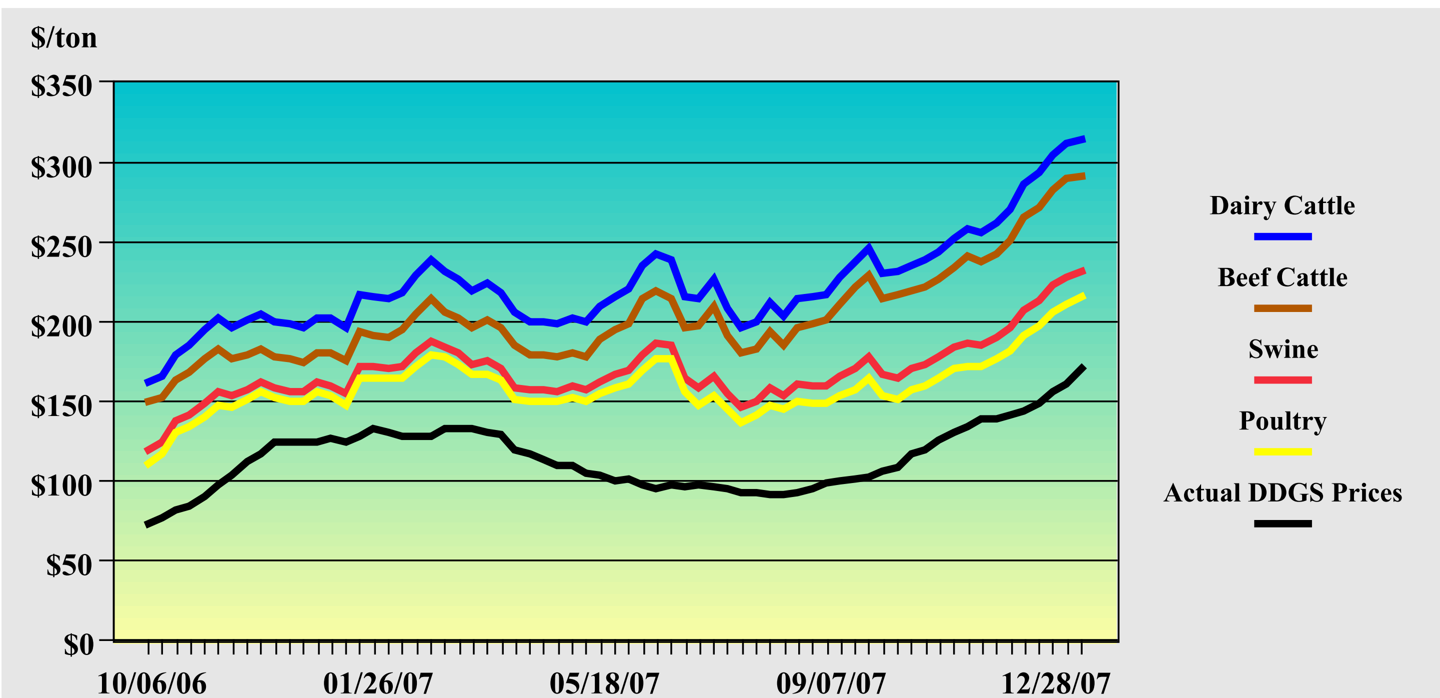

Figure 2. Imputed DDGS Values to Livestock

meal in the feed ration, namely dairy cattle. DDGS will enter the least cost ration as long as the market price is at or below their maximum willingness to pay. If dairy cattle have consumed all they are able to because of maximum inclusion limitations, the animal that values DDGS second most highly, beef cattle, will have to consume DDGS in order for the market to clear. This means the market price for DDGS must be at or below the maximum willingness to pay to beef cattle, dairy producers then enjoy surplus because they will pay a price below their maximum willingness to pay. Knowing the number of animals on feed of each species, and their maximum willingness to pay, the entire demand curve for DDGS can be constructed. The market price for DDGS will have to equal, in equilibrium, the maximum willingness to pay of the marginal species. This assumes that DDGS are of uniform quality and that all livestock producers are able to handle the DDGS in their operation. These assumptions, although somewhat demanding, allows the mechanics of the market to be analyzed. Since DDGS are a byproduct of the ethanol process, their supply is perfectly inelastic with respect to own price, and is fixed by the size of the ethanol industry in this market. When corn is $4.65/bushel and soybean meal is $337/ton the maximum willingness to pay for DDGS of our different livestock types is given in Table 5. From this, the implied demand curve for DDGS can be constructed (Figure 3).

Table 5. Imputed Maximum Willingness to Pay for DDGS ($/ton)

Beef Cattle	Dairy Cattle	Hogs	Poultry
$293.07	$318.16	$236.14	$220.43

Values computed using AMS/USDA Iowa Ethanol Report corn price of $4.65/bu and CBOT soybean meal price of $337/ton on January 14, 2008.

To Fractionate or Not

Ethanol producers have the ability to fractionate corn before creating ethanol, but they will only do so if they can generate more value than the traditional ethanol-DDGS model. The Renew Energy method of fractionation produces three coproducts: a high protein product, a high fat corn germ product, and a high fiber product. To place values on these products, assumptions about the nutrient content of these new byproducts are made. Then the value of these products according to nutrients' shadow values can be determined from the Corn-SBM only ration.[6] The nutrient content for the new coproducts are for every bushel of corn processed, seven pounds of the high protein meal, four pounds of corn germ, and four pounds of bran are produced (Singh, 2006). Table 6 contains the nutrient values.

The imputed per bushel and per ton values for processed corn are presented in Tables 7 and 8 respectively. The per bushel value of the fractionated products is lower for all livestock types. Table 8 shows that the high protein meal has the highest per-ton value followed by corn germ, and then corn bran. Although the high protein meal coproduct has a higher per ton value than DDGS, the weighted average per ton value across all three coproducts is lower than DDGS. These data indicate that at current corn and soybean meal prices there seems to be little incentive for other ethanol plants to adopt the Renew Energy fractionation procedure.[7]

Corn and Soybean Meal Displacement in Livestock Rations and GHG Implications

Ethanol coproducts displace corn and soybean meal that would have been used to feed livestock. Because this displaced feed does not have to be produced, the savings in greenhouse gas emissions from not producing them is counted as a credit towards corn ethanol. The livestock will be fed, and if

[6] An alternative method is to solve for the implicit value of these new coproducts reflect the value of the new coproducts if they exceed the value of DDGS because the new coproducts would replace DDGS and would be valued on replacing corn and soybean meal in rations.

[7] This conclusion may not hold if other attributes of the Renew Energy coproducts, such as high consistency, are highly valued by feeders. This conclusion also does not imply that other fractionation processes, such as those which result in food grade corn oil, may not generate more value than DDGS.

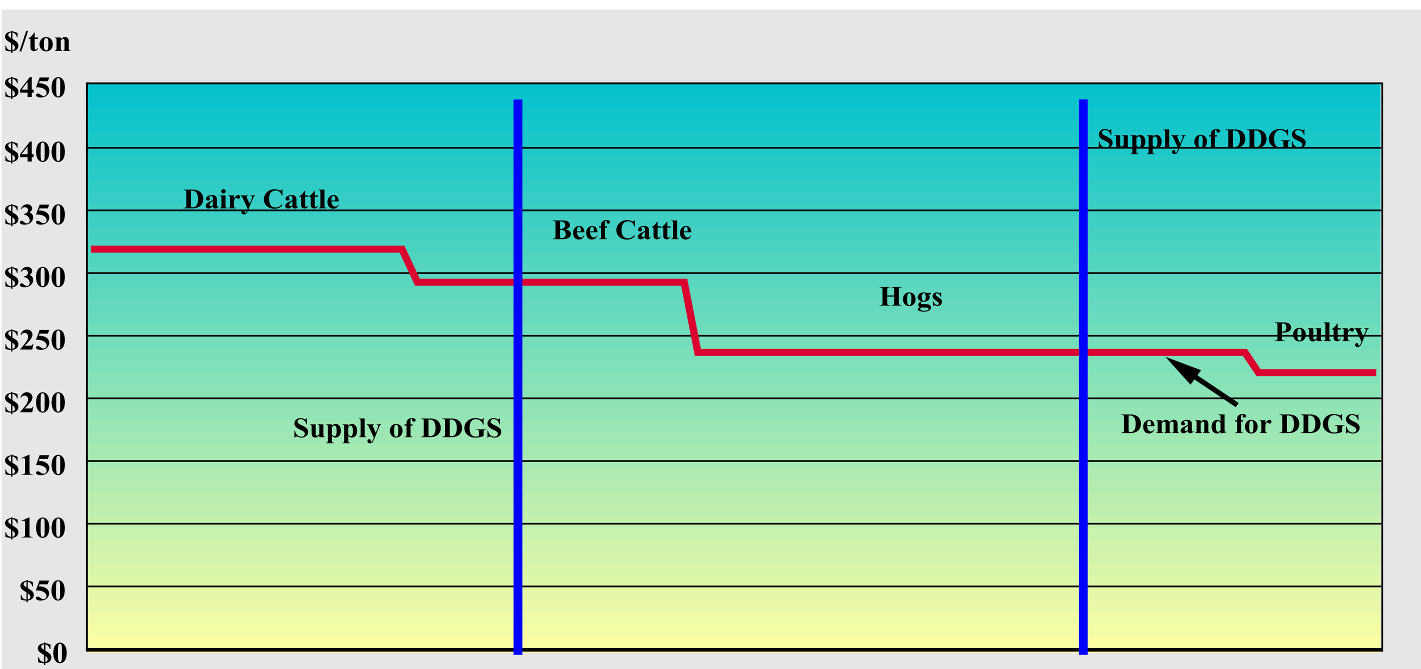

Figure 3. Market for DDGS

Table 6. Nutrient Values of New Byproducts from Renew Energy's Jefferson Ethanol Plant

Nutrient	High Protein Meal	High Fat Corn Germ	Corn Bran
NE (Mcal/lb)	1.68	1.73	1.41
ME (Mcal/lb)	1.842	1.727	1.293
Protein	45%	15.06%	5.41%
Lysine	1.27%	0.75%	0.23%

Table 7. Imputed Coproduct Revenue Per Bushel of Corn Processed

Livestock Type	High Protein Meal	High Fat Corn Germ	Corn Bran	Total Revenue per Bushel of Fractionated Products	Total Revenue per Bushel of DDGS
Beef Cattle	$1.28	$0.45	$0.30	$2.04	$2.49
Dairy Cattle	$1.28	$0.45	$0.30	$2.04	$2.70
Hogs	$0/96	$0.45	$0.29	$1.70	$2.01
Poultry	$0.96	$0.45	$0.29	$1.70	$1.87

Values computed using AMS/USDA Iowa Ethanol Report corn price of $4.65/bu and CBOT soybean meal price of $337/ton on January 14,2008.

Table 8. Imputed Coproduct Value ($/ton)

Livestock Type	High Protein Meal	High Fat Corn Germ	Corn Bran	DDGS
Beef Cattle	$366.45	$225.88	$150.85	$293.07
Dairy Cattle	$366.45	$225.88	$150.85	$318.16
Hogs	$388.92	$218.62	$132.11	$236.14
Poultry	$274.99	$224.85	$143.54	$220.43

Values computed using AMS/USDA Iowa Ethanol Report corn price of $4.65/bu and CBOT soybean meal price of $337/ton on January 14,2008.

they are fed corn and soybeans, fertilizer and diesel fuel are used in that process. The GREET model (Wang, 2005) and the EBAMM model (Farrell *et al*., 2006) provide estimates of the amount of feed displaced. However, their estimates of the amount of feed displaced are much higher than suggested by this study. Hennessy, Rubin and Babcock (2008) calculate that 0.356 pounds of CO_2 equivalent are reduced per pound of corn displaced from feed rations and 0.3321 pounds of CO_2 equivalent are reduced per pound of soybean meal displaced.

Table 9 shows the amount of feed displaced by DDGS and the resulting value per gallon or ethanol at a CO_2 price of $100 per ton, a corn price of $4.65/bu and a soybean meal price of $337/ton. Table 10 does the same for the fractionated coproducts. At a carbon price of $100 per ton, the value of the carbon credit per gallon of ethanol is about 5% of the current price of ethanol and about 20% the market value of distillers grains.

Potential Ethanol-Livestock Integration

Although the per-ton value of DDGS is greater than the per-ton total value of fractionated products, if fractionated products are more suitable for feeding hogs than DDGS, then a greater proportion of the coproducts can be fed to Corn Belt livestock, thereby saving some shipping costs. In addition, because a greater proportion of hogs than cattle are finished in proximity to ethanol plants, fractionated products may lead to greater integration of livestock operations with ethanol plants.

Approximately 53% of U.S. market hogs are raised in Iowa, Minnesota, Illinois, Nebraska, and South Dakota. This represents about 58 million hogs based on total U.S. hog slaughter in 2007. The least-cost amount of DDGS fed per hog per day is 1.38 pounds. This implies that these 58 million hogs could consume all the DDGS produced from 4.82 billion gallons of ethanol. The per-hog daily feeding rate of the three coproducts produced in the fractionation process is 0.186 pounds for high protein meal, 1.047 pounds for corn germ, and 1.28 pounds for bran. At these feeding rates, it would take 19 billion gallons of ethanol to produce bran in surplus of what could be consumed by 58 million hogs, 15.5 billion gallons to produce excess germ, but only 1.6 billion gallons to produce surplus high protein meal.[8] This suggests

[8] High protein meal is a good substitute of soybean meal. The amount of this coproduct included in hog rations at the imputed price from Table 7 is likely much lower than that which would be included if it were priced at, say the poultry valua-

Table 9. Carbon Credit to Biofuel Plants from Feeding DDGS to Livestock

Livestock Type	Feed Ingredient	Feed Displaced Per Bushel of Corn Processed[a]	Reduction in CO_2 per Gallon of Ethanol Produced	Total Value of Production at a CO_2 Price of $100 Per Ton
		(lb/bu)	(lb/gal)	($/gal)
Beef Cattle	Corn	10.59	1.35	0.12
	Soybean Meal	9.56	1.13	
Dairy Cattle	Corn	14.97	1.90	0.13
	Soybean Meal	8.67	1.03	
Hogs	Corn	16.56	2.11	0.12
	Soybean Meal	3.75	0.44	
Poultry	Corn	17.81	2.26	0.12

Table 10. Carbon Credit to Biofuel Plants from Feeding Fractionated Coproducts to Livestock

Livestock Type	Feed Ingredient	Feed Displaced Per Bushel of Corn Processed[a]	Reduction in CO_2 per Gallon of Ethanol Produced	Total Value of Production at a CO_2 Price of $100 Per Ton
		(lb/bu)	(lb/gal)	($/gal)
Beef Cattle	Corn	11.98	1.52	0.11
	Soybean Meal	5.22	0.62	
Dairy Cattle	Corn	12.54	1.59	0.10
	Soybean Meal	4.69	0.56	
Hogs	Corn	14.32	1.82	0.09
	Soybean Meal	1.27	0.15	
Poultry	Corn	13.79	1.75	0.10
	Soybean Meal	2.93	0.35	

[a]Values computed using AMS/USDA Iowa Ethanol Report corn price of $4.65/bu and CBOT soybean meal price of $337/ton on January 14, 2008. The price of the coproducts was fixed at the levels reported in Table 7 for each species.

that fractionating corn before it is processed into ethanol may reduce the need to transport coproducts a far distance from ethanol plants.

Conclusion

The use and value of coproducts of producing corn ethanol are critical issues facing the industry as it expands to meet the increased ethanol mandates of the Energy Independence and Security Act. Significantly higher corn and soybean meal prices have led the U.S. livestock industry to bid up the price of DDGS grains as a substitute feed ingredient. Higher prices for DDGS have, in turn, helped the ethanol industry offset increased feedstock prices. With ethanol set to expand to meet the new mandates, the cost of shipping DDGS to new feeders (perhaps overseas) will only increase, which will reduce the equilibrium price paid for DDGS. Future values of DDGS may be enhanced if they can offset the greenhouse gas emission of ethanol plants or if they can be reformulated into coproducts that can be fed at higher rates than DDGS.

tion or if the feed had to be transported a far distance.

Fractionation of corn before it is processed into ethanol can create new coproducts that have the potential of increasing value to ethanol producers. The maximum willingness to pay for DDGS and new coproducts that are created by the fractionation process adopted by Renew Energy at its plant in Jefferson, Wisconsin, are calculated by determining the amount of corn and soybean meal displaced after DDGS and the new coproducts are allowed to enter least cost feed rations. Contrary to expectations, the maximum willingness to pay per ton of DDGS by livestock feeders that are near Iowa ethanol plants is greater than the value of coproducts calculated by taking the weighted average of the maximum willingness to pay for each coproducts, weighted by the share of coproducts produced per bushel of corn processed. Only one of the coproducts—high protein meal—has an imputed per ton value that is greater than DDGS. This lower value suggests that ethanol plants may be slow to adopt fractionation processes for their plants.

Two of the new coproducts can be fed to hogs at much higher rates than DDGS. This implies lower shipping costs because they can be fed to the animal species most in abundance where ethanol is produced. This savings of shipping costs will increase their value, suggesting that they will have an equilibrium market price closer to the calculated maximum willingness to pay than for DDGS.

Because feeding coproducts displaces corn and soybean meal in rations, the greenhouse gas emissions associated with the feeding of corn and soybean meal can help offset the ethanol plant emissions. How least-cost feed rations change after allowing coproducts to enter rations is a natural way to estimate feed displacement. The results of this study indicate that feed displacement rates commonly used in the literature are too high. At a CO_2 price of $100 per ton, the value of greenhouse gas credits from coproducts is about 5% of the value of ethanol or 20% of the value of DDGS, which suggests that high-priced CO_2 can create a significant new revenue stream.

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Economic Analysis of Farm-Level Supply of Biomass Feedstocks for Energy Production Under Alternative Contract Scenarios and Risk

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Introduction

Farmers, agribusiness, policymakers, and others have shown considerable interest in the potential for on-farm production of lignocellulosic biomass for energy production (English *et al*., 2006). Perlack *et al*. (2005) estimates that more than a billion tons of lignocellulosic feedstock such as corn stover, wheat straw, and switchgrass could be produced annually in the United States. Compared to other agricultural commodities, transportation costs from grower to processor for lignocellulosic biomass feedstocks will be relatively high, due to the bulkiness and low energy density of lignocellulosic feedstocks. This transportation cost factor will likely result in a more locally-grown market situation for biomass feedstock. Thus, the development of biobased industries, at least initially, will hinge on the local availability of sufficient, cost competitive biomass feedstocks.

One possible alternative for supplying biomass to the biorefinery is a vertically integrated system where the plant leases (or purchases) lands and directly manages the production, harvest, storage, and transportation of feedstocks (Epplin *et al*., 2007). Another alternative for the processing plant is to enter into long-term production and harvest contracts with individual farmers (Epplin *et al*., 2007). This research analyzes the potential of a West Tennessee grain farm to supply lignocellulosic biomass under contract to a biorefinery. Under this market scenario, the processor likely will have an interest in providing production contracts or other incentives to induce farmers to supply sufficient feedstocks to keep the plant operating at capacity.

A number of factors may influence farmers' willingness to supply biomass feedstocks such as corn stover, wheat straw, and/or switchgrass to a local processing facility. For example, how do biomass crops such as switchgrass compare to traditional crops with respect to costs of production, yields, price potential in terms of its energy equivalent to gasoline or coal, net returns, and risk (variability of net revenues) under different management practices, weather conditions, energy market conditions, government policies, and contract pricing arrangements provided by the processing plant? Supplying biomass feedstocks will require changes in the way farmers manage their operations.

The ability of farmers to respond to a potential market for biomass feedstocks will be constrained by on-farm economic, structural, and resource constraints (e.g., time constraints, equipment constraints, land ownership, debt structure, farm size, production activities (i.e., crop, livestock), soil type and topography, farm program participation, etc.). For example, who would pay for investment in perennial crop establishment, harvest equipment, and storage for the biomass? Would the farm have enough labor resources to grow and harvest the crop? Farmers who must bear all of the feedstock price, production risks, and financial risks may not be willing to supply biomass or be willing to supply limited amounts of biomass at all to a processing facility. The willingness of farmers to provide biomass feedstocks will be a function of biomass feedstock profits, variability of profits, and correlation of profits relative to traditional crop profits. These factors will vary with respect to the contractual incentives that may be offered by the processing facility. Thus, an understanding of the factors that will affect farmer decisions to supply biomass feedstocks is essential.

Currently, research about the potential risks and risk management benefits of on-farm biomass production is lacking. In addition, analysis of the impacts of potential biomass contract structures on risk and return and farmer willingness to supply biomass is also limited. Larson *et al*. (2005) evaluated the risk management benefits of a marketing contract with a penalty for production underage or excess production is sold at the spot market price based on the energy equivalent value as a substitute for gasoline on farmer willingness to supply switchgrass, corn stover, or wheat straw. However, the Larson *et al*. (2005) study did not evaluate other potential contract alternatives such as acreage contracts (Paulson and

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Babcock, 2007), gross revenue contracts (Garland, 2007), or other financial incentives that could be used to induce on-farm biomass production for a processor. Thus, the objective of this research is to evaluate the ability and willingness of farmers to provide lignocellulosic biomass feedstocks under risk given their on-farm situation and potential contractual arrangements with user facilities.

Methods and Data

A farm-level model was developed to evaluate contract biomass feedstock production under risk for a northwest Tennessee 2,400 acre grain farm. The farm was assumed to produce corn, soybeans, and winter wheat (Tiller, 2001). The representative farm also was assumed to have the opportunity to provide biomass feedstocks to a local single-user facility that produces ethanol. The farm was assumed to be able to produce three energy crop production alternatives: corn stover, wheat straw and switchgrass. Thus, the representative farm had the choice between producing corn grain only or corn grain and corn stover. Similarly, the representative farm could produce wheat grain only or wheat grain and wheat straw for sale to individual, wholesalers, and retailers or wheat straw for ethanol production.

A quadratic programming model incorporating farm labor and land quality constraints, biomass yield variability, crop and energy price variability, alternative contractual arrangements, and risk aversion was developed for the analysis. The objective function was to maximize the certainty equivalent value of whole farm net revenues for different levels of risk significance (McCarl and Bessler, 1989). Risk significance levels (α) of 50, 60, 70, 80, and 90 percent were used to generate risk-efficient farm plans for different levels of absolute risk aversion. The risk levels model the certainty of obtaining or exceeding a maximized lower level confidence limit on net revenues (Dillon, 1999). Thus, for a risk neutral decision maker a 50% percent certainty that the actual net revenues will meet or exceed expected net revenues. For risk-averse decision makers, a higher probability of certainty is required on net revenues; thus, risk significance levels (α) of higher than 50% is required.

The three resource constraints specified in the model were for soil type, labor, and available field days for wheat straw and corn stover harvest. Total land was restricted to 2,400 acres and land for each soil type was restricted to 1,200 acres of Collins soils, 528 acres of Loring soils, and 672 acres of Memphis soils. Six bimonthly labor periods were specified in the model. Labor requirements by period were from crop budgets by Gerloff (2007a; 2007b). Labor availability by period was for a family of four (Johnson, 1991). In addition to family labor, it was assumed that the farm could hire an additional 2,000 hours of labor per year at $8.50/hour (Gerloff, 2007a). Hired labor was assumed to have an efficiency of 90% in the model to account for the extra management time for the farm operator (Musser, Mapp, and Barry, 1984). The number of suitable days available to harvest corn stover and wheat straw after grain harvest was constrained to 21-10 hour days. For the soybean-wheat double crop, the available days to harvest straw between the wheat grain harvest and the planting of the soybean crop was assumed to be 10-10 hour days.

The potential biomass contracting alternatives modeled for the West Tennessee representative crop farm were: 1) a spot market contract (SPOT) where biomass is priced yearly on its current energy equivalent value as a substitute for gasoline at the processing plant gate, 2) a standard marketing contract (STANDARD) with a penalty for production underage or excess production is sold at the spot market price (Musser, Mapp, and Barry, 1984; Paulson and Babcock, 2007), 3) an acreage contract (ACREAGE) which provides a guaranteed annual price on the actual biomass produced in each year on the contracted biomass acreage (Paulson and Babcock, 2007), and 4) a gross revenue contract (REVENUE) which provides a guaranteed annual gross revenue per acre from biomass based on a guaranteed contract price times expected yield per acre over the life of the contract (Garland, 2007).

The four potential types of contracts that could be used to encourage biomass production offer different levels of biomass price, yield, and production cost risk sharing between the representative farm and the processor. The SPOT contract assumes that all of the output price, yield, and production cost risk from biomass production is borne by the farmer. With the STANDARD contract, a portion of the price risk on expected production is shifted from the producer to the biorefinery. All of the price risk is shifted from the farmer to the processor with an ACRAGE contract but the farmer still incurs the entire yield and production cost risk. On the other hand, the gross revenue contract provides the greatest potential risk benefits to the farmer because all of the biomass price and yield risk is assumed by the processor. In addition, a contract provision for switchgrass that provides a financial incentive to reduce production cost risk by covering the materials cost of establishing the switch grass stand was also modeled. The gross revenue contract and the planting incentive are two potential switchgrass production incentives that are being consider for contract production for the cellulosic ethanol pilot plant being constructed for Tennessee Biofuels Initiative (Garland, 2007). The time period for each of the four types of contracts modeled was assumed to be 5 years (Garland, 2007).

A 99 year distribution of net revenues for each the crop activity was simulated for use in the quadratic programming model to determine risk-efficient farm plans under the alternative contracting scenarios. The variables treated as random in the simulation of net revenues were crop prices, crop yields, nitrogen fertilizer price, diesel fuel price, and selected biomass harvest and transportation costs as a function of harvested yield. The ALMANAC crop model (Kiniry *et al*., 2005) was used to simulate random crop yields for the continuous crop and crop rotations on the Loring, Memphis, and Collins soils for the representative farm. A 99 year set of real, detrended, and correlated prices for corn, soybeans, wheat, wheat straw, corn stover, switch grass, nitrogen fertilizer, and diesel fuel were simulated using the @Risk simulation model in Decision Tools (Palisade Corporation, 2007). Energy equivalent price series for switchgrass, corn stover, and wheat straw as an ethanol based energy substitute for gasoline were constructed using wholesale gasoline price data for 1977 through 2004 (U.S. DOE, 2008) and biomass conversion to ethanol factors from Wang, Saricks, and Santini (1999). The number of gallons of ethanol assumed to be produced per dry ton (dt) of biomass was assumed to be 69.2 gallons for wheat straw, 72 gallons for corn stover, and 76 gallons for switchgrass. Contract prices for corn stover and wheat straw were adjusted downward by 5 percent and 9 percent, respectively, from the contract price for switchgrass to reflect the lower gallons per dt produced.

Corn, soybean, wheat, and soybean-wheat production costs were derived from University of Tennessee Extension budgets (Gerloff, 2007a). All three biomass crops were assumed to be harvested using a large round bale system with the bales being moved to the edge of the field before transport to the user facility. Switchgrass production costs were estimated using a budget produced by University of Tennessee Extension (Gerloff, 2007b).

Results and Discussion

The important findings from this research were as follows. First, under the SPOT scenario, biomass prices averaged \$27.68/dt (standard deviation of \$9.34/dt) for wheat straw, \$29.44/dt (standard deviation of \$15.50/dt) for corn stover, and \$34.77/dt (standard deviation of \$7.43/dt) for switchgrass. When biomass crops were priced annually based on the energy equivalent price, the production of biomass crops did not enter into the optimal crop mix for any risk significance level except the most risk-averse 90 percent level. For this level of risk aversion, only 36 acres on switchgrass was planted on the poorest quality Collins soil. No other biomass crops were planted on the rest of the farm. Thus, an average of only 324 dt of biomass would be supplied by the representative farm under the SPOT contract scenario. In general, the net revenues from biomass crops were not high enough under SPOT contract prices to induce biomass production Results indicate that a contract price above the energy equivalent price would be needed to encourage biomass production on the representative farm.

Second, the ACREAGE and REVENUE contracts were more effective at inducing maximum farm biomass production at lower contract prices than the STANDARD contract for a risk neutral decision maker (Figure 1). Under the assumption of risk neutrality, the same amount of biomass was supplied by the representative farm under the REVENUE contract as under the ACREAGE contract. Expected biomass crop net revenues were identical for both contract structures. Most of the biomass supplied by the representative farm under the STANDARD, ACREAGE, and REVENUE contracts was from switchgrass. In addition, some corn stover was produced but no wheat straw was supplied for ethanol production by the representative farm.

Third, because the REVENUE contract reduced biomass crop net revenue variability relative to the ACREAGE contract, the REVENUE contract provided more risk benefits to the representative farm under the assumption of risk aversion (Figure 2). In addition, because of the greater price and yield protection offered with the REVENUE contract, switchgrass production was generally induced at lower contract prices than with the STANDARD contract. Fourth, results of this study suggest that a planting incentive to offset part of the cost of establishing switchgrass may be effective at inducing biomass larger production at lower contract prices. The incentive may provide a method for the processor to reduce average per ton cost of material at the plant gate for perennial biomass crops such as switchgrass.

Finally, as more of the farm crop area was planted into biomass crops at higher contract prices, the greater the annual variation in biomass supplied to the processing plant. Thus, for a biorefinery, there may be a relationship between the annual variation in biomass material supplied and the cost of biomass materials. A higher contract price may induce more production on an individual farm. This could result in fewer farms in a more concentrated geographic area being needed to supply the plant. The biomass materials transportation cost may be lower but the biomass storage cost incurred to ensure a steady supply of feedstock to the plant may be higher with the increased variability of annual biomass production with higher contract prices.

Summary and Conclusions

This study evaluated the potential for a northwest Tennessee 2,400 acre grain farm to supply lignocellulosic feedstock to a biorefinery under alternative contract arrangements. The four potential types of contracts analyzed in this study offer different levels of biomass price, yield, and production cost risk sharing between the representative farm and the processor. Results indicate that a contract price above the energy equivalent price in a spot market type contract would be needed to induce biomass production on the representative farm. A contract that makes annual payments based on the

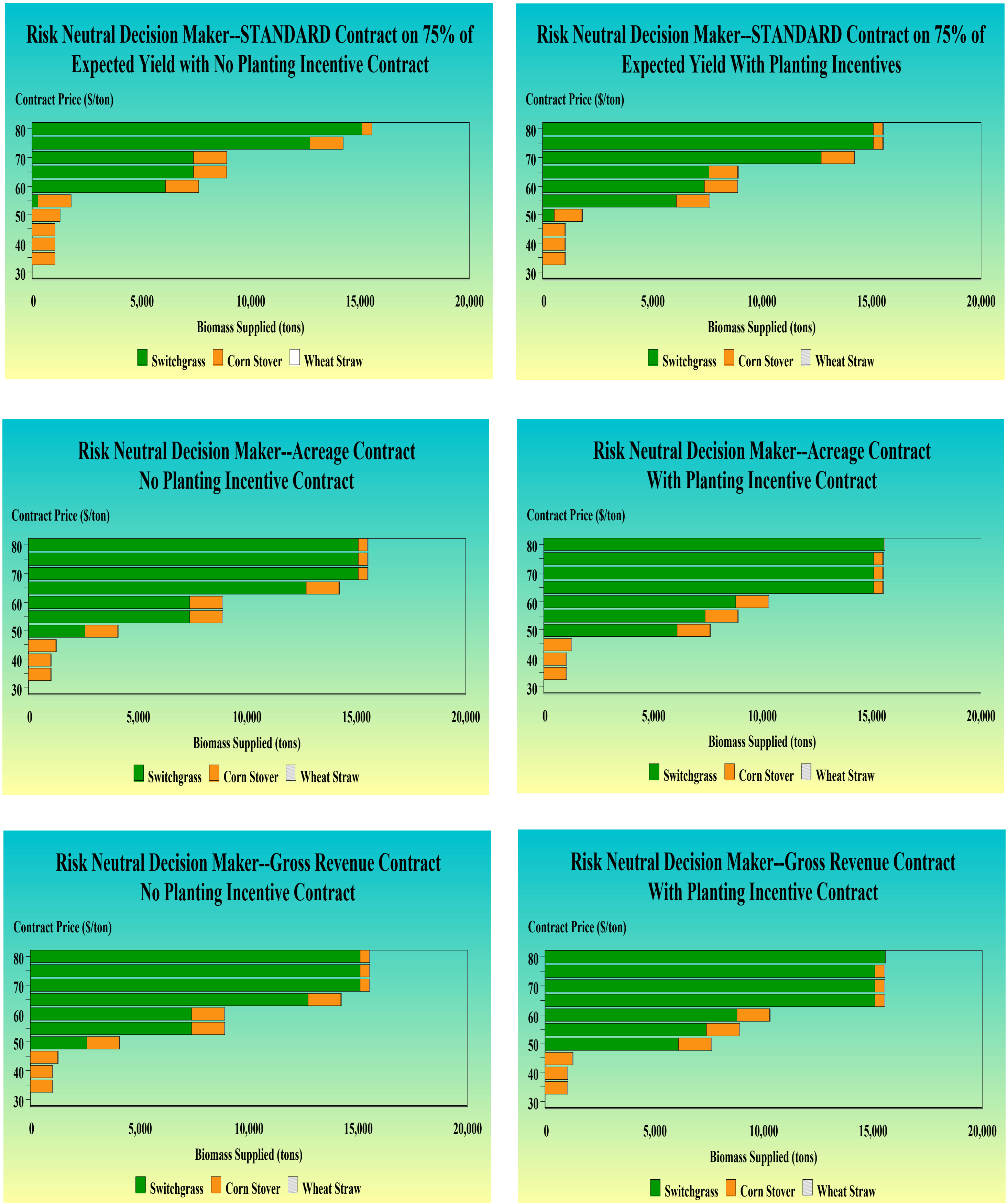

Figure 1. Representative Farm Biomass Supplied at Different Contract Prices for the STANDARD, ACREAGE, and REVENUE Contract Scenarios Assuming a Risk Neutral Decision Maker

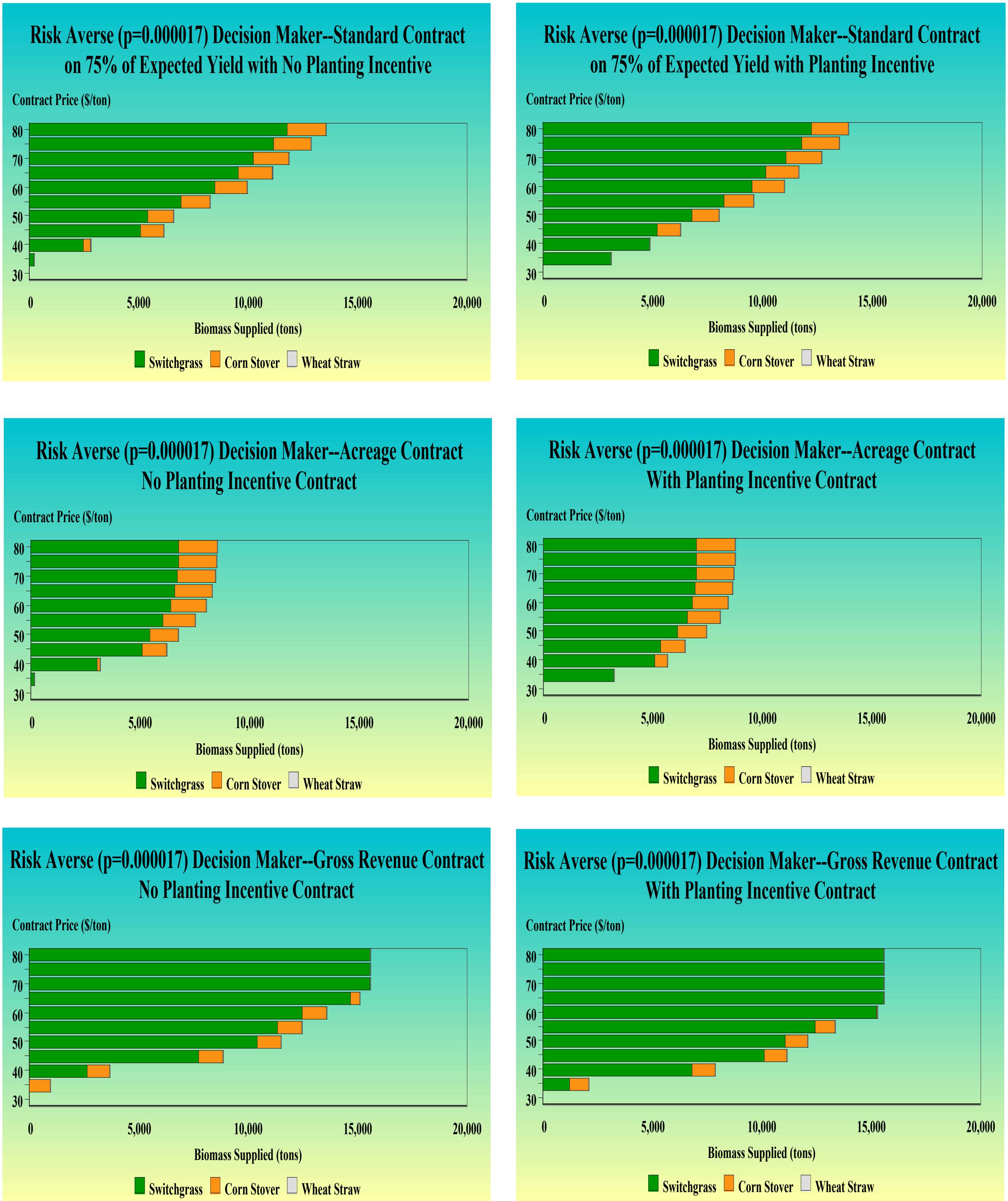

Figure 2. Representative Farm Biomass Supplied at Different Contract Prices for the STANDARD, ACREAGE, and REVENUE Contract Scenarios Assuming a Risk Averse Decision Maker (90 Percent Risk Significance Level)

expected biomass yield over the life of the contract rather than on annual yield induced the largest amount of production (primarily switchgrass) under risk aversion. Because of the price and yield protection offered with more this type of contract, biomass production was generally induced at lower contract prices. In addition, a contract with a provision to offset part of the cost of establishing a perennial crop such as switchgrass may be effective at inducing larger biomass production at lower contract prices. Finally, the annual variation in biomass supplied to the biorefinery was larger as more of the farm crop area was planted into biomass crop at higher contract prices. The increased variability in biomass production has implications on storage and transportation costs for a biorefinery needing a steady, year-round supply of biomass materials for processing.

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Economic and Environmental Impacts of Biofuels Expansion: The Role of Cellulosic Ethanol

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Introduction

Within the past three years, politically, there has been a significant movement towards an energy future with a substantially larger renewable energy component. A major driver for this movement is the perception that importing over 60% of our oil reduces our national security. An ethanol subsidy in place, increased oil demand and, hence, increased gasoline prices, along with the reduction in use of MTBE as an oxygenate, have resulted in ethanol becoming highly profitable. This profitability and perception that independence from foreign oil is a goal for America has resulted in significant growth in the corn-ethanol industry. As the industry grew, so did the demand for feedstocks. With that increased demand, increased commodity prices followed.

The use of bioenergy feedstocks to produce transportation fuels could not only help reduce reliance on foreign oil, but could also provide significant environmental benefits and invigorate rural economies. Agriculture is well positioned as a feedstock source, because the fuels can be utilized with current engine technologies and are compatible with the current distribution infrastructure. Ethanol production increased from 2.8 billion gallons in 2003 to nearly 4.9 billion gallons in 2006 (Renewable Fuels Association, 2007). The rapid buildup in the past three years of ethanol production has increased farm income and rural economic development in certain regions of the United States. Ethanol production has expanded beyond the Midwest region where 17 states have ethanol plants in 1999 to 26 states in 2007.

The Energy Policy Act of 2005 established a renewable fuel requirement for the nation, mandating 7.5 billion gallons of renewable fuels by 2012 (U.S. Congress, 2005). Ethanol and biodiesel are both defined as eligible renewable fuels. A more sweeping renewable fuels standard was proposed as part of The Biofuels Security Act of 2007 (sponsored by Senator Tom Harkin and co-sponsored by Senators Biden, Dorgan, Johnson, Lugar, Obama, and Salazar). This proposal would require 10 billion gallons of renewable fuels by 2010, 30 billion by 2020 and 60 billion by 2030 (U.S. Congress, 2007a). Furthermore, the Governors' Ethanol Coalition has recommended that replacing at least 25 percent of petroleum used as transportation fuels by the year 2025 (Governor's Ethanol Coalition, 2006). Subsequent to the 2005 Energy Policy Act, the Energy Independence and Security Act of 2007 was enacted. A renewable fuel standard schedule is created with applicable volume of renewable fuel increasing from 9.0 billion gallons in 2008 to 36 billion gallons in 2022. By 2016, 22.25 billion gallons of ethanol production is required (U.S. Congress, 2007b).

Numerous profit and non-profit organizations have developed initiatives attempting to move renewable fuel production from its current status toward one that will impact this nation's land resource and rural areas. De La Torre Ugarte *et al*. (2003) and Walsh *et al*. (2003) evaluated the impacts of bioenergy crop production on the agricultural sector. The realized net farm income increased and government payments decreased compared to the USDA baseline as dedicated energy crop production increased. The 25x'25 group set forward a national goal to meet 25% of the energy needs in the year 2025 with renewable energy. In a study conducted by the University of Tennessee, 15.45 Quads of energy would come from renewable and sustainable biomass feedstocks and another 6 quads would come from wind (English *et al*., 2006). In subsequent analysis conducted for the Governors Ethanol Coalition (De La Torre Ugarte, 2006), the estimated impacts resulting from the production of 60 billion gallons of ethanol and a smaller amount of biodiesel were revealed. In another study, an analysis was conducted that examined the impacts of meeting increased biopower, biofuel, and bioproducts demands (De La Torre Ugarte, 2007). Each of these studies used a simulation model called POLYSYS and evaluated the economic and land use pattern changes as a result of various levels of new bioproduct production; however, little attention

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was paid toward the environmental impacts resulting from increased agricultural demands.

Objectives

The goal of this study is to provide not only an economic analysis of agriculture's ability to contribute to the Congressional goal of supplying 18 billion gallons by 2016, but to also evaluate the impact the pursuit of this goal could have on this nation's environment if cellulosic ethanol is not feasible by 2016. The first objective of the study is to evaluate the ability of production agriculture to contribute 18 million gallons of corn-ethanol. The second objective is to estimate the potential environmental impacts on the nation's resources as a result of this emerging industry.

Methodology

Energy targets for ethanol were defined for the years 2006 through 2016. This information, along with the assumption that the ethanol must be produced from corn or other traditional feedstocks, was then introduced into POLYSYS, a regional/national agricultural simulation model, to estimate the quantity of ethanol to be produced from agriculture, as well as the price, agricultural income, and other agricultural sector impacts deriving from producing such a level of energy production. Results from POLYSYS were used to evaluate the environmental implications through the use of indicators. An Environmental POLYSYS Sub-module (EPS) was developed to provide indicators on changes in the environment. Changes in chemical and fertilizer applications were indicated by changes in expenditures for these inputs. Changes in erosion are provided through the Universal Soil Loss Equation assuming current tillage practices are constant. The changes in erosion are placed into the Micro Oriented Sediment Simulator (MOSS) (Alexander and English, 1988) to provide regional estimates of the costs incurred due to sedimentation and deposition. Changes in carbon sequestration and in carbon emissions were estimated using Carbon Management Response (CMR) curves and per unit carbon emissions from direct fuel usage and are embodied in the production of inputs.[2] For further information on POLYSYS and its use in this analysis see De La Torre Ugarte and Ray (2000) and English *et al*. (2007).

The focus of the analysis is on comparing the impacts that producing ethanol will have on the nation's agricultural sector and its environment. To adequately interpret the results coming from POLYSYS, it is important to refer the simulation values to the 2007 USDA baseline (USDABASE). The baseline represents the best estimate of what would occur without meeting pre-specified energy goals. Results under four scenarios were compared to USDABASE. The first three scenarios project the impacts of attaining the ethanol targets of 14 (14BILETH), 16 (16BILETH), and 18 (18BILETH) billion gallons of ethanol and the fourth scenario assumes that the level of ethanol never exceeds 8.6 billion gallons, or the amount of ethanol assumed to be produced in the USDABASE in 2007 (FLATETH) (Figure 1). In all of these

[2]The carbon analysis in this section incorporates changes in carbon emissions and soil carbon as a result of changes in land use. It does not compare the carbon footprint of ethanol to that of gasoline production. Nor does it include the carbon emissions likely to occur as a result of feedstock and product distribution.

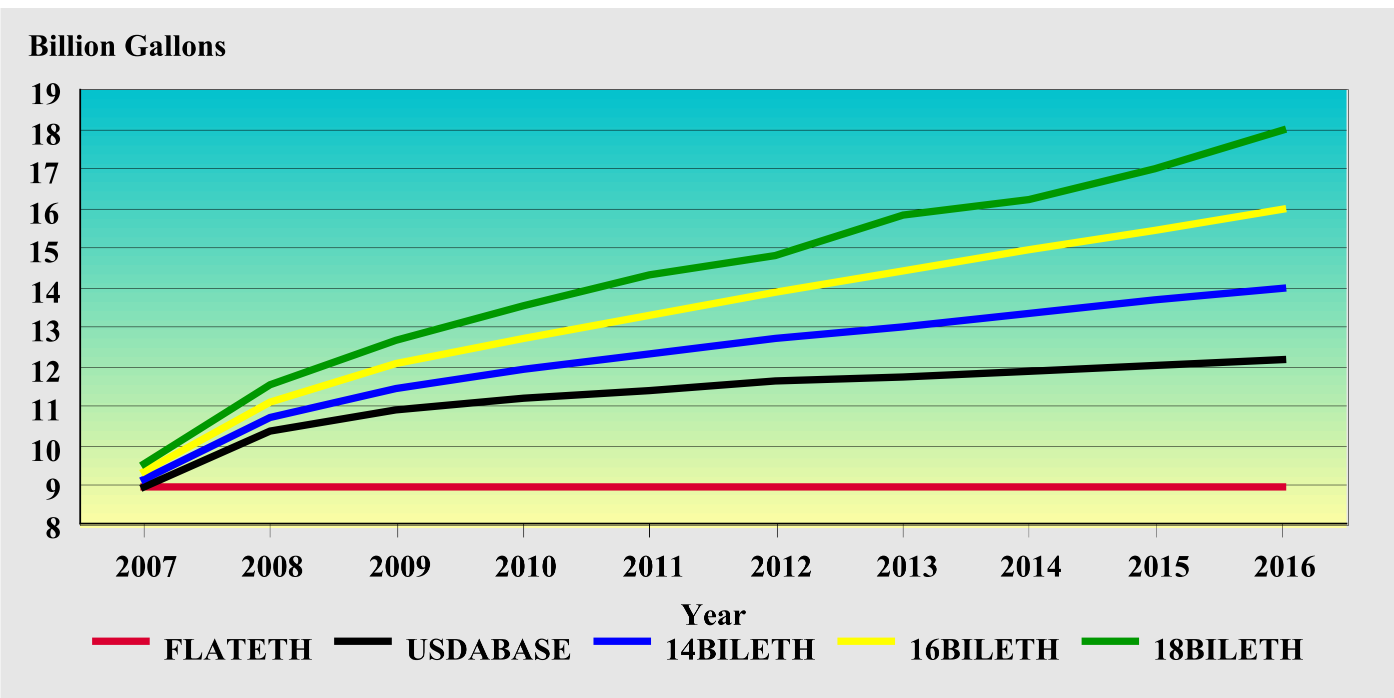

Figure 1. Ethanol Production for the Various Scenarios Analyzed

scenarios, corn grain was the feedstcok assumed through the year 2016. Yields for grain and other crops increased at the USDA expected rate. However, sensitivity analysis was conducted on corn yield as some have indicated much greater yield potential by 2016. Results from a solution that allowed corn yield to increase to 200 bushels by 2016 were also examined in this analysis. Results from these four scenarios are compared with the extended baseline to illustrate how various paths of ethanol industry expansion may influence the agricultural sector. In addition, the results of the 18BILETH scenario was compared to FLATETH in order to discover the impacts that additional growth in the ethanol industry will have compared to 2007's estimated level of ethanol production.

Results

Under each of the scenarios, the desired targeted production of ethanol can be achieved for the years 2007 through 2016. As specified, for each of the scenarios except FLATETH, the use of corn reaches a peak in 2016. With the changes in ethanol demand, major changes occur in the demand for corn, prices in agricultural commodities, land use patterns, and agricultural sector net returns. These economic and land use changes impact the environment through changes in chemical expenditures, fertilizer expenditures, soil erosion and sedimentation, and carbon sequestration and emissions.

Economic and Land Use Impacts

Agricultural Production

In the USDABASE, by 2016, 14.09, 2.24, and 3.08 billion bushels of corn, wheat, and soybeans, respectively, are produced. In addition, 320, 125, and 210 million bushels of sorghum, oats, and barley are produced. Also, 230 million cwt of rice and 22.8 million bales of cotton are produced. If ethanol production were to remain at the 2007 levels by 2016, a reduction in annual corn production of 1.3 billion bushels would result, along with increases in soybeans, wheat, and cotton (Table 1). However, increasing the ethanol production to 18 billion gallons is projected to increase corn production by 1.57 million bushels but decrease soybeans, wheat, and cotton production. As demand for ethanol increases, the production of corn increases in response to this change but the productions of other crops typically decrease.

Estimated Commodity Price Impacts

As expected, increasing the amount of ethanol produced from corn causes increased prices for all commodities. In the baseline, commodity prices are at higher average prices

Table 1. Change in Commodity Production for the Alternative Scenarios, 2007, 2010, 2013, and 2016

Scenario and Crop	Units	Projected for the Year of: 2007	2010	2013	2016
		---------- Millions of Units ----------			
FLATETH-USDABASE					
Cotton	bales	0	0.17	0.27	0.11
Corn	bushels	0	-457	-19	-1,304
Soybeans	bushels	0	132	-21	362
Wheat	bushels	0	12	12	22
14BILETH-USDABASE					
Cotton	bales	0	-1.83	-2.77	0.19
Corn	bushels	0	320	486	312
Soybeans	bushels	0	-26	-67	-32
Wheat	bushels	0	-29	12	-41
16BILETH-USDABASE					
Cotton	bales	0	0.15	0.02	-2.49
Corn	bushels	0	171	357	1,190
Soybeans	bushels	0	-25	-48	-191
Wheat	bushels	0	-11	-35	-33
18BILETH-USDABASE					
Cotton	bales	-0.49	-0.92	-1.99	-1.53
Corn	bushels	-55	749	1,155	1,567
Soybeans	bushels	21	-147	-297	-186
Wheat	bushels	4	-2	34	-129

than those prices that have occurred during the past 10 years. Corn price is projected to average $3.48/bushel in the USDABASE. As ethanol production increases, all commodity prices increase reflecting the increased demands being placed on land resources. Corn price increases by an average of 5.2 % as we move from 12 billion gallons to 18 billion gallons (Table 2).

Livestock prices are also impacted by changes in ethanol production. In the USDABASE scenario, the farm price for beef ranges from $80.57/cwt to a high of $83.59/cwt with an average price over the ten year time frame of $81.43/cwt. The pork and poultry farm price in the USDABASE scenario averages $45.67/cwt and $43.19/cwt respectively. As ethanol demand increases to 18 billion gallons (18BILETH), the average prices increase for beef, pork and poultry by $1.20, $1.07, and $0.66/cwt respectively.

Agricultural Land Use Changes

Use of agricultural cropland changes when compared to the baseline as agriculture attempts to meet the changes in ethanol demanded. In the USDABASE scenario, 90 million acres are planted to corn in 2016, an increase of 4 million compared to the land needs projected for 2007. To accommodate this increase, a decrease in soybean and wheat acreages are projected. As ethanol demand increases as reflected in the 18BILETH scenario, further increases in planted corn acreage is projected with 100 million acres of corn planted by 2016. This increase in corn land of nearly 10 million additional acres when compared to the BASEUSDA scenario is coupled with decreases in wheat, soybeans, cotton, and rice of 3.64, 2.88, 1.03, and 0.16 million acres respectively. The projected change in planted corn acres is estimated at 18.5 million acres when ethanol production remains flat at slightly over 8 billion gallons (FLATETH scenario) compared to the 18BILETH scenario, a change of 22% in planted corn acres.

Changes in land use occur in most areas of the United States. The increase in corn acreage occurs throughout the United States with concentrations in eastern Colorado, north Texas, southern and eastern Nebraska as well as the traditional Corn Belt. Soybeans leave the Corn Belt and move toward the South and Great Plains. Wheat production shifts from the Great Plains and the Corn Belt and increases in the western states as well as the South and Appalachian regions. Cotton shifts from the South westward into primarily irrigated regions of the country.

Changes in Agricultural Sector Net Returns and Government Payments

Agricultural net farm income in the USDABASE scenario averages $65.2 billion per year over the ten year period. If ethanol production increases to 18 billion gallons per year by 2016, net farm income is projected to increase by over $5 billion per year creating a win for agriculture and agricultural resource owners (Table 3). If the nation maintains production at projected 2007-2008 levels, agricultural net farm income will decrease by $5.5 billion per year on average from the baseline. As ethanol production increases, net farm income increases, and government payments decline.

Table 2. Three Year Average Percent Change in Commodity Prices for the Alternative Scenarios

		Three Year Average Projected for:				
Scenario and Crop	Units	2007-2009	2010-2012	2013-2015	Ending Price	10 Year Average
14BILETH						
Cotton	pound	0.0%	0.6%	4.9%	0.5%	2.4%
Corn	bushels	1.5%	1.4%	3.1%	9.1%	4.5%
Soybeans	bushels	0.0%	0.5%	4.5%	3.6%	2.2%
Wheat	bushels	0.1%	0.7%	1.0%	2.9%	1.3%
16BILETH						
Cotton	pound	0.6%	0.5%	-0.2%	7.1%	1.6%
Corn	bushels	0.4%	0.7%	7.3%	-3.6%	2.8%
Soybeans	bushels	0.3%	1.3%	4.2%	8.7%	3.5%
Wheat	bushels	0.2%	0.3%	3.4%	1.9%	1.7%
18BILETH						
Cotton	pound	0.7%	0.3%	1.7%	-2.5%	1.2%
Corn	bushels	1.1%	3.1%	1.2%	10.4%	5.2%
Soybeans	bushels	0.1%	0.1%	6.6%	-1.2%	2.0%
Wheat	bushels	0.2%	1.4%	1.4%	9.9%	2.8%

Table 3. Realized Net Farm Income over the Ten Year Period of Analysis

Scenario	Projected for the Year of: 2007	2010	2013	2016	Total	Average
	------ Million Dollars ------					
FLATETH	62,300	61,785	58,277	56,084	595,358	59,536
USDABASE	62,300	68,300	65,800	62,800	651,700	65,170
14BILETH	62,592	69,772	68,128	65,545	670,312	67,031
16BILETH	62,986	71,692	70,427	67,284	686,462	68,646
18BILETH	63,580	73,103	74,859	70,897	707,065	70,707

Total payments over the ten year period of analysis are estimated at $115 billion. With only nine percent of the payments in countercyclical and loan deficiency payments, very little change in government payments can occur as a result of increased income. As ethanol production increases, the loan deficiency and countercyclical payments decline. This analysis assumes that the government program stays in place as it was in 2007 and that CRP land does not shift into production. It is likely that CRP program payments would have to increase as contracts expire to maintain the current land base in the CRP program. This is not accounted for in this analysis.

Changes in the Environmental Impact Indicators

In this manuscript, most of the environmental impact indicator comparisons will be conducted using the 18BILETH versus the USDABASE or FLATETH scenarios. Similar comparisons could have been made for the 14BILETH and the 16BILETH scenarios. The comparisons are made on chemical and fertilizer expenditures, along with nitrogen use, soil erosion and sedimentation and the estimated associated costs, plus carbon sequestration and emissions.

Non-Fertilizer Chemical Use

In the year 2016, non-fertilizer chemical use increased by a projected $271 million under the 18BILETH scenario when compared to the USDABASE scenario. The trend over the 10 year horizon is an increase in non-fertilizer chemical expenditures above the changes that occur in the USDABASE scenario. During the entire span of years, an increase above the USDABASE scenario of $487.5 million is projected, or an average increase of $487,549 per year in non- fertilizer chemical expenditures.

Not all regions of the country experience increases in non-fertilizer chemical expenditures however. While the average increase in non-fertilizer chemical expenditures for an ASD is $160,000 each year, in 2016, 90 ASDs out of 305 experience either no change or decreases in non-fertilizer chemical expenditures. The 18BILETH scenario has 88 ASDs with zero or reductions in chemical expenditures when compared to the FLATETH scenario.

Fertilizer Expenditures

In the year 2016, fertilizer expenditures increase nearly $300 million under the 18BILETH scenario when compared to the USDABASE scenario, and increase by over $600 million when compared to the FLATETH scenario. The trend over the 10 year horizon is an increase in fertilizer expenditures as corn acreage expands above the changes that occur in the USDABASE scenario. During the entire span of years, an increase above the USDABASE (FLATHETH) scenario of $1.3 ($2.4) billion is projected, or an average increase of $130 million per year in fertilizer expenditures.

In examining regional changes in fertilizer expenditures, decreases in fertilizer use are projected in parts of the delta, as cotton acreage is reduced, and in the Northern Plains, as corn and soybeans replace wheat. Areas with large increases in nitrogen expenditures fall within the Mississippi River Basin (Figure 2). Though not evaluated in this study, the increase in nitrogen expenditures will elevate concerns regarding nutrient movement leading to a greater likelihood the Gulf might experience additional hypoxia.

Soil Erosion and Sedimentation

Increasing ethanol production from 8.6 billion gallons (FLATETH) to 18 billion gallons in 2016 will result in an increase of 25.8 million tons of erosion. Although this increase in erosion is projected to be distributed throughout the nation, most occurs in the Corn Belt region. Nearly all ASDs in Iowa and Illinois are projected to have increased erosion levels exceeding 100,000 tons/year by 2016.

Increased suspended sediment estimates are projected to exceed 1.7 million tons per year in Illinois, 1.5 million per year in Louisiana, and 1.0 million tons per year in Iowa and Ohio when comparing the 18BILETH to FLATETH. A comparison of annual sediment deposits for these same two scenarios shows increases estimated at 1.2 million tons for Illinois, 0.94 million tons for Iowa, and 0.88 million tons for Ohio. The estimated change in cost damages as a result of these increases in both suspended and deposited sediment range from $36.6 to $150 million per year with an estimated value of $70.48 million per year (2005 dollars).

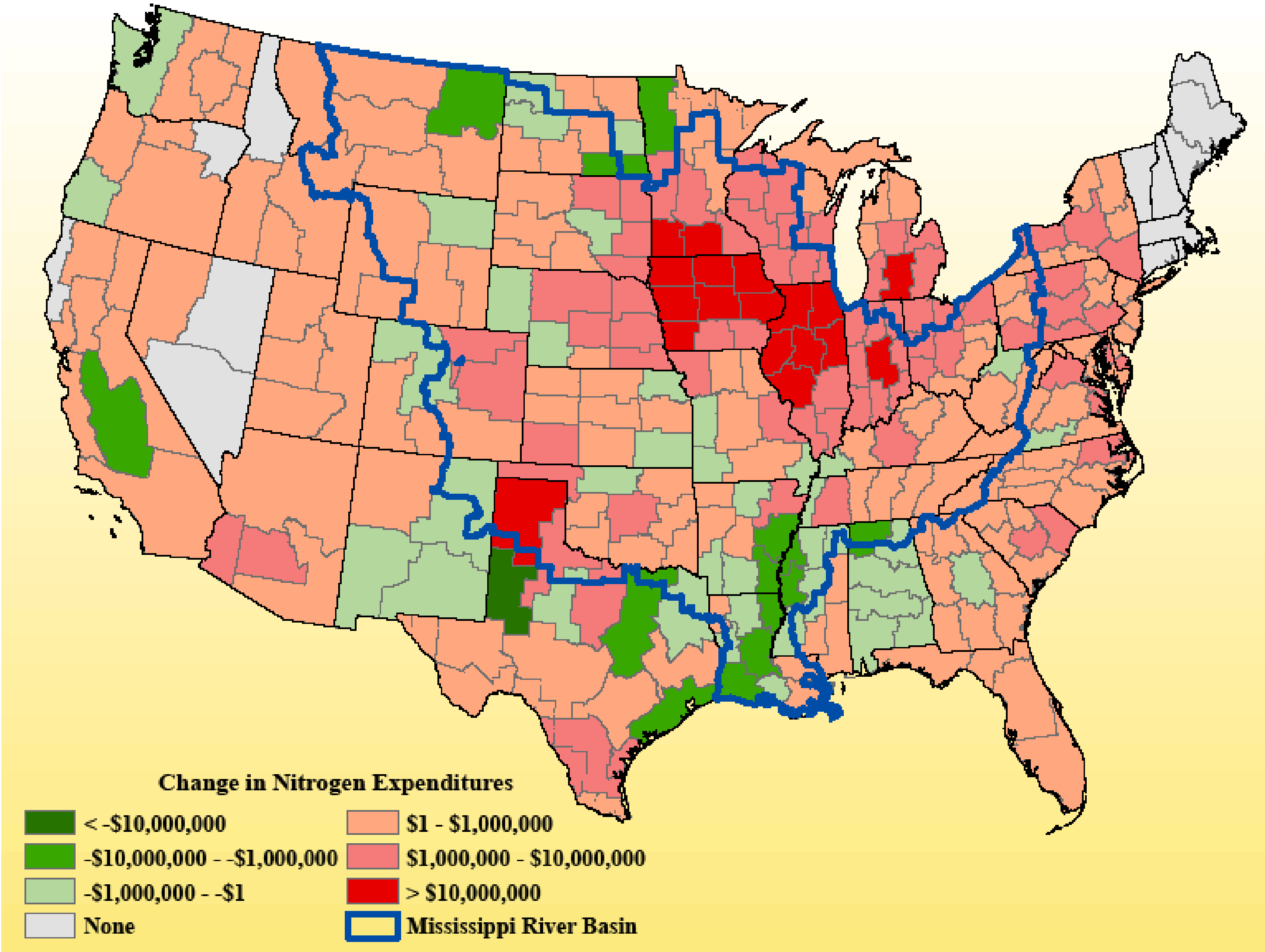

Figure 2. Change in Nitrogen Expenditures, 18BILETH vs FLATETH

Carbon Emissions and Carbon Sequestration

Carbon emissions in producing agricultural commodities, not including livestock, are lowest for the FLATETH scenario and highest for the 18BILETH scenario (Figure 3). The estimated difference between these two scenarios is slightly more than four million metric tonnes over the 10 year period. There is little change in the initial years of the analysis when comparing carbon emissions of the USDABASE, 14BILETH, 16BILETH, and 18BILETH scenarios to the FLATETH scenario. The largest changes appear to take place under the 18BILETH and 16BILETH in the years 2014-2016. When reviewing the data, however, it must be remembered that the analysis is not incorporating the carbon emissions from fuels that are being replaced by ethanol, nor do they include the carbon emissions as a result of transportation of the feedstock or the emissions resulting from distributing the ethanol once it is produced.[3]

Increased Average U.S. Corn Yield Impacts

Compared to the recent past, Monsanto has publicly indicated that future corn yields will increase at a much faster rate. To examine the potential impacts of an accelerated corn yield, corn yield was increased to 200 bushels by 2016 (Figure 4). This increase in yield would result in a 22% decline in corn commodity prices in the 18 billion gallon scenario. On average 3.6% less corn acreage is required to meet expected demands. Total crop acres in production change very little. Realized net farm income declines from a yearly average of

[3]The carbon analysis in this section incorporates changes in carbon emissions and soil carbon as a result of changes in land use. It does not compare the footprint of ethanol to that of gasoline production. Nor does it include the carbon emissions likely to occur as a result of feedstock and product distribution.

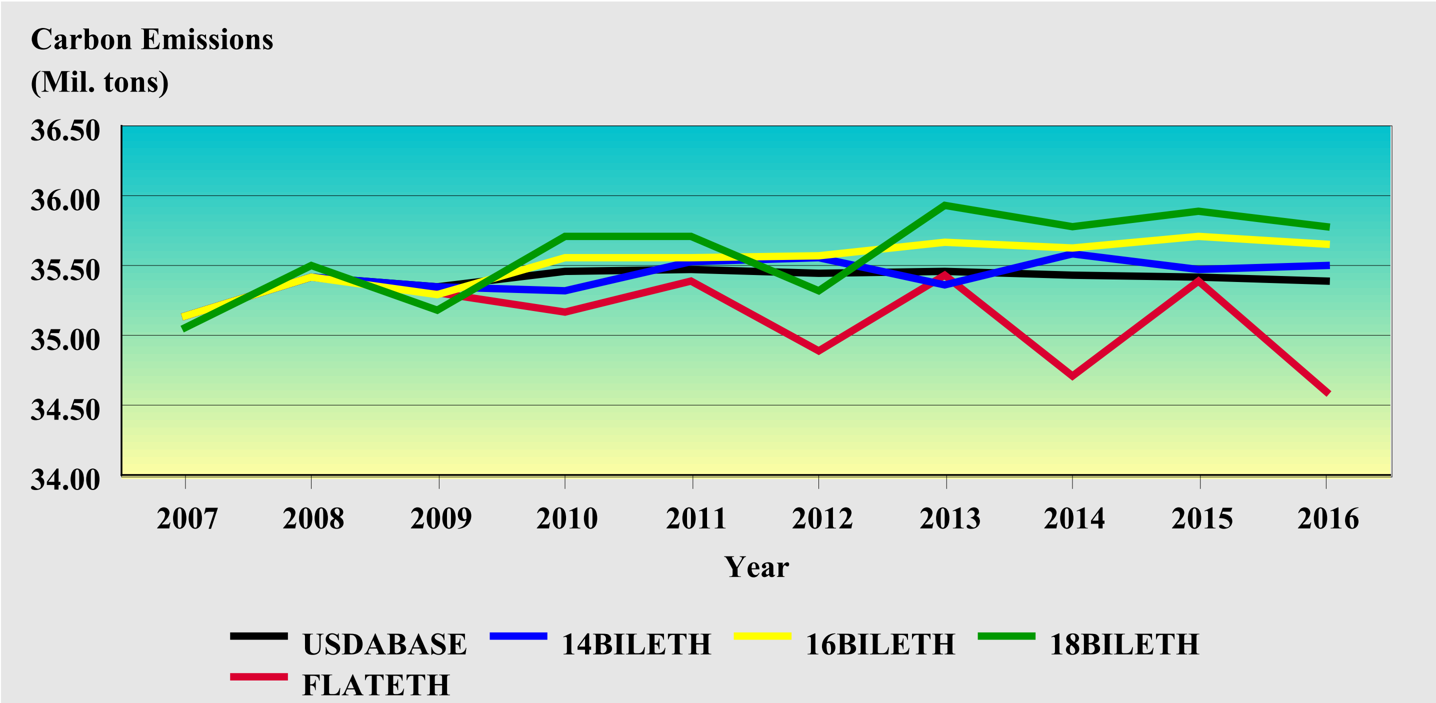

Figure 3. Carbon Emissions in Metric Tonnes for the Five Scenarios

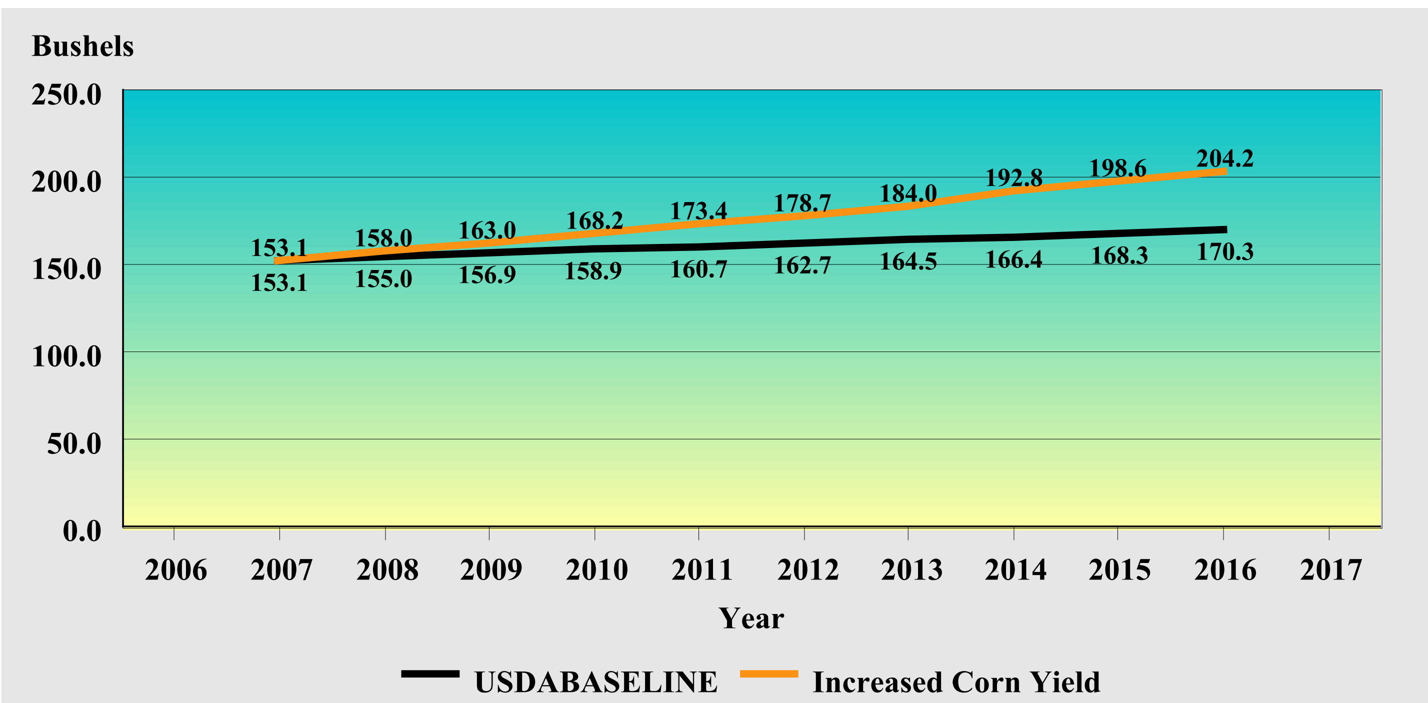

Figure 4. Projected Corn Yields, 2007 through 2016, for the 2006 USDA Baseline and the High yield Sensitivity Alternative

$66.9 billion reflected in the 18BILETH solution to $55.7 billion when corn yields increase.

Conclusions

The analyses performed indicate that U.S. agriculture can increase ethanol production from grains to 18 billion gallons over the next ten years. The analysis provides a comparison of the projected impacts of moving from an agricultural sector that produces sufficient feedstock for an 8.6 billion (FLATETH) gallon per year ethanol industry to an ethanol industry of 12 (USDABASE), 14 (14BILETH), 16 (16BILETH), or 18 billion (18BILETH) gallons. Overall, for the period 2007 to 2016, the estimated accumulated gains in net farm income exceeds $55 billion, with an accumulated potential savings in government payments of 2.4 percent assuming no changes in direct and CRP payments when compared to the USDABASE scenario. Realized net farm income over the ten year period of analysis increases $112 billion as a result of the ethanol industry increasing in scale from 8.6 billion gallons to 18 billion gallons. Increasing corn yields from the 2006 USDA Baseline each year of the analysis culminating in a 19% change by 2016, resulted in decreased acres planted in corn, reduced net farm income primarily as a result of decreased corn prices, and little change in total land in production.

Land use shifts occur as corn production increases as a result of increased returns for this crop. As land moves away from other crops into corn, prices for those crops are bid up. Cotton shifts westward and wheat shifts into the southeast. Corn production increases throughout the United States, but the largest increases occur in the western Corn Belt and eastern Nebraska. Soybeans shifts out of the Corn Belt into the Southeast. By 2016, corn acreage increases to 100 million acres in the 18BILETH scenario, an increase of 10 million acres compared to the USDABASE and an increase of more than 19 million acres when compared to the FLATETH scenario.

Resulting land use shifts and increases in corn acreage significantly impact the environmental indicators in this analysis. Use of both non-fertilizer chemicals and fertilizers increase. Soil erosion and sedimentation increase. Soil carbon sequestered as a result of agricultural production activities decrease and carbon emissions as a result of agricultural crop production activities increase. It is important to note, however, that under the assumptions of the analysis, no change in tillage practices were assumed. Changes toward no-till would reduce the amount of soil erosion, the amount of carbon emitted and the amount of carbon sequestered. However, chemical inputs would likely increase as chemicals are used instead of mechanical means for weed control.

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Estimating and Comparing Alternative Ethanol Processes and Feedstock Choices

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Introduction

Annual production of ethanol for fuel in the United States has risen from 175 million gallons in 1980 to nearly 6.5 billion gallons in 2007 (Renewable Fuels Association (RFA), 2008). While nearly all of the U.S. ethanol supply is currently derived from corn, concerns about environmental sustainability and potential impacts on the food supply chain have brought corn-based ethanol out of favor with some. The economic future of the grain-based ethanol industry has also been increasingly questioned in recent months, as declining ethanol prices have contributed to numerous cancellations of planned ethanol plants and expansions (Ngo, 2007). The demand for ethanol seems to have stagnated, even as crude oil price has continued to set record highs. Discretionary ethanol blending above that mandated by the Renewable Fuels Standard (RFS) relies on economics, as refineries will use more ethanol when it is economically advantageous to do so. These concerns have made it imperative that the ethanol industry take larger strides in developing and adopting low cost ethanol processing alternatives – regardless of source. Two options currently being explored are 1) The cellulosic process, where ethanol is produced using enzymatic breakdown of cellulosic materials and 2) the Brazilian "squeezing" method, where ethanol is produced from sugar that is squeezed from sugar producing crops such as sugarcane and sweet sorghum.

In contrast to grain-based ethanol, cellulosic ethanol can be made using any cellulosic-based feedstock, with focus on crops not competing with the food or feed industries. The Brazilians have had enormous success with the "squeezing" method, however, this method has yet to gain traction in the United States – due in large part to U.S. sugar policy. Even though cellulosic ethanol may be theoretically preferable to grain based ethanol, the ability to convert cellulose to ethanol on a commercial basis continues to elude the biofuels industry. Cellulosic production processes, such as MixAlco and other enzymatic processes, have been proven in the laboratory and are now in the process of being attempted on larger scales (Lau, 2004 and Farm Panel, 2007). For both the Brazilian and cellulosic processes, a number of different feedstocks are available for ethanol production. This study models feedstock production options for cellulosic and Brazilian processes at the farm level to determine the delivered cost to a biorefinery of a given capacity. The economic feasibility of ethanol production with these feedstocks is then modeled across the MixAlco cellulosic and Brazilian process alternatives to determine which type of ethanol production process and feedstock mix has the potential to produce ethanol at the lowest average total cost relative to grain.

Existing Studies

In the early 1990's Oak Ridge National Laboratory (ORNL) began to put forth research on the viability of switchgrass as a cellulosic biomass crop. The results of that research, which continues today, suggest that switchgrass may be one of the most advantageous crops for U.S. cellulosic feedstock production (ORNL, 2007). As a result of the ORNL findings, the majority of economic research has focused on switchgrass as the dominant cellulosic energy crop, where subsequent studies use an average conversion rate of 90 gallons of ethanol per dry ton.

In 2003, the USDA released its findings on the economic impacts of bioenergy crop production on U.S. agriculture (De La Torre Ugarte *et al.*, 2003). Their macro analysis, using the POLYSYS modeling framework, estimates shifts in acreage, production, and changes in prices for the major U.S. crops when a combination of switchgrass, poplar, and willow are introduced as dedicated energy crops on CRP land. The delivered prices for cellulosic feedstocks, which are exogenous to their model, range from $30 to $32.90 per dry ton (De La Torre Ugarte *et al.*, 2003).

In 2006, the University of Tennessee released an analysis of the feasibility of America's farms, forests, and ranches providing 25 percent of the U.S. total energy needs by 2025, while still providing a safe, abundant, affordable supply

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of food, feed, and fiber (English *et al.*, 2006). They found that the goal is achievable using a combination of forestry, food processing wastes, and dedicated energy crops such as switchgrass. Under their assumptions, the addition of dedicated, cellulosic energy crops to the U.S. crop mix benefits farmers as it raises crop prices and farm incomes.

In 2007, Mapemba *et al.* estimated the cost to procure, harvest, store, and transport cellulosic feedstock to a biorefinery in the southern Great Plains. Their research focused on switchgrass hay being the delivered feedstock, and they analyzed alternative production scenarios on CRP lands. They recognized that transportation costs would comprise the majority of the delivered price. Their model also accounted for differences in potential harvesting periods between regions, and estimated average hauling distances. They estimate a delivered cost per dry ton of switchgrass to be between $26 and $58 depending on the biorefinery size and alternative CRP planting flexibilities (Mapemba *et al.*, 2007).

The work done by Mapemba *et al.* was later refined for a paper presented at the AAEA meetings in July 2007. The work included a two-stage contracting mechanism between farmers and biorefineries. Using a competitive bidding process, they estimated the contract prices needed to entice producers to begin growing dedicated energy crops, and the cost of harvesting and transporting the biomass to a biorefinery. Their results were some of the first to suggest that the previously estimated costs of delivered feedstock, which were all around $30/ dry ton, were actually too low. They estimated that actual costs would likely range between $50 and $65 per dry ton depending on available harvesting periods (Epplin *et al.*, 2007).

In November 2007, the Council for Agricultural Science and Technology (Fales, Hess, and Wilhelm, 2007) released a report verifying that under current infrastructure assumptions, the transportation and preprocessing costs of delivering cellulosic biomass range from 50% to 75% of the total delivered cost of feedstock. They further asserted that if these feedstock logistic costs continue to exceed 25% of total cellulosic ethanol production costs then very little margin would remain in the system for biomass producers and biorefineries (Fales, Hess, and Wilhelm, 2007).

While taking these findings into account, this study seeks to take a closer look at firm level production costs across different production processes in a specified region. If it is assumed that both cellulosic and Brazilian style ethanol production are superior to grain-based ethanol based on implications for the food supply-chain, and the two methods are at least as environmentally sustainable as grain-based ethanol, then the question is: Which of the three processes is economically preferable for the biofuels industry? The answer to that question depends not only on differences in technology and salable by-products, but also on the choice of feedstock input mix and scale.

Energy Crops

The specific type of technology employed will certainly impact the type of energy crop that the biorefinery must use as its primary input. The feedstock used must be both environmentally and economically sustainable within the geographic area chosen for the biorefinery. Crop density (acres planted per square mile) and energy yield are two vital components in feedstock choice. The crop chosen must have adequate energy yield per acre (gallons of ethanol that can be produced), which is a function of the crop yield. Sufficient crop density of the chosen feedstock is also required so that transportation costs can be minimized, as research done by Mapemba *et al.* (2007) has shown that approximately two-thirds of the cost of producing feedstock is the cost of harvesting and delivering the crop to the biorefinery. Discussions with university agronomists have revealed potential feedstocks, sugarcane and hybrid sorghum, that may be most suitable for ethanol production (Rooney, 2007). Different varieties of each crop have been developed to maximize either sugar yield per acre (for the Brazilian process) and/or maximize biomass yield per acre (for the cellulosic process). Both crops are recognized for their relatively low input usage, and are especially suited for climates such as those found in the southeastern United States. Grain-based ethanol production is primarily dominated by corn. While grain sorghum is also an alternative, currently it is not widely used.

Agronomically, it may seem logical to grow these energy crops in areas where per acre yield is maximized (based on soil type, water availability, etc.), economics, however, may yield a different conclusion. While per acre yields of dedicated energy crops may be highest in a particular geographic area, the price that a biorefinery would have to pay a farmer to forgo his next best alternative and grow the dedicated feedstock may be economically prohibitive. Because of competing alternatives, perhaps "marginal" growing areas may be better suited economically for energy feedstock production and biorefinery location. For this study, the coastal region of southeast Texas has been identified as a potential area suitable for the production of new varieties of energy crops. Cursory examination of the area suggests that both sugarcane and hybrid sorghum varieties should grow well. Growers in the area have the technical expertise to grow energy crops, and rainfall is abundant. The availability of suitable farmland, which is close to potential refinery building sites, and the fact that relatively few economically viable crop options are available to growers, suggest that this area may be a wise choice for biorefinery location (Farm Panel, 2007).

Data and Methods

Crop Mixes

Crop mixes for the Brazilian method were limited to those yielding high squeezable sugar content. Potential crops were identified by studying the Brazilian ethanol industry and through interviews with university agronomists and extension economists. Attention was given to those crops that the agronomists and economists believed to be most suitable for the growing conditions in southeast Texas. Texas A&M University plant breeders revealed new hybrids expected to maximize squeezable sugar per acre in the targeted geographic region. These potential feedstocks are sugarcane and a hybrid sweet sorghum variety (Rooney, 2007). Plant breeders also identified the most feasible harvest periods for each crop as well as parameters for yield estimates. Harvested biomass must be processed for sugar quickly and cannot be stored for any meaningful length of time. The fluid in the plant containing the sugar begins to escape after the plant is harvested. To operate in as many months possible each year, the biorefinery must have constant access to a sugar-based feedstock supply coming directly out of the field. The feasible crop mixes were identified such that the overlap of the harvest periods for each crop was minimized.

Agronomists and ethanol industry representatives were consulted to determine the most feasible types of cellulosic ethanol crops for the growing region (Rooney, 2007 and Farm Panel, 2007). Feedstocks most attractive for this process are those that yield a high amount of cellulosic material per acre, including sugarcane and high biomass hybrids of sorghum. Since cellulosic ethanol production has yet to occur on a commercial basis, the potential yields and harvesting periods of these hybrid crops were based on experimental plots in the targeted geographic region. Loss of sugar during storage of cellulosic crops is of little consequence; however, the biorefinery should use a crop mix that minimizes storage costs while providing needed feedstock on a year-round basis. Alternative harvesting/storage techniques were identified such that biomass could be delivered to the biorefinery in months where harvesting is not possible due to climatic conditions.

Figures 1 and 2 provide a description of the annual feedstock mix choices included in the study for each process. For grain-based ethanol production, both corn and grain sorghum were selected as potential feedstocks. It was assumed the plant would purchase corn or grain sorghum on the market and then have the grain trucked or railed in on a year-round basis. Cellulosic feedstock options were identified as hybrid sorghum greenchop (HSGC), hybrid sorghum hay (HS hay), hybrid sorghum high biomass (HSHB) and sugarcane. Feedstock options for the Brazilian method were identified as sugarcane and hybrid sweet sorghum (HSS) with corn or grain sorghum serving as a backup for ethanol production after the harvest periods for sorghum and sugarcane have ended. For the cellulosic and Brazilian processes, it is assumed all feedstocks, except those for the grain backup, will be grown in the surrounding area. Final delivered feedstock costs to the biorefinery rely on a combination of factors. These include the contract prices paid to growers to attract the required amount of acres, and harvest and transportation costs.

Minimum Contract Prices to Induce Growing

Price, yield, and cost data for existing non-energy crop alternatives were provided by a panel of producers in the identified potential growing region (Farm Panel, 2007). Estimates of energy crop yields and costs of production were reached using a combination of information from the panel farmers, representatives from the cellulosic ethanol industry, and Agricultural Extension agronomists (Rooney, 2007 and Farm Panel, 2007). December 2007 FAPRI baseline estimates for U.S. crop prices and inflation rates were localized and used to estimate alternative crop budgets through 2017 (FAPRI, 2007). Budgets for program crops included estimated loan deficiency payments. Historical yield, price, and inflation rate data were used to create Monte Carlo simulations of estimated net returns per acre for 2008-2017. Using stochastic dominance analysis as the ranking procedure between crop choices, estimated minimum grower contract prices were produced endogenously for each energy crop.

Estimation of Actual Prices Paid to Growers

Minimum contract prices per unit of feedstock were based on the expected values of crop yields. However, since it is assumed that the biorefinery – grower contract have some portion of payments that is fixed on a per acre basis, the actual price paid per unit of feedstock depends on yield risk. To make contract price per unit a stochastic variable, random yield shocks were introduced into the model once the initial contract specifications were made. This method accounted for the time lag between original contract negotiations and actual harvest. The random shocks to yield were draws from a multivariate GRKS distribution, while extreme weather shocks to yield were simulated using a Bernoulli random variable (Richardson, Schumann, and Feldman, 2007). The probability of an extreme weather shock occurring was based on historical data provided by the grower panel. The actual yield loss due to extreme weather depended on the particular crop, and was estimated by the Extension agronomists.

Estimation of Harvest and Transportation Costs

Based on interviews with ethanol industry representatives, it is assumed that the biorefinery would be responsible for the harvesting and transportation of costs for biomass produced for both the Brazilian method and the cellulosic method (Rooney, 2007 and Farm Panel, 2007). Grain prices to the biorefinery were considered FOB, then localized with a trans-

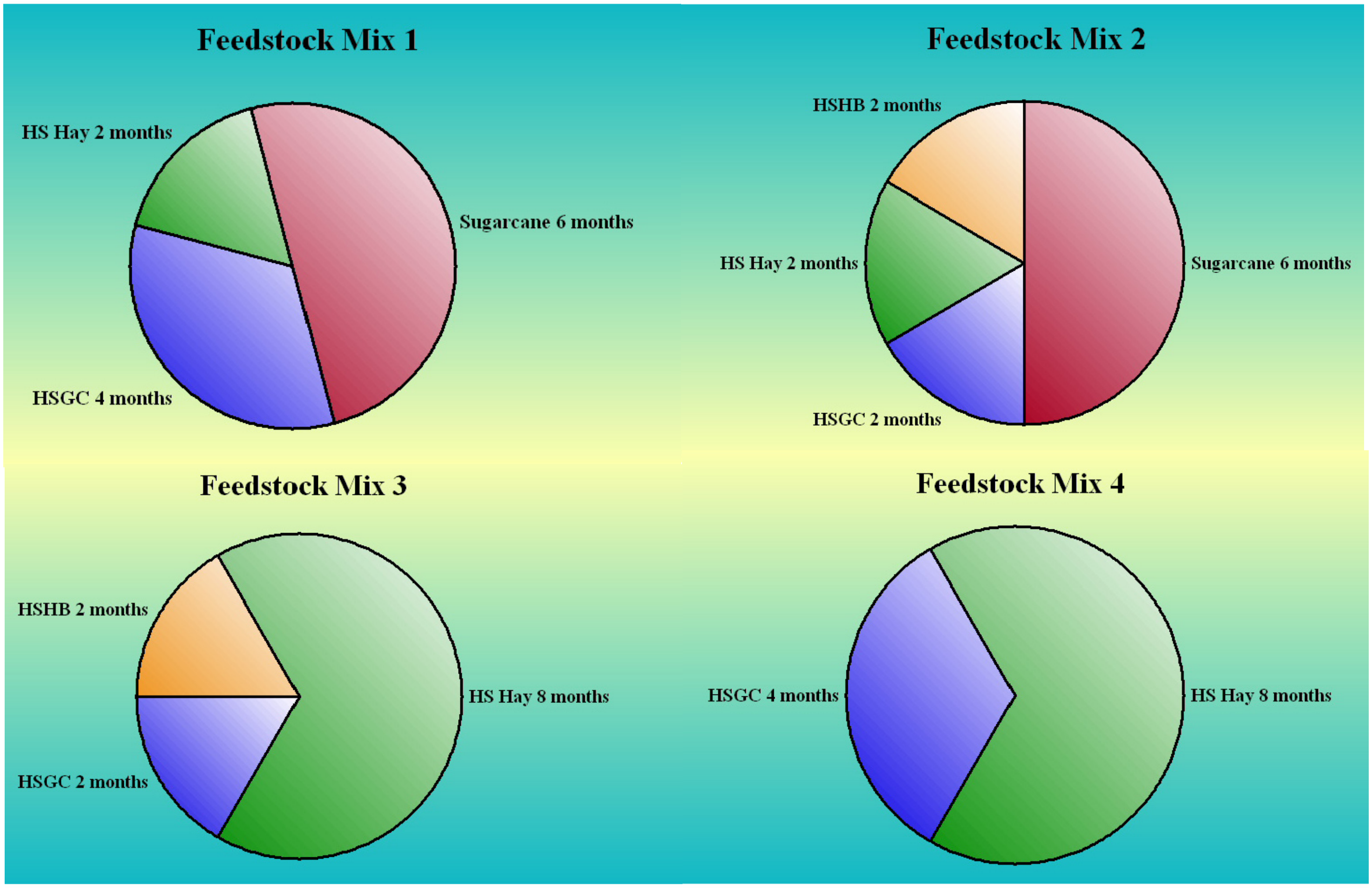

Figure 1. Feedstock Options Analyzed for the MixAlco Cellulosic Ethanol Production Process

portation wedge. Harvest costs per unit of feedstock were based on the 2004 Texas Custom Rates Statistics publication (USDA/NASS, 2004) and then adjusted using FAPRI baseline inflation estimates through 2017.

Transportation costs per unit of feedstock were modeled as a function of the average distance hauled and the variable transportation cost per mile. The average distance hauled for each feedstock did not depend on stochastic yields, because the actual acreage contracted is a function of the expected yield at the time the contract is negotiated. Contracted acres needed was modeled as a function of the dry matter tons of each feedstock needed (given choice of crop mix and scale of biorefinery), the expected dry matter yields per acre, and the expected biodensity of each crop per square mile. Work done by McCarl *et al*. was critical in estimating the expected biodensities (2000). Once total planted acres needed were estimated, average hauling distances were calculated using work done by French, which accounts for a square road system (1960). Variable transportation costs per mile were based on the 2004 Texas Custom Rates Statistics publication (USDA/NASS, 2004) and were adjusted using FAPRI baseline inflation estimates through 2017.

Total Delivered Cost of Feedstock

Table 1 provides a summary of the average delivered price of each feedstock to the plant by process. Delivered costs of grain feedstocks were estimated using the FAPRI baseline for U.S. price projections and using a basis to localize to the study region. Historical prices were used to add variability to point estimates using Monte Carlo draws from a multivariate empirical distribution to estimate percent deviations from point forecasts, as outlined by Richardson, Klose, and Gray (2000). Probabilistic forecasts of delivered costs for biomass feedstocks were made by simultaneously simulating actual prices paid to growers and harvest/transportations costs. Forecasts were made for each potential crop mix under each of the biorefinery scale choices.

Estimation of Actual Ethanol Output

Total acreage of biomass contracted (as estimated above) depends on the size of the biorefinery in terms of planned scale of ethanol output. For grain-based production, where grain is purchased from the market rather than through contracted growers, actual ethanol output is assumed to reach full capacity.

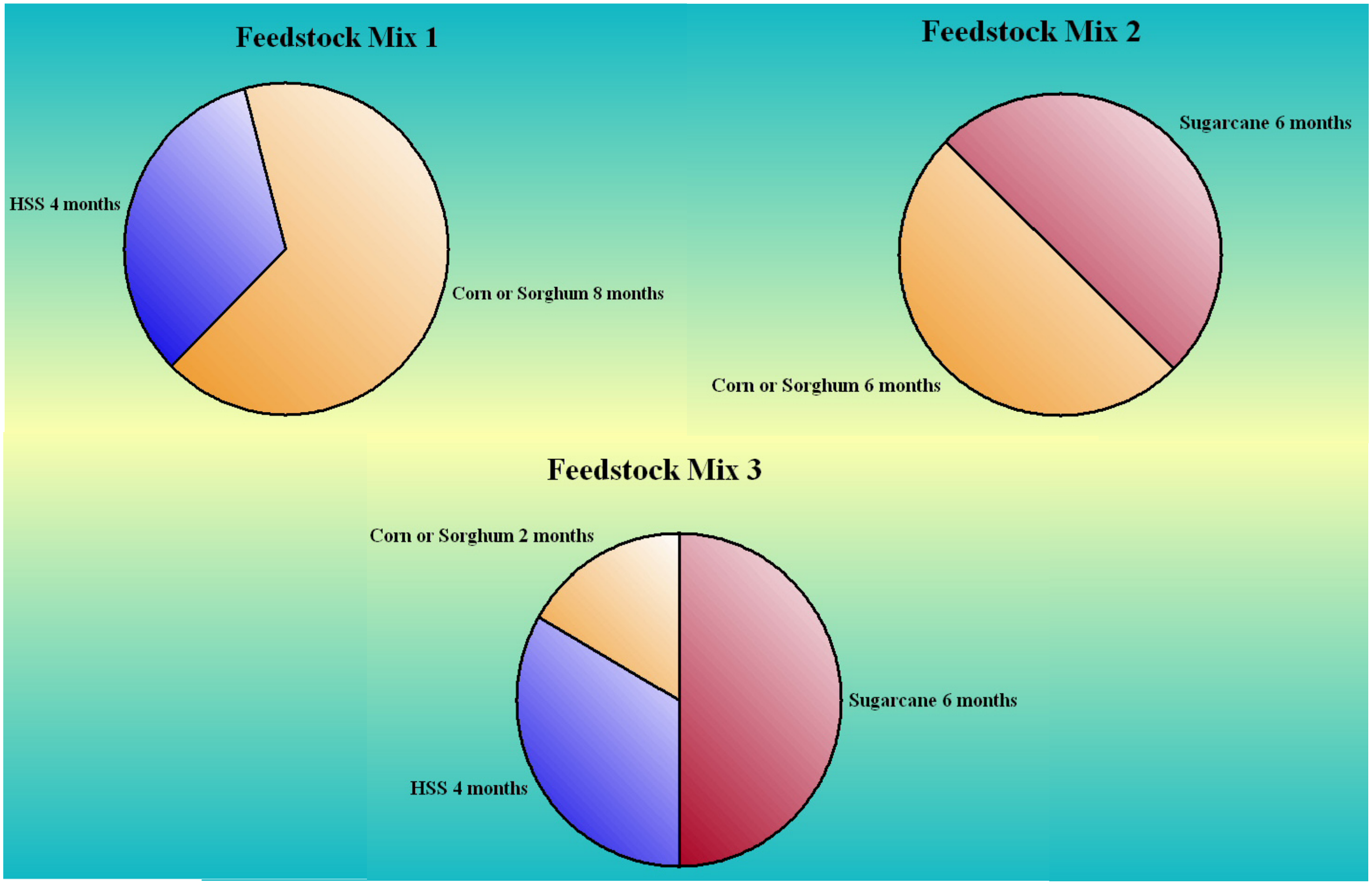

Figure 2. Feedstock Options for the Brazilian Ethanol Production Process

Since biomass-based ethanol, either Brazilian method or cellulosic, is based on contracting acreage of dedicated energy crops, actual ethanol production is subject to yield risk as well as conversion risk and shutdown risk. The yield risk was incorporated into the model when estimating the actual price paid to growers. Any excess biomass (due to higher than expected crop yields) is assumed to be used for energy generation within the biorefinery, providing an additional revenue stream.

Selected input assumptions are outlined in Table 2. The fixed costs associated with each type of production process under each scale choice were estimated using cost information from Lau (2004), and Brazilian ethanol industry repre-

Table 1. Average Delivered Feedstock Costs across Each Feedstock Mix for Grain, Cellulosic, and Brazilian Ethanol Production Processes

		Feedstock Mix			
		1	2	3	4
Grain					
Corn	$/bu	3.34			
Sorghum	$/bu	3.18			
Cellulosic					
HSGC	$/ton dry matter	87	85	85	87
HS Hay	$/ton dry matter	116	116	121	121
HSHB	$/ton dry matter	--	75	75	--
Sugarcane	$/ton dry matter	88	88	--	--
Brazilian					
HSGC	$/ton dry matter	89	--	89	
Sugarcane	$/ton dry matter	--	89	89	

Table 2. Operational Input Assumptions across Grain, Cellulosic, and Brazilian Ethanol Production Processes for a 25 Million Gallon Facility

	Units	Value
Grain Ethanol		
Proposed Capital Cost	$/gallon of ethanol	2.25
Ethanol Processing Costs	$/gallon of ethanol	0.61
Grain Ethanol Yield:		
Corn	gallons/bushel	2.75
Sorghum	gallons/bushel	2.75
DDGS Yield	gallons/bushel	18.00
Local Basis:		
Corn	$/bushel	0.05
Sorghum	$/bushel	0.15
Denaturant Added	fraction	0.05
Cellulosic Ethanol		
Proposed Capital Cost	$/gallon of ethanol	0.63
Percent Dry Matter:		
Sweet Sorghum	fraction	0.30
Sweet Sorghum Hay	fraction	0.85
Sweet Sorghum HB	fraction	0.40
Sugarcane	fraction	0.33
Ethanol Processing Costs	$/gallon of ethanol	1.25
Cellulosic Ethanol Yield:		
Yield for Contracting Acres	gallons/ton of dry matter	90.00
Yield Parameters for Production:		
Min	gallons/ton of dry matter	70.00
Med	gallons/ton of dry matter	90.00
Max	gallons/ton of dry matter	110.00
Denaturant Added	fraction	0.05
Brazilian Ethanol		
Proposed Capital Cost	$/gallon of ethanol	6.07
Percent Dry Matter:		
Sweet Sorghum	fraction	0.30
Sugarcane	fraction	0.33
Brazilian Ethanol Yield:		
Sweet Sorghum	gallons/ton of dry matter	49.00
Sugarcane	gallons/ton of dry matter	61.68
Cane Processing Costs	$/gallon of ethanol	0.19
Ethanol Processing Costs	$/gallon of ethanol	0.38
Grain Ethanol Backup		
Grain Ethanol Yield:		
Corn	gallons/bushel	2.75
Sorghum	gallons/bushel	2.75
DDGs Yield	pounds/bushel	18.00
Ethanol Processing Costs	$/gallon of ethanol	0.61
Denaturant Added	fraction	0.05

Table 3. Average Total Cost of Producing Ethanol across Each Feedstock Mix for Grain, Cellulosic, and Brazilian Production Processes for a 25 Million Gallon Facility

	Year 1
Grain	1.99
Corn	2.02
Sorghum	1.96
Cellulosic	2.56
Feedstock Mix 1	2.46
Feedstock Mix 2	2.44
Feedstock Mix 3	2.65
Feedstock Mix 4	2.67
Brazilian	2.41
Feedstock Mix 1	2.37
Feedstock Mix 2	2.32
Feedstock Mix 3	2.54

sentatives (Campos, 2006; Chaves, 2006; Fernandes, 2003). All fixed cost estimates from previous works were inflated to arrive at estimates for 2007, using FAPRI's inflation rate estimate for fixed costs. Stochastic estimates of fixed cost per gallon of ethanol produced were then estimated for each forecast period using the stochastic estimates of ethanol output.

For consistency, a 25 million gallon capacity level was selected for each process in this study. The per unit variable costs of production were based on research done by Bryan and Bryan International (2004) for the grain-based ethanol process, research conducted by Lau (2004) for the cellulosic process, and industry representatives for the Brazilian process (Campos, 2006; Chaves, 2006; Fernandes, 2003). All variable costs were inflated to the current time period, and then for each year 2008-2017 using FAPRI baseline inflation estimates (FAPRI, 2007). Total variable costs were dependent on the stochastic estimates of ethanol production.

Estimating Total Average Cost per Gallon of Ethanol

Following Richardson *et al.* (2006), a Monte Carlo simulation model was developed to analyze the future performance across each alternative production scenario. Stochastic accounting relationships, which are based on the fixed and variable input parameters and prices outlined above, are maintained throughout a 10 year planning horizon to analyze financial performance under risk. The model is programmed in Microsoft© Excel, using standard accounting relationships, and made stochastic using Simetar©, an add-in for Excel (Richardson, Schumann, and Feldman, 2007). Each production scenario is simulated at the 25 mmgy capacity level for 500 iterations. Stochastic estimates of total average cost per gallon of ethanol were produced for each combination of production process, crop mix, and choice of scale. Estimated total costs were divided by the stochastic estimates of ethanol production in each iteration of the Monte Carlo simulation for each year forecasted. Estimated distributions of total average cost per gallon under each scenario were then compared to find the optimal production process and feedstock mix at different production levels.

Results

Results of the analysis focus on the total cost of production for one year at the 25 million gallon capacity level. These results identify the grain process as returning the lowest average total cost of production, followed by the Brazilian and cellulosic processes. Table 3 summarizes the average total cost of production for each process and feedstock mix. For grain ethanol, sorghum proved to be the feedstock of choice, as its average total cost of production is slightly lower than that of corn. For cellulosic production, the second production scenario of HSGC for two months, HS hay for two months, HSHB for two months, and sugarcane for six months returned the lowest total cost of production. For the Brazilian process, the scenario of sugarcane for six months with a grain backup for six months, returned the lowest total cost of production. Table 4 demonstrates the sensitivity of the cost of producing grain ethanol at high grain prices, or values more consistent with recent trends. Cellulosic costs of production do not change since grain is not included in the feedstock mix. When comparing across each production process at higher grain prices, the first and second feedstock mixes for the cellulosic process become competitive at grain prices of $4.50 per bushel. Because of the grain backup included in the Brazilian process feedstock mixes, the grain process remains economically preferable to this process as grain prices increase.

Table 4. Sensitivity of Average Total Cost of Producing Ethanol at High Grain Prices for a 25 Million Gallon Facility

		Grain Price, FOB				
	$/bu	4.00	4.25	4.50	4.75	5.00
Grain	average	2.28	2.37	2.46	2.55	2.63
Corn	$/gallon	2.27	2.35	2.44	2.53	2.61
Sorghum	$/gallon	2.30	2.39	2.48	2.56	2.65
Cellulosic	average	2.56	2.56	2.56	2.56	2.56
Feedstock Mix 1	$/gallon	2.46	2.46	2.46	2.46	2.46
Feedstock Mix 2	$/gallon	2.44	2.44	2.44	2.44	2.44
Feedstock Mix 3	$/gallon	2.65	2.65	2.65	2.65	2.65
Feedstock Mix 4	$/gallon	2.67	2.67	2.67	2.67	2.67
Brazilian	average	2.56	2.60	2.64	2.68	2.72
Feedstock Mix 1	$/gallon	2.58	2.64	2.70	2.76	2.82
Feedstock Mix 2	$/gallon	2.48	2.53	2.57	2.62	2.66
Feedstock Mix 3	$/gallon	2.61	2.63	2.64	2.66	2.68

Conclusions

As pressures continue to mount concerning the net environmental impacts of grain-based ethanol and its potential impacts on the food supply chain, alternative feedstocks and processes may begin to play a larger role. Based on current corn and grain sorghum price estimates, grain-based ethanol production should continue to have a place in the future of the biofuels industry. As grain prices increase above these baseline estimates, cellulosic and Brazilian methods become more economically competitive. When looking at the current market environment for attracting acres for energy crops and the technologies available, the cellulosic process and the Brazilian processes appear to be less economically feasible than grain-based ethanol production in the United States. As new crop varieties and new conversion technologies continue to develop, it is possible that cellulosic ethanol production will become more economically favorable by the time it becomes technologically feasible on a commercial basis. While the sugar "squeezing" method is dominant in Brazil, the higher cost of attracting acres and growing feedstocks in the United States makes the Brazilian method more costly than that of grain-based production. As plant geneticists continue to develop sugarcane varieties that can potentially increase sugar yields by 50%, perhaps the feedstock costs can be offset and the Brazilian method can have a place in the U.S. ethanol industry (Informa Economics, 2007). Under current price projections and assumptions made in this study, alternatives to grain-based ethanol in the U.S. may be looming, but they have yet to become economically viable.

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Viability of Cellulosic Feedstock Production from Producer to Biorefinery

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Introduction

Annual production of ethanol for fuel in the United States has risen from 175 million gallons in 1980 to 6.5 billion gallons in 2007 (Renewable Fuels Association (RFA), 2008). While nearly all of the U.S. ethanol supply is currently derived from corn, concerns about environmental sustainability and potential impacts on the food supply chain have brought corn-based ethanol out of favor with some. Advanced biofuels such as cellulosic ethanol are expected to be the preferable long-term source of renewable energy (Council for Agricultural Science and Technology (CAST), 2007). The recently enacted Energy Independence and Security Act of 2007, mandates that the United States produce 16 billion gallons of cellulosic biofuel by 2022, representing 44% of the total biofuel mandate (Wyant, 2007). The push for cellulosic ethanol has prompted the U.S. Department of Energy (US-DOE) to award millions in cellulosic research grants (US-DOE, 2008). The southeastern United States, from the upper coast of Texas to northern Florida, is viewed by some private sector grant recipients as potentially being the most agronomically favorable geographic region for cellulosic feedstock (biomass) production. However the economics of such production, particularly for newer varieties of sorghum and sugarcane, have yet to be fully explored. Tembo, Epplin, and Huhnke (2003) and Mapemba *et al*. (2007) have studied similar economic issues pertaining to perennial grasses in the southern Great Plains.

The specific type of technology employed will potentially impact the type of biomass that the biorefinery must use as its primary input. The type of biomass used must be both environmentally and economically sustainable within the geographic area chosen for the biorefinery. Crop density (acres planted per square mile) and energy yield are two vital components in biomass choice (De La Torre Ugarte *et al.*, 2003 and English *et al.*, 2006). The crop chosen must have adequate energy yield per acre (gallons of ethanol that can be produced), which is a function of the crop yield. Sufficient crop density of the chosen feedstock is also required so that transportation costs can be minimized, as it is estimated that the cost of harvesting and transporting biomass can comprise up to 75% of the total cost of biomass production (CAST, 2007; Epplin *et al.*, 2007; and Mapemba *et al.*, 2007). Discussions with university agronomists have revealed two potential feedstocks, sugarcane and hybrid sorghum, which may be most suitable for cellulosic ethanol production (Rooney, 2007). Varieties of each crop have been developed to maximize biomass yield per acre.

Farmers in the Upper Coast region of Texas have begun to ask whether the geographic, agronomic, and economic conditions present in the area make them suitable candidates to produce cellulosic feedstock, and if so, what types of specific energy crops should be pursued. Cursory examination of the area suggests that both hybrid sorghums and sugarcane should grow well. Growers in the area have the technical expertise to grow energy crops, and rainfall is abundant. The availability of abundant and suitable farmland, which is close to potential refinery building sites, and the fact that relatively few economically viable crop options are available to growers, suggest that this area may be a wise choice for locating a biorefinery.

Economic Problem

What is the cost and viability of obtaining cellulosic feedstocks in the Upper Coast region of Texas, and what is the potential on-farm financial impact of dedicating acreage to energy feedstock production in that region?

Hypothesis

The financial impact on the farm (and therefore the viability of obtaining a critical mass of feedstock) will depend on the specific set of dedicated energy crops grown, the alterna-

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tive crop mixes available to the farm, and the profit potential of the biorefinery at the necessary feedstock contract prices.

Research Outline

1) Estimate the most cost effective and agronomically feasible dedicated energy crop mix for cellulosic ethanol production in Southeast Texas,

2) Estimate the contract price per ton needed for farmers to grow cellulosic feedstock and forgo their next best alternative in Southeast Texas,

3) Determine the financial impact on the whole farm of switching from its current crop mix to one consisting of dedicated energy crops, and

4) Estimate the cost per ton to harvest and transport alternative cellulosic crops to a biorefinery located in Southeast Texas.

Methodology

Module 1: Estimation of Minimum Contract Prices, Delivered Price, and Least-Cost Energy Crop Mix

Agronomists, local producers, and ethanol industry representatives were consulted to determine the most potentially feasible types of cellulosic ethanol crops for the growing region (Rooney, 2007 and Farm Panel, 2007). Feedstocks most attractive for this process are those that yield a high amount of cellulosic material per acre, including sugarcane and high biomass hybrids of sorghum. The most suitable sources of biomass were identified as hybrid sorghum hay (HS Hay), hybrid sorghum green chop (HS GC), high-biomass sorghum green chop (HB), and billeted, sugarcane (Cane).[2] The farm panel also identified rice and pasture hay as the most viable alternatives to growing dedicated energy crops in the geographic area.

A two-stage contract structure was assumed. The growing contracts included a stage-1 payment per acre equal to the expected variable production costs. The per production unit stage-2 payment was set equal to the price needed to cover 150% of fixed costs per acre based on expected yields. This structure gives the producer incentive to meet or exceed yield expectations. While both the biorefinery and the producer share downside yield risk, the biorefinery is faced with the risk of dealing with excess biomass production. Two-stage contract structures have been proposed in recent biomass production research (Clark, English, and Garland, 2007; Epplin *et al.*, 2007).

Price, yield, and cost data for existing non-energy crop alternatives were provided by local producers. Estimates of energy crop yields and costs of production were reached using a combination of information from the panel farmers, representatives from the cellulosic ethanol industry, and Agricultural Extension agronomists. The agronomists also estimated the potential harvest periods in the geographic region for the alternative energy crops. The harvest periods were used to constrain the analysis to only those energy crop mixes that could feasibly supply year-round feedstock to the biorefinery. The least-cost crop mix to the biorefinery was then identified.

FAPRI (2007) baseline estimates for U.S. crop prices and inflation rates were localized and used in conjunction with our panel data to estimate alternative crop budgets through 2017 (Farm Panel, 2007). Using the proposed contract structure and the estimated enterprise budgets, grower contract prices were estimated for each energy crop in each year. Once the contract prices were fixed, yield, input cost, and price (for non-energy crops) risk was introduced into the budgets using Monte Carlo simulation to draw from a combination of empirical and GRKS distributions (Richardson, Klose, and Gray, 2000). The method produced probabilistic forecasts of net returns per acre for 2008-2017, for both energy crops and non-energy alternatives. Stochastic efficiency analysis was performed on the simulated outcomes of net returns to determine if growers would indeed have an adequate incentive to produce dedicated energy crops.

Based on interviews with ethanol industry representatives, it was assumed that the biorefinery would be responsible for the harvesting and transportation of biomass (Farm Panel, 2007). Harvest costs per unit of feedstock were based on the 2004 Texas Custom Rates Statistics publication (NASS, 2004) and then adjusted using FAPRI baseline inflation estimates through 2017 (FAPRI, 2007). Transportation costs per unit of feedstock were modeled as a function of the average distance hauled and the variable transportation cost per mile. Contracted acres needed was modeled as a function of the dry matter tons of each feedstock needed, the expected dry matter yields per acre, and the expected bio-density of each crop per square mile. Feedstock needs were based on a conversion rate of 90 gallons per ton of dry matter (De La Torre Ugarte *et al.*, 2003; English *et al.*, 2006; Richardson *et al.*, 2006; Epplin *et al.*, 2007; and Mapemba *et al.*, 2007). Once total planted acres needed were estimated, average hauling distances were calculated using work done by French, which accounts for a square road system (1960). Variable transportation costs per mile were based on the 2004 Texas Custom Rates Statistics publication (NASS, 2004) and were adjusted using FAPRI baseline inflation estimates through 2017. Total delivered

[2] Each of the three sorghums evaluated is a distinct hybrid. While we have chosen to call one of the sorghum varieties "high biomass", all three varieties are designed to maximize biomass yield per acre. The HB crop is allowed to mature more thoroughly than the green chop or hay varieties, and is cut only once per season. The HB crop becomes more "woody" like cane and is therefore less resistant to lodging during harsh weather conditions than typical sorghum crops. However, the stalk diameter of HB sorghum is still considerably less than cane, so harvesting cost for the HB crop is lower. The HB type of crop is harvested similarly to typical green chop, but is assumed to be cut at 40% dry matter as opposed to green chop at 30%.

costs per ton of dry matter to the biorefinery for each feedstock were estimated by summing the contract price to grow, the harvest cost, and the transportation cost, all on a ton dry matter basis.

Monte Carlo estimates of the average cost of feedstock per delivered dry ton were produced under alternative energy crop mixes, and included consideration of harvest periods for each energy crop and differing yield risks depending on the type of crop. The least-cost energy crop mix (based on delivered cost) was identified. Table 1 gives a summary of the exogenous variables and assumptions used in this analysis, including the information received from the farm panel and the agronomists. Note that grass hay is assumed to be previously established. Planting costs for the annual crops are accounted for under growing costs. Therefore, only the perennial cane crop has separate establishment costs.

Module 2: Financial Impacts on the Farm

The Financial and Risk Management Assistance program (FARM Assistance) consists of a state-of-the-art computerized decision-support system and extension risk management specialist working one-to-one with producers to provide individualized economic and risk assessment evaluations. Alternative management plans and new technologies can be analyzed relative to their risk impacts on the financial condition of the operation over a ten-year planning horizon (Klose and Outlaw, 2005).

While Module 1 identifies potential biomass pricing and costs of production, Module 2 analyzed the farm level impacts to a producer's overall financial performance and risk exposure. In this module a 10-year simulation of financial performance and position using stochastic commodity prices and yields was used to simulate farm level performance for the 2007-2016 period. Utilizing the FARM Assistance approach, a model farm was developed to represent actual producers in the production region. A baseline scenario of the model farm provides the current financial outlook for a 3,000 acre farm producing rice and hay (Farm Panel, 2007). The energy crop scenarios include shifting half of the available acreage to the production of 1) hybrid sorghums and 2) sugarcane, while the farm continues rice and hay production on the remaining acreage.

Results

Most Cost Effective and Agronomically Feasible Energy Crop Mix for Biorefinery

Due to differences and overlaps in potential harvest periods, the four most agronomically feasible energy crop mixes were found to be 1) hybrid sorghum green chop (HS GC) four months, hybrid sorghum hay (HS hay) two months, sugarcane (cane) six months, 2) HS GC two months, HS hay two months, hybrid sorghum high biomass (HS HB) two months, cane six months, 3) HS GC two months, HS hay eight months, HS HB two months, and 4) HS GC four months, and HS hay eight months. Average delivered price was estimated for the four scenarios, and the least cost alternative was found to be HS GC two months, HS hay two months, HS HB two months, and cane six months. Cane and HS hay were the most costly crops (HS hay being most expensive), but while the use of HS hay could be minimized, the October through March harvest period for cane made it the only viable crop during that part of the year. Subsequent results reported in this paper pertain to the least cost alternative crop mix only.

Estimated Contract Prices to Grow Feedstocks (2008-2017)

The estimated contract price to grow sugarcane was found to be lower than the sorghum alternatives by approximately \$9 per dry ton in each year. Cane averaged \$29 per dry ton while HS hay, HS GC, and HS HB averaged \$38, \$38, and \$40 per dry ton respectively. In the case of cane, lower annual input costs made up for its high establishment cost, which was spread over a six year life of the crop. Slightly lower input costs for HS hay and HS GC made these crops less costly to produce than the HS HB. Contract prices for all four crops rose steadily over the 10-year planning horizon, tracking the general inflationary trend. Table 2 contains the complete set of contract prices, including the base year, 2007.

Estimated Returns to Growers (2008-2017)

The 10-year average of annual net returns per acre was highest for cane (\$68) versus the hybrid sorghum crops at \$50 for HS GC, \$57 for HS hay, and \$55 for HS HB. Both rice and pasture hay were expected to yield net economic losses averaging -\$133 and -\$158 per acre respectively. While rice had the highest potential annual returns (\$600/acre) it also had the highest potential loss (-\$700). Cane exhibited the least variability in net returns due it having the least yield risk. Under the proposed contract structure, producers are expected to have less than a 5% chance of losing money growing cane, a 20% chance growing the hybrid sorghums, 70% growing rice, and 80% growing pasture hay. Table 3 shows descriptive statistics for net returns in 2012, which was found to be representative of each of the ten years simulated.

Stochastic Efficiency with Respect to a Function (SERF) analysis was applied to the simulated net returns to rank the crop choices while accounting for risk over a relevant range of risk attitudes (Figure 1). The results indicate that estimated contract prices are adequate to rank all energy crops above the non-energy alternatives over the entire range of attitudes toward risk. A complete explanation of the SERF method can be found in Hardaker *et al.*, 2004.

Whole-Farm Financial Implications (2007-2016)

The model farm used to analyze the farm level impacts of producing the specified energy crops represents a 3,000

Table 1. Exogenous Variables and Assumptions

Baseline Assumptions Year	2007					
Annual Biorefinery Output in Gallons	25,000,000					
Gallons Ethanol Per Ton Dry Matter	90					
Percent of Land Farmable in the Area	90%					
Percent of Farmland Converted	30%					
Operating Loan Rate	8.5%					
Fraction of Year for Growing Portion of Operating Loan	0.5000					
Fraction of Year for Harvesting Portion of Operating Loan	0.1667					
Intermediate Term Loan Rate	8.5%					
Crop	Rice	Grass Hay	HS Hay	HS GC	HB	Cane
Crop Yield/Acre (Wet Ton) (Cwt for Rice)	75.00	9.00	17.65	50	37.5	45
Percent Dry Matter (Decimal Form)			0.85	0.3	0.4	0.34
Crop Rotation (Years)			3	3	3	0
Fixed Hauling Cost Per Acre	0	0	0	0	0	0
Hauling Cost Per Wet Ton (up to 1 mile) (Cwt for Rice)	1.50	16.67	16.67	3.35	3.35	3.35
Variable Hauling Cost Per Wet Ton Per Mile (over 1 mile)	0	1.09	1.09	0.3	0.3	0.3
Fixed Portion of Harvesting Cost Per Acre	55	27	0	0	0	144
Variable Harvest Cost Per Wet Ton	0	36.67	36.67	6.47	6.47	10
Other Revenue Per Acre	0	0	0	0	0	0
Establishment Costs ($ Per Acre)						
Planting						660
Herbicides						47
Number of Years to Spread Establishment Cost						6
Variable Growing Cost ($ Per Acre)						
Seed/Tech	75	0	100	100	100	0
Chemicals	95	10	47	47	47	0
Fertilizer	120	123	120	120	120	27.5
Labor	40	12	20	20	20	12
Fuel	33	8	20	20	20	8
Repair & Maintenance	33	3	15	15	15	3
Other/Custom/Irrigation	80	0	0	0	0	0
Direct Fixed Growing Expenses Per Acre	80	80	80	80	80	80
Cash Rent	50	25	50	50	50	50
Months that Crop Supplies Biorefinery			April & Sept	May - June	July - August	Oct - March
Yield Parameters (Wet Ton) (Cwt for Rice)						
Min	50	6	10	26	20	30
Mid	75	9	17.65	50	37.5	45
Max	85	12	24	66	50	60
Percent of Crop Recovered if Weather Disaster	0.3	0.5	0.5	0.3	0.5	0.75

Table 1 (Cont). Exogenous Variables and Assumptions										
Probability of Disaster	0.1									
FAPRI U.S. Baseline Estimates										
Year	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Rice Price ($/cwt)	10.52	10.60	11.03	10.99	11.23	11.26	11.07	11.06	11.30	11.40
All Hay Price ($/ton)	113.96	111.60	111.85	113.09	114.63	115.80	116.73	116.24	115.60	114.84
FAPRI Projected Inflation Rates					Percent Change					
Agricultural Chemicals	1.46	1.08	1.20	1.44	1.23	1.40	1.55	1.56	1.48	1.48
Seed	3.91	3.62	2.38	1.83	1.66	1.58	2.15	2.33	2.21	2.26
Nitrogen Fertilizer	5.78	8.44	1.94	-1.34	-1.17	-1.31	0.75	1.46	1.01	1.54
Wage Rates	4.82	4.00	2.60	2.24	1.58	1.56	2.24	2.24	2.08	2.18
Petroleum Fuel, Oils	2.87	1.60	1.40	-0.46	-0.97	-0.76	0.31	0.72	0.28	0.60
Repairs	5.27	5.19	3.09	2.15	1.84	1.66	2.18	2.33	2.18	2.22
Interest	4.92	5.13	5.24	5.30	5.33	1.52	1.71	1.81	0.73	0.73
Farm Services	4.29	3.71	2.47	1.99	1.79	1.65	2.18	2.33	2.20	2.22
Rent	4.27	2.21	1.31	0.91	0.32	0.24	0.23	0.16	0.18	0.18
Direct Fixed	-4.53	-3.17	-3.04	-2.56	-2.05	1.19	1.34	1.38	1.38	1.38
Beaumont Area Price Wedges										
Rice	0									
Hay	-35									

Table 2. Estimated Contract Prices Based on Expected Yields ($/Ton Dry Matter), 2008-2017

Year	HS GC	HS Hay	HS HB	Cane
2008	36.24	36.23	38.45	27.51
2009	37.35	37.34	39.75	28.19
2010	37.75	37.75	40.21	28.59
2011	37.80	37.79	40.22	28.91
2012	37.83	37.82	40.24	29.18
2013	38.03	38.02	40.41	29.53
2014	38.53	38.53	40.93	30.04
2015	39.13	39.13	41.56	30.60
2016	39.66	39.66	42.12	31.07
2017	40.26	40.26	42.76	31.59

Table 3. Descriptive Statistics for Simulated Net Returns in 2012 ($/Acre)

Statistical Measure	Rice	Pasture Hay	HS GC	HS Hay	HS HB	Cane
Mean	-88.70	-113.21	49.18	55.39	53.78	66.99
StDev	245.04	125.95	70.30	65.18	73.97	34.11
CV	-276.27	-111.25	142.96	117.67	137.54	50.92
Min	-705.54	-435.86	-210.54	-174.38	-200.84	-32.70
Max	587.70	248.36	213.11	224.00	233.41	193.61

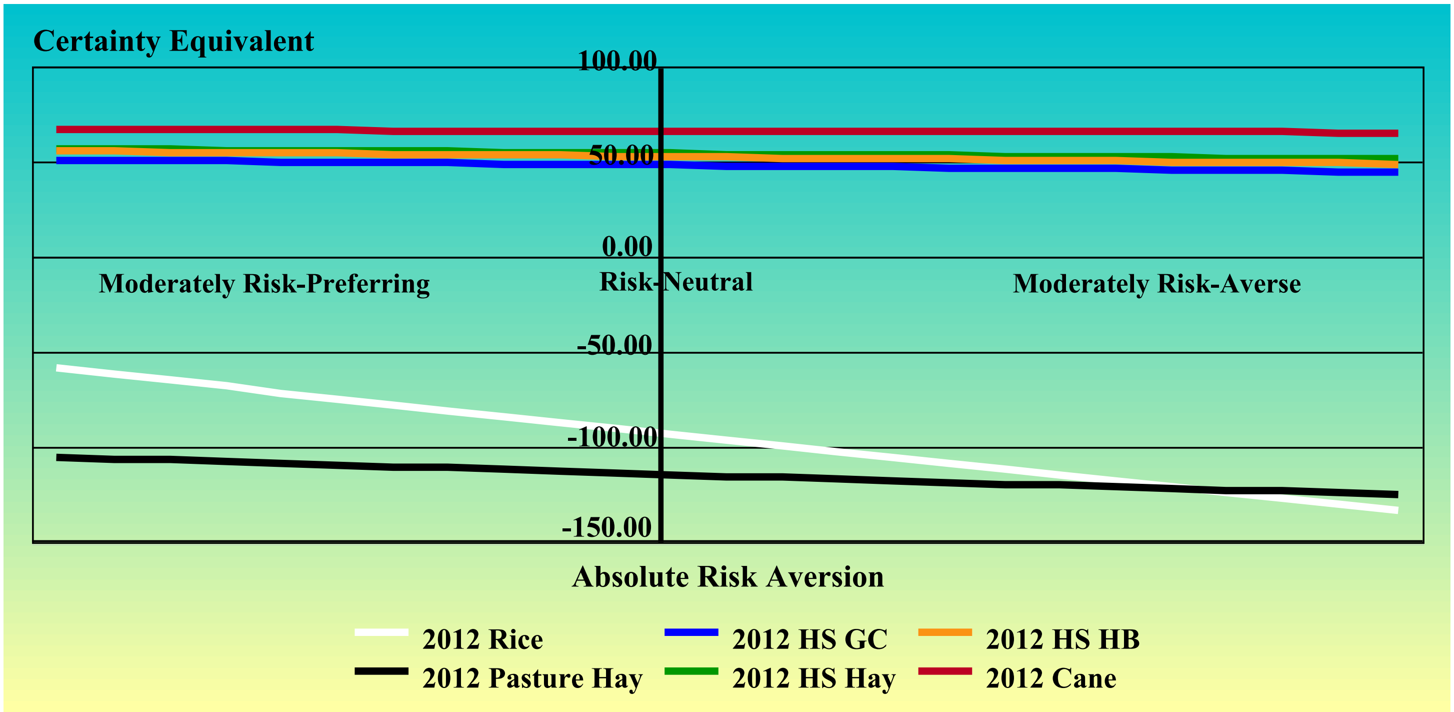

Figure 1. Stochastic Efficiency with Respect to A Function (SERF) under a Negative Exponential Utility Function for Net Returns Per Acre in 2012

acre rice and hay farm in the upper coast region of Texas in the area of Beaumont. On half of the land (1,500 acres), the farm produces rice on a three year rotation, planting 500 acres and idling 1,000 acres. Coastal hay is produced on the remaining 1,500 acres. It is assumed that most of the land was historically in crop production, and therefore the farm continues to carry 1,500 base acres (1,000 acres of rice base, 400 acres of corn base, and 100 acres of sorghum base). The sole proprietor is assumed to own half of the acres and cash lease the remaining half. Assumptions of cost of production and contract prices match those used for the broader analysis in this research. The Baseline scenario indicates a viable operation, on average generating positive net farm income and cash flow, as well as real net worth growth.

Rice and Hay Baseline

Table 4 provides the key indicators for the baseline and alternative financial projections. The farm generates approximately $1.5 million in annual receipts with a 0.81 average expense-to-receipts ratio. Following a profitable year in 2007, the farm settles into a steady pattern of an annual average net cash farm income (NCFI) of about $200,000. In each year NCFI can range from negative $150,000 to a high of $600,000. The analysis suggests a 50% probability of NCFI falling between zero and $350,000.

The ten-year outlook suggests an average cash flow growth, indicating the level of profit is sufficient to cover non-farm expense requirements such as family living costs, taxes, and capital purchases. On average, the cash balance grows to $236,000 by the year 2016 (Figure 2). Figure 2 also provides a picture of the cash flow risk as measured by the probability of the farm experiencing a negative cash position in any given year. While the farm has a stable average cash outlook, it carries about a 30% chance of not achieving a positive cash flow in each year of the projection.

A healthy profit level and cash position allow the farm to project positive growth in real net worth (RNW) as well. On average, real net worth grows from $2.6 million to just over $3.5 million (Table 4). The range of possibilities for ending real net worth start with a low of about $2.7 million suggesting a slight chance of no equity growth relative to the 2007 starting equity. On the other hand, the farm could experience equity growth bringing RNW to as much as $4.5 million by 2016.

Rice, Hay, and Hybrid Sorghum

For the hybrid sorghum scenario, it is assumed that half of the productive land is dedicated to growing hybrid sorghum. The crop mix consists of 750 acres of hay, 750 (250 planted annually) acres of rice land, and 1,500 acres devoted to hybrid sorghum. Production constraints prevent the producer from planting hybrid sorghum continuously. Similar to rice in the area, agronomists suggest a three year rotation. Of the 1,500 acres devoted to hybrid sorghum, the farm annually produces 1,000 acres of sorghum for grain and 500 acres of biomass sorghum (approximately 167 acres each of hybrid

Table 4. Selected Estimated Variables in the Base Scenario and the Energy Alternatives, 2007-2016

Year	Base	Hybrid Sorghums	Sugarcane		Base	Hybrid Sorghums	Sugarcane
	Crop Receipts ($1000)				Net Cash Farm Income ($1000)		
2007	1,507.33	1,304.97	1,144.89	2007	349.75	336.89	-649.20
2008	1,387.75	1,273.04	1,293.47	2008	212.47	291.19	527.18
2009	1,373.58	1,266.88	1,302.38	2009	195.57	285.81	568.40
2010	1,365.19	1,264.91	1,247.07	2010	193.68	288.73	541.45
2011	1,377.83	1,272.40	1,203.62	2011	200.57	291.61	506.92
2012	1,385.37	1,275.14	1,118.72	2012	214.84	296.45	433.47
2013	1,407.49	1,291.22	703.74	2013	230.64	309.12	106.51
2014	1,394.69	1,289.85	1,133.25	2014	218.04	305.97	-797.53
2015	1,391.89	1,288.39	1,363.43	2015	210.06	298.64	607.31
2016	1,381.77	1,286.01	1,376.20	2016	191.72	291.06	650.75
Average	1,397.29	1,281.28	1,188.68	Average	221.73	299.55	249.53
	Government Payments ($1000)				Ending Cash Reserves ($1000)		
2007	94.58	89.03	89.03	2007	141.60	135.64	-754.13
2008	104.97	97.95	97.95	2008	174.92	224.62	-341.50
2009	106.68	99.69	99.69	2009	183.61	297.21	-21.71
2010	105.24	98.63	96.63	2010	186.91	362.46	210.98
2011	97.87	93.79	93.79	2011	178.84	412.00	398.75
2012	96.73	92.24	92.24	2012	196.23	486.06	554.87
2013	96.53	92.15	92.15	2013	225.91	568.03	493.54
2014	97.41	92.70	92.70	2014	240.47	642.60	-435.97
2015	102.40	95.72	95.72	2015	239.56	703.72	20.48
2016	98.06	93.84	93.84	2016	236.06	770.20	389.14
Average	100.05	94.57	94.57	Average	200.41	460.25	51.44
	Disaster & Indemnities ($1,000)				Real Net Worth ($1000)		
2007	4.59	2.29	2.29	2007	2,700.82	2,694.98	1,823.51
2008	7.88	3.94	3.94	2008	2,954.83	3,002.85	2,455.92
2009	6.66	3.33	3.33	2009	3,062.23	3,169.88	2,867.68
2010	10.01	5.01	5.01	2010	3,155.00	3,318.25	3,177.38
2011	10.44	5.22	5.22	2011	3,240.79	3,453.19	3,441.12
2012	12.08	6.04	6.04	2012	3,324.18	3,582.37	3,643.67
2013	8.99	4.49	4.49	2013	3,413.75	3,711.42	3,646.61
2014	8.90	4.45	4.45	2014	3,484.81	3,826.61	2,909.84
2015	15.72	7.86	7.86	2015	3,536.30	3,921.73	3,354.38
2016	11.91	5.95	5.95	2016	3,573.24	4,006.47	3,697.39
Average	9.72	4.86	4.86	Average	3,244.59	3,468.77	3,101.75
	Total Cash Receipts ($1000)				Debt to Asset Ratio (%)		
2007	1,606.50	1,393.30	1,236.22	2007	27.19	27.10	48.44
2008	1,500.61	1,374.92	1,395.36	2008	25.56	24.91	34.61
2009	1,486.93	1,369.91	1,405.40	2009	24.43	23.29	26.66
2010	1,480.45	1,368.55	1,350.71	2010	24.21	22.55	23.40
2011	1,486.14	1,371.41	1,302.62	2011	23.84	21.86	21.46

Table 4 (Cont.). Selected Estimated Variables in the Base Scenario and the Energy Alternatives, 2007-2016							
Year	Base	Hybrid Sorghums	Sugarcane		Base	Hybrid Sorghums	Sugarcane
	Total Cash Receipts ($1000)				Debt to Asset Ratio (%)		
2012	1,494.17	1,373.42	1,216.99	2012	23.03	20.69	19.86
2013	1,513.01	1,387.87	800.39	2013	22.47	19.91	19.75
2014	1,501.01	1,387.00	1,230.41	2014	22.44	19.48	30.57
2015	1,510.01	1,391.97	1,467.01	2015	21.81	18.46	23.27
2016	1,493.73	1,385.80	1,475.99	2016	21.18	17.45	19.10
Average	1,507.06	1,380.71	1,288.11	Average	23.62	21.57	26.71
	Crop Expenses ($1000)				Average Annual Operating Expense/Receipts		
2007	1,066.42	877.12	1,669.46	2007	0.75	0.71	1.45
2008	1,095.21	899.42	625.45	2008	0.80	0.73	0.51
2009	1,098.34	903.03	627.70	2009	0.82	0.74	0.51
2010	1,095.41	903.79	626.97	2010	0.82	0.74	0.53
2011	1,092.07	905.00	626.35	2011	0.81	0.74	0.55
2012	1,084.17	903.00	623.22	2012	0.80	0.74	0.59
2013	1,088.05	908.46	544.02	2013	0.80	0.74	0.81
2014	1,088.80	913.06	1,816.60	2014	0.81	0.75	1.58
2015	1,102.19	924.74	636.21	2015	0.81	0.75	0.50
2016	1,103.65	930.60	638.41	2016	0.82	0.75	0.50
Average	1,091.43	906.82	843.44	Average	0.81	0.74	0.76

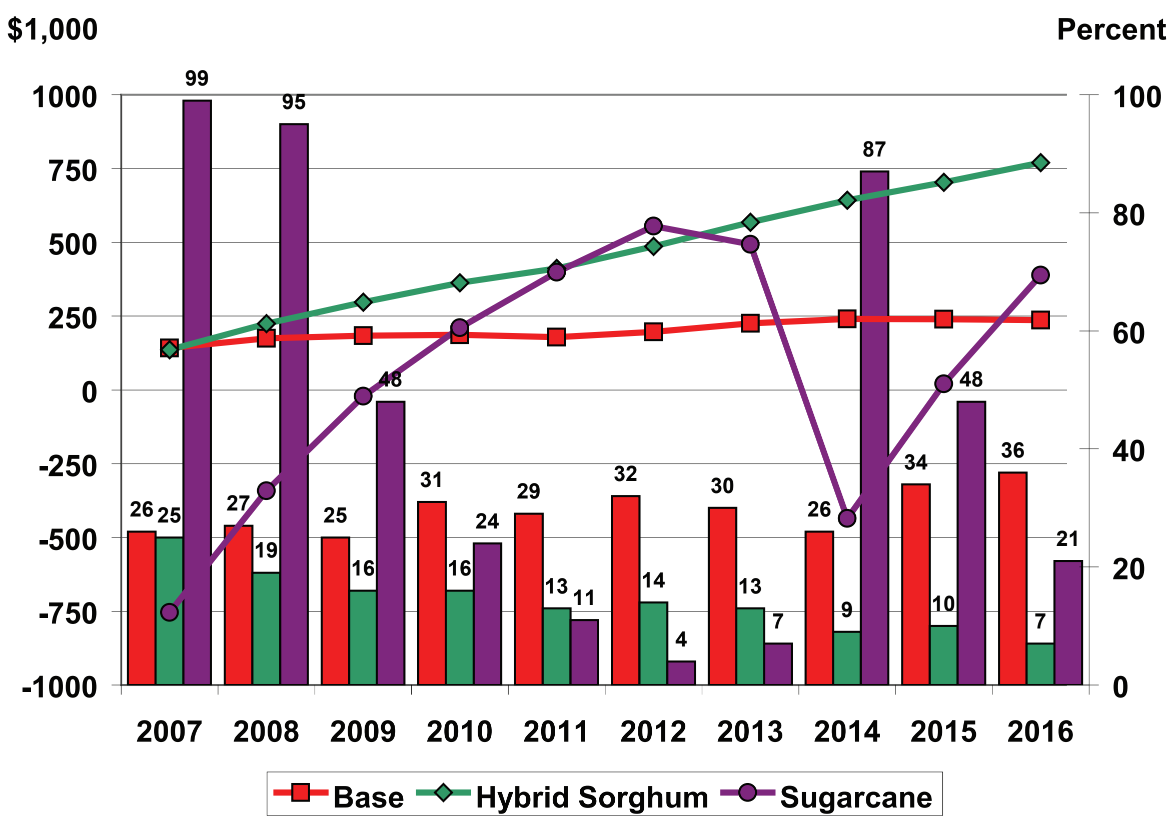

Figure 2. Ending Cash Reserves and Probability of Having to Refinance Operating Note for the Base, Hybrid Sorghum, and Sugarcane Scenarios.

sorghum hay, hybrid sorghum green chop, and hybrid sorghum high biomass).

The general financial outlook for the operation is improved under the hybrid sorghum scenario relative to the baseline. The dictated contract prices and assumed cost of production for the hybrid sorghum improve the efficiency of the operation, as evidenced by a 0.74 expense-to-receipts ratio compared to 0.81 for the baseline (Table 4). Both receipts and expenses are reduced, but the improved efficiency generates a higher average NCFI. NCFI over the ten-year period averages $300,000, an improvement of $80,000 annually over only producing rice and hay. The increased profitability generates even greater growth in cash position over time. Figure 2 shows the final cash position in 2016 grows to just over $750,000, while the probability of negative cash balances is also steadily improved to below 10% by 2016. Growth in real net worth is also indicative of the improved profitability, growing to an average of $4.0 million compared to $3.5 million for the baseline (Table 4).

Rice, Hay, and Sugarcane

Similar to the first alternative, the sugarcane scenario assumes half of the land is switched to sugarcane production. The crop mix consists of 750 acres of hay, 750 (250 planted annually) acres of rice land, and 1,500 acres devoted to sugarcane. Overall the farm's financial performance and position are improved with the addition of sugarcane production. The average NCFI improves from $220,000 in the baseline to approximately $250,000 annually for the sugarcane scenario (Table 4). However, sugarcane, being a perennial crop with a definitive life-cycle, adds an important consideration for the producer. The sugarcane crop is established in the first year of the analysis, produces the highest yields in years 2-4, and then yields taper-off in the 5th and 6th years of the crop.

The sugarcane crop cycle is evident in the outlook for NCFI (Table 4), where 2007 reflects the initial cost of establishing 1,500 acres of sugarcane. Minimal cost of production and stable yields are evident from 2008 through 2012 where NCFI averages in the range of $550,000 annually. Production and price risk (for non-energy crops) create a range of NCFI from $300,000 to $800,000 over the same 5 year period. In 2013 the sugarcane land is idle, and 2014 reflects the establishment cost for the next sugarcane crop. The nature of the sugarcane production is most critical to the farm's cash flow position. Figure 2 illustrates the high probability of negative cash positions associated with the crop establishment years, as well as the years needed to recover to a healthy cash level. Even with a year of no sugarcane production, the farm appears to be on a cash flow trend that is slightly improved over the baseline, but requires more management effort. Table 4 provides projections of RNW under sugarcane production, which is slightly improved on average. The financial outlook for sugarcane ignores any financing and accounting adjustments that could smooth the financial measures over time. All cash expenses are paid in the year incurred, profits assume cash accounting, cash shortages are financed for a 1 year term, and the established sugarcane is never considered an asset. In reality, a manager could finance the cost of sugarcane establishment over several years, capitalize the investment in establishing the crop, and depreciate the expense over the life of the crop. Another option would be to stagger the establishment of sugarcane acreage so that not all of the acreage is idle or established in a single year.

The long-term commitment required for producing sugarcane presents another dynamic for the producer-biorefiner relationship. The analysis of both hybrid sorghum and sugarcane production assumes the contract would be available and in place for the ten-year planning horizon. Hybrid sorghum contracts could possibly exist with shorter duration, while a producer would likely require a longer term commitment from the biorefinery to invest and commit to sugarcane production.

Delivered Cost to Biorefinery Including Growing, Harvesting, and Transportation (2008-2017)

Table 5 presents the range of variability in the biorefinery's growing costs per dry ton. While the expected contract prices per unit are fixed, the first portion of the contact is a lump-sum per acre based on expected variable production costs. The second, per unit, portion is paid on actual production. Therefore the actual, total price paid per unit is a random variable, because of variations in yield. The growing costs shown in Table 5 represent a simulation of the weighted average growing cost over the four energy crops based on the minimum cost crop mix. The average price paid ranges between $34 and $38 per dry ton, including prices that range between $25 and $57 in year 2008, to a range of $28 to $71 by 2017. The absolute minimum price is $25 in 2008, and the maximum is $85 in 2015.

As Table 5 indicates, the harvest and transportation costs per dry ton for the crop mix tend to be approximately $51. The absolute minimum is $41 in 2013, the maximum is $68 in 2017. The average total delivered price per dry ton averages approximately $87 over the ten year projection period. The simulated outcomes of total delivered cost range between a minimum of $69 in 2013, to a maximum of $141 in 2015 (Table 5).

Table 5. Descriptive Statistics for Simulated Key Output Variables for Biorefinery, 2008-2016					
Year	Mean	StDev	CV	Min	Max
Key Output Variable: Growing Cost to Biorefinery 2008-2017					
			($/Dry Ton)		
2008	33.73	5.02	14.89	25.40	57.40
2009	34.74	5.36	15.44	26.04	72.80
2010	35.17	5.37	15.27	26.40	63.16
2011	35.42	5.78	16.31	26.38	65.15
2012	35.55	5.63	15.84	26.20	70.23
2013	35.85	5.77	16.09	26.67	73.77
2014	36.40	5.92	16.25	27.06	63.39
2015	37.06	6.30	16.99	27.40	84.94
2015	37.50	5.68	15.15	26.98	61.16
2017	38.19	6.42	16.82	28.20	70.53
Ket Output Variable: Harvest & Transportation Cost 2008-2017					
			($/Dry Ton)		
2008	49.71	3.02	6.08	43.82	60.28
2009	50.55	3.48	6.88	42.96	61.56
2010	51.29	3.88	7.56	42.34	63.55
2011	51.10	3.89	7.62	42.21	66.69
2012	50.62	3.85	7.60	41.51	65.70
2013	50.26	4.01	7.97	40.95	64.21
2014	50.42	3.94	7.81	41.48	64.87
2015	50.81	4.16	8.18	41.62	64.51
2015	50.93	4.06	7.96	41.45	67.27
2017	51.27	4.24	8.27	41.28	67.50
Ket Output Variable: Total Delivered Cost 2008-2017					
			($/Dry Ton)		
2008	83.44	6.89	8.26	71.07	116.45
2009	85.28	7.40	8.67	70.72	131.91
2010	86.46	7.66	8.86	71.20	120.69
2011	86.52	8.07	9.33	71.69	127.00
2012	86.17	7.81	9.06	70.78	132.30
2013	86.11	8.21	9.54	68.70	134.58
2014	86.83	8.14	9.37	69.92	124.37
2015	87.87	8.78	10.00	71.36	140.85
2015	88.43	7.87	8.90	71.60	124.45
2017	89.46	8.88	9.92	71.29	133.91

Summary and Conclusions

Recent changes to U.S. energy policy indicate that the United States is committed to the successful, commercial introduction of cellulosic biofuels (Wyant, 2007). The economics of delivering biomass to biorefineries is the central theme of this paper. A Monte Carlo simulation and farm panel data was used to estimate the expected potential returns to agricultural producers when growing dedicated energy crops--hybrid sorghum hay, hybrid sorghum green chop, hybrid sorghum high biomass, and sugarcane. A whole-farm simulation model was then used to estimate the overall financial impacts on a model farm that begins to dedicate acreage to energy crop production. Estimates of the harvest and transportation costs of getting biomass from the farm to the biorefinery were also made.

If contract prices assumed in this analysis are viable, dedicated energy crops can be an economic option for agricultural producers in the Upper Coast region of Texas. Cane appears to be the most favorable crop in the more general modeling framework, but when evaluated on a net income, cash flow, and net equity basis for a representative farm the hybrid sorghums may be as favorable. Cane is more resistant to the potentially harsh weather conditions and therefore has less yield variability than the sorghum crops. Cane is also less sensitive to changes in annual input costs. However, planting cane does require a relatively large capital commitment for establishment and gives the producer less planting flexibility than the direct seeded sorghum crops. Farmers should note that contract prices based on expected outcomes can result in actual outcomes that are far less favorable, because of yield risk.

Harvesting and transportation costs account for at least 50% and in some cases 75% of the total delivered cost to the biorefinery. The contract structure proposed ensures that both the grower and the biorefinery share downside yield risk. However, the contracting scenario places additional risk on the biorefinery due to the potential of excess feedstock relative to its capacity constraint. Not accounting for either the ability of the biorefinery to purchase feedstocks from other sources when yields on contracted acreage are low, or for potential secondary markets for excess feedstock produced is a limitation of this study.

The results found in this analysis are generally similar to other studies after adjusting for differences in crops, time-frame, and technological assumptions. The contract prices calculated here are similar to those used by De La Torre Ugarte *et al.*, 2003; English *et al.*, 2006; and Epplin *et al.*, 2007. While most of the previous economic research done in delivering biomass has focused on wood wastes and switchgrass, this research focuses on new hybrid varieties of sorghum and sugarcane. If these crops can deliver the proposed yields on a consistent, commercial basis, then they may offer a suitable biomass alternative once cellulosic fuel production becomes commercially viable.

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Millions of Acres for Dedicated Energy Crops: Farms, Ranches, or Plantations?

Francis M. Epplin[1]

Introduction

The Energy Independence and Security Act of 2007 contains a provision that by 2022, 21 billion gallons of ethanol will be produced in the U.S. from non-cornstarch products (e.g. sugar or cellulose) (Congressional Research Service, 2007). Perlack *et al*. (2005) have estimated that it is technically feasible for the U.S. to produce more than a billion tons annually of cellulosic biomass that could be used as biorefinery feedstock. If cellulosic biomass could be converted into ethanol at a rate of 90 gallons per dry ton, a billion tons could be used to produce ethanol containing approximately 26 percent of the BTUs of the 2005 U.S. net crude oil imports. Some biomass could be obtained from wood wastes. However, use of a billion tons annually can be expected to require a combination of crop residues (e.g. corn stover, wheat straw) and the development of dedicated energy crops such as miscanthus and switchgrass.

If and when an economically competitive cellulosic feedstock biorefinery system that depends on the use of dedicated perennial grasses is developed, a substantial quantity of traditional agricultural resources would be required to produce, harvest, store, and transport feedstock to biorefineries. From 33 to 78 million acres would be required to achieve the stated goal of 21 billion gallons, with a conversion rate of 90 gallons per dry ton, and a perennial grass yield of 3 to 7 dry tons per acre. In 2007, U.S. farmers planted 60 million acres to wheat, 64 million acres to soybeans, 94 million acres to corn, and 11 million acres to cotton. A dedicated energy crop could become a major competitor for agricultural lands.

U.S. farms come in many sizes; however, the size of farms that produce the bulk of food, feed, and fiber is largely determined by underlying economic factors. For most agricultural crops, seasonality of production, harvest window, and size economies specific to harvest have a big influence on the size of operation necessary to attain the low cost point on the long run average cost curve (Allen and Lueck, 1998; Cheung, 1969; Wright and Brown, 2007). In the absence of government policies that favor one size relative to another, size economies are likely to play a big role in the structure of firms that produce, harvest, and deliver dedicated energy crops.

Relative to grain, cellulosic biomass from mature perennial grasses is bulky and difficult to transport. In the U.S., feedstock acquisition logistics for grains such as wheat and corn are relatively simple. Users may post a competitive price and grain will be delivered by the existing marketing system. The infrastructure for production, harvest, storage, transportation, and price risk management of grain is well-developed. The structure of farms used to produce grain and the infrastructure required to harvest, store, and transport grain in the U.S. has evolved over time. Infrastructure required to deliver a steady flow of large quantities of cellulosic biomass from fields where it could be produced and harvested, to biorefineries where it would be processed, remains to be developed.

Figure 1 contains a chart of the estimated farm gate production costs for switchgrass. The relative share of harvest cost to total production costs is substantially greater for a perennial grass for biomass than for annuals such as corn and wheat for grain. Epplin *et al*. (2007) estimate that harvest costs (mowing, raking, baling, field stacking) will account for 45 to 65 percent of the total farm gate costs (including the cost of establishment, land, and fertilizer) to produce a ton of switchgrass. Perrin *et al*. (2008) found that over a five year period across ten farms in the Northern Plains, switchgrass harvest costs accounted for 24 percent of the total farm gate production costs. On the other hand, harvest costs account for less than 15 percent of the total farm gate cost of production for corn grain.

The most economical system for production of cellulosic biomass will depend on a number of factors and is likely to differ across feedstock source and regions. In February of 2007, the U.S. Department of Energy announced that six proposed scaled-up cellulosic ethanol plants had been selected to

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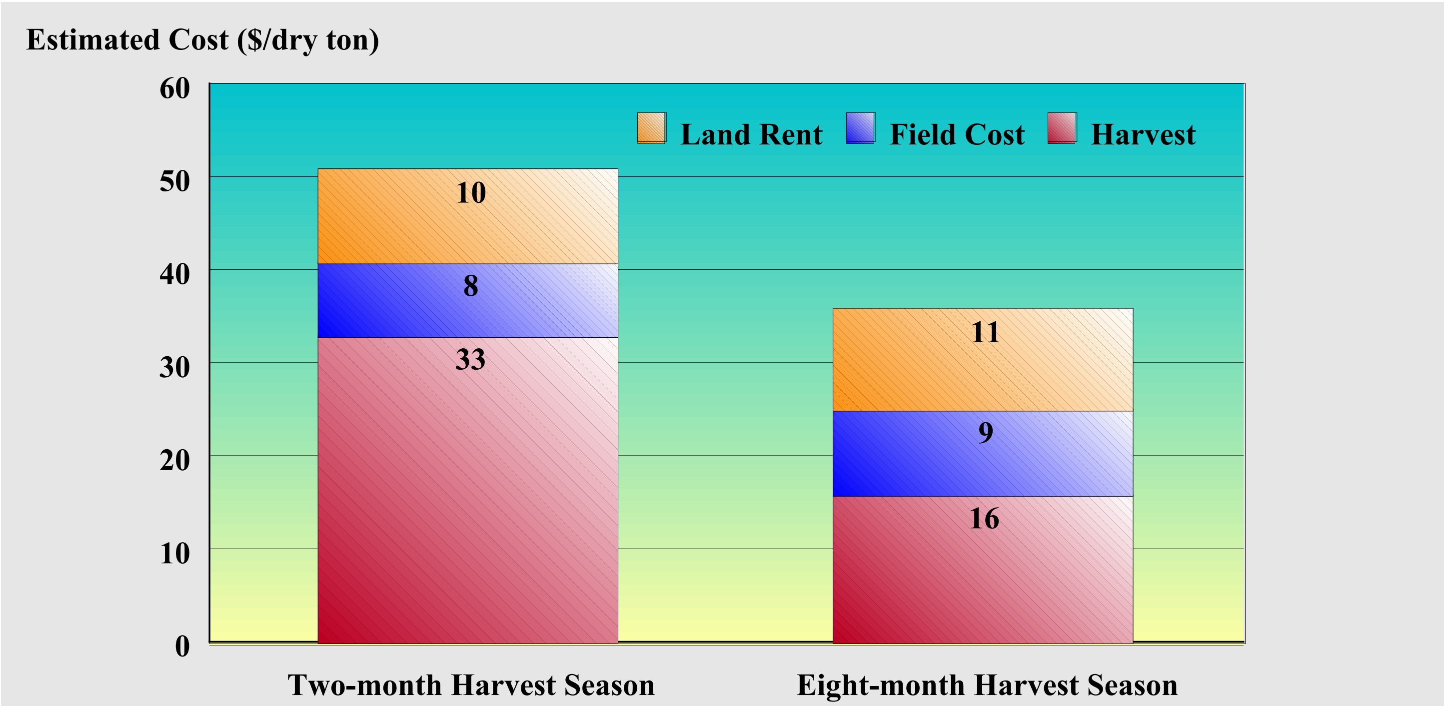

Figure 1. Estimated "Farm Gate" Cost to Produce a Ton of Cellulosic Biomass from Switchgrass (Epplin *et al*., 2007)

receive up to $385 million in federal investment funds (U.S. Department of Energy, 2007). Alico, one of the six companies, proposed to use feedstock produced exclusively on the more than 130,000 acres owned by the company. If existing companies with large land holdings manage cellulosic biomass as proposed by Alico, the consequences on farm structure may be minimal.

Another of the companies, BlueFire Ethanol, proposed to use 700 tons per day of sorted green waste and wood waste from landfills. Companies that follow the model proposed by BlueFire would also likely have little effect on conventional agriculture. A third company, Broin, proposed to use 842 tons per day of corn fiber, cobs, and stalks. If the feedstock is limited to residue and byproducts of an existing crop such as corn, the consequences on farm structure may be minimal. However, the most efficient method of crop residue acquisition, harvest, storage, and transportation remains to be determined.

Two of the companies, Abengoa and Iogen, proposed to use a combination of crop residues, switchgrass, and other feedstocks. Impacts on existing farm structure are more likely if perennial grasses such as switchgrass and miscanthus become the predominant feedstocks. And, based on the estimates produced by Perlack *et al*. (2005), a dedicated energy crop will be required to achieve a billion tons annually of cellulosic feedstock. Perlack *et al*. (2005) anticipate that 55 million acres of U.S. cropland, idle cropland, and cropland pasture could be seeded to a dedicated perennial energy crops with little economic consequences for food and fiber production. Similarly, English *et al*. (2006) conclude that with some economic incentives, switchgrass could be established on more than 100 million U.S. acres.

Based on small plot research, in years after switchgrass is established, in some environments, it requires very little annual maintenance (Fuentes and Taliaferro, 2002). Other than harvest, most stands can be maintained with one trip per year to broadcast fertilizer. If competition from weeds and pests is negligible, switchgrass production may require very little "farming". The structure is likely to be determined by the most cost efficient harvest, storage, and transportation system.

Objective

The purpose of the research reported in this paper is to identify factors that will ultimately determine the most efficient harvest system for a dedicated energy perennial grass such as switchgrass. The policy goal of 21 billion ethanol gallons per year from cellulose or sugar, may require 33 to 78 million acres. The harvest system that evolves is expected to have a large influence on the structure of farms that produce the feedstock.

Assumptions

For the purpose of discussion consider the following assumptions: (1) for the region of interest switchgrass is the most efficient dedicated energy crop; (2) the region has sufficient land to produce enough switchgrass biomass annually to support at least one cost efficient cellulosic biorefinery; (3)

the biorefinery can afford to pay a price for switchgrass feedstock that is sufficient to bid the quantity of required land in the region from current use to switchgrass production; (4) the biorefinery seeks to maximize returns above costs; (5) land owners seek to maximize returns to their scarce resource, land; (6) the biorefinery expects to require a continuous flow of switchgrass feedstock (24 hours per day, 7 days per week, throughout the year) perhaps 2,000 dry tons of biomass per day operating 350 days per year; (7) feedstock storage at the biorefinery is limited to no more than that required for one month; and (8) the number of acres required to support a 2,000 tons per day biorefinery would depend on the switchgrass yields which depend on climate and soils.

To facilitate the analysis several additional assumptions were employed. Research and development is ongoing in an attempt to develop economically competitive methods to produce ethanol from cellulose (Aden *et al*., 2002; McKendry, 2002; Mosier *et al*., 2005; Service, 2007; Wyman, 1994). Examples include enzymatic hydrolysis, acid hydrolysis, gasification, gasification-fermentation, liquefaction, and mixalco. The optimal feedstock characteristics may depend on whether the processing system that "wins" requires dry versus wet and/or loose versus dense biomass. For purposes of discussion it is assumed that an economically competitive gasification-biofermentation system will be developed. Several private and public research entities are attempting to develop gasification-biofermentation technology (Klasson *et al*., 1990; Rajagopalan, Datar, and Lewis, 2002). However, the technology remains to be proven economically viable at a commercial scale.

It is anticipated that a gasification-biofermentation biorefinery could process a variety (switchgrass, miscanthus, corn stover, wheat straw, sugarcane bagasse) of dry and dense or loose feedstock. Current commercially available forage harvest systems include those that produce (1) small bales; (2) large cylindrical solid bales; (3) large rectangular solid bales; (4) loosely chopped material; (5) pressed modules based on cotton module systems; and (6) chopped relatively wet material for ensilage systems (Cundiff, 1996; Cundiff and Marsh, 1996; Gallagher *et al*., 2003; Kumara and Sokhansan, 2007; Sokhansanj and Turhollow, 2002; Worley and Cundiff, 1996). For large volume, and current forage harvest technologies, to collect for field storage and transport substantial distances, large rectangular (approximately 4 feet by 4 feet by 8 feet) solid bales is the least-cost system for harvesting biomass from perennial grasses in the Southern Plains (Thorsell *et al*., 2004).

One advantage of establishing switchgrass as a bioenergy crop in the Southern Plains is that it could be harvested once per year anytime between July and February of the following year (Epplin *et al*., 2007). This extended harvest season is likely to result in the development of harvest units that include an economically efficient set of machines and workers. Harvest units could develop in a manner similar to custom grain harvesting firms that harvest a substantial quantity of the grain produced in the Great Plains. The cost economies are such that it is difficult for a moderate sized wheat producer to justify combine ownership. For many farms in the region hiring a custom harvester is more economical than either combine ownership or leasing.

Custom grain harvest firms exploit the economies of size associated with ownership and operation of grain harvest machines. Kastens and Dhuyvetter (2006) found that a typical custom grain harvest company harvests 28,049 acres per year, with 4.1 combines, 6.3 trucks, and 10.3 workers. These harvest companies may begin their season in regions where the crops mature first and migrate as the harvest season progresses. For example, some harvest firms begin harvesting wheat in Texas in May and travel north as the crop matures.

Modeling

In the absence of government policies that place restrictions on land ownership and resource use, structure will be largely determined by the underlying economics. Economic models have been constructed to estimate production costs and identify potential bottlenecks and constraints (Hess, Wright, and Kenney, 2007; Mapemba *et al*., 2007; Petrolia, 2006; Tembo, Epplin, and Huhnke, 2003).

Thorsell *et al*. (2004) introduced the concept of an economically efficient harvest unit for switchgrass. Figure 2 contains a chart of the estimated costs to harvest a ton of biomass with Thorsell's (2001) defined harvest unit as a function of the number annually harvested acres. This is the long run average cost of machine ownership and operation. The chart shows the magnitude of the potential economies of size that could be expected to result from a coordinated harvest system. For a relatively low yielding feedstock, such as two tons per acre, the lowest costs per ton were achieved at a harvest unit capacity of 27,420 acres per year. Thorsell's harvest unit includes nine tractors, three balers that produce large rectangular (approximately 4 feet by 4 feet by 8 feet) solid bales, three sets of tandem mowers, three sets of tandem rakes, one bale transporter, and ten workers to maintain and operate the machines. For a relatively high yielding feedstock such as five tons per acre, the lowest costs per ton were achieved at an annual harvest unit capacity of approximately 11,000 acres. Few U.S. farms could independently take advantage of these harvest cost economies.

Because of differences in weather requirements between mowing and baling, Hwang (2007) modified Thorsell's (2001) harvest unit concept by separating the mowing unit from the raking-baling-stacking unit. Hwang (2007) incorporated the modified harvest unit system into a multi-region, multi-period, mixed integer mathematical programming model simi-

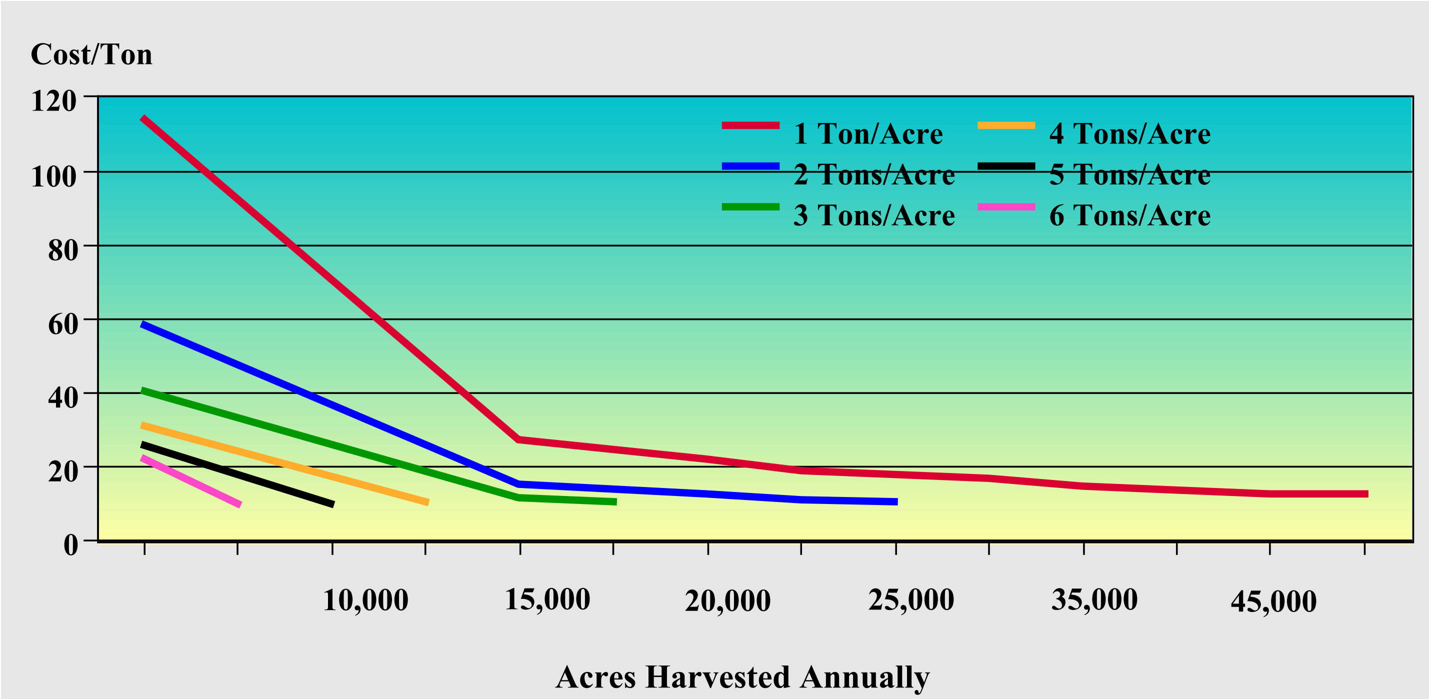

Figure 2. Total Cost to Mow, Rake, Bale, and Field Stack Switchgrass Biomass for Alternative Switchgrass Yields and Acres Harvested Annually ($/dry ton) (Thorsell, 2001)

lar to that described by Tembo, Epplin, and Huhnke (2003) and Mapemba *et al*. (2007). The model was formulated and solved to determine the cost to produce, harvest, store, and transport a flow of switchgrass biomass to a biorefinery and identify the optimal biorefinery location from among several potential sites.

Expected yields used in the model were obtained from Graham, Allison, and Becker (1996) and Fuentes and Taliaferro (2002). Fuentes and Taliaferro (2002) reported switchgrass yields from two Oklahoma locations over seven years. The best yielding plots at both locations included a blend of the cultivars Alamo and Summer. Over the seven years, mean yields from this blend at Chickasha (average annual precipitation of 35 inches) were 6.0 tons per acre but ranged from 4.0 tons per acre in 1998 to 9.8 tons per acre in 1995. At Haskell (44 inches of average annual precipitation) the annual yield over the seven years averaged 8.5 tons per acre, ranging from a low of 5.4 tons per acre in 1999 to 11.5 tons per acre in 1994 (Fuentes and Taliaferro, p. 278).

Expected biomass yields differ across months of the year due to stage of growth and field losses that occur after plant maturation (Figure 3). Biorefinery size was based on biomass feedstock requirements of 2,000 dry tons per day (Epplin *et al*., 2007). The model endogenously determines the number of harvest machines. Shipment and processing of biomass can be done in any of 12 discrete periods (months of the year). In months when biomass is harvested, it may be placed in storage or transported directly from the field to the biorefinery. Two harvest seasons were modeled. The first harvest season extended from July through February of the following year (eight-month system), while the second was restricted to July and August (two-month system). This restriction was imposed to determine how the length of the harvest season affects the number of required harvest machines and fixed and variable costs of operating them (Epplin *et al*., 2007).

Results

Figure 4 illustrates the number of tons harvested per month for the eight-month and two-month harvest systems. Harvested tons differ across months because the number of harvest hours per day varies with average day length, and the number of harvest days varies with expected weather. If harvest is restricted to July and August, more than 390,000 tons would be scheduled for harvest in July and an additional 345,000 tons in August. If harvest could be spread over eight months, only 135,000 tons would be scheduled for harvest in July. Relatively few tons are harvested in October because of weather-related constraints on the number of harvest days. The expected October harvest is 40,000 tons. As reported in Figure 5, the optimal number of harvest units for raking-baling-stacking required to harvest feedstock for the 2,000 tons per day biorefinery increases from 19 for the eight-month harvest system to 56 for the two-month harvest system. The average investment in harvest machines increases from $10.8 to $26.7 million as the length of the harvest season declines from eight to two months (Figure 6).

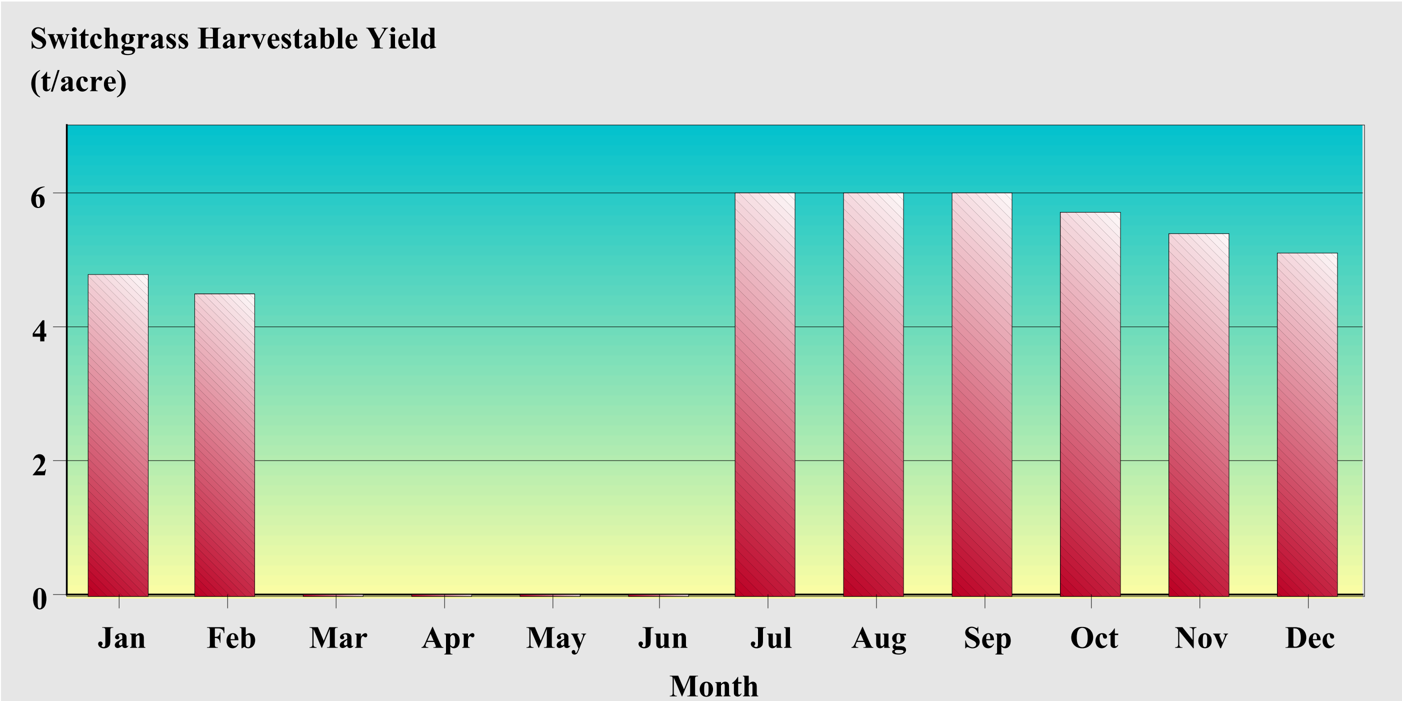

Figure 3. Switchgrass Expected Harvestable Yield (Dry Tons Per Acre) Ranges from 3.75 to 6.50 Dry Tons Per Acre Depending on Oklahoma County and Month of Harvest

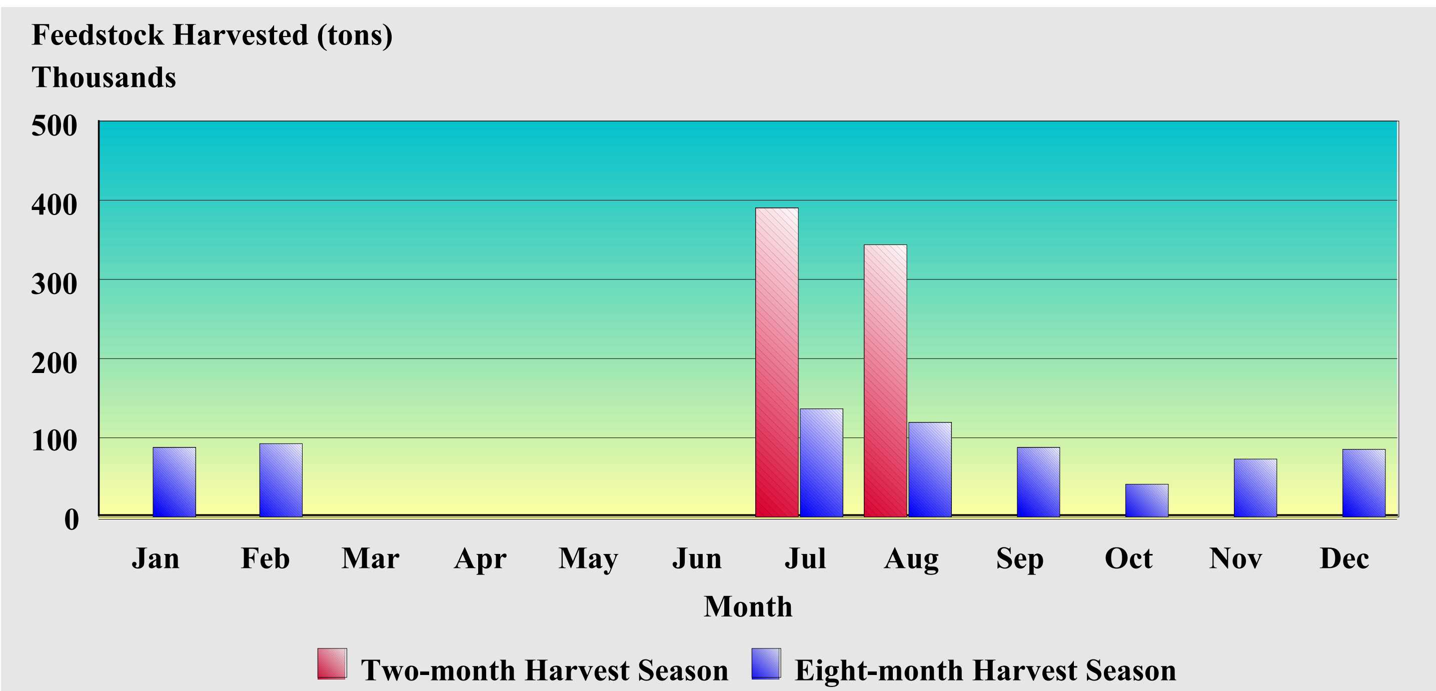

Figure 4. Switchgrass Harvested Per Month for Both a Two- and Eight-Month Harvest Season to Provide a Flow of Feedstock to a 2,000 Dry Tons Per Day Biorefinery in Oklahoma (Epplin *et al*., 2007)

Figure 7 includes a chart of the estimated number of acres harvested per year per raking- baling-stacking harvest unit for both the two- and eight-month harvest season to provide a flow of 2,000 dry tons per day. Estimated "farm gate" costs for producing, harvesting, and field stacking switchgrass is included in the chart in Figure 1. The chart includes the total costs for land rent, establishment amortized over 10 years, an annual application of fertilizer, and a single harvest per year. Land rental costs and other non-harvest costs per ton are slightly greater for the 8-month harvest system. This re-

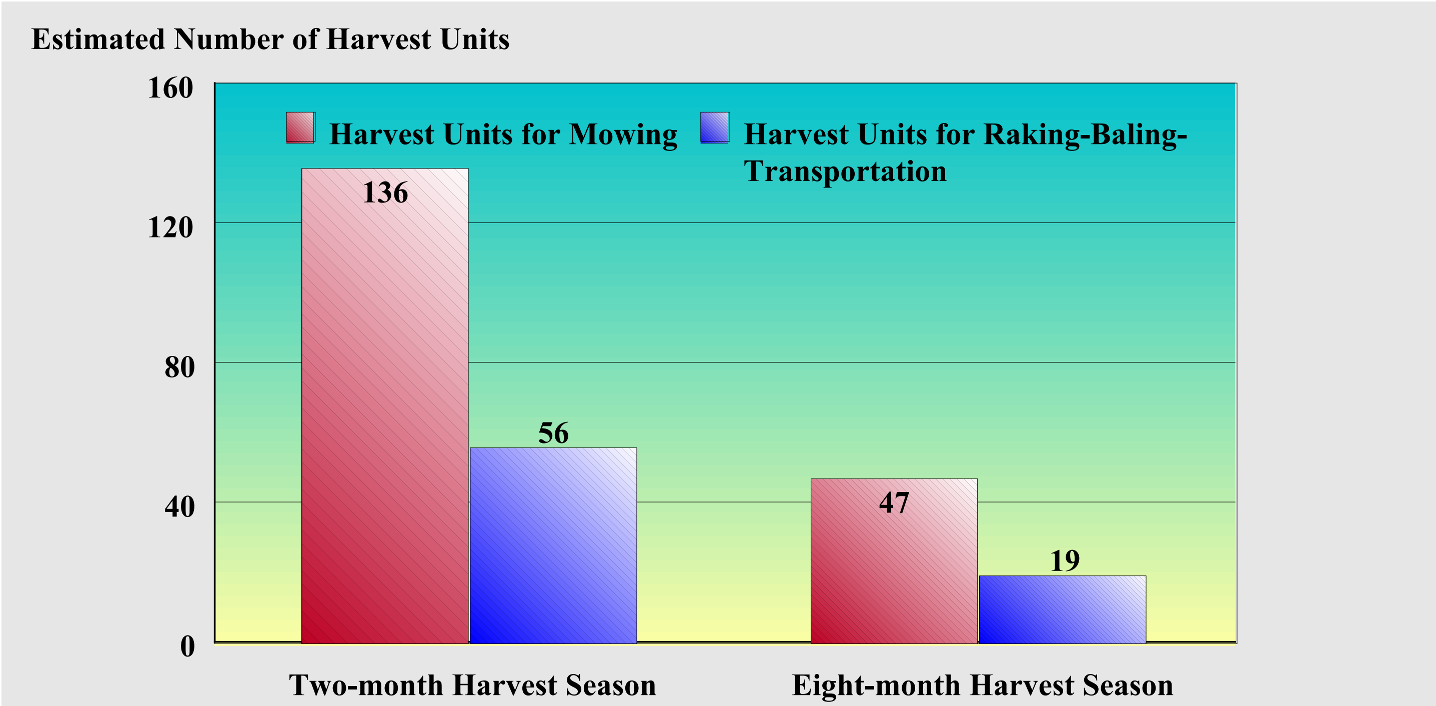

Figure 5. Estimated Number of Harvest Units for Two- and Eight-Month Harvest Season to Provide a Flow of 2,000 Dry Tons Per Day (Hwang, 2007)

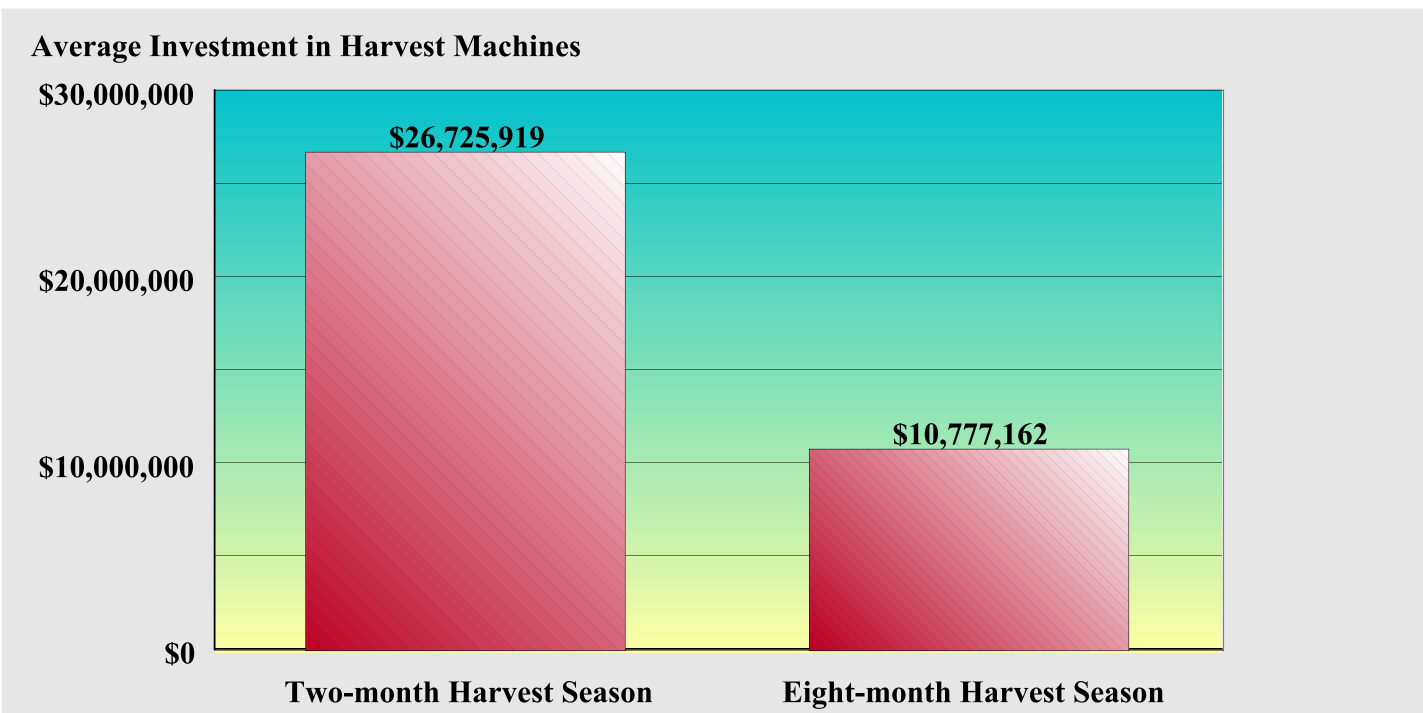

Figure 6. Average Investment in Harvest Machines for Two- and Eight-Month Harvest Season to Provide a Flow of 2,000 Dry Tons Per Day (Hwang, 2007)

sults because harvestable yield per acre declines as harvest is delayed past peak yield (Figure 3). However, the estimated harvest cost per ton is substantially greater for the two-month harvest system. Since fewer machines are required, the investment required and hence the fixed cost of harvest machines is substantially greater if the harvest window is limited to two months per year.

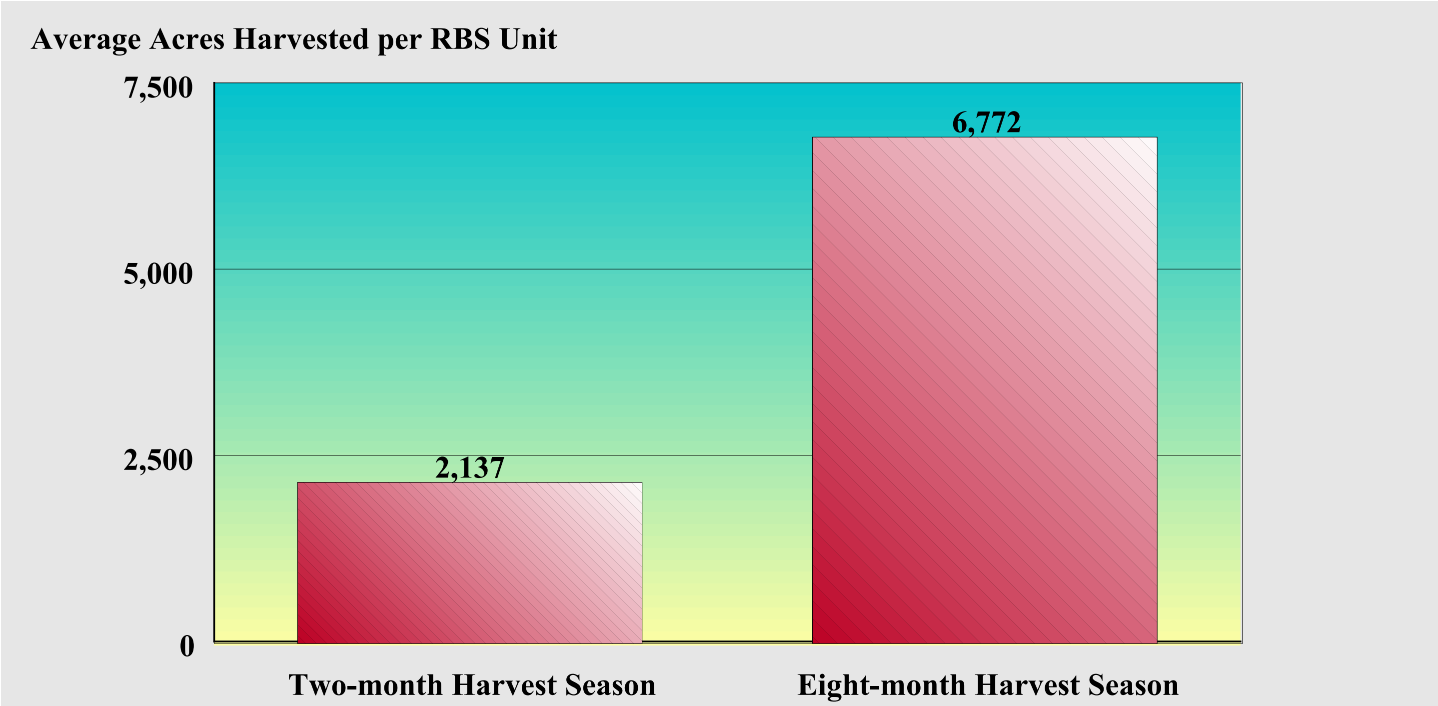

Figure 7. Estimated Number of Acres Harvested Per Year Per Raking-Baling-Stacking Harvest Unit for Two- and Eight-Month Harvest Season to Provide Flow of 2,000 Dry Tons Per Day

Discussion

Harvest would extend over as many months as permitted by weather, feedstock sources, and policy. Given the quantity of biomass required, and the lack of an existing infrastructure to harvest a continuous flow of massive quantities of biomass, it is likely that a system of harvest would develop that exploits the economies of size associated with harvest machines. It remains to be seen if independent companies, such as those that exist for grain harvest in Great Plains, develop. Alternatively, harvest crews and harvest machines could be managed as wholly owned subsidiaries of biorefineries.

Given the rather substantial cost economies associated with harvest machines, and given that the costs of harvest may account for 45 to 65 percent of the total farm gate costs of production, and given that a biorefinery is expected to require a continuous flow of feedstock, if switchgrass or some other perennial grass, is established on millions of acres, it is likely that a highly coordinated harvest system will develop. Established stands of an indigenous perennial grass such as switchgrass are expected to require little management, perhaps one trip across the field for fertilization per year, followed later in the year by harvest. Except for the activities associated with harvest, established stands of switchgrass are not likely to require much activity.

The incentive structure required to bid 33 to 78 million acres from current use, to establish switchgrass, or some other dedicated energy crop, remains to be determined. It would be very risky for a biorefinery to depend on spot markets for feedstock. In the absence of spot markets, obtaining a reliable flow of feedstock from a dedicated energy crop such as switchgrass could involve: (1) contracts with individual growers; (2) contracts with a group of growers through a co-operative arrangement; (3) long-term land leases similar to Conservation Reserve Program (CRP) leases; and/or (4) land acquisition. The most cost efficient from among these systems remains to be determined. However, land owners have experience with engaging in long term (10-15 year) CRP contracts. More than 30 million acres have been under CRP contract. These contracts may provide a blueprint for biorefineries that need to insure a reliable flow of feedstock and for landowners that desire a reliable rent and little risk.

The structure of a mature cellulosic feedstock production and delivery system remains to be determined. However, production characteristics and harvest cost economies could result in a structure for perennial grass production for use as a dedicated energy crop that more nearly resembles the structure of U.S. timber production rather than the atomistic system that we observe for U.S. grain, oilseed, and fiber production. If the low-cost feedstock is a perennial with a long stand life and wide harvest window such as miscanthus or switchgrass, market forces may drive the structure toward vertical integration. For a mature industry, feedstock production, harvest, and transportation may be centrally managed and coordinated.

A number of additional issues remain. A system to manage the risk associated with feedstock yield variability and the risk of fire of standing and stored switchgrass will be required. It is not clear how a biorefinery would respond to short crops. In years of above average yields, not all acres would have to be harvested. However, in years of below average yields, the biorefinery may not have sufficient feedstock to operate throughout the year.

The grain-ethanol program has increased the cost of inputs (land, fertilizer, machinery) required to produce switchgrass and thus the cost to produce switchgrass. Finally, the ultimate challenge is to discover, develop, design, and demonstrate an economically competitive biorefinery technology necessary for a profitable business model.

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