19. Ethanol Markets and the Development of a Cellulosic Ethanol Industry

Dave Lambert **<lambertd@ksu.edu>**

Dave Lambert received his Ph.D. from Oregon State University. He began his academic career at the University of Nevada, Reno, in 1984 teaching courses in microeconomics and decision analysis and conducting research on the use of public lands in the Intermountain West. Lambert left Nevada in 1998 to become the Department Chair in Agribusiness and Applied Economics at North Dakota State University. In his eleven years at North Dakota, he combined his administrative duties with teaching and continuing a research program in production economics. Lambert has served as the Vice President of the Western Agricultural Economics Association and chaired several committees of the Agricultural and Applied Economics Association. He recently ended a three year term as the Managing Editor of the Journal of Agricultural and Resource Economics. Although administrative tasks occupy most of Lambert's current time, he will be teaching a graduate course in Production Economics this Fall and maintains research interests in production economics and energy policies. This presentation is based on research begun at North Dakota investigating the use of crop residues in an emerging cellulosic ethanol industry.

Abstract/Summary

To meet federal mandates on the production of next-generation biofuels, cellulosic ethanol production is targeted to expand from near-zero production in 2010 to over 16 billion gallons by 2022. Dedicated energy crops, herbaceous crop residues, and woody plant byproducts are expected to provide most of the feedstock. This presentation provides an overview of ethanol policies and projects possible logistical systems for an herbaceous crop residue-based ethanol industry.

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David K. Lambert
Department of Agricultural Economics
Kansas State University
August 2010

The global consumption of petroleum (including motor fuels) has been increasing steadily for decades (figure 1). Given some year to year variation, worldwide petroleum consumption has increased an average of about 1.6 percent between the early 1980s and 2009. Currently, global daily consumption is approximately 85 million barrels of oil. Petroleum use in the U.S. has increased from an average of 17 million barrels per day in 1980 to a peak in 2005 of about 21 million b/d, an average increase of about 0.35%/year. Consumption outside of the U.S. has increased at an even greater rate, from roughly 46 million b/d in 1980 to a high in 2008 of about 66 million b/d (figure 2). Although the U.S. remains the greatest single consumer of oil, the U.S. share of total oil use has fallen from 26 to 23 percent since the early 1980s. The fall in global demand since 2007 has been due to economic contractions and will likely return to traditional growth rates for at least the next few years.

Figure 1. Total Global Petroleum Production and Use (Thousand barrels per day)

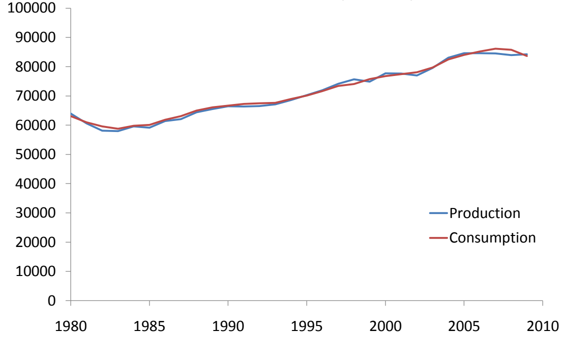
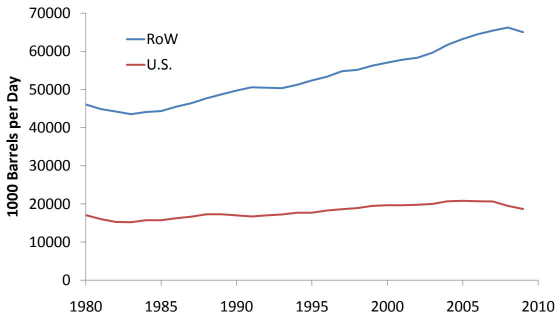


Figure 2. Total Petroleum Consumption



Reliance on domestic petroleum supplies has led to reductions in U.S. known reserves (figure 3). As supply falls and demand increases, reduced supplies impose higher extraction costs for U.S. produced petroleum, with greater reliance on procuring oil from foreign sources (figure 4). Although the recession has reduced petroleum demand, about 12 million barrels per day were imported in 2009, representing about 62% of total crude oil and petroleum products used in

2009. By comparison, the U.S. relied on oil imports for only about 37% of consumption in 1981. About half of the imports in 2009 came from four exporting countries: Canada (899,370 b/d), Mexico (450,525 b/d), Venezuela (393,426 b/d), and Saudi Arabia (369,488 b/d).[1]

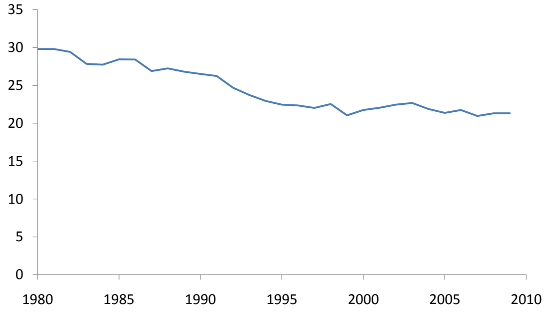


Figure 3. U.S. Proven Petroleum Reserves (Billions of barrels)

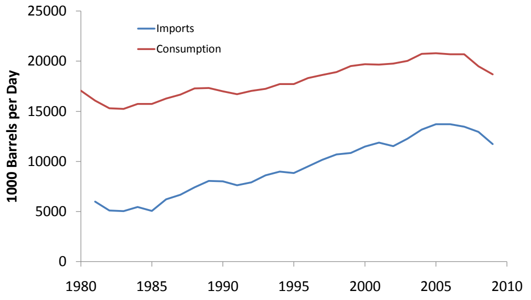


Figure 4. Total U.S. Consumption and Imports

In light of greater global petroleum demands, forecasts of achieving "peak oil" production by 2020 by the International Energy Agency (*The Economist*, December 10, 2009), and growing aversion to the external costs of petroleum extraction (e.g., Deepwater Horizon) and use (release of greenhouse gases), President Bush called for the end of America's addiction to foreign oil in his State of the Union address of 2006. In referring to America's addiction to oil, Bush called for increasing use of renewable liquid fuels in powering America's transportation system, including increases in research funding in "cutting edge methods of producing ethanol, not just from corn but from wood chips, stalks, or switchgrass." (*The Washington Post*, January 31, 2006). Figure 5 reflects the impacts of this government support for the ethanol industry.

Ethanol History

The Energy Information Agency (*EIA.gov*) provides an overview of ethanol's history as an energy source. Early use of ethanol included development of internal combustion engines that

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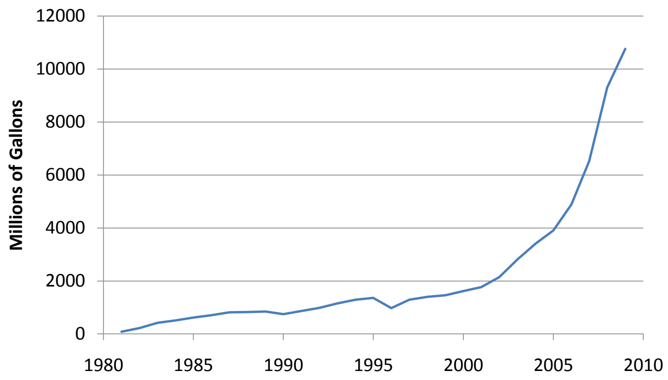
[1] By comparison, estimates released in June 2010 indicate flows from the Deepwater Horizon disaster in the Gulf of Mexico at 35,000-60,000 b/d (*The Economist*, June 17, 2010). This is not to minimize the economic and ecological damages of the blowout, but the loss represents approximately 0.3% of total daily use in the U.S. This likely explains the lack of a discernable impact on oil prices in global markets due simply to the Gulf catastrophe.

ran on ethanol (1826).[2] Henry Ford's first automobile, the quadricycle, built in 1896 ran on ethanol. The model T, first produced in 1906, was a flexible fuel vehicle, with the potential to run on pure ethanol or gasoline, or a mix of the two. Ethanol continued to be a motor fuel or motor fuel additive through the first half of the 20th century, due in part to increasing demand for petroleum during the war years. Even during the 1930s, over 2000 Midwestern gasoline stations sold gasohol, which included a 6-12% blend of ethanol.

Figure 5. U.S. Fuel Ethanol Annual Production



Recognition of the growing frailty of a U.S. economy increasingly dependent on foreign petroleum sources arising from the market disruptions of the 1973 Arab oil embargo, federal legislators responded with increasing support for a domestic renewable fuels industry. The Energy Tax Act of 1978 authorized a 10% gasohol blend, with the ethanol share of motor fuel being exempt from the federal gasoline excise tax. The excise tax was $0.04 per gallon of motor fuel at the time, resulting in a $0.40 tax credit per gallon of ethanol blended into gasoline at the 10% blend ratio. Although the motor fuel excise tax has varied over the years, the ethanol tax credit authorized 32 years ago remains in effect today. In addition to the tax credit, the Energy Security Act of 1980 established a national goal of a 10% ethanol blend in all motor fuels. The 1978 Act also provided incentives for investment in ethanol plants by authorizing a billion dollars in loan guarantees for new plant construction.

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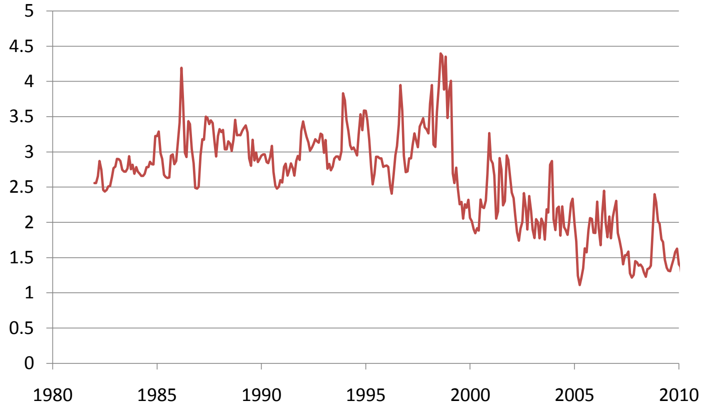
[2] Recall that the first successful oil well, the Drake Well, drilled exclusively for finding oil was drilled in 1859 in northwestern Pennsylvania

As seen in figure 5, the early subsidies, blend recommendations, and loan guarantees had little impact on ethanol production. Even with the government subsidies, rack prices for ethanol averaged over 300% higher than prices for gasoline until 2000 on an energy content basis (figure 6). In spite of the higher relative cost of ethanol, though, ethanol production has increased over the last thirty years. Increasing government subsidies, elimination of MTBE as an approved fuel oxygenator over the last decade, federal Renewable Fuel Standards established in the 2005 Energy Policy Act along with state mandates for increasing ethanol mixtures in motor fuel, and technological advances reducing the cost of ethanol production spurred increased ethanol production from about the year 2000. The cumulative effects of these year-on-year increases have resulted in production increases from 83 millions of gallons in 1981 to over 10 billion gallons produced in 2009. Ethanol comprised approximately seven percent of the total U.S. motor fuel consumption of 137.7 billion gallons in 2009.

Figure 6. Ratio of Ethanol to Gasoline Prices
(BTU equivalency basis)



http://www.neo.ne.gov/statshtml/66.html

Nearly all of the ethanol currently produced in the U.S. is derived from corn. However, future increases in the production of corn-based ethanol are problematic. Assuming a conservative 2.5 gallons of ethanol produced per bushel of corn, the 10.8 billion gallons of ethanol produced in 2009 required about 4.3 billion bushels of corn. Total U.S. corn (for grain) production in 2009 was 13.1 billion bushels, indicating that about one-third of the corn produced was used in the production of fuel. Other food and industrial uses totaled about 1.6 billion bushels, animal feed consumed 5.4 billion bushels, and approximately 2.0 billion bushels were exported. Other authors have pointed out that continuing increases in the production of corn-based ethanol will have direct impacts on other corn users and will impact other crop supplies through land use changes favoring corn production (Keeney and Hertel, 2009).[3] Based only on corn-based ethanol, meeting the national goal of 36 billion gallons of ethanol production by 2022 would require approximately 14 billion bushels of corn, higher than the entire U.S. corn output of any recent year.

There is also concern over the net energy gained from corn-based ethanol production. Life-cycle analyses calculate the energy yield of various fuel sources relative to energy inputs consumed in producing the fuel. Davis, Anderson-Teixera, and DeLucia (2009) provide a survey of the literature, finding the fossil energy ratio, or FER, to be highest for lignocellulosic crops (reported FER estimates include values of 5.60, 2.19-4.30, and 1.80), potentially high for switchgrass (4.43, though one study reported an FER ratio of 0.44), and variable for corn-based ethanol production. In the case of corn, FER estimates ranged between 1.08 and 1.95, though several studies reported a net loss with FER values from 0.69 to 0.99. A recent analysis published by the United Nations estimates FER ratios of 1.4 for corn-based ethanol, 5.0 for cellulosic ethanol, and 10.0 for sugar cane ethanol (United Nations, 2008). Efficient pricing of both energy inputs and outputs, technological improvements in cellulosic production, and removal of barriers to international trade would place corn-based ethanol at a disadvantage to production technologies relying on other feedstocks.

The Congressional Budget Office published an analysis of both the costs to the U.S. Treasury of the ethanol tax subsidy, greenhouse gas effects of increasing ethanol production from both corn and cellulosic technologies, and the land use impacts as farmers plant more land to corn in response to high prices driven in part by increasing demands from ethanol producers (CBO, 2010). Amongst other findings, the CBO report estimates an approximate $6 billion reduction in federal excise tax receipts resulted from biofuel tax credits in 2009. Taxpayer costs of reducing petroleum-based motor fuel by one gallon through increased use of corn-based ethanol was $1.78 per gallon of ethanol. Life-cycle analysis indicated the greenhouse gas reduction resulting from

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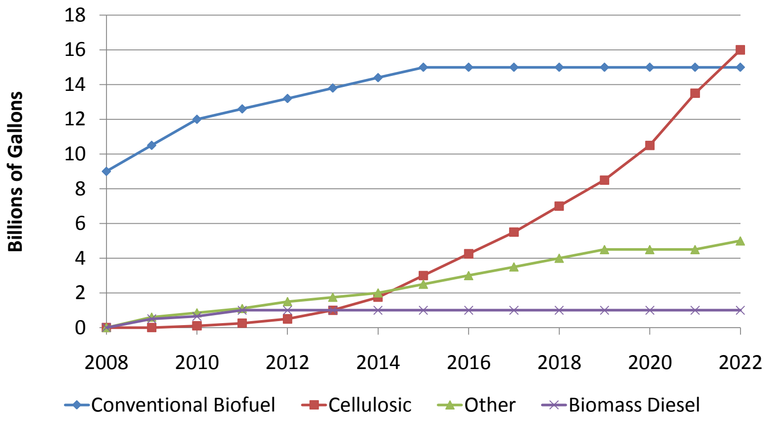
[3] Planted corn acreage averaged 77 million acres in the 1990s and increased to 83 million acres for 2001-2010. Recent years have seen even greater increases, with 93.5 million acres planted in 2007, 88.8 million acres planted in 2010. Yield increases have been even greater, with total production averaging 8.8 billion bushels in the 1990s, but reaching 13.1 billion bushels in 2009 (*National Agricultural Statistics Service*).

substituting ethanol for gasoline cost $754 per metric ton of CO_2e reduction.[4] Issues raised in this CBO report led the leaders of the National Cattlemen's Beef Association, the American Meat Institute, the National Pork Producers Council, and other groups representing corn users to address a letter to the Senate Leadership on July 16, 2010 asking for an end to the federal tax credits for Volumetric Ethanol Excise Tax Credit as they expire at the end of December 2010 and the current tariff of $0.54 per gallon on ethanol imports (*BEEF*, 2010).

Because of these energy, agronomic, and market concerns associated with corn-based ethanol, there is increasing research in non-corn based ethanol production. Future fuels may derive from herbaceous and woody plant materials, municipal wastes, animal wastes, and even biological innovations leading to fuel production from algae. Federal guidelines in the Energy Information and Security Act of 2007 set a 2022 production target of 36 billion gallons of transportation fuel to come from ethanol and biodiesel (figure 7). Since current technologies would require all of the U.S. annual corn production be used in ethanol production to achieve the 36 billion gallon target, EISA sets a target plateau of 15 billion gallons of annual ethanol production from corn by 2015, with subsequent growth to occur primarily in advanced biofuels.

Figure 7. EISA Targets for Ethanol Production



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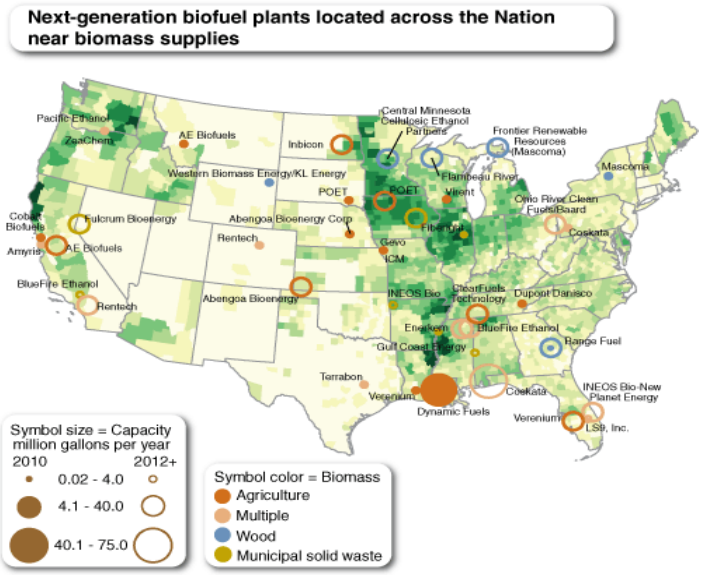
[4] The cost of reducing carbon via the ethanol tax credit performs poorly when the nearby futures (September 10) for carbon on the European exchange is €14.23 per metric ton (data accessed July 21, 2010)

In spite of considerable research in recent years, commercial "advanced" biofuel production is almost nonexistent. Total production capacity[5] in 2010 of cellulosic biofuel is projected to be 10.1 million gallons (Coyle, 2010). Despite EISA mandates of a billion gallons in 2012, Coyle estimates that production capacity will only increase to 291 million gallons in the next two years.

However, the federal government established targets in the 2007 EISA for the use of ethanol as a motor fuel supplement. Targets stipulate 16 billion gallons per year of ethanol shall be produced by cellulosic methods by 2022. Should commercial-scale technology be developed, and should demand and supply conditions lead to markets for cellulosic ethanol, much of the production will occur in regions of the country in which herbaceous and woody feedstocks are currently available. Specifically, the Midwest, where most of the current corn-based ethanol is produced, will likely be the center of cellulosic production from herbaceous crop residues (i.e., straw, corn stover, corn cobs) or dedicated energy crops (e.g., switchgrass, sorghum) (figure 8).

Figure 8. U.S. Biomass Supply



Note: The darker the green, the greater the density (tons per county) of cropland and forestland biomass.
Source: *Next-Generation Biofuels: Near-Term Challenges and Implications for Agriculture*, by William Coyle, BIO-01-01, USDA, Economic Research Service, available at: www.ers.usda.gov/publications/bio0101/

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[5] Production is likely less than the capacity figures released by the producers since many of the plants are demonstration or pilot plants not producing on a continuous, commercial scale.

What is cellulosic ethanol?

Ethanol in the United States is currently produced almost entirely from corn. In 2009, 11.1 billion gallons of ethanol and biodiesel were produced in the United States; 10.8 billion gallons were ethanol produced from corn-based technologies. Ethanol from corn and other sugar based feedstocks (e.g., sugar cane) begin with the microbial fermentation of sugars. Following fermentation, water is removed in a distillation phase. Following distillation, ethanol is blended with gasoline and sold as motor fuel.

Cellulosic ethanol production from raw inputs such as herbaceous crops and grasses, woody plant materials, aquatic plants, municipal wastes, or manures is similar to sugar-based production once the raw inputs have been converted to sugars. Conversion requires pretreatment of the raw input to break down the cellulose and hemicellulose (approximately 40-50% and 20-30% of the material, respectively) into sugars. Once sugars have been produced, fermentation and distillation is similar to the corn-based ethanol process.

In addition to cellulose and hemicelluloses, biomass inputs contain lignin. Lignin is a complex chemical compound forming an integral part of plant cell walls. Herbaceous and woody feedstocks for cellulosic ethanol production contain sizable shares of lignin. Lignin cannot be converted to sugars for ethanol production. However, as a byproduct of the pretreatment stage, lignin can be used to provide heat and electricity needed to run the pretreatment and refining processes. The potential for using lignin to produce heat and power in the cellulosic ethanol production process is partly responsible for the much greater reduction in life-cycle carbon release from cellulosic versus corn-based ethanol, which relies primarily on natural gas or coal for heat and power.

Harvest of woody and herbaceous feedstocks for use in cellulosic ethanol production pose logistical challenges. In addition to the fieldwork necessary to collect and bale the feedstock, storage and transportation of the bulky input can be expensive. It is projected that approximately 60 to 90 gallons of ethanol can be produced from a ton of harvested crop residue. Thus, a 100 million gallon per year (MGY) ethanol plant would require delivery of between 1.1 and 1.7

million tons of feedstock per year. Assuming 17 ton truck capacities and year-round, 24 hour per day operation, truck deliveries would need to occur every 5-8 minutes.

In addition to frequent deliveries, the supply area for a large cellulosic ethanol plant would be large. Average Kansas winter wheat, corn, and sorghum yields for 2005-2009 are presented in table 1. Conversion of bushels to pounds of grain per acre result from conversion factors published by Murphy (1993).[6] Grain yields in tons per acre can be converted to estimates of dry matter straw and stover supplies based on conversion factors in Heid (1984).[7] Based on Kansas grain yields, crop residue straw and stover yields would range from about two to six tons per acre. Most analysts recommend removal of no more than 30-40 percent of the crop residue from fields. Exceeding these limits can have detrimental effects on soil nutrient carryover, water retention, and soil erosion. Using an approximate 33% removal rate, the last column of table 1 represents the acreage needed for providing biomass sufficient for a 100 MGY refinery based on a conversion ratio of approximately 70 gallons of ethanol per ton of biomass (Kerstetter and Lyons, 2001).

Table 1. Kansas Crop and Residue Yields

Crop	2005-9 Average Yield (bu/ac)	Maximum Crop Residue Yield (tons/ac)	Acres to Supply 100 MGY Cellulosic Plant
Winter Wheat	37.4	1.91	2,228,100
Corn	135.4	5.69	747,300
Sorghum	75.6	2.12	2,007,600

Source: National Agricultural Statistics Service and author's calculations

Therefore, if a cellulosic refining plant were completely surrounded by corn yielding 135.4 bu/ac, approximately 747,300 acres would be required within a circle with a maximum distance of 19.3 miles from the plant to the outer ring of corn production. A circle with a radius of 33.3 miles of winter wheat would need to be harvested to produce 1.4 million tons of biomass for a

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[6] Each bushel of corn and sorghum contain 56 pounds of grain. Wheat yields 60 pounds per bushel (Murphy, 1993).

[7] The ratio of crop residue to grain is assumed to be 1.5:1 for corn, 1:1 for grain sorghum, and 1.7:1 for winter wheat (Heid, 1984).

100 MGY plant. Both of these assumptions are based on an area of solid crop production characterized by the average Kansas crop yields reported in table 1. In reality, supply areas would be much larger due to variations in yields as well as other crops, roads, towns, and other land uses existing within such a wide area surrounding a proposed cellulosic ethanol plant.

By comparison, based on average Kansas corn yields per acre, approximately 295,000 acres of corn production is needed to supply the 40 million bushels needed for annual corn-based ethanol production of a 100 MGY plant using the conservative 2.5 gallons of ethanol per bushel of corn conversion factor. The much larger supply area for a crop residue based cellulosic refinery comparable in size to the corn-based facility raise several management issues. First, transportation costs to supply a plant from distant fields may be a major cost component in cellulosic ethanol production. Second, economies of scale might favor larger plants, but trade-offs between transportation costs and lower average total costs of the larger plant need to be considered. Third, given the large supply area, refiners would best secure feedstock supplies through long-term contracts with farm suppliers. Failing to secure feedstock supplies could greatly increase risks associated with procurement costs or plant capacity utilization.

Several authors have recently analyzed crop residue-based ethanol systems as conversion technologies approach commercialization. Petrolia (2008) estimated the costs of recovery of corn stover in Minnesota. Harvest, storage, transportation, and densification resulted in delivery costs of corn-stover feedstock to a refinery ranging from about \$60/ton to \$100/ton, depending upon the intensity of collection technology employed and scale of the receiving refinery. Kang et al. (2010) explored optimal locations for corn-based and cellulosic ethanol plants in Illinois over the 2007-2022 period. Feasibility of the cellulosic plants coupled with EISA mandates resulted in a potential for 18 cellulosic plants in the state by the end of their study period. Perkis, Tyner, Preckel and Brechbill (2008) identified regions of Indiana best suited for cellulosic ethanol production based on corn stover (NW Indiana) or on a dedicated energy crop such as switchgrass (SE Indiana). Lambert and Middleton (2010) demonstrated the feasibility of an ethanol industry based on crop residues in northeastern North Dakota. Their results suggested that economies of scale for both ammonia fiber expansion (AFEX) pretreatment facilities and for biorefineries favored co-locating both plants. Tembo, Epplin, and Huhnke (2003) developed a mixed integer programming model to determine the feasibility of harvesting herbaceous crop residues, native forages, biomass harvested from improved pastures, and dedicated energy crops. An ethanol selling price of $0.90 per gallon resulted in six ethanol refineries being constructed in Oklahoma under their base scenario. This early model was refined to consider biomass harvest from Conservation Reserve lands in Mapemba, Epplin, Taliaferro, and Huhnke (2007).

All of these authors report the potential feasibility of cellulosic ethanol plants under their base assumptions regarding costs and output prices. It is of course interesting that all of these studies find cellulosic ethanol production to be feasible, based on cost estimates from a commercial technology that did not exist at the time of any of the reported research.

Logistical characteristics and feasibility of cellulosic ethanol production in Kansas

How sensitive are the feasibility findings and network designs to uncertainties regarding the parameters affecting profitability? If ethanol prices exceed production costs, a cellulosic ethanol proposal could be a good investment. As output prices, input costs, crop residue supplies, and technical characteristics of biofuel processing change, does the feasibility of the cellulosic ethanol system become more problematic?

The model applied in this paper is based on research initially conducted at North Dakota State University. In this earlier study (Lambert and Middleton, 2010), we considered seven counties in the northeast corner of the state, with some overlap in three northwestern Minnesota counties. Results did indicate a local cellulosic ethanol plant was feasible given regional crop yields and harvest, transportation, and refining costs. The optimal plan was to build a single, large ethanol refinery of capacity 103 MGY somewhat centrally located. The analysis has been expanded to the rest of North Dakota, South Dakota, and Minnesota. The pertinent part of this analysis is that crop production in the Northern Plains, deriving mostly from wheat and other small grains and corn, is similar to crop yields seen across Kansas. For example, grain production ranged from about 25 bu/acre in Grant County in Western North Dakota to average yields of over 150 bu/acre in the more productive counties of southern Minnesota.

A logistics model for HCR-based cellulosic ethanol production

A mixed integer programming model is used to determine optimal HCR harvesting and storage, and to determine scale and location of feedstock pretreatment facilities and ethanol refining plants. Potential feedstock supplies are based on average Kansas corn, wheat, sorghum, and other small grain yields. Grain production is converted to potential straw and stover supplies, limited to maximum removal of 35% of the crop residue.

Model assumptions are presented in table 2.

Table 2. Base scenario parameter assumptions

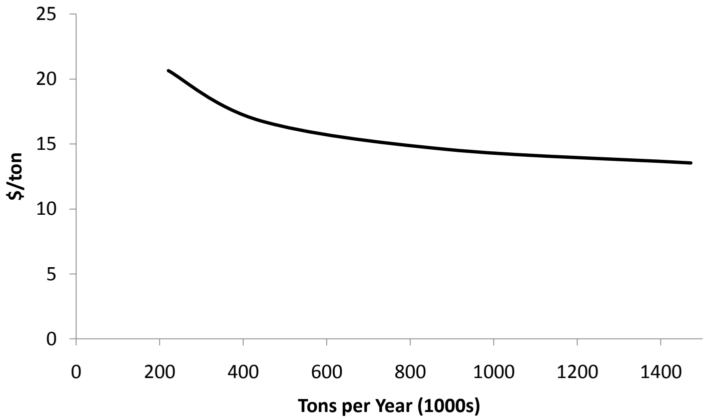
HCR harvest cost	$8.00/ton	Crop residue yield	1.1 tons/ac
Soil nutrient values removed	$12.27/ton	Storage – Raw residue	$0.30/ton/month
Truck capacity	17 tons	Storage - pretreated	$0.15/ton/month
Transport costs	$0.19/ton/mile		

Pretreatment plants and refineries are assumed to be characterized by increasing returns to scale (Carolan, Joshi and Dale, 2007). Increasing returns to scale are characterized by a downward sloping average total cost curve, as illustrated in figure 9. The MIP model was therefore modified to allow selection of scale of plant as well as location. Plant costs are listed in table 3. Costs include both variable cost per ton of feedstock processed plus investment cost amortized over 20 years. Given the structure of the model, these fixed costs are combined with variable costs to yield average total costs per ton of feedstock processed.

Table 3. Average total costs per ton of feedstock for AFEX pretreatment and ethanol processing

Plant capacity (tons/year)	Pretreatment	Ethanol Processing
220,590	$20.65	$57.56
441,511	$16.78	$52.63
883,022	$14.59	$47.71
1,766,044	$12.70	$42.78

Figure 9. AFEX Pretreatment ATC



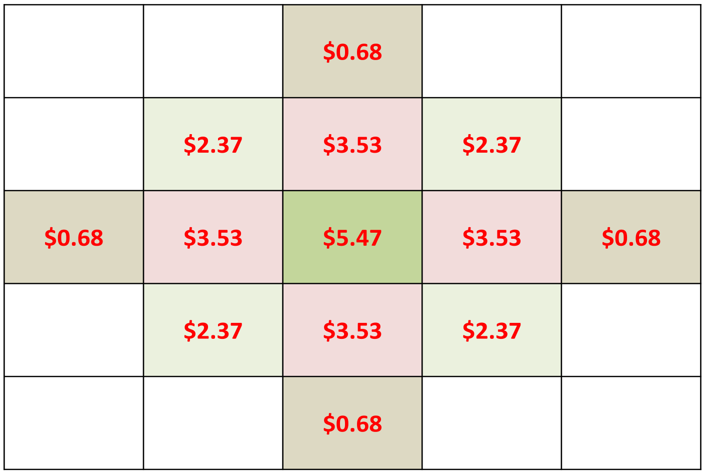
Model results - The base scenario

The initial analysis used the parameter values reported in table 2 and the pre-treatment and refining costs of table 3. Subject to all of the assumptions, harvest and use of crop residues to produce ethanol appears to be feasible for ethanol prices of about $1.22/gallon. The largest scale pre-treatment plant and refinery was built, with an input of 1.8 million tons of crop residue and production of 116.6 million gallons of ethanol per year. The pretreatment plant and the refinery are co-located in the center of the study area.

Transportation costs of the raw residue are low compared to investment and processing costs, so the collection area may be large when HCR yield per acre is low. The total cost to ship crop residue was $8.1 million. These transportation costs are low compared to the $22.4 million and $75.6 million annual amortized investment and operating costs of the pretreatment and refinery plants, respectively.

Because of the higher costs of shipping from more distant feedstock sources, the marginal value of the feedstock falls as distance from the pretreatment and refinery facilities increases. The distribution of the crop residue marginal values across the study area is presented in figure 10. In order to maintain the plant at its full capacity of about 1.8 million tons of feedstock, refiners would be willing to pay an additional $5.47 per ton for supplies from the central cell (i.e., the location of the plant with a 4.75 mile average haul distance from farms within the cell). By sourcing a ton of biomass from the central cell, processors would eliminate the need to buy biomass from the most distant cells, thus saving transportation costs. This savings is $5.47, or the difference between biomass delivery from the farthest distance ($9.06 per ton) and from farms located in the same cell as the processor ($0.90 per ton). The total value of this local supply of feedstock is thus $26.64 per ton (the $20.27 necessary to cover harvest and soil nutrient replacement costs, the $0.90 transportation cost, and the $5.47 marginal value of local versus the most distant sources of biomass). Conversely, the negligible marginal value of an additional ton of HCR from the fringes of the supply area indicate a willingness on the part of the refiner to pay an additional $26.64 per ton for HCR from this farthest location, where the total value derives from harvest, storage, and actual transportation costs incurred. Thus, assuming harvest cost and HCR quality are identical, the refiner would be willing to pay $26.64 per ton of HCR, with transportation cost and marginal values derived from the MIP solution moving in equal and opposite directions as distance from the central plant changes (e.g., as distance increases, transportation costs go up and marginal values for additional crop residues go down equally). This estimated value of $26.64 per ton is comparable to the $40 per ton often assumed as the delivered price of farm crop residues (Leistritz 2007).

Figure 10. Marginal Values of extra HCR



		$0.68		
	$2.37	$3.53	$2.37	
$0.68	$3.53	$5.47	$3.53	$0.68
	$2.37	$3.53	$2.37	
		$0.68		

Scenario Analysis

Scenario analysis allows testing the sensitivity of the model results as we change the assumptions from the base model. The following assumptions in the base model were changed:

1. Crop yields and thus crop residue supplies;
2. Pre-treatment and refinery plant investment and operating costs; and
3. Instead of ethanol production, permit pretreated feedstock to be fed to livestock.

Alternative Scenario #1 – Change crop yields

The value of harvested crop residues depends not just on distance from plant, but on yields per acre as well. As yields decline, transportation costs will increase as supplies must be sourced from farther and farther away from the plant. Table 4 shows how these transportation costs are affected as yields change. When the breakeven ethanol price is reached, the optimal solution is still to build the largest ethanol refinery, with the pretreatment facility located at the same site. All that changes in the model with the changing yields is transportation costs. Consequently, breakeven prices fall as yields increase and HCR supplies are increasingly available from fields closer to the plant (figure 11).

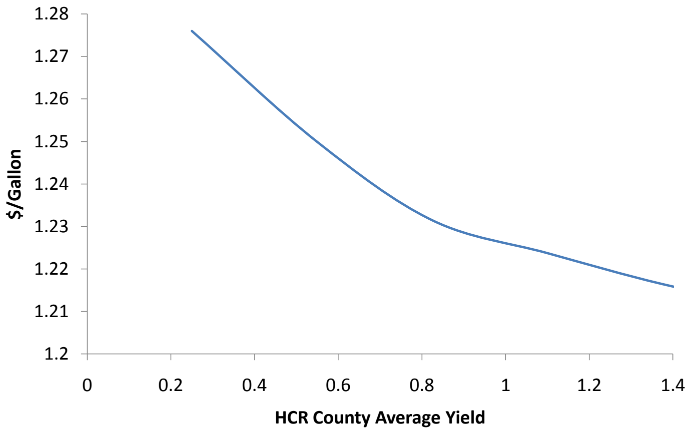
Table 4. Crop Residue Yields and Transportation Costs

	Crop Residue Yields				
	0.55	0.83	1.10	1.38	1.65
Straw Transport (millions)	$11.12	$8.97	$8.07	$7.22	$6.57
Total Cost (millions)	$145.78	$143.63	$142.73	$141.88	$141.23
Harvested HA (millions)	3.21	2.14	1.61	1.28	1.07

Alternative Scenario #2 – Vary plant investment and operating costs

No commercial scale HCR-based cellulosic ethanol plants are currently operating in the United States. The total costs for pretreatment and refinery plants are thus rough estimates from several sources. Should commercial plants eventually come online, their actual costs may vary from the costs assumed in the model.

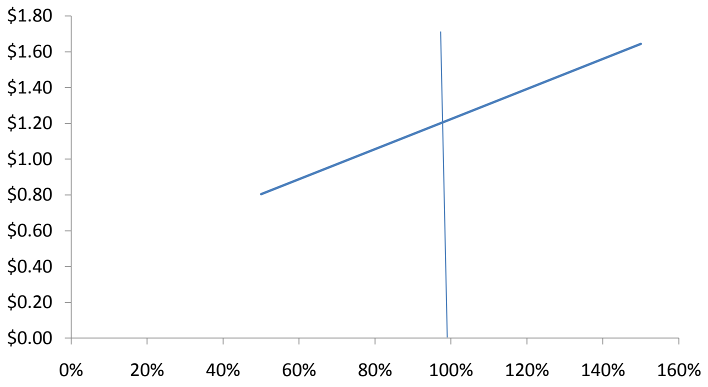
Figure 11. Ethanol Cost per Gallon as a function of HCR Yield



Under the base scenario, total pretreatment and refining costs were about $98.0 million per year for the large plant. As costs were varied between 50% to 150% of the costs in table 3, total plant costs ranged from $49.0 to $147.0 million per year. Since plant costs were the major cost in ethanol production, these variations had significant impact on the costs of producing cellulosic ethanol. At the lower fixed and variable costs (50% of base), the cost per gallon of pretreatment and ethanol production was approximately $0.42 per gallon. Under the base cost assumptions, production costs were about $0.85 per gallon. If the base case costs underestimate actual fixed and variable costs to the extent that actual costs are 150% above the base scenario, ethanol production costs would be about $1.26 per gallon. None of these estimates include the harvest, transportation, and other costs necessary to support a local ethanol complex.

Breakeven prices per gallon of ethanol varying pretreatment plant and refinery amortized investment and annual operating costs from 50%-150% of the base scenario costs of $98.0 million are displayed in figure 12. Under the base scenario, breakeven prices were $1.22 per gallon. Breakeven prices ranged from $0.80 o $1.64 per gallon under the range of plant costs considered.

Figure 12. Breakeven Price per Gallon as Plant Costs Vary



Alternative Scenario #3 – Use of AFEX-treated feedstock for livestock feeding

Nutrient value of AFEX treated herbaceous crop residue is comparable to grains and other livestock feeds. Bals et al. (2010) recently analyzed protein availability and digestibility by ruminant animals of both traditional and nontraditional (including corn stover and wheat straw) feed sources. Bals et al. found the primary advantage of AFEX treatment was to decrease the amount of indigestible aNDFom (48-h neutral detergent fiber) prevalent in the nontreated feedstuffs considered. In particular, AFEX treatment improved the digestibility of corn stover and late harvested switchgrass by 52% and 128%, respectively, over untreated samples. Crude protein content of all of the treated feedstuffs, including wheat straw, also increased with AFEX treatment, increasing to over 100 g/kg (i.e., 10%) of dry forage. Although based on traditional ammoniation processes, shown by Bals et al. to be inferior to the potential feed value improvements resulting from the AFEX process, Oosting, Vlemmix, and Van Bruchem (1994) provide supporting evidence of the gains from ammoniation in the feed value of wheat straw. Carolan, Joshi, and Dale (2007) found AFEX-treated corn stover and AFEX-treated switchgrass had crude protein levels of 10 and 12 percent and net energy of 0.86 and 0.87 (Mcal/lb), respectively, both feed values being comparable to such traditional feeds as sorghum , wheat, or shelled corn.

In the base scenario analyses of this research, no livestock feeding of AFEX treated HCR was permitted. This constraint was relaxed, and feeding was permitted under scenario 3. Other authors have allowed animal feeding by imposing upper limits on the quantity of pretreated crop residues that could be diverted to animal feed. Carolan, Joshi, and Dale (2007) placed upper limits of 25% of AFEX-treated feedstock that could be used as animal feed. Based on comparable feedstuff prices, the authors assumed a feed value of $98.50 per ton of AFEX-treated crop residues. Conversely, our analysis assumed investors consider either feed or refining options based on relative returns. In other words, feed was not constrained to 25% of the total pretreated supply, but could range between zero and 100% of the harvested feedstock based on relative prices and costs.

In the first analysis, breakeven prices of the AFEX-treated crop residues without the option of ethanol production were calculated. With values above about $30.75/ton, investment in pretreatment plants for the production of livestock feed became feasible. Harvest and pretreatment increased from the breakeven price to about $33/ton. At the higher price, all of the available crop residue was harvested and pretreated. Rather than a centrally located large pretreatment plant, the optimal configuration when only further processing into ethanol was considered, several smaller scale plants were built. However, economies of scale were still important, and the plants built did pretreat 1.2 and 0.6 million tons of crop residue for the study area considered.

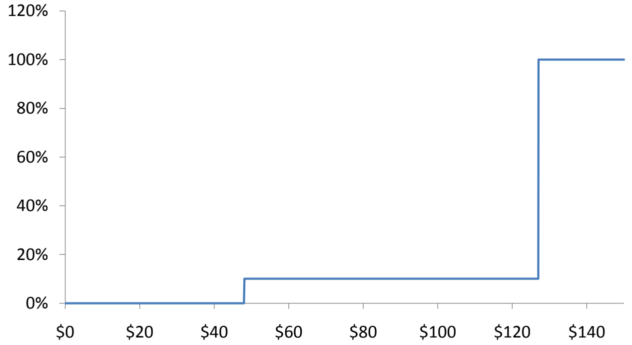
The large model used in the previous analyses could not be solved when feeding and refining options were both available. Thus, the study area size was reduced to 80x80 km (i.e., four cells by four cells). Since relative prices determine the optimal levels of ethanol and animal feed production, ethanol prices were fixed at the long term average of $2.27 per gallon and feed values were varied.

All harvested crop residues were used for ethanol when feed prices fell below $48 per ton. One refinery was built centrally, and crop residue in more distant cells was not harvested. Between $48 and $127 per ton of animal feed, the centralized refinery was built, yet distant pretreatment plants were also built to provide both feedstock for the refinery and as animal feed.

Based on the assumed harvest, transportation, storage, and pretreatment costs, these results suggest considerable value potentially exists for AFEX-treated crop residue. Using the parameter values from the base scenario, with the exception of allowing animal feeding, no residue was harvested for feed at AFEX-treated feed prices below $48 per ton. At this low price, only residue within about 40 miles of the centralized pretreatment and refinery plants was harvested for ethanol production.

Figure 13. Proportion of Treated HCR Used as Animal Feed

Note – proportion fed between $48 and $127 will depend upon the size of the region being considered



At a feed value above $127 per ton of animal feed, no treated crop residue was used for ethanol production when ethanol prices were $2.27 per gallon. All residue supplies were harvested and converted to AFEX-treated livestock feed. Two pretreatment plants were built, one processing 0.6 million tons per year and one pretreating 1.2 million tons per year. No refinery was built.

Addition of the feeding option demonstrates that a potential market for AFEX-treated crop residues exists, with or without a biomass ethanol industry. Combining feeding operations with cellulosic ethanol production appears feasible for feeding values between $48 and $127 per ton. Since the nutrient value of AFEX-treated feed may be as high as $98/ton based on Carolan, Joshi, and Dale’s estimates, opportunities may exist to develop commercial AFEX pretreatment facilities, develop long term contracts to ensure the delivery of pretreated feedstock to biofuel refineries, while maintaining local markets for animal feed to provide some risk protection to farmers and investors through diversification of crop residue markets.

Conclusions

Petroleum consumption has increased steadily over time, both within the U.S. and around the world. Improving economic conditions in the developing world has contributed to faster rates of demand growth outside the U.S. and, in light of finite supplies, led to increased prices. Governments, companies, and individual consumers are seeking alternative technologies and consumption choices in response to higher petroleum prices.

Promotion of ethanol as a fuel expander gained renewed support following the OPEC supply disruptions of the 1970s. Tax credits were implemented in 1978 to promote blending of ethanol with petroleum in motor fuels. Additional government support for the industry included investment credits for new plants and Renewable Fuel Standards mandating ethanol blends in the 2005 Energy Policy Act.

A variety of concerns related to corn-based ethanol led former-President George Bush to promote cellulosic ethanol in his State of the Union message of 2006. The quantity of corn-based ethanol capable of meeting U.S. fuel targets was capped at 15 billion gallons. Increasing emphasis was consequently placed on “cutting edge methods” to produce ethanol from both traditional corn and alternative sources. Although such cutting edge methods have as yet failed to realize commercial success, federal targets still foresee 16 billion gallons of cellulosic ethanol production by 2022.

It is likely that alternative methods of fuel production will be developed in the coming years. The research reported in this report is similar to other findings that the harvest, transportation, pretreatment, and refining of herbaceous crop residues might yet be a feasible process for producing ethanol. Based on the hypothetical costs used in the study, a breakeven price of $1.22 per gallon of ethanol might be sufficient to develop local cellulosic ethanol production facilities.

Using these results, numerous additional questions arise that should be subjected to research scrutiny. Research should address the external costs and benefits associated with the development of a cellulosic industry. Life-cycle analysis can determine the fossil energy ratio and greenhouse gas emissions of cellulosic production and use. The relative contribution of liquid fuel-powered vehicles in the entire portfolio of personal and freight transportation options needs to be addressed.

Based on the limited assumptions of the current research, however, there does appear to be a role for the use of crop residues in energy production. One of these roles appears to be the production of ethanol.

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