2008

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[ENVIRONMENTAL AND ECONOMIC ASSESSMENT OF ETHANOL PRODUCTION SYSTEMS IN MINNESOTA]

Final Report to the Minnesota Pollution Control Agency
March 19, 2008

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ABSTRACT

Minnesota is at the forefront of ethanol mandates and is a key player in ethanol production. With 15 more ethanol facilities expected in the next few years, Minnesota has a large role and stake in the ethanol industry. Currently, all the ethanol production in Minnesota uses a conventional corn starch to ethanol production process. This report outlines that production process, providing key unit processes and their associated costs. It discusses the greenhouse gas emissions and water usage of current facilities. As the ethanol industry continues to grow, cellulosic biomass will supplement and likely supplant some of the corn starch feedstocks, using either a biochemical or thermochemical process. This report outlines the most common biochemical process, its costs and environmental consequences and briefly touches on the costs and environmental consequences of a thermochemical gasification process. The conclusion points to some key questions for Minnesota on how the ethanol industry may evolve in the coming years.

REPORT SUMMARY

The political will for ethanol continues to grow. Powered by issues of energy security, rural development, and environmental performance, Minnesota plays a large role, and maintains a significant stake, in the rapidly growing global ethanol industry. Rising oil, natural gas, and corn prices, along with increased regulatory pressures toward lower-carbon transport fuels, have elevated the necessity to rapidly shift future ethanol production to cellulosic feedstocks. In the coming years, cellulosic biomass will supplement and likely supplant some of the corn starch feedstocks used in ethanol production, utilizing biochemical or thermochemical processes. This report attempts to synthesis the existing literature with regard to economic and environmental aspects of cellulosic ethanol production, vis-à-vis conventional corn starch ethanol. Our main findings are as follows:

1. Compared to grain-based ethanol, cellulosic ethanol offers:

    - Greater overall greenhouse gas reduction, although some individual GHGs may increase somewhat;

    - Large initial water requirements for production (particularly, within biochemical processes). However, as the experience of initial cellulosic plant technologies educates the industry, water consumption per gallon ethanol produced is expected to decrease – approaching and possibly surpassing water-efficiency levels of current corn starch facilities;

    - Higher capital costs, but, based on current corn prices and energy costs, relatively comparable operating cost structures. It must be noted that this snapshot of cost estimates could significantly change in the near future, should demand for residual biomass increase.

2. In order to maintain its current market position, and under recently enacted policy targets, Minnesota is expected to produce 2.9 – 3.2 billion gallons of ethanol by 2022, with “advanced biofuels” representing over half of that production.

3. Utilizing biochemical processes, we estimate that Minnesota could produce 375 million gallons per year from corn stover resources (though some researchers have estimated nearly 1 billion gallons from this resource) and approximately 95 million gallons from existing straw and haw resources.

4. Within the next 15 years in Minnesota, nearly 600 million to 1.3 billion gallons of ethanol capacity is expected to be supported by new, displaced, or not readily

accessible biomass sources. Excluding corn stover and hay/straw, Minnesota could theoretically produce up to 1 billion gallons of ethanol (from approximately 15 million dry tons of biomass) utilizing thermochemical processes, if **all** remaining biomass from residual and waste sources were to be employed.

5. Under realistic adoption and biomass utilization rates significant land conversion to energy crops, additional collection of forest biomass, or biomass diverted from current production systems could be expected. Significant land use change to support the biofuel effort should be preceded by better understanding of impacts due to those changes.

6. Studies exploring the impacts on water consumption and quality attributed to future ethanol production in Minnesota have only recently begun. While total water consumption from this sector is expected to represent a very small fraction of total water consumption in the state (less than 1%), local impacts could be significant as facilities grow in scale, co-locate with existing corn-starch facilities, or utilize greater percentages of feedstocks requiring irrigation.

7. Most available research efforts are focused on biological routes for converting lignocellulosic feedstocks such as corn stover, wood residues, and energy crops like switchgrass into cellulosic ethanol has focused on biochemical processes, however thermochemical processes are anticipated to be commercial within a year.

Currently, Minnesota has 17 operating corn starch ethanol plants with capacity to produce 680 million gallons, four more are under construction (398 million gallons of capacity), and another 11 in the planning stages (795 million gallons of capacity) (Minnesota Pollution Control Agency 2007). If all these facilities come online, within the next several years, Minnesota could have the capacity to produce nearly 1.9 billion gallons of corn starch ethanol. Part of the push for this ethanol production comes from Minnesota and National political mandates. Minnesota was the first state in the union to mandate a 10% ethanol blend mandate and is the only state with a 20% ethanol blend mandate (to be implemented in 2012). Furthermore, Minnesota has the goal to produce a quarter of its required ethanol content for gasoline needs from cellulosic materials (approximately 500 million gallons in 2012). At the federal level, The Energy Independence and Security Act of 2007 calls for 36 billion gallons of renewable biofuel annually by 2022, of which only 15 billion gallons of that target can be met by conventional corn-starch based ethanol. Under these policy conditions, we estimate that Minnesota could reasonably seek to produce 1.6 to 1.8 billion gallons of advanced biofuels (including cellulosic ethanol), bringing total ethanol production in the state to between 2.9 and

3.2 billion gallons by 2022, 4 to 5 times current capacity. Assuming similar scale and development forces that shaped the conventional ethanol industry will also drive a new cellulosic-based industry (resulting in average plant capacity of just over 50 million gallons per current and planned facility), it is possible that the state could house as many as 40 new ethanol facilities within the next 15 years.[1]

Fueling this demand from currently available biomass feedstocks in the state will be difficult. According to the United States Department of Agriculture National Agricultural Statistics, Minnesota harvested 6,850,000 acres of corn in 2006, which would also result in 23,306,213 dry tons of on-field corn stover biomass (United States Department of Agriculture, 2006). In addition, Minnesota has 5,783,002 annual tons of energy crops (NREL 2005), 6,272,204 tons of crop processing residues, 2,974,245 tons of wood residues, 1,176,279 tons of manures and animal processing wastes, and 1,657,373 tons of biomass from municipal solid wastes and wastewater sludge (CEE 2007). It is very difficult, based on current information, to determine the extent to which these resources will be able to meet projected biofuel production targets. We estimate that the corn stover resource may produce between 375-992 million gallons of ethanol, depending on a variety of assumptions (detailed later). Therefore, we feel it is reasonable to conclude that currently productive crop and forest lands would need to be diverted to ethanol feedstock markets to produce the additional 1.7 – 2.1 billion gallons of ethanol (1.64 -1.8 billion gallons of advanced biofuels, including cellulosic ethanol) estimated to be produced in Minnesota over the next 15 years.

The majority of current ethanol facilities in the United States use a similar production process that uses corn starch as a feedstock. As of 2005, nearly 70% of these facilities used a dry mill production process. In the dry mill process, the entire grain kernel is ground into a flour which is converted to ethanol during a fermentation process, creating carbon dioxide and distillers grain. In this report, 8 unit operations for this corn starch process are identified with capital and operational costs estimated by unit operation. Similarly, the most common and widely discussed cellulosic biochemical process, dilute acid hydrolysis, is also presented based on 10 unit operations. Finally a generic cellulosic thermochemical process is also discussed. Major costs and environmental impact comparisons by process are presented in Table S1, below.

[1] This number could be significantly lower, perhaps 15-20, if cellulosic facilities can more quickly ramp up to "optimal" or near optimal scale (124 million gallons per year for corn stover facilities, according Suh 2008).

The price of corn makes up the largest component of the costs of ethanol, with reported values of \$0.823 - \$0.908 per gallon ethanol, based on corn prices of \$2.35 - \$2.52 per bushel. Based on an average 2007 corn price of \$3.40, costs associated with the corn feedstock increase to an estimated \$1.22 - \$1.31 per gallon of ethanol (\$1.89 – \$1.97 per gallon at \$5.00/bushel corn). Far behind corn prices, but still significant is the price of fuel (often natural gas) at \$0.046 - \$0.123 per gallon of ethanol. With natural gas prices up nearly 70% over the past five years, energy costs associated with production are also expected to be a significantly higher percentage of total costs. Of particular note, is that the overall cost structure of both corn starch and cellulosic ethanol production processes, especially given increased corn prices, are remarkably similar and cost competitive with an unrefined oil price of \$2.38/gallon (at \$100/barrel oil prices). That said, capital costs associated with cellulosic ethanol production remain a significant barrier.

With regard to environmental impacts of ethanol production in the state, conventional corn starch ethanol production is estimated to provide a 13 to 19% decrease in total greenhouse gas (GHG) emissions over gasoline. These reductions are thought to increase to 28-39% if natural gas is used as the energy source and to 39-52% if biomass fuels (stover, DDGS , or wood chips, for example) are used for boiler fuel instead of their current uses. With regard to cellulosic ethanol the total reduction in GHG over petroleum varies by study, however, we estimate 85% to 104% reductions in GHG emissions per gallon of ethanol used to displace an energy-equivalent amount of gasoline. Significant discussions around “indirect” GHG impacts of biofuel production (land-use change, production shifts to lesser productive regions, etc.) are currently underway. We acknowledge that current corn starch based expansion in the state (particularly the 15 conventional facilities in various stages of planning, representing nearly 1.2 billion gallons of production) would most certainly lead to changes in crop rotations and production shifts to other potentially less efficient areas of production where GHG, erosion and water quality impacts associated with land-use change are likely. These calculations, however, are outside the scope of this report.

Water consumption per gallon of cellulosic ethanol produced is not expected to improve dramatically over conventional corn starch ethanol; in fact it may get worse before it gets better. Particularly, with a biochemical process, early plants could use substantially more water to create an equivalent amount of ethanol (as happened with corn starch plants). Although some proprietary processes, in planning stages, have reported that cellulosic ethanol can be produced with less than 1 gallon of water (Squatriglia 2008), our current findings indicate that water consumption will most likely remain comparable to corn starch processes. Based on these projections, we estimate that the ethanol industry in Minnesota will consume between

7.7 and 14.0 billion gallons of water, annually, by 2022[2]. While, overall, this represents only 0.6% – 1.1% of total Minnesota water use in 2000 (MN DNR Waters 2000), these impacts will be felt on a region-specific basis. Additional research addressing the impact of this new consumption on local and regional water systems, as well as impacts to water quality, is imperative.

Table S1: Summary Comparison of Cost and Environmental Impacts of Corn Starch and Cellulosic Ethanol

		Conventional Corn Starch Ethanol	**Cellulosic Ethanol**	
			Biochemical Process	*Thermochemical Process*
2006 Costs	*Costs per Gallon Ethanol*	\$1.03 - \$1.07	\$1.25 - \$1.82 (“nth” plant estimates)	\$1.55 (“nth” plant estimates)
	Major Costs	Feedstock, electricity/steam	Capital, Enzyme	Capital
Environmental Impact	*Greenhouse Gas Emissions*	13 to 19% decrease over gasoline	Huge decrease, 85% to potentially over 100% reduction over gasoline	Unknown, though likely will lead to large overall decreases over gasoline
	Water	Minnesota plants range from 3.5 - 6 gallons water per gallon ethanol and average 4.1	9.5 gallons water per gallon ethanol initially with future projections of 2-6 gallons for the “nth” plant	2 - 6 gallons water per gallon ethanol for the “nth” plant

[2] Estimates assume that both cellulosic ethanol and starch ethanol is able to reach a 2.5 gal/gal water ratio by 2022, thus requiring continued water efficiency improvements in the industry. None of these estimates include water use associated with irrigation.

1. INTRODUCTION

The political will for ethanol continues to grow. In November 2007, six Midwest governors, including Minnesota's governor Tim Pawlenty, signed an agreement aimed at reducing greenhouse gas and boosting renewable energy. For Minnesota, this agreement would increase the number of gas stations offering E85 gasoline to 15% by 2015. At a national level, President Bush, in his 2007 State of the Union address, suggested a rise in ethanol use for motor fuels that would require a seven fold increase in current ethanol production. The ethanol industry has dramatically grown in the past few years due to this growing political interest, though commercially the industry remains focused on conventional corn starch to ethanol production. However, research has been exploring the option of using cellulosic materials for feedstocks for biochemical or thermochemical production processes that convert biomass to ethanol. While some of these processes are still in the research and pilot phase, the first United States commercial thermochemical cellulosic ethanol plant began construction in mid November 2007.

Table 1: Minnesota Ethanol Capacity and Current Expansion

COMPANY	LOCATION	FEEDSTOCK	CURRENT CAPACITY (mgy)	UNDER EXPANSION (mgy)	YEAR STARTUP
Current MN Ethanol					
Agri-Energy, LLC	Luverne, MN	Corn	22		1998
Archer Daniels Midland	Marshall, MN	Corn	40		1988
Bushmills Ethanol, Inc.	Atwater, MN	Corn	48		2005
Central MN Ethanol Coop	Little Falls, MN	Corn	22		1999
Chippewa Valley Ethanol Co.	Benson, MN	Corn	46		1996
Corn Plus, LLP	Winnebago, MN	Corn	47		1994
DENCO, LLC	Morris, MN	Corn	25		1991
Granite Falls Energy, LLC	Granite Falls, MN	Corn	48		2005
Heartland Corn Products	Winthrop, MN	Corn	100		1995
Heron Lake BioEnergy, LLC	Heron Lake, MN	Corn	50		2007
Land O' Lakes	Melrose, MN	Cheese whey	3		1986
Minnesota Energy	Buffalo Lake, MN	Corn	19		1997
POET	Bingham Lake, MN	Corn	35		1997
	Glenville (East), MN	Corn	41		1999
	Lake Crystal, MN	Corn	54		2005
	Preston, MN	Corn	42		1998
MN Ethanol Under Expansion					
Al-Corn Clean Fuel	Claremont, MN	Corn	38	15	1996
BioFuel Energy - Buffalo Lake Energy, LLC	Fairmont, MN	Corn		115	
Otter Tail Ag Enterprises	Fergus Falls, MN	Corn		57.5	
US BioEnergy Corp.	Janesville, MN	Corn		100	
VeraSun Energy	Welcome, MN	Corn		110	
Total Current Capacity (estimated)			**680.00**		
Total Under Construction/Expansions (4)				**397.50**	
Total Capacity (current/under contruction)			**1,077.50**		

Source: Minnesota Department of Agriculture (http://www.mda.state.mn.us/renewable/ethanol/capacities.htm)

Minnesota is poised to continue to be a leader in ethanol production and initiatives. Currently, Minnesota has 17 operating ethanol plants with capacity to produce 680 million

gallons, four more are under construction (398 million gallons of capacity), and another 11 in the planning stages (795 million gallons of capacity) (Minnesota Department of Agriculture 2007). If all these facilities come online, within the next several years, Minnesota could have the capacity to produce nearly 1.9 billion gallons of ethanol (See Table 1 and Figure 1) – or, more than 3 times current Minnesota ethanol production. This level of growth, prior to any cellulosic biofuel development, will certainly result in environmental impacts at both the local and global level, specifically with regard to water consumption and greenhouse gas emissions, respectively.

Part of the push for this ethanol production comes from Minnesota's political mandates. Minnesota is the only state with a 20% ethanol blend mandate (DTN Ethanol Center 2007). Furthermore, Minnesota has the goal to produce a quarter of its required ethanol content for gasoline needs from cellulosic materials (CEE 2007)[3]. As political will and industry capacity continue to grow, Minnesota will likely see more push and change towards using cellulosic biomass materials (initially corn stover). At the federal level, the Energy Independence and Security Act of 2007 calls for fuel producers in the US to use "at least 36 billion gallons of renewable biofuel annually by 2022". Additional requirements include 21 billion gallons of "advanced biofuel" by 2022, 16 billion gallons of cellulosic biofuel by 2022, and 1 billion gallons of biodiesel by 2012. Under these policy conditions, we estimate that Minnesota will seek to produce 1.64 billion gallons of advanced biofuels (including cellulosic ethanol) and an additional 151 million gallons of conventional corn-starch ethanol (above the 397.5 million gallons currently under expansion), in order to maintain its current share of national ethanol production.[4] Alternatively, Minnesota is currently producing 9.8% of the nation's soybeans and 8.7% of the nation's corn grain, therefore it could be said that approximately 9% or 3.2 billion gallons of biofuels could be expected to be grown in Minnesota. We, therefore, anticipate that current policy mandates will drive Minnesota ethanol production to between 2.9 and 3.2 billion gallons by 2022, 4 to 5 times current capacity.

This transition will be further fueled by the harsh economic climate for current conventional ethanol facilities. Minnesota's fuel ethanol rack price fell for 2007, from $2.58 per gallon to $2.14 per gallon while natural gas prices have remained high since 2005 (Graph 1) (Hugoson 2007).

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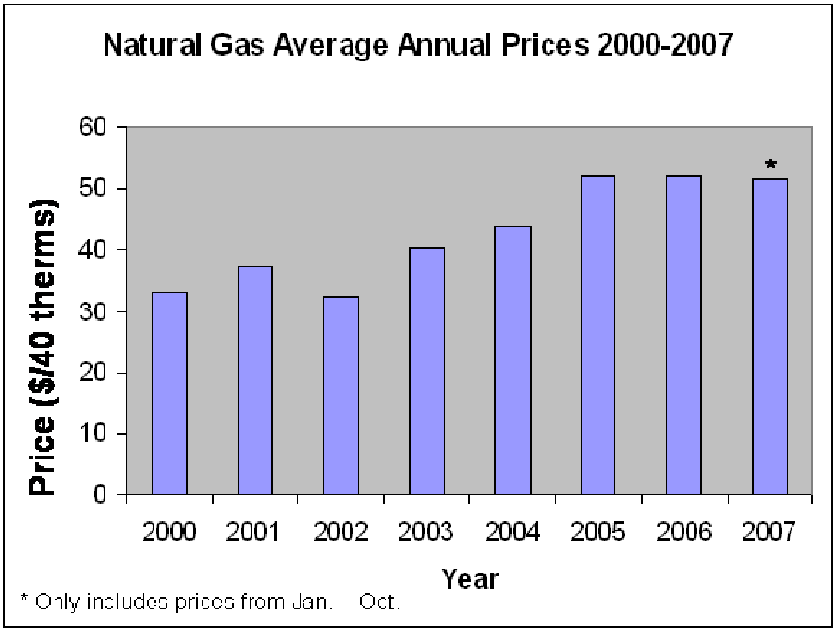
[3] Based on Minnesota gasoline consumption of approximately 2.7 billion gallons, we estimate that approximately 500 million gallons of cellulosic ethanol would need to be produced in Minnesota to meet the needs of this goal.

[4] Based on Renewable Fuels Association data, Minnesota currently produces 8.2% of U.S. ethanol (680 million gallons / 8309 million gallons).

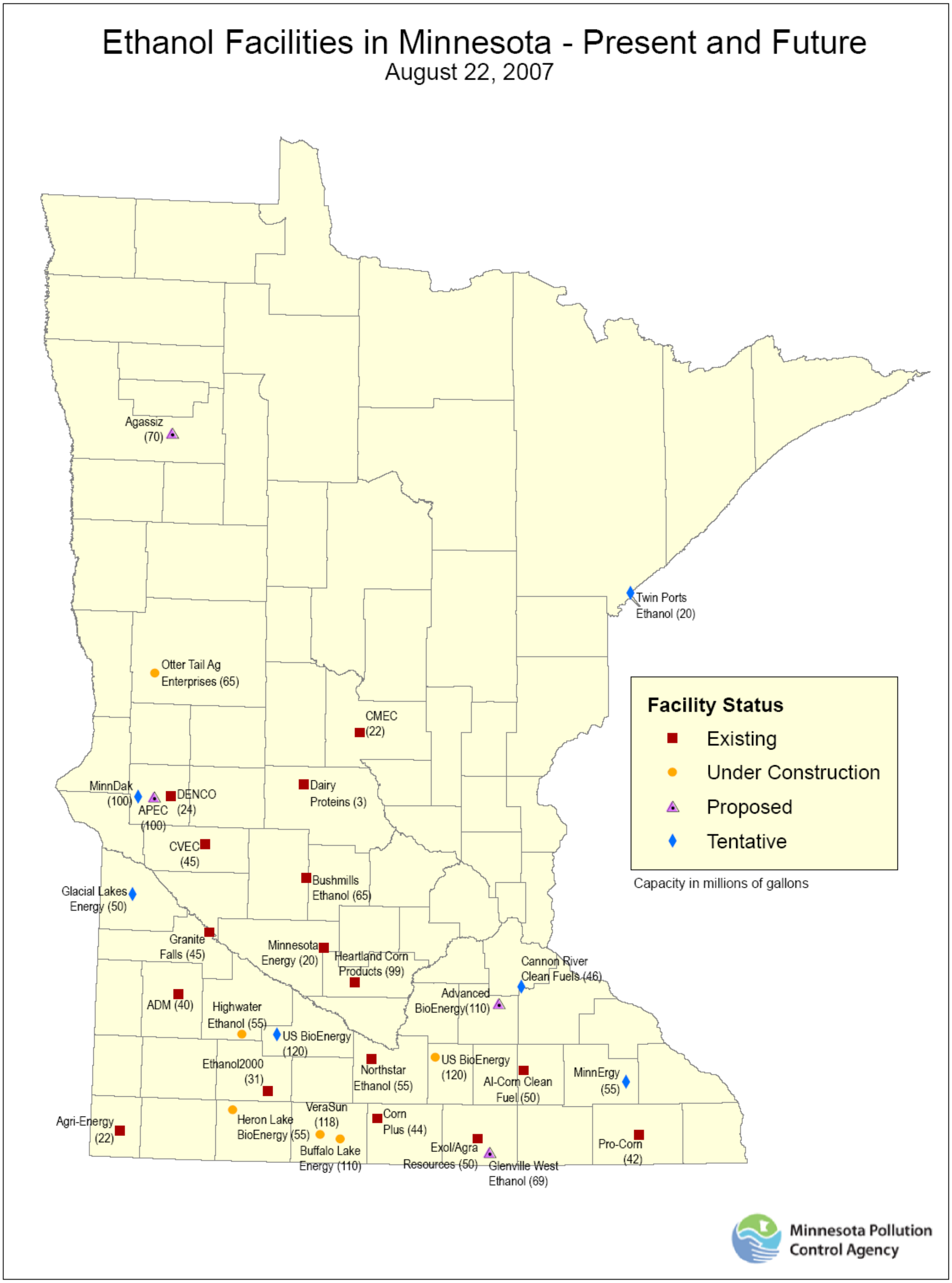
Graph 1: Natural Gas Average Annual Prices 2000-2007



Data compiled from (U.S. Department of Labor 2007)

In addition to high natural gas prices, recent low ethanol prices hurt the current industry, generating even more interest in alternative feedstocks and production processes that reduce dependence on corn and natural gas inputs (i.e. biochemical/thermochemical cellulosic production technologies). What these processes look like is outlined in this report, though how Minnesota will evolve into cellulosic biomass ethanol production is uncertain.

Figure 1: Ethanol Facilities in Minnesota



Source: Minnesota Pollution Control Agency 2007

2. MINNESOTA'S BIOMASS POTENTIAL

Minnesota has a significant biomass base to draw upon for its renewable energy needs. However, to meet the national and state ethanol mandates and goals, Minnesota will need to expand its biomass potential, especially as biomass for ethanol competes with biomass for other commodities like energy and food. Most studies of Minnesota's biomass have focused on the biomass potential for electricity, though very little biomass-generated electricity is planned between 2006-2015 (Bailey and Morris 2006).

Not surprisingly, Minnesota's current ethanol facilities are located in the counties with the most corn grain biomass (Figures 1 and 2). Of course, these areas are also where the most corn stalk (i.e. stover) residue resides, making good site locations for cellulosic ethanol facilities (Figure 3). According to the United States Department of Agriculture National Agricultural Statistics, Minnesota harvested 6,850,000 acres of corn in 2006, which would also result in 23,306,213 dry tons of on-field corn stover biomass (United States Department of Agriculture, 2006). If all of Minnesota's corn grains were used for ethanol, Minnesota could produce just over three billion gallons of ethanol, though currently Minnesota only uses about 20% of its corn crop to produce 667 million gallons of ethanol (Minnesota Department of Agriculture 2007). Minnesota also has other potential biomass sources besides corn and its stover. A recent study conducted by CEE (2007) for Xcel Energy identifies over 37 million dry tons of biomass in Minnesota from residual and waste streams (see Table 2). If Minnesota was to grow switchgrass as a dedicated energy crop, it could likely be grown on the more marginal lands that currently grow hay/straw on conservation reserve lands (Figure 5) or on lands that currently grow hay/switchgrass (Figure 6). Combined, these lands are estimated to produce just under 5 million dry tons of biomass (CEE 2007). Overall, Minnesota has 5,783,002 annual tons of energy crops (including switchgrass, but not grain) (NREL 2005). Finally, Minnesota also has important resources in its wood, paper, and pulp industry in the North, though its potential for ethanol is less well quantified.

Table 2. Minnesota Biomass Inventories from Residual and Waste Sources

CATEGORY	ESTIMATED DRY TONS
Crop Residues	**24,961,280**
Corn Stalks/Stover	19,985,390
Hay/Straw from CRP	18,698,598
Other Crop Residuals	3,106,031
Crop Processing Residuals	**6,272,204**
Ethanol DDGS	1,651,860
Soybean Meal	1,721,561
Wheat Flour	1,522,101
Other	1,376,683
Wood Residues	**2,974,245**
Logging Residues	839,507
Mill Residues	548,372
Brushlands and CRP	930,983
Urban Wood Waste	655,383
Manures	**586,640**
Animal Processing Waste	**589,639**
Municipal Solid Waste	**1,509,551**
WWTP Sludge	**147,822**
Total	***37,041,381***

Source: BioPet version 1.1 (http://mncee.org/public_policy/renewable_energy/biomass/biopet.exe)

Figure 2: Corn Grain Availability in Minnesota

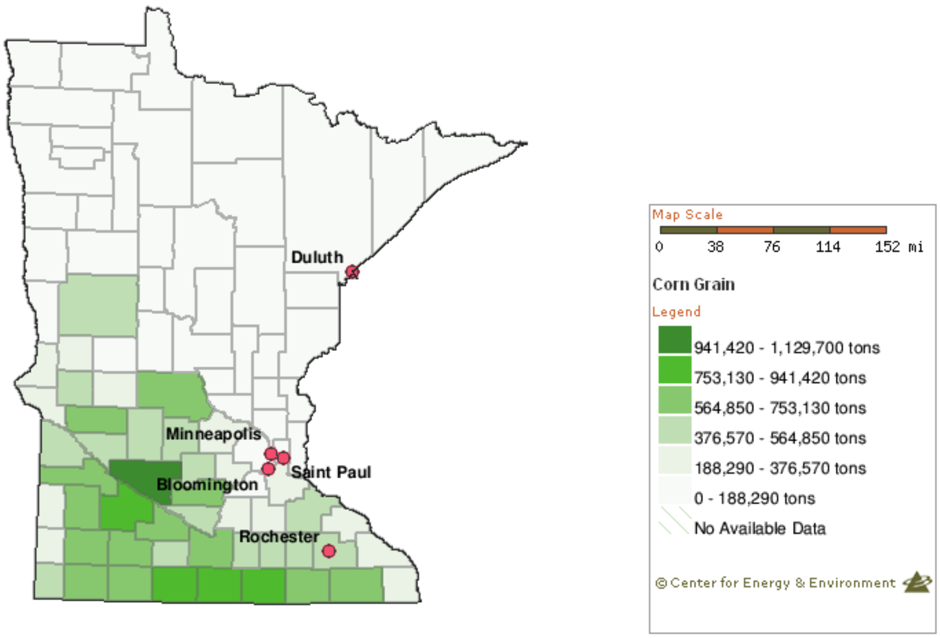


Figure 3: Corn Stalks/Stover Availability in Minnesota

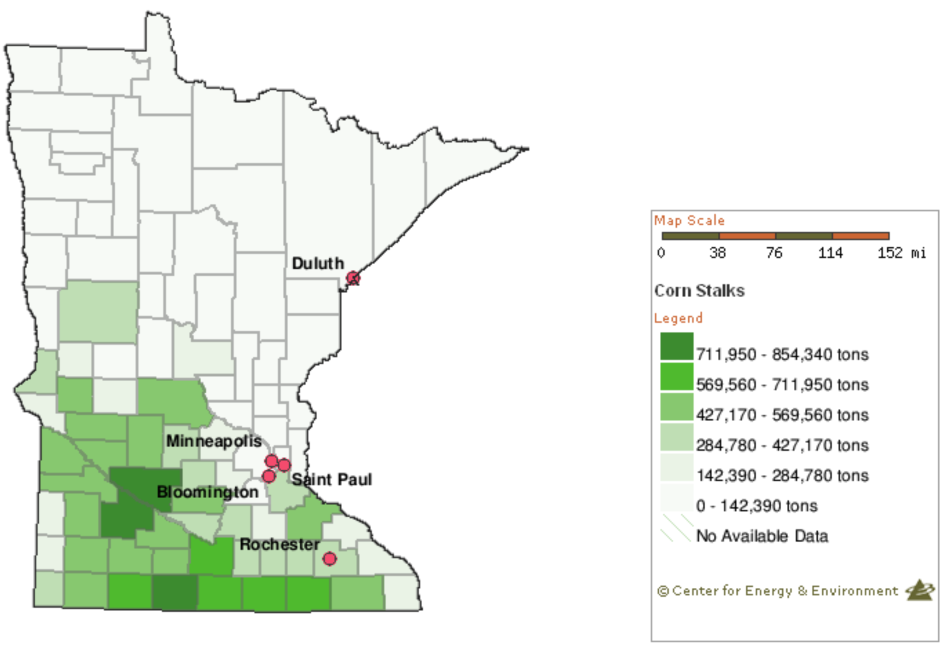


Figure produced by the Center for Energy & Environment gopher application http://gopher.mncee.org/MapApp.php. Data are from a three year survey period of 2002-2004.

Figure 4: Hay/Straw Availability from CRP lands in Minnesota

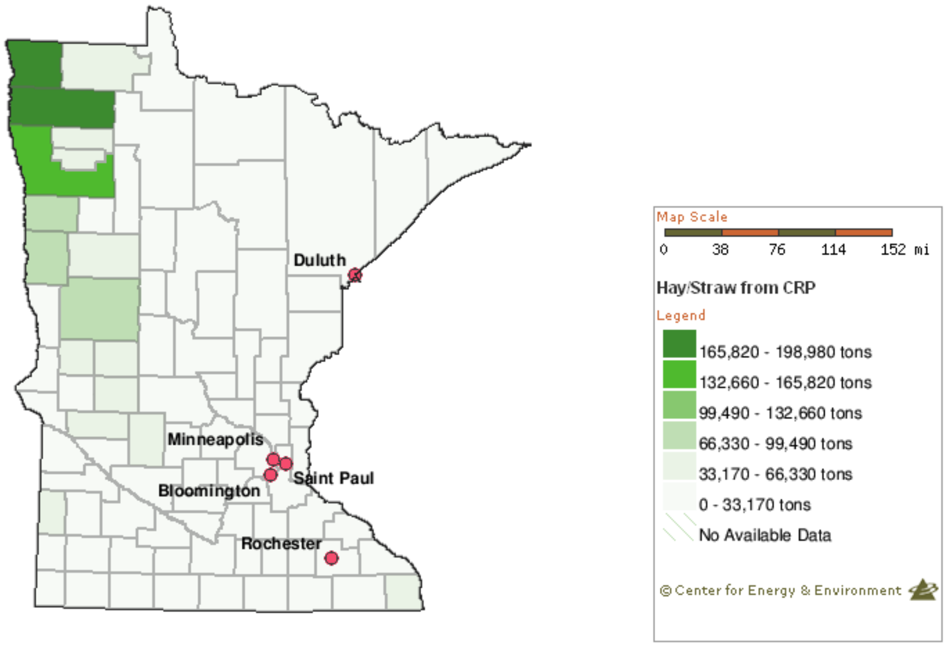
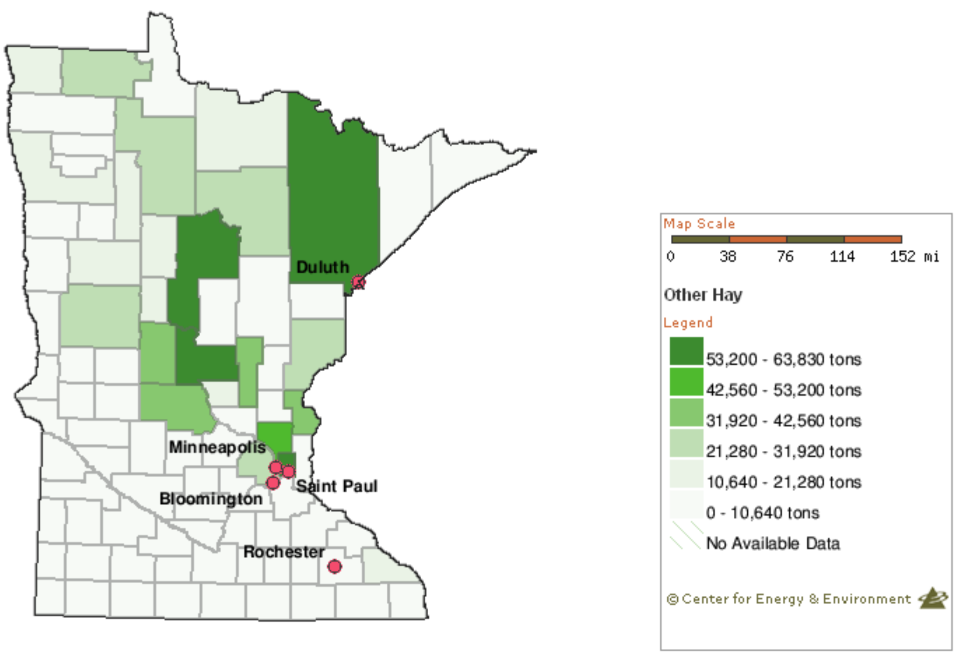
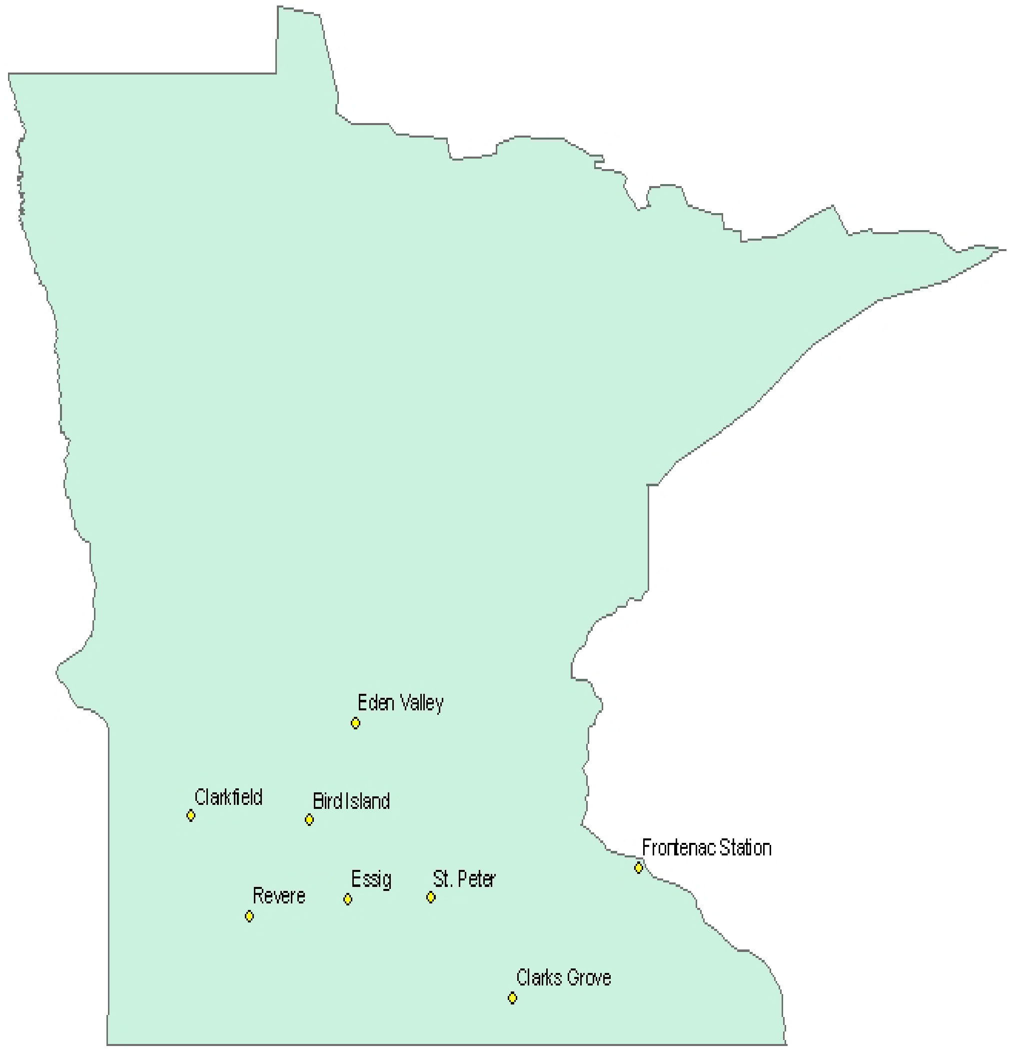


Figure 5: Other Hay Availability in Minnesota



Figures produced by the Center for Energy & Environment gopher application http://gopher.mncee.org/MapApp.php. Data are from a three year survey period of 2002-2004.

Figure 6: Estimated Future Corn Stover Cellulosic Production in Minnesota



Source: Suh et al. (2008)

Suh et al. (2008) have studied Minnesota's stover availability and predicted the size and location of Minnesota's future stover-based cellulosic ethanol plants. They modeled the optimal number of stover cellulosic ethanol plants for Minnesota, predicting an optimal eight stover cellulosic ethanol plants located throughout the southern portion of the state (Figure 4)[5]. The optimum stover plant requires a large initial capital investment and processes an estimated

[5] Suh et al.'s (2008) result assumes truck or pipeline transportation (rail transportation suggests seven optimal facilities) and assumes 50% farmer participation and 70% stover removal from fields.

4360 tons of feedstock daily (annual production is about 124 M gallons). Using more conservative stover removal assumptions than Suh et al. (2008), we estimate that Minnesota could produce approximately 375 million gallons of ethanol from its corn stover availability through biochemical cellulosic ethanol production[6]. Extrapolating these potential yield rates to other forms of biomass, one might expect another 95 million gallons available from energy crops. Much smaller biomass estimates have been made surrounding wood residues (3 million tons), manures and animal processing wastes (1.2 million tons), and municipal wastes (MSW and wastewater sludge producing 1.5 million and 148 thousand tons, respectively). While it is difficult to estimate the ethanol production resulting from these potential biomass resources, it is reasonable to conclude that even under a scenario of complete biomass utilization for ethanol, current biomass residue and waste streams (i.e. non-crop and non-timber biomass) are insufficient in producing the additional 1.7 – 2.1 billion gallons of ethanol necessary to meet the estimated 2.8 – 3.2 billion gallons expected to be produced over the next 15 years. This is not to say that sufficient biomass does not exist in Minnesota. CEE (2007) identifies over 1.1 billion tons of biomass, annually, from crops and timber. However, access to this resource would most likely result in increased crop switching or land-use change, and potentially lead to indirect environmental and economic effects associated with the pushing of commodity production (food or industrial production) to less efficient production systems (Searchinger 2008).

3. ETHANOL PRODUCTION TECHNOLOGIES

3.1 CONVENTIONAL CORN STARCH ETHANOL

The majority of current ethanol facilities in the United States use a similar production process that uses corn starch as a feedstock. As of 2005, about 67% of these facilities use a dry mill production process (Tiffany 2005). The dry-mill process takes about three days to turn corn starch into ethanol and the process can be broken down into seven unit processes with two outputs (Figure 7). Corn grown and dried on farms throughout the state (unit process A) is transported to the facility via truck and rail (unit process B). Once at the facility the corn

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[6] Assuming 40% of the total stover available is removed from the fields and that farmer participation is 50%. Prior studies suggest that stover removal rates of 70% are possible under no-till practices (Sheehan et al. 2004; typically cited removal rates range from 10%-40% when no-till is not specified (Aden et al. 2002, Kaylen et al. 2000, McAloon et al. 2000, Sheehan et al. 2004, Wallace et al. 2005). Ethanol production from a thermochemical process, under the same participation and removal assumptions, is estimated to be 284 million gallons (Putsche 1999).

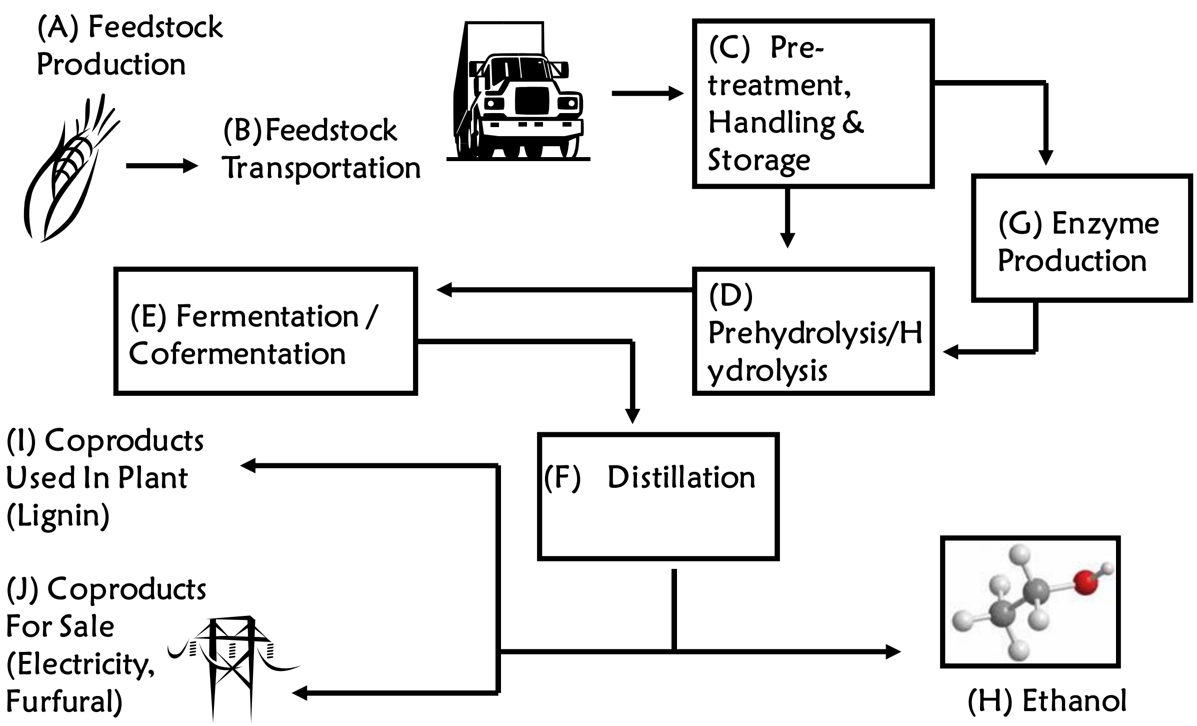
kernels are stored until they are ready to be used for ethanol production. When needed for production, the corn is first ground into a fine powder (unit process C). This powder is then mixed with water and alpha-amylase (an enzyme) and heated during liquefaction (unit process D). The heat liquefies the starch. The resulting mash is then cooled and gluco-amylase (another enzyme), is added to the mixture (unit process E). The second enzyme creates sugars from the liquefied starch, a process known as saccharification that takes approximately six hours. After saccharification the mash is cooled and then fermented by adding yeast during an approximately 50 hour long process (unit process F). The fermentation produces ethanol and carbon dioxide. The carbon dioxide can be cooled, liquefied and sold from this production step (though as discussed below, carbon dioxide is typically not sold). The remaining ethanol, termed “beer” at this stage is distilled to remove the about 10 percent alcohol from the non-fermentable solids (unit process G). The resultant alcohol is 95 percent pure. The solids, termed stillage, are removed and further processed. The 95 percent pure alcohol goes through a dehydration process to remove the five percent water content making the ethanol 200 proof (Tiffany & Eidman 2003). At this stage the ethanol is anhydrous (without water). During the denaturing process, a poison is then added to the anhydrous ethanol, usually gasoline or raffinate, to make the ethanol poisonous, preventing human consumption. The ethanol is then ready to be shipped to blending facilities (output H). The remaining stillage is centrifuged and heated to concentrate and remove the grain residues (distiller’s grains). These grains are then mixed with concentrated syrup (liquefied contents left over from the production process) and dried (output I). For each gallon of ethanol produced, a dry-mill ethanol facility produces about six pounds of dried distiller’s grains (DDGS) (Wang et al. 2007). These dried distillers grains are then sold as livestock feed and usually contain 11% moisture, 26% crude protein, 10% crude fat, and 12% crude fiber (Tiffany & Eidman 2003). Sometimes, the distiller’s grains are not dried, but sold for cattle feed at 65% moisture, though these wet distillers grains are only consumable for about five days (Tiffany 2007).

The other common co-product for conventional ethanol plants is carbon dioxide. Plants can bottle their carbon dioxide and sell it for flash freezing or for soda pop production; however, due to the high fixed costs of the equipment necessary for capturing the carbon dioxide, most plants under 40 MM in size do not capture their carbon dioxide (Tiffany & Eidman 2003). In 2002, only a third of the ethanol plants in their USDA ethanol study captured and sold carbon dioxide (Shapouri & Gallagher 2005), and only one plant in Minnesota (Kelly 2008).

Wet mill processing is the other method of ethanol production from corn starch, though as previously stated, it is less widely used (only 1 facility in Minnesota, ADM Marshall, employs the wet mill process). The production process is similar to dry milling, but wet milling uses a water / sulfur dioxide mix to soften the corn kernels before liquefaction. By softening the corn

kernels, the kernels can be degermed and the oil can be extracted. The kernels are then ground and the starch is used for ethanol production as in the dry mill process (Wang et al. 2007).

Figure 7: Conventional Corn Starch Ethanol Unit Operations

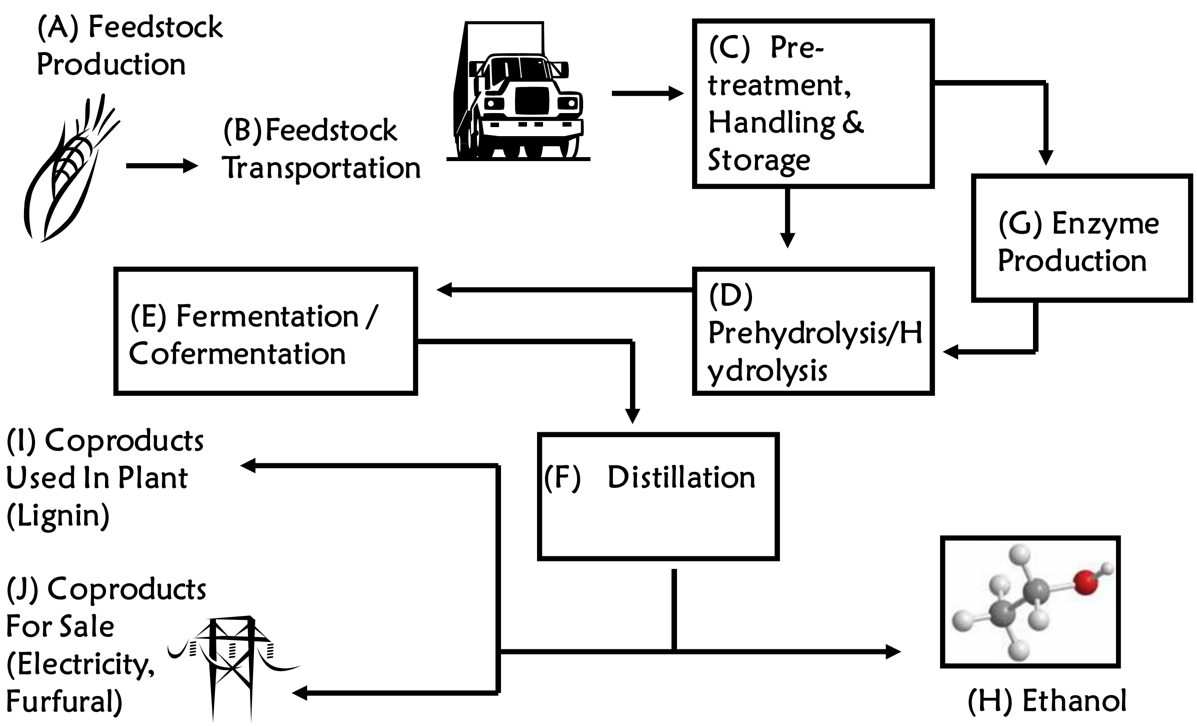


3.2 CELLULOSIC ETHANOL – BIOCHEMICAL PROCESS

There are various production technologies for converting cellulosic material into ethanol, though none are at the commercial stage of development. The most common and widely discussed process in the literature is using a biochemical process known as dilute acid hydrolysis, which is the process described below. There are two other biochemical processes mentioned in the literature including enzymatic hydrolysis and concentrated acid hydrolysis (which are not discussed in this report), as well as thermochemical processes that are discussed in the next section. Furthermore, the feedstock options for dilute acid hydrolysis are many, including corn stover, switchgrass, wood chips, etc. However, most commonly discussed, and the feedstock considered in this report, is corn stover (the stalks, leaves, cobs and husks of the corn plant). The dilute acid hydrolysis production process for converting corn stover to ethanol is similar to that of converting corn starch to ethanol and can be broken down into six unit processes (with potentially a seventh unit process) and many outputs that are lumped into three general output groups (Figure 8). It is important to note that the process outlined in

Figure 8 and described below is based on theoretical and pilot facility designs, since no commercial facilities are operating and generating publicly available performance data.

Figure 8: Biochemical Process Cellulosic Ethanol Unit Operations



The production process begins with the removal of the corn stover from the farmer's field. Currently this is accomplished with a second pass (after the corn grains have been harvested), but the technology exists to allow for a single pass collection process that harvests both corn grains and stover[7] (unit process A). The stover is baled and sent to the facility by truck or rail (unit process B). At the plant, the stover is reduced in size and stored until needed for production (unit process C). From this stage, the production process deviates from that of converting corn starch to ethanol due to a key additional step that is required for converting cellulose to ethanol. The sugars in the plant material must first be freed from the cellulosic material. To do this requires two steps (unit process D). First dilute acid and steam convert

[7] Only a certain percentage of stover can be removed from fields, depending on soil quality, type, landscape attributes, etc. Often studies assume 10-40% of the stover can be removed, which is assumed to be sustainable. Larger amounts of stover, up to about 70%, can be removed if farmers use no-till farming practices (Sheehan et al. 2004). NOTE that no-till is less common in areas of very cold winters and/or heavy soils (as in NW MN).

hemicellulose to sugar at a high temperature and then hydrolysis converts the cellulose to sugar (Kaylen et al. 2000). After hydrolysis, there is cellulosic residue and lignin left over which can either be burned within the plant to produce electricity or sold as a co-product. The acid is removed from the solids and the solids are neutralized with lime to remove anything liberated in pretreatment that is toxic to the fermenting organisms. Saccharification occurs in conjunction with co-fermentation using a cellulose enzyme (unit process E). This process takes several days and by the end, most of the cellulose and xylose has been converted to ethanol[8]. The "beer" is distilled to remove water and residual solids (unit process F).

There are three general outputs from this stage onwards. One is ethanol (output H). The other two are either outputs reused in the plant (output I) or those that can be sold (output J). Outputs reused in the plant are used to produce the plants steam and electricity needs. For example, solids collect at the bottom of the distiller and they are used in the boiler. The condensed bottom liquids from the distiller are concentrated via evaporation and the resulting evaporated condensate is reincorporated into the production process, with the remaining concentrated syrup is used in the fluidized bed combustor. In this process, anaerobic and aerobic digestion is used to treat wastewater (including part of the evaporator condensate) and the biogas from the anaerobic digestion is also sent to the combustor.

There are various outputs that can be sold. The dilute acid hydrolysis production process generally produces excess steam (at amounts greater than can be used by the facility's generator), additional electricity can be sold to the electrical grid (Aden et al. 2002). Aden et al. (2002) estimate that a 70 MM gallon capacity plant will produce 2.28 kWh of extra electricity per gallon ethanol. Other coproducts include biogas, CO_2 and furfural (a liquid used in the manufacture of plastics, as a solvent, and used in producing a variety of other products). Producing these coproducts, especially higher end products like furfural can be key in making dilute acid hydrolysis economically feasible (Kaylen et al. 2000).

3.3 CELLULOSIC ETHANOL – THERMOCHEMICAL PROCESS

Another production possibility for converting cellulosic feedstocks into ethanol is to use a thermochemical process, most likely gasification. There has been less literature and seemingly less public research on this process. Generally, gasification consists of heating

[8] Plants may purchase or produce their own enzymes. If they produce their enzymes they need the necessary equipment (unit process G), though as the industry becomes commercially viable most plants will likely purchase their enzymes as is done in the corn starch production process.

biomass in the absence of oxygen which produces carbon monoxide and hydrogen, i.e. syngas. Facilities are then able to convert the syngas into a variety of products, including ethanol. The technology for gasification is well known and established; economics has prevented the proliferation of gasification (DOE 2005). Ethanol thermochemical facilities can use a variety of feedstock options. They can use coal or natural gas, but are also able to use a wide variety of cellulosic biomass as a feedstock, including woody materials, stover, grasses, etc. South Africa has used gasification to produce transportation fuels since Apartheid. They used coal rather than biomass for a feedstock, but the production process is the same. However, this technology was only economically viable because of the world-wide oil embargo that prevented cheaper petroleum from entering the country (DOE 2005).

4. ETHANOL PRODUCTION COSTS

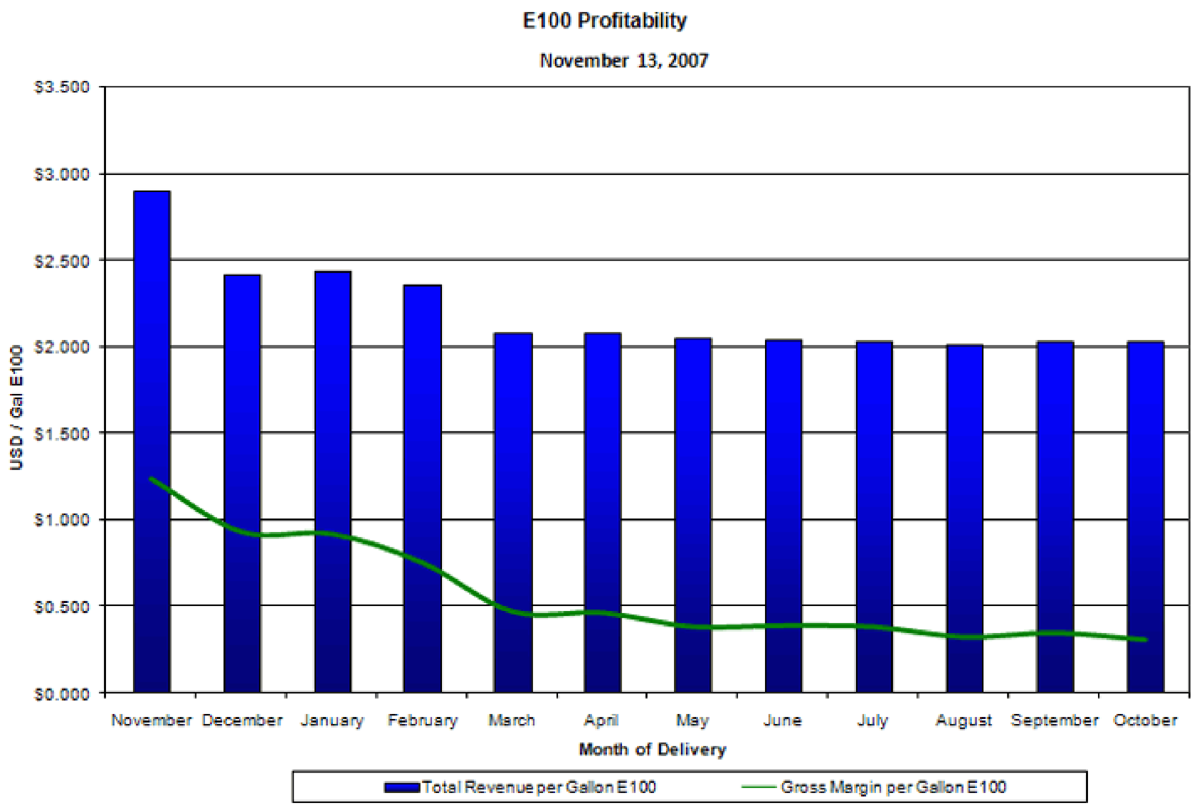
4.1 CONVENTIONAL CORN STARCH ETHANOL COSTS

The costs in general for dry mill processing are well known (although plant specifics are often kept secret due to industry competition). These costs have decreased over the course of growth in the ethanol industry partially due to major improvements in the corn starch ethanol production. Some of these improvements include new processing techniques and technological advances. By re-using energy from liquefaction and saccharification, ethanol plants can now remove water from the ethanol in the distillation column, saving more than 70% in thermal and electrical energy needs per gallon of ethanol (Shapouri & Gallagher 2005). Technological advances include improvements in fermentation allowing for simultaneous fermentation and saccharification as well as thermo-tolerant yeast and improvements in yeast production (Shapouri & Gallagher 2005). There have been improvements in the enzymes as well. For example, the alpha amylase now is able to make some of the corn protein available as food to the yeast due to the addition of some protease to the alpha amylase (Wallace et al. 2005). All of the improvements to ethanol production have helped to lower production costs and consequently costs have fallen over time. In 2000 dollars, the cost of ethanol production from corn starch in 1978 was $2.47 per gallon, falling to $1.43 per gallon in 1994 and then $0.88 per gallon in 2000. Capital costs have also fallen, again using 2000 dollars, for a 50 MM gallon per year plant was $2.07 per gallon a year, falling to $1.25-$1.50 per gallon a year in 2000 (McAloon et al. 2000). However, due to rising costs of inputs (esp. natural gas and corn); recent years' ethanol production costs have been rising.

Ethanol plants are more profitable when there are low corn prices, excellent highway and rail line access, and low natural gas costs because corn, and subsequently natural gas costs are the dominant costs of the ethanol industry (Tiffany & Eidman 2003; Wang et al. 2007). For

example, natural gas costs are 30% of a plant's operating budget (Tiffany & Eidman 2003). However, as aforementioned, natural gas prices have remained high since 2005 (Graph 1). Consequently, ethanol plant profitability is predicted to continue to fall in the next year (Graph 2).

Graph 2: Ethanol Industry Profitability



Graph produced by (DTN Ethanol Center 2007). It shows "an average ethanol plant's profitability per gallon of ethanol (E-100) produced beginning in November 2006 until October 2007. The blue bars represent the total revenue per gallon of Ethanol that the average plant in the Heartland will generate while the green line represents the plant's gross margin per gallon of ethanol."

Producing ethanol from corn starch costs around $1.03-$1.07[9] and yields between 2.68 and 2.85 gallons of ethanol per bushel of corn (McAloon et al. 2000; Shapouri & Gallagher 2005; Wallace et al. 2005). The capital and variable costs of the different unit processes are broken down in Table 3, though the costs are not comprehensive, but rather costs associated with

[9] Prices are in US 2006 dollars using the U. S. Bureau of Labor Statistics Consumer Price Index inflation conversions.

specific unit processes are included wherever possible to allow for a comparison with cellulosic ethanol production.

Table 3: Capital and Variable Costs[5] of Conventional Corn Starch Ethanol Production

Unit Process	Capital Costs[1]	Variable Costs[1]
A) Feedstock Production		Feedstock Costs: \$0.823[2] - \$0.908[3] / gallon ethanol Bushel corn: \$2.35[2] - \$2.52
B) Feedstock Transportation		
C) Feedstock Handling (Storage, Milling)	\$3,150,000[2]	
D) Liquefaction		Enzymes: \$0.041 / gallon of ethanol[3] Water: \$0.002 / gallon of ethanol[3] Chemicals: \$0.026 / gallon of ethanol[3]
E) Saccharification	\$2,780,000[2]	
F) Fermentation	\$5,570,000[2]	Yeast: \$0.0052[3] - \$0.054[2] / gallon of ethanol
G) Distillation/ Dehydration/ Denaturing	Distillation: \$6,420,000[2] Solid / syrup separation / drying: \$12,700,000[2]	Denaturant: \$0.036[2] - \$0.038[3] / gallon of ethanol Fuels: \$0.046[2] - \$0.123 / gallon of ethanol[3]
(I) Co-products – payments back to plant		DDG credit: \$0.29[3] - \$0.35[2] / gallon ethanol or \$70/ton[4] CO_2 credit: \$0.009 / gallon of ethanol[3]

[1] All prices are converted to US dollars 2006
[2] McAloon et al. 2000 – 25 MM gallon/year facility
[3] Shapouri & Gallagher 2005 – Prices taken from their large (40MM-100MM) capacity plants.
[4] Kelly Davis personal communication 2007
[5] Costs listed above do not represent total costs for ethanol production. Other cost items include (but are not limited to): waste water (capital cost \$1,210,000 (McAloon et al. 2000)); storage of non feedstocks at the plant (capital cost \$1,820,000 (McAloon et al. 2000)); air compressor costs (capital costs \$121,000 (McAloon et al. 2000)).

As aforementioned, it is corn prices that make up the largest component of the costs of ethanol, with reported values of \$0.823 - \$0.908 per gallon ethanol, based on corn prices of \$2.35 - \$2.52 per bushel, reported in 2006 dollars. Far behind corn prices, but still significant is the price of fuel (often natural gas) at \$0.046 - \$0.123 per gallon of ethanol. In their study on

the economic factors that affect the success of dry mill ethanol plants, Tiffany & Eidman (2003) find that, *ceteris paribus*, for a 40 MM gallon per year plant, profits decrease by US2002 $165,818 for every one cent increase in corn prices. Similarly, with every one cent per dekatherm increase in natural gas prices, plant profits decrease by US2002 $16,464 per year (Tiffany & Eidman 2003). These impacts are significant, particularly with regard to soaring corn prices. Based on an average 2007 corn price of $3.40 (Leibtag 2008), costs associated with the corn feedstock increase to an estimated $1.22 - $1.31 per gallon of ethanol; at $5.00/bushel corn, feedstock costs might be as high as $1.89 – $1.97 per gallon. Simply for the sake of comparison, the cost of $100/barrel light crude oil, prior to refining, is $2.38 per gallon.

Low ethanol prices compound these profit losses. With low ethanol prices, ethanol plants are even more sensitive to changing prices, with a one cent decrease in fuel ethanol price; plant profits decrease US2002 $480,000 per year (Tiffany & Eidman 2003). These price sensitivities make ethanol a risky business, especially today when the prices of corn and natural gas are high. In fact, based on the figures provided in Graph 2, while margins were down approximately $.95 per gallon (year over year, ending November 2007), roughly $.80 of that decrease can be attributed to the fall in price (operating costs, thus increasing by approximately $.15 per gallon).

4.2 BIOCHEMICAL CELLULOSIC ETHANOL COSTS

The costs for dilute acid hydrolysis using corn stover are less well known than are the costs for conventional ethanol production, largely because this process is not yet commercially available. Governmental researchers have been the primary contributors to estimating costs, and most often assume the “nth” plant in their analyses. Consequently the costs listed below also assume the “nth” plant, but thus do not reflect the costs faced by the first start up plants that may arise in the next five to ten years (Table 2). Pioneer plant costs are going to be even higher than “nth” plant costs unless the plant finds a “special niche” that provides the plant with a cost advantage. Aden et al. (2002) suggest that such niches might be "feedstock costs (very low or negative for environmental wastes), used equipment (making use of related equipment that has been shut down), co-location with existing facilities (biomass combustors and waste treatment facilities), or a combination of these."

All costs are converted to 2006 US dollars and are assuming a dilute acid hydrolysis production process, though plant size and feedstocks do vary for each source, giving a range of potential prices. Furthermore, the costs are not comprehensive, but broken down by unit process and included when possible to make comparison possible with a conventional corn starch ethanol facility. Some of the price variation is also due to the fact that some reports are

older (e.g. 1996) and prices may have been high at the time of the study, but have actually decreased over time due to higher supply, improvements in production, etc.

Table 4: Capital and Variable Costs[9] of Biochemical Process Cellulosic Ethanol Production

Unit Process	Capital Costs[7]	Variable Costs[7]
A) Feedstock Production[10]		Double Pass Stover Collection: $41.00 - $53.90[1,2,5] Single Pass: $38.60[1] (Includes a $12.90 farmer premium payment and money necessary for increased fertilizer use. The number is slightly inflated because it is an average of all plants, including last ones that have to go further to get their stover.) $0.391[1] - $0.593[2] / gallon of ethanol
B) Feedstock Transportation		Cost for 22.4 dry tons of baled stover / load for one way[3]: $3.60 for 0-25 miles $ 2.35 for 26-100 mile trips $1.90 for trips over 100 miles In general: $0.193 / ton / mile for round trip required for truck[4]
C) Handling, Storage	$6,540,000[2] - $8,780,000[1] - $11,800,000[5]	Unloading / Stacking Costs: $1.15 / ton[3]
D) Prehydrolysis / Hydrolysis	$31,400,000[1] - $36,100,000[2] .	Sulfuric Acid: $0.013[1] - $0.017[2] - $0.072[4] / gallon of ethanol Lime: $0.012[2] - $0.026[1,4] / gallon of ethanol Nutrients for Enzymes: $0.0365[1]
E) Fermentation / Co-fermentation	$11,000,000[1] - $17,400,000[2]	
F) Distillation	$17,300,000[2] - $ 25,500,000[1] - $41,700,000[5].	Denaturant: $0.016[4] - $0.022[5] - $0.036[2]

[10] Average harvesting cost in MN for getting at least 1,000 lbs of stover per acre is US2006 $22.76 per ton, which includes $3.53 to replace nutrients from removed stover (Petrolia 2006).

G) Enzymes	Produced on Site: $21,900,000[2] .	Enzymes - Purchased: $0.103 - $0.413[1,5,6] / gallon ethanol Enzymes – Produced on Site: $0.031[2] / gallon fuel ethanol
(I-J) Co-products – payments back to plant	Combustor boiler and turbogenerator subsystem (required to produce steam and electricity from the lignin and any remaining cellulose/hemicellulose)[8] $44,800,000[1] - $45,400,000[2]	Electricity Sold to Grid: $0.133 / gallon fuel[2] Furfural: $822 / ton[4] Biogas: $3.25 / MBTU[4] Cellulosic Residue: $1.29 / MBTU[4] CO_2: $12.85 / ton[4]

[1] Aden et al. 2002 – 69.3 MM gallon / year – corn stover
[2] McAloon et al. 2000 – 25 MM gallon / year – corn stover
[3] Petrolia 2006 – corn stover
[4] Kaylen et al. 2000 – 69.3 MM gallon / year (used equations given by authors to calculate the costs for an ethanol plant the same size as Aden et al. 2002) – energy crops, crop residue, and woody biomass
[5] Wallace et al. 2005 – 50 MM gallon / year – corn stover
[6] Tiffany 2005 – corn stover
[7] All prices are converted to US dollars 2006
[8] If the plant does not use the lignin for steam and/or electricity and uses a natural gas-fired boiler instead, boiler costs are cheaper. However there are then substantial landfill costs to dispose of the lignin residue and costs for the boiler fuel (natural gas) (McAloon et al. 2000).
[9] Costs listed above not represent total costs for ethanol production. Other cost items include (but are not limited to): waste water treatment (capital cost $3,860,000 (Aden et al. 2002) - $ 10,900,000 (McAloon et al. 2000)); storage of chemical, enzymes, etc needed for production (capital cost $2,340,000 (Aden et al.2002)) - $2,540,000 (McAloon et al. 2000)); utilities required for cooling/chilled/process water, plant air, and a clean-in-place system (capital cost $5,500,000 (Aden et al.2002) - $6,660,000 (McAloon et al. 2000).

Producing ethanol from corn stover using dilute acid hydrolysis costs about $1.63 - $1.82 per gallon ethanol, with yields of 72 - 89.7 gallons of ethanol per dry ton stover (Aden et al.2002; Wallace et al. 2005). However, Aden et al. (2002) used a cost of $1.25 per gallon of ethanol to calculate optimal plant size and minimum ethanol selling price and found that a 70 MM gallon facility could be economically viable. However, Aden et al.'s (2002) study shows a proof of economic viability when their model conditions are met and whether these exact modeled economic conditions can be met as cellulosic ethanol grows is unknown[11]. Another study suggests total costs of $1.37 per gallon cellulosic ethanol, with future prices as low as $0.89 per gallon (Mielenz 2001). Finally, Suh et al.'s (2008) results suggest total costs of $1.41 to $1.83 depending on the transportation mode for hypothetical facilities in Minnesota.

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[11] For example, Aden et al. (2002) assume purchased enzymes with a ten fold decrease in price and single pass stover collection.

Therefore, cellulosic ethanol production has the potential to reduce costs from these estimated ranges, though even at $1.25, the prices are still significantly higher than the $1.03-$1.07 cost of conventional ethanol production.

Cellulosic ethanol production is in its infancy compared to conventional corn starch production. The industry is still working on technological and production improvements. Currently, the major costs for producing ethanol from dilute acid hydrolysis are capital and enzyme costs (Tiffany 2005). Total capital costs are equal to $6.59 per gallon of ethanol for a 25 MM gallon per year facility or $5.21 per gallon of ethanol for a 50 MM gallon per year facility (McAloon et al. 2000).

Enzyme costs are the other often-cited prohibitive cost for cellulosic ethanol production. These costs depend on whether the enzymes are produced at the plant or bought. More recent studies suggest that the industry will buy the enzymes rather than producing them, allowing the plants to forgo the capital costs required for enzyme production. Enzymes can be purchased for an estimated $0.103 - $0.413 per gallon ethanol.

4.3 THERMOCHEMICAL CELLULOSIC ETHANOL COSTS

The costs for thermochemical cellulosic ethanol are generally unknown. Only a few studies have produced cost estimates. Gasification as a process for making syngas today still usually cannot compete with cheaper petroleum, though it has been economically viable when using natural gas instead of biomass (DOE 2005). However, the first commercial biomass gasification plant broke ground on construction in November 2007 in Georgia. Range Fuels will initially build a 20 MM gallon a year plant, using left over wood residues as a feedstock. Their plan is to eventually increase the size of the facility to 100 MM gallons a year.

The costs of this new ethanol plant in Georgia are unknown. However, the National Renewable Energy Laboratory contracted one of the main high-tech companies in the ethanol industry, Delta-T Corporation, to look into the costs of gasifying biomass to produce ethanol. Their analysis is summarized below (Table 5), with all values reported in 2006 US dollars, along with previous NREL estimates conducted in 1999 (Putsche 1999). Expected yields from a grassroots biomass syngas-to-ethanol facility with no external fuel source provided to the gasifier, are 70-105 gallons of ethanol per ton of dry biomass fed. The economics of this route appear to be competitive with today's corn-based ethanol and projections for direct fermentation of biomass.

Table 5: Estimated Costs of Thermochemical Cellulosic Ethanol Production

Item	*15 Million Gallon Capacity*[1]	*48.5 Million Gallon Capacity*[2]
Total Annual Costs (per gallon ethanol)	*$1.55*	*$1.33*[3]
Total installed Equipment Costs	$34,400,000	$153,600,000
Total Annual Variable Operating Costs	$7,920,000	33,804,500[4]
Total Annual Fixed Operating Costs	$4,250,000	N/A

[1] Assuming a feedstock cost of $15/dry ton for corn stover (NREL 2002)
[2] Assuming a feedstock cost of $25/dry ton of biomass (Putsche 1999).
[3] Represents a rational price at a zero net present value for the project, with 100% financing and 10% real after-tax discounting.
[4] Represents total cash costs of operations, including fixed and variable costs.

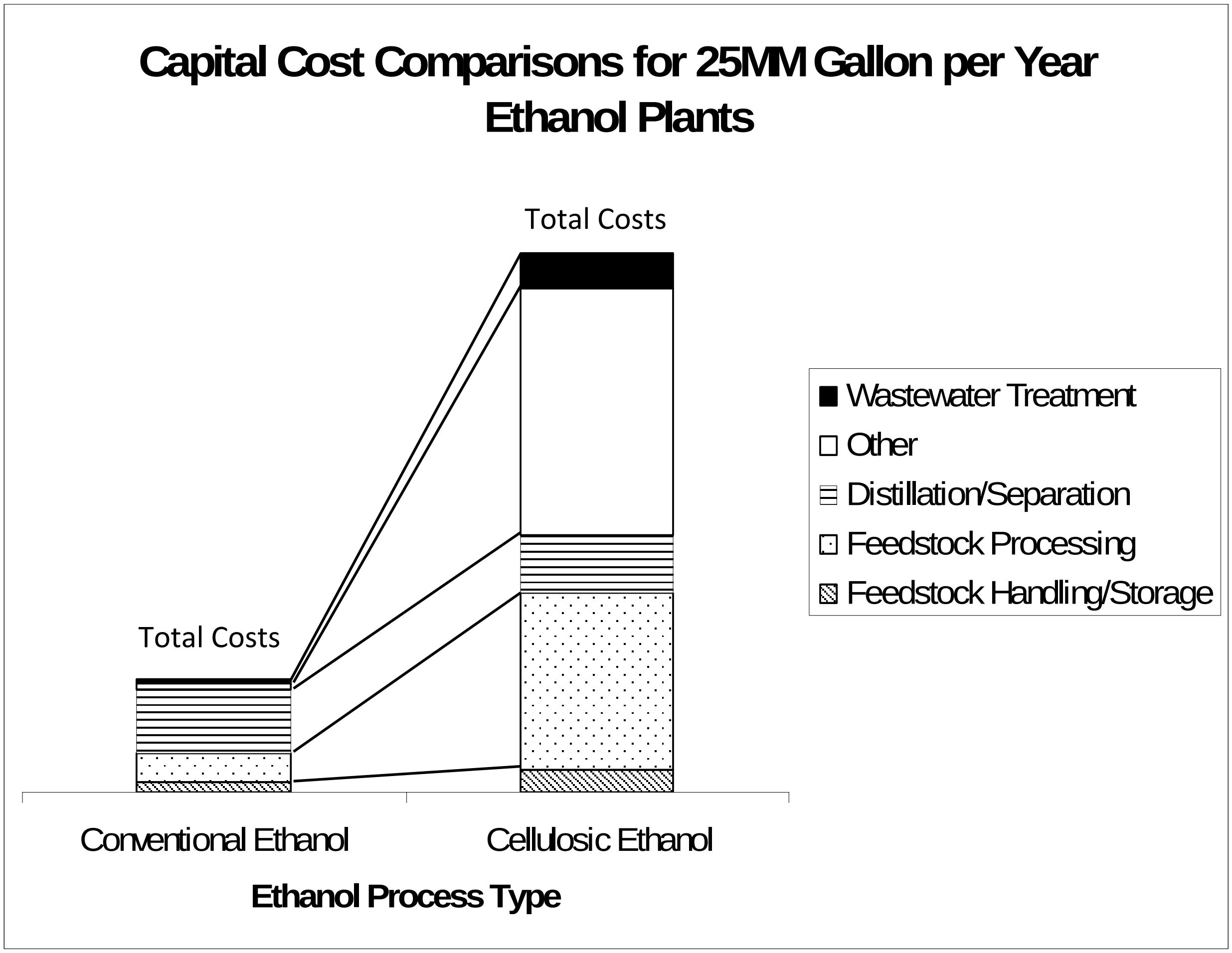
4.4 COMPARISON OF COSTS

Direct comparison of the costs from the different unit processes listed above for conventional corn starch and biochemical cellulosic ethanol is problematic due to different plant sizes and assumptions built into each study and due to the lack of data for thermochemical production. However, there is published literature on comparison of corn starch and biochemical corn stover cellulosic ethanol. One key study was a joint project between the United States Department of Agriculture (USDA) and the National Renewable Energy Laboratory (NREL), authored by McAloon et al. (2000). They held plant size constant at 25 million gallons per year, assuming the "nth" plant for cellulosic ethanol. Using two previously created NREL/USDA models they were able to make cost comparisons between the two production processes. However, even by just looking at the range of costs in the literature given in previous sections it is obvious that both cellulosic ethanol production processes are not yet economically competitive with conventional corn starch production (Table 6).

Table 6: Cost Comparison Summary Table

		Conventional Corn Starch Ethanol	**Cellulosic Ethanol**	
			Biochemical Process	*Thermochemical Process*
Costs	*Costs per Gallon Ethanol*	$1.03 - $1.07	$1.25 - $1.82	$1.55
	Major Costs	Feedstock, electricity/steam	Capital, Enzyme	Capital

Graph 3: Capital Cost Comparisons



Graph made using data from (McAloon et al. 2000) with all values converted to 2006 US dollars.

[1] "Other" represents air compressor costs for conventional ethanol and utility, boiler/turbogenerator, and enzyme production costs for cellulosic ethanol. However, some studies assume enzymes can be purchased and thus other costs would decrease by just over $21,900,000.
[2] Distillation/Separation includes the equipment needed for distillation as well as solid/syrup separation and drying (in the case of conventional ethanol production)
[3] Feedstock processing includes the equipment costs required to get the feedstock from its initial state to the distillation stage. For conventional ethanol this includes the saccharification and fermentation processes. For cellulosic ethanol, this includes the prehydrolysis/hydrolysis and fermentation/co-fermentation processes.

One key in the cost differences is the capital costs that dominate cellulosic ethanol technology. For conventional plants, feedstock and handling is three times cheaper than for cellulosic plants. Fermentation is two to three times cheaper for conventional plants, and the capital cost for the prehydrolysis and hydrolysis necessary for biochemical cellulosic production is over ten times the cost of the simpler saccharification process of conventional ethanol plants.

From McAloon et al.'s (2000) modeling cost comparison the magnitude of these cost differences are obvious (Graph 3).

An important factor in capital costs for cellulosic ethanol in the McAloon et al. (2000) study was the inclusion of equipment for producing the requisite enzymes. However, more recent studies of biochemical cellulosic ethanol assume plants will purchase their enzymes. Even then, compared to conventional ethanol costs for enzymes and yeast (~$0.05 per gallon of ethanol), costs for cellulosic production are orders of magnitude higher ($0.103 - $0.413 per gallon of ethanol).

Despite the high purchase costs of these enzymes, the costs are actually lower than the predicted stover costs of $0.391 - $0.593 per gallon of ethanol so although enzyme costs are touted as significant, it seems that as with conventional ethanol production, feedstock costs are also significant for cellulosic ethanol. Though as McAloon et al.'s (2000) study also shows, the feedstock costs for conventional ethanol are the largest proportional cost of ethanol production (Graph 4).

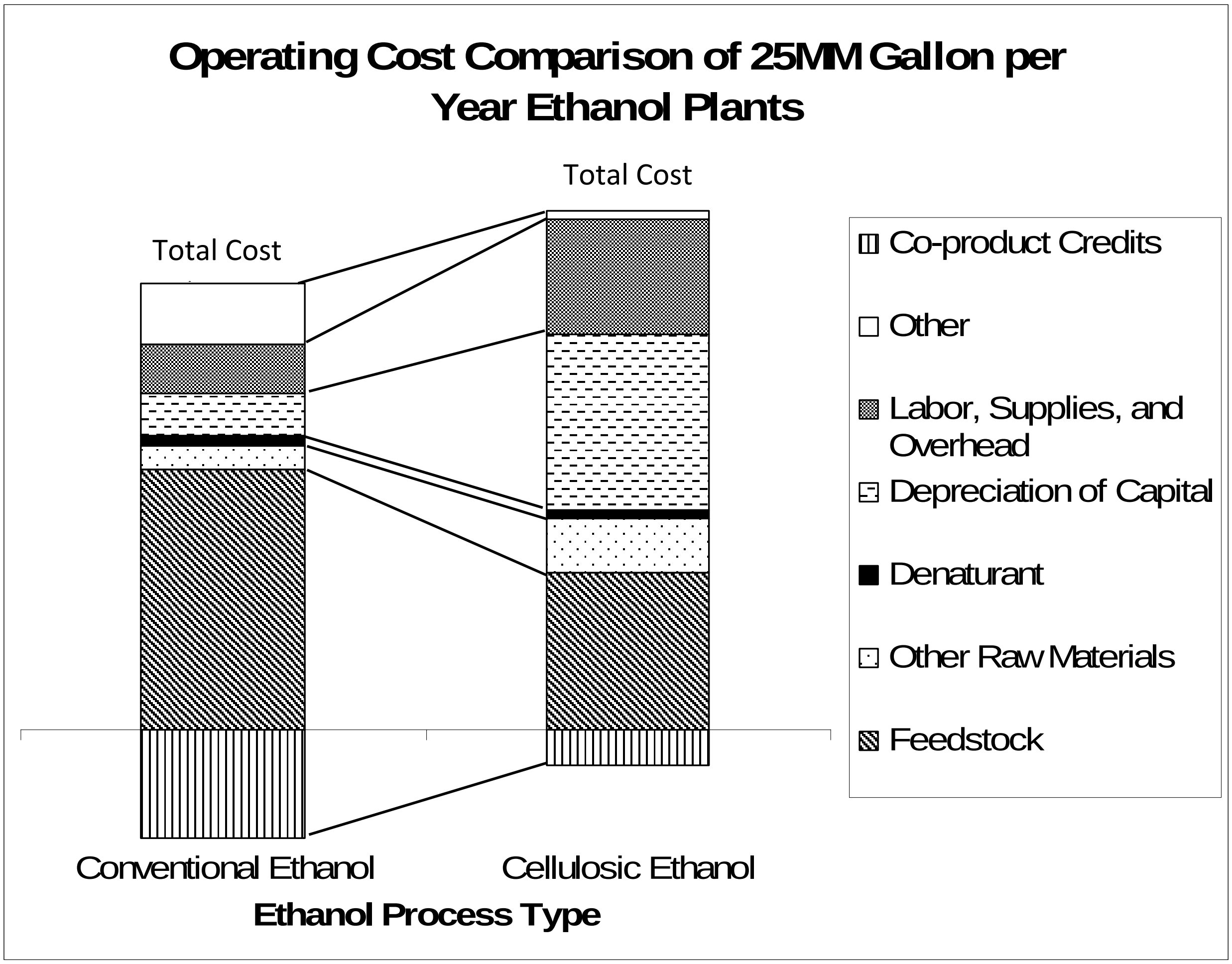
Although there is not direct cost comparison data available for thermochemical cellulosic ethanol, it appears that the total costs for producing ethanol from biomass using gasification are within range of producing ethanol using dilute acid hydrolysis, though still significantly higher than conventional ethanol production (Table 4). Although the capital costs for gasification are high, they are less than that of biochemical ethanol production[12]. Furthermore, there are some other advantages of gasifying biomass over the biochemical processing that can ultimately lead to lower costs including: the high temperatures of gasification kills any microbial infections that can plague biochemical process, there is no reliance on enzymes and yeast for conversion efficiencies, and gasification has less piping and tankage requirements, which decrease the plant footprint requirements (Delta-T Corporation, 2002).

It is important to recognize that there are a number of substantially lower cost (and water usage) estimates being reported by producers, which unfortunately cannot be verified yet. Of particular note, are the recent claims from Coskata, a thermochemical ethanol producer with backing from General Motors, that ethanol can be produced at under $1 per gallon, with water consumption of less than one gallon per gallon of ethanol (Squatriglia 2008). The

[12] The gasification plant costs are based on a smaller facility than the biochemical process capital costs and therefore the cost difference may not be significant, though are still probably lower.

company plans to have its first commercial-scale plant producing up to 100 million gallons of ethanol a year by 2011.

Graph 4: Operating Cost Comparisons



Graph made using data from (McAloon et al. 2000) with all values converted to 2006 US dollars. "Other" represents utility costs for conventional ethanol and waste disposal costs for cellulosic ethanol.

5. ENVIRONMENTAL IMPACTS OF ETHANOL PRODUCTION

5.1 CONVENTIONAL CORN STARCH ETHANOL

It is difficult to link the environmental impact of corn production to specific unit processes. In general, conventional ethanol production provides a 13 to 19% decrease in total greenhouse gas (GHG) emissions over gasoline production, with plants producing about 195 g

CO_2 per bushel of corn[13] (Farrell et al. 2006; Wang et al. 2007). Of the greenhouse gas emissions from corn starch ethanol production, 34-44% come from the agricultural practices of growing corn (Farrell et al. 2006). Ethanol facilities can increase their GHG reductions to 28 – 39% if they use natural gas as an energy source (over average), which is the case with many current ethanol facilities (Wang et al.2007) and most in Minnesota. About a third of the natural gas thermal energy is used to dry the distiller's grains, making it the large single contributor to greenhouse gas emissions (Wang et al. 2007). However, with increasing natural gas prices, some plants are looking into replacing natural gas and using biomass as their fuel source. One Minnesota ethanol plant, Central Minnesota Ethanol Cooperative, gasifies wood wastes eliminating their need for natural gas. Another Minnesota ethanol facility, Chippewa Valley Ethanol Cooperative, has also decided to switch from natural gas to biomass. They will be bringing their gasifier online in early 2008, burning woodchips and in the future, possibly stover (Kelly Davis personal communication 2007). Besides insulating the facility from the effect of high natural gas prices, using stover, DDGS and/or wood chips for fuel leads to further reductions in greenhouse gas emissions. Total GHG reductions for using these alternative fuel sources are 39-52 % over gasoline production (Wang et al. 2007). However, when conventional ethanol facilities use coal as their energy source, all the environmental benefits vanish and unfortunately, with the rising costs of natural gas some plants are considering making this switch to coal (Wang et al. 2007).

Another common environmental concern surrounding the ethanol industry is their water requirements. Average water usage for dry mill ethanol production is around 4 to 4.7 gallons of water per gallon ethanol (range 1-11), though Minnesota plants range from 3.5 to 6.0 gallons of water per gallon ethanol[14] (Keeney & Muller 2006; Shapouri & Gallagher 2005). These numbers have substantially decreased over time and were originally as high as 15 gallons of water per gallon ethanol, declining to 5.8:1 in 1998 and finally to 4.2:1 in 2005 (Keeney & Muller 2006; Shapouri & Gallagher 2005). Of key importance in minimizing total water usage is the number of times the facility is able to recycle their water in the cooling towers. Chippewa Valley Ethanol Cooperative uses less than 4 gallons of water per gallon of ethanol and this is partially due to their ability to recycle their cooling tower water five times (some plants can only recycle three times) (Kelly Davis personal communication 2007). However, recycling water cannot drastically reduce the current average water use due to the resulting highly

[13] This figure includes an average of different plants' energy source options including natural gas, combined heat and power, coal, use of biomass feedstocks, etc.

[14] For comparison, the petroleum industry uses about 1.5 gallons water / gallon of gasoline (Schnoor et al. 2007b).

concentrated salts. Longer term solutions will require reduced use or recovery of evaporation water (Kelly 2007).

Despite declining per gallon ethanol requirements, total water required by the ethanol industry continues to rise due to increasing numbers of plants and increasing plant capacities. Keeney & Muller (2006) use Minnesota water usage by ethanol plants and extrapolate out to the entire United States ethanol industry. They predict that the industry will require almost 30 billion gallons of water by 2008. This outstanding number does not include the use of water for irrigation. For those acres irrigated, Minnesota currently averages 1001-2000 gallons of water per bushel of corn (Schnoor et al. 2007a). Reports of the amount of irrigated corn in Minnesota vary from as low as 2% to as high as 48% and when using irrigated corn, the water usage for an ethanol plant increases over 100 times to 785 gallons of water per gallon of ethanol (Aden 2007; United States Department of Agriculture 2003). Although the amount of irrigated corn in Minnesota is lower than much of the great plains states, as more marginal lands are used in the state, irrigation will likely only increase, assuming that marginal lands will require additional inputs (including water) to produce reasonable yields.

5.2 BIOCHEMICAL CELLULOSIC ETHANOL

Cellulosic ethanol has a huge environmental potential. This potential is due to three main factors outlined in Lynd (1996). First, upon combustion, biomass releases the same amount of CO_2 it previously consumed and thus no new atmospheric carbon is introduced. Second, cellulosic energy crops have lower fossil fuel inputs than conventional row crops and finally the coproducts of cellulosic ethanol (e.g. lignin, syrups) can be used to meet plant energy requirements, eliminating the need for fossil fuel energy sources. The magnitude of the potential only increases with improvements in feedstocks (using those that require less petroleum based harvest equipment, fertilizers, etc.). The total reduction in GHG over petroleum varies by study. Wang (2005) predicts an 85% reduction in GHG emissions per gallon of ethanol used to displace an energy-equivalent amount of gasoline. Sheehan et al. (2004) conducted a life cycle analysis of corn stover and found that for each kilometer traveled using 100% ethanol, greenhouse gas emissions would decrease by 254 g / km, which equates to a 106% reduction over using gasoline[15]. However, when concerned with specific greenhouse gases, cellulosic ethanol may increase emissions, depending on the feedstock. Sheehan et al. (2004) found that carbon monoxide, sulfur oxide, and nitrous oxide emissions will increase by

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[15] A greater than 100% reduction can occur from carbon sequestration in the soil.

17%, 305%, and 924% respectively over gasoline for an E85 blend of cellulosic ethanol. The authors attribute these high results primarily from lignin combustion for sulfur oxides and farm soil emissions for nitrous oxide.

For Minnesota, the eight hypothetical cellulosic ethanol facilities predicted by Suh et al. (2008) suggest that the amount of carbon dioxide produced in the state is highly dependent on the transportation mode of stover. Most significant, pipeline transportation of stover from storage facilities to ethanol plants is four times greater than truck transportation, and forty times greater than rail. However, corn grain also requires feedstock transportation (though admittedly at higher densities) and thus cellulosic ethanol still should decrease total carbon dioxide emissions over gasoline and conventional starch ethanol.

Although the greenhouse gas reductions are significant over conventional ethanol production, biochemical cellulosic production does not fare better when it comes to water usage. Cellulosic ethanol produced via dilute acid hydrolysis is predicted to initially require about 9.5 gallons of water per gallon of ethanol (Schnoor et al. 2007b). However, as happened for conventional ethanol production, water usage for cellulosic ethanol production will likely decline as the industry matures. The projected water use for the "nth" cellulosic ethanol plant will likely be between two to six gallons of water per gallon of ethanol (Pate et al. 2007). If cellulosic ethanol production can achieve these reductions in water usage, it will be on par with conventional ethanol production. However, just as with conventional ethanol production, total water usage by the industry will grow as more ethanol plants (conventional and cellulosic) come online and these water usage numbers do not include any irrigation requirements for feedstocks.

5.3 THERMOCHEMICAL CELLULOSIC ETHANOL

The environmental benefits of gasification over biochemical and conventional ethanol production are currently ambiguous, largely due to insufficient data. There is limited research on the emissions from burning different feedstock in a gasifier and there are concerns about increased nitrous oxide emissions from gasifying some feedstocks such as dried distillers grains (Kelly Davis personal communication 2007). However, there are previously mentioned environmental benefits to using biomass over natural gas for gasification, and environmental benefits to using cellulosic feedstocks over corn starch. Thus, gasification will likely yield environmental improvements over conventional ethanol facilities, though their benefits compared to biochemical cellulosic production are unknown.

The water usage for gasification is also uncertain, but a recent report they Phillips et al (2007) suggests that it could be as low as 2 gallons of water per gallon of ethanol. However, gasification will likely fall in a similar range to future predicted biochemical water use of 2 - 6 gallons water per gallon ethanol (Schnoor et al. 2007b). As before, while these water uses may seem reasonable on a plant basis, the combined water usage of the industry will remain a concern.

5.4 COMPARISON OF ENVIRONMENTAL IMPACTS

Using ethanol over gasoline leads to overall reductions in greenhouse gas emissions (Table 5). The reductions are modest for conventional ethanol production, though by making small alterations in the production process, e.g. using natural gas, plants can attain the higher end of their greenhouse gas reduction potential. Cellulosic ethanol production (both biochemical and thermochemical) likely surpass conventional corn starch reductions, though estimates for thermochemical production are sparse. However, estimates for biochemical cellulosic ethanol are very promising, with 85% or greater reductions in greenhouse gases. Of most concern for cellulosic ethanol production is the potential for individual greenhouse gases to increase (e.g. nitrous oxide), even with overall decreases in emissions.

Table 7: Greenhouse Gas Emissions of Ethanol Production

	Conventional Corn Starch Ethanol	Biochemical Cellulosic Ethanol	Thermochemical Cellulosic Ethanol
Greenhouse Gas Emissions[1]	13 – 39 % reduction Total reduction depends on processing (wet vs. dry mill) and largely on energy and steam use.	85% – >100% reduction -Individual gasses, e.g. nitrous oxide, will increase	Unknown, though likely will lead to significant reductions overall, with concerns over individual gas increases

[1] These reduction estimates do not take water vapor into consideration, something that is currently under debate in the scientific community.

Water usage for the different ethanol production technologies does not vary much, especially when considering the “nth” cellulosic ethanol plant. For all three technologies water usage will likely range between two and six gallons of water per gallon of ethanol (Table 6). These numbers reflect the continual improvement the industry has had in water usage, with

most current water usage stemming from evaporation loss at the cooling towers and from the evaporators during the distillation unit process (Schnoor et al. 2007b). One important short term water use consideration is how fast cellulosic ethanol water usage will decrease from its predicted initial usage of 9.5 gallons of water per gallon of ethanol to a more comparable 2 – 6 gallons. As aforementioned, early ethanol facilities used as much as 15 gallons of water per gallon of ethanol. In the last ten years, ethanol water usage at conventional plants has decreased by about 30%, from a Minnesota average of 5.9 gallons of water per gallon of ethanol to an average of 4.1 (Kelly 2007; Minnesota Department of Natural Resources 2007). It is likely that some of the water usage learning curve has already been incorporated into cellulosic ethanol production. However, if cellulosic ethanol water usage decreases at the same rate as water usage has in the last ten years of current ethanol industry, it will take over ten years for cellulosic ethanol to decrease to its predicted range of 2 – 6 gallons of water per gallon of ethanol.

Compared to petroleum refining ethanol production uses slightly more water, 1 – 2.5 verses 2 – 6 gallons of water per gallon of fuel (Table 6); however there can be significant uses of water in the oil extraction process and in irrigation. Overall, water usage for ethanol and petroleum are likely comparable (Gleick 1994).

Table 8: Water Usage in Ethanol Production

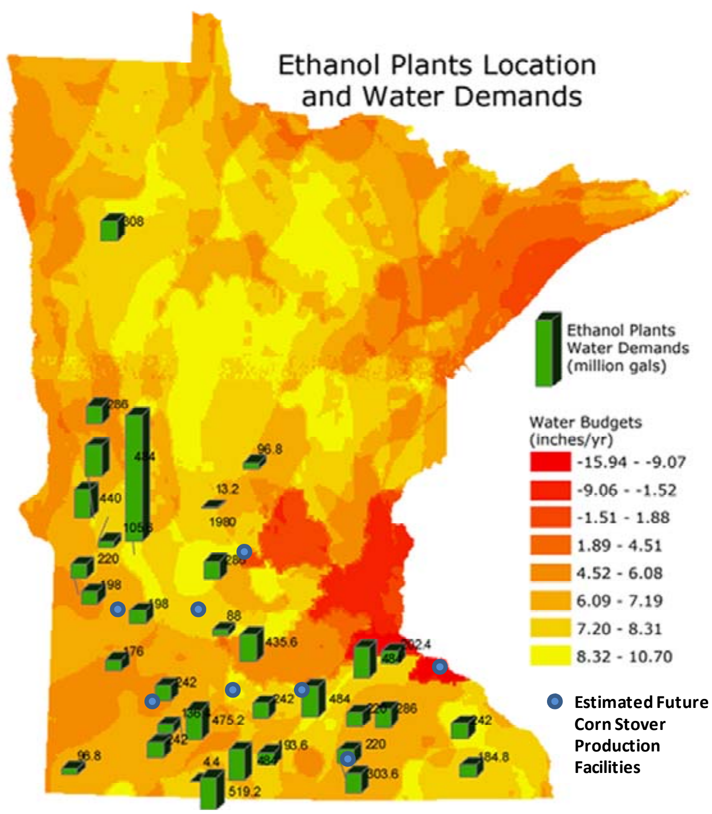
Water Usage	Conventional Corn Starch Ethanol	Biochemical Cellulosic Ethanol	Thermochemical Cellulosic Ethanol	Petroleum[2]
Gallons of water used per gallon of ethanol / petroleum production[1]	3.5 – 6 average of about 4.1	9.5 initially, decreasing to 2-6 over time	2 – 6	1.5 – 2.5

[1] Water usage at the production plant / refining plant only, thus does not include water used during other parts of the process (e.g. irrigation for corn and oil extraction), which can be significant.
[2] (Gleick 1994)

Given the local impacts of water consumption, it is important to begin to assess the likely impact on local water supplies due to cellulosic ethanol development in the state. The recent work of Chiu et al. (2008) provides a spatial representation of water budgets for Minnesota that is the routing of precipitation through the pathways of evaporation, infiltration, and overland flow. This routing of groundwater and overland flow defines the delivery patterns to particular streams, lakes, and wetlands; and largely shapes the nature of these aquatic

systems. Overlaid on this map (see Figure 9) are ethanol production facilities currently in operation, under construction, and in planning. Finally, we have overlaid the estimated optimum corn-stover facilities identified by Suh (2008), and presented in Figure 9. The preliminary nature of the studies used to generate this analysis do not allow for a direct assessment of ethanol production on water systems, however, it does imply that the impacts of future ethanol water demand will vary depending on location. In particular, suggested large corn stover cellulosic ethanol facilities in Frontenac Station and Eden Valley are of particular interest – each in low water budget regions. Other future stover-based ethanol facilities of potential concern are those suggested in regions with significant planned production of tradition corn-starch ethanol. Stover-based cellulosic ethanol production in the West-Central (Clarksfield) and South-Central (Revere) regions of the state would theoretically be located in close proximity of newer, and larger, traditional ethanol facilities. Future research is required to determine the impact of State regulatory or incentive actions on the optimal location of future facilities.

Figure 9: Water Budgets and Potential Ethanol Production in Minnesota



Adapted from: Chiu et al. 2008 and Suh 2008

6. CONCLUSIONS

The current corn starch ethanol industry is well established. It has overcome many of the cost and technical barriers that hindered ethanol production over a decade ago. However, there are still opportunities for environmental improvement within the industry that may end up making economic sense in the face of high natural gas prices. As previously mentioned, there are two ethanol facilities in Minnesota that have or soon will be replacing their natural gas requirements by burning biomass. Besides the aforementioned environmental benefits of doing so, switching to a biomass gasifier provides greater economic resilience to natural gas and even corn prices (Tiffany 2007). This may also be beneficial in that as more and more ethanol plants come online, there may be a potential glut in the DDGS market (there is a limit to the amount of DDGS that can be fed to livestock), and currently DDGS makes up 15-20% of the total plant revenue (Tiffany & Eidman 2003). If this occurs, it may be that using DDGS in a gasifier and perhaps then being able to sell excess electricity back to utilities may prove to be a better economic and environmental choice.

Cellulosic ethanol production using a biochemical process is not yet commercially viable. There are some pilot facilities in Canada and the United States, but commercial production is likely a few years off. This is largely due to the high capital costs and the enzymes used in the cellulosic process. Current research is focused on improving cellulose thermostability and improving binding to the hemicellulose and cellulose while reducing nonspecific binging to lignin (Mielenz 2001). With improved enzymes that can make better use of cellulosic materials and policy incentives promoting the use of cellulosic material, biochemical conversion of biomass to ethanol can play a substantial role in meeting energy requirements.

Without a doubt, the ethanol industry is moving towards cellulosic feedstocks. The environmental benefits are great and costs, though still significant, continue to fall. The question, however, is how cellulosic feedstocks will be processed. The initial "next step" for Minnesota has already been answered with two ethanol facilities choosing to install biomass gasifiers to power their plants. This seems an obvious and easy step to take in the face of decreasing returns to current ethanol production. Fortunately for Minnesota, such a switch will improve the state's total greenhouse gas emissions, though depending on the cellulosic feedstock there may be concerns about increases in specific emissions (e.g. nitrous oxide). With gasifiers installed, it may be an easier evolution to use a thermochemical process to convert cellulosic biomass to ethanol. Although, the ease with which a current conventional plant with a biomass gasifier can switch to full biomass gasification production is not entirely known. In general, the majority of the existing literature centers on the possibilities of co-locating conventional and biochemical ethanol facilities, or otherwise supplementing conventional with cellulosic. There is minimal research into how an individual plant or a state

might switch from conventional ethanol production to cellulosic ethanol production. A large and important unanswered question is how will, at the incremental level, one facility or the state as a whole convert from conventional to cellulosic ethanol.

Another question facing Minnesota surrounds which feedstocks will be used in both biochemical and thermochemical cellulosic processes. Corn stover and switchgrass are the most talked about feedstocks for Minnesota, though there are a variety of other possibilities. The potential for feedstocks with preexisting collection systems (e.g. municipal solid wastes, waste water, sludge, landfill materials, forest slash, etc.) may provide a small, but significant amount of feedstock for cellulosic ethanol production in that they reduce the transportation costs faced by the facility. The paper and pulp industry is another of Minnesota's assets and already accounts for why biomass is the second largest category of renewable energy in the US. The paper and pulp industry currently combust their wastes for energy and their potential as a feedstock for ethanol may be great, although what would replace those energy sources for pulp and paper – and with what ecological effect - is uncertain.

Finally, Minnesota will have to see how the production of ethanol from biomass will compete with biomass for electricity. There are no large tracts of unused land left in Minnesota. Some studies have suggested that using biomass for electricity has a greater improvement in greenhouse gas reductions than using biomass for ethanol. As these industries grow and expand into renewable energy sources they will continue to compete with one another. How that competition plays out in Minnesota will have a large impact on the future of the cellulosic ethanol industry.

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