FACTORS INFLUENCING THE FEASIBILITY OF SWITCHGRASS FEEDSTOCKS: FROM A BIOREFINERY'S PERSPECTIVE

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ABSTRACT

Research suggests that biomass with high cellulose content like switchgrass is more efficient for producing ethanol than corn grain. The objective of this study is to evaluate factors influencing the economic feasibility of ethanol production from a biorefinery's perspective using switchgrass as the only feedstock. The research conducted utilizes a model which considers switchgrass procurement costs, transportation costs, storage costs, dry matter loss, biorefinery construction costs, operating and maintenance costs, and ethanol production in determining the break-even price of ethanol. The break-even prices of ethanol estimated range from $2.02 to $2.45 per gallon. The sensitivity analysis demonstrated that when the conversion rate increases, the ethanol break-even price drops. Additionally, switchgrass price has a positive impact on the ethanol break-even price. However, it becomes less sensitive as the biorefinery size increases. Discount rate also has a positive impact on the ethanol break-even price. Using the ethanol market price data collected by the Agricultural Marketing Resource Center, a small biorefinery would be profitable the majority of the time, if traditional round bales are used.

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CHAPTER I

INTRODUCTION

Energy costs in the United States have been volatile, but steadily mounting over the past decade. Energy prices have been rising since 2002 (U.S. Department of Energy 2012). The over-reliance on imported crude oil has become a tremendous burden on the United States, because 44% of the United States' foreign trade deficit is composed of oil imports. The control that OPEC, or the Organization of the Petroleum Exporting Countries, has over the majority of the world's oil reserves is the primary driver for the instability and increase in fuel prices. More than 80% of the proven oil reserves in the world are located within OPEC Member Countries according to current evaluations (Organization of the Petroleum Exporting Countries 2012). As a result, the United States spends billions of dollars annually protecting the Persian Gulf and maintaining relations with OPEC oil producers to ensure the reliable importation of its primary energy sources (Growth Energy 2008). Therefore, the United States is largely dependent upon crude oil imports from OPEC member countries to meet its energy needs (U.S. Energy Information Administration 2011).

The United States' dependence upon foreign oil, as its primary energy source, is taking an enormous toll on the economy due to the direct and indirect costs that are being incurred (Growth Energy 2008). Likewise, the environment is being negatively affected by the impacts of utilizing fossil fuels as primary energy sources. Methyl tertiary-butyl ether (MTBE), an additive derived from petroleum, which is generally used as an oxygenate in gasoline has been banned in multiple states because of the negative effects MTBE has on the environment and human health (Keller et al. 1998; Gallagher et al. 2003). In addition, the increased carbon dioxide

concentration in the atmosphere and associated climate change issues are largely due to the use of fossil fuels, such as oil and gasoline. Therefore, dependency on imported oil and environmental concerns are the main drivers for bioenergy research (McLaughlin 1999). Additionally, national security, farm income, potential job creation, sustainability, and potential impacts on rural communities are forces influencing the shift away from such heavy dependence on fossil fuels to alternative energy sources such as ethanol (Lehmann 2007; Growth Energy 2008).

Ethanol production from biomass has gained interest from farmers, policy makers and others due to the considerable progress that has been made in cellulosic ethanol production practices (English et al. 2006). Ethanol produced from cellulosic biomass is more abundant and environmentally-friendly than grain ethanol (Perlack et al. 2005). The United States government mandated that renewable substitutes for fossil fuels, oil specifically, be developed (Thorsell et al. 2004). The Energy Policy Act of 2005 (EPAct 2005, P.L. 110-58) established the first Renewable Fuels Standard (RFS) in federal law, requiring increased volumes of ethanol and biodiesel to be blended with the United States' fuel supply between 2006 and 2012 (American Coalition for Ethanol 2012). Following, the Energy Independence and Security Act of 2007 (P.L. 110-140, H.R. 6) (EISA) was amended and increased the RFS, thus mandating nine billion gallons of renewable fuel use in 2008 and 36 billion gallons to be produced by 2022 in the United States (U.S. Congress 2007; Larson et al. 2010). According to the modified RFS, corn-based ethanol (conventional biofuel) in effect will be capped at 15 billion gallons by 2015. Twenty-one of the 36 billion gallons in 2022 must be derived from advanced biofuel such as cellulosic and non-corn-based ethanol (American Coalition for Ethanol 2012).

With the combined efforts of the government and research institutes, ethanol is slowly becoming a primary substitute for petroleum oil and is used as a fuel oxygenate. The demand for ethanol has substantially increased due to the rising demand for MTBE substitutes. Additionally, the United States government offered the Volumetric Ethanol Excise Tax Credit (VEETC), generally referred to as the "blender's credit", in 2004. This credit encourages oil companies to blend ethanol with gasoline. In 2009 the original tax credit was $0.51 per gallon of pure ethanol ($0.51 per gallon for E10, and $0.42 per gallon on E85). The credit has since been reduced to $0.45 per gallon. VEETC was set to expire in 2010, but several members of Congress introduced H.R. 4940 in order to extend VEETC at $0.45 per gallon for five years (Renewable Fuels Reinvestment Act 2010).

Research suggests that crops and/or biomass with high cellulose content are more efficient production materials than corn grain. Lignocellulosic biomass (LCB), a combination of cellulose, hemicellulose and lignin, from dedicated energy crops such as switchgrass, corn stover, and wheat straw has been viewed as the most competitive ethanol feedstock in the United States (De La Torre et al. 2007). The cellulose and hemicellulose can be converted to sugar for ethanol production and the lignin can be burned for electricity (Wyman 2008). Among all biomass feedstocks, switchgrass demonstrates the most potential for growth in the United States. It is commonly recognized as a potential leading crop for energy production (McLaughlin 2002). Theoretically, a substantial amount of ethanol production mandated by the government could be produced using switchgrass as the primary feedstock.

Switchgrass is a warm season, perennial grass that is native to the United States and is generally grown on marginal land. It can grow up to nine feet tall and extend its root system up to nine feet, eighty-four inches. Switchgrass can be grown in a variety of soils including the

marginal lands that are not suitable for growing soybeans and corn. Because Tennessee is primarily composed of marginal crop land that is not suitable for producing row crops such as corn and cotton, switchgrass has a competitive advantage compared to traditional food crops (Wang 2009). Switchgrass can be planted in May or June and is harvested once per year. Switchgrass is typically harvested in the fall or winter after a killing freeze into round or rectangular bales (Jensen et al. 2007; Rinehart 2006).

There could be many positive impacts associated with using switchgrass as an ethanol feedstock. It would allow the United States to become less dependent upon foreign oil. Additionally, local growers and biorefineries would profit from the production. Rural economies could benefit and American dollars would not have to leave communities where the switchgrass is grown and produced. However, due to limitations in current conversion technologies, the cost of producing ethanol from switchgrass is uncertain with critical challenges in the conversion of cellulose and hemicellulose to a transportation fuel. Efforts are being made to improve the hydrolysis of lignocellulosic materials. Pretreatment of lignocellulosic materials to remove lignin and hemicellulose can significantly enhance the hydrolysis of cellulose. Optimization of the cellulose enzymes and the enzyme loading can also improve the hydrolysis. Simultaneous saccharification and fermentation effectively remove glucose, which is an inhibitor to cellulase activity, thus increasing the yield and rate of cellulose hydrolysis (Sun and Cheng 2002). Studies have indicated cellulosic ethanol production cost estimates range from \$0.21-\$1.25 L^{-1} (\$0.80-\$4.73 per gallon adjusted to 2010 dollars). However, the estimates show a substantial range depending on the assumptions of ethanol conversion rates, biorefinery investment costs, feedstock costs, and ethanol production processes (Haque and Epplin 2012). Though substantial research has been conducted regarding the ethanol content of switchgrass, little research has been

done to model and determine the break-even price of ethanol for a cellulosic ethanol biorefinery when using switchgrass as the only feedstock.

The objective of this study is to evaluate factors influencing the economic feasibility of ethanol production from a biorefinery's perspective. More specifically the study seeks to find the base value and range of the investment costs associated with different levels of ethanol production. The break-even price of ethanol produced using switchgrass as the only feedstock will be determined and analyzed in different scenarios regarding the ethanol conversion rate, biorefinery investment, feedstock investment, and other relevant factors.

CHAPTER II

LITERATURE REVIEW

Ethanol production is a process in which feedstock production, harvest, transportation, storage, biorefinery size, biorefinery construction investment, and biorefinery operating and maintenance costs are used to determine the break-even price of ethanol. Many studies exist concerning break-even analysis of inputs, such as switchgrass, used for ethanol production. Each portion of information uniquely contributes to the literature by employing a variety of methods and data analysis techniques. Additionally, the dry matter and storage losses which occur are key factors influencing the ethanol production level. Much research has been conducted regarding switchgrass production; however, little research has been done regarding biorefineries and ethanol production.

In the model outlined below, we assume that the biorefinery will be a profit maximizing firm (Nicholson 2005). Therefore, the break-even price of ethanol will be determined by subtracting costs such as switchgrass contract price, transportation, storage, biorefinery investment, and operating and maintenance costs from the total revenue. The revenue is calculated by multiplying the quantity of ethanol by the break-even ethanol price. The quantity is determined by multiplying the amount of biomass processed by the conversion rate after accounting for dry matter loss.

2.1 Switchgrass

2.1.1 Production and Harvest

The main costs considered in the production of switchgrass are: machinery costs, establishment costs, yearly maintenance costs, and harvest costs (Mooney et al. 2009). Machinery costs are made up of capital recovery, maintenance, repairs, fuel and lube, taxes, insurance and housing of the machinery. Switchgrass establishment costs include: machinery and labor time, seed, herbicides, fertilizers, and the interest on operating costs. Annual maintenance costs vary based on nitrogen treatments. They typically include: machinery and labor, herbicides, fertilizers, and the interest on variable operating costs. Harvest costs are made up of machinery and labor (e.g. mowing, raking, baling, staging, and loading), bale twine, and interest on variable operating costs (Mooney et al. 2009). Farm scale production costs for ten switchgrass growers in the central plains were estimated to be $46-$78 per dry ton (Perrin et al. 2008). Mooney et al. (2009) concluded maximum yields occurred at 67 kg of nitrogen ha^{-1}on well-drained soils and at higher nitrogen levels on less-well-drained soils and the yield response to seeding rate was insignificant. The production cost of switchgrass may be as high as $74.30 per ton (Duffy and Nanhou 2002).

Switchgrass is harvested once per year when yield per acre is maximized (Haque and Epplin 2012). The switchgrass is generally harvested within a four month window. This generally occurs in the fall or winter after a killing freeze (Rinehart 2006). Nutrients move into the root system after a freeze which minimizes the harvest of nutrients and their replacement, but maximizes the harvestable LCB for ethanol conversion (Larson 2010). Harvesting switchgrass in Oklahoma during September and October yields the maximum dry matter yield of switchgrass

(Haque and Epplin 2012). However, the harvest window may be extended, but may yield dry matter losses of 5% per month between the months of November and March (Haque and Epplin 2012). For a harvest window of two months, the estimated cost to lease land, produce, harvest, store switchgrass is $52.75 per ton (Epplin et al. 2007). However, for a harvest window of eight months, the cost is estimated to be $36.88 per ton of switchgrass (Epplin et al. 2007).

2.1.2 Contracts

Epplin et al. (2007) suggests that the possible development of a lignocellulosic biomass-to-ethanol industry may follow one of two options. The first is for the biorefinery to enter into long-term production and harvest contracts with individual farmers that are located within a specified distance of the biorefinery (Larson et al. 2010). The alternate option is for ethanol production to become more vertically integrated. The biorefinery would lease land and directly mange the production, harvest, storage, and transportation of the feedstock (Haque and Epplin 2012).

Production contracts between the farmers and the biorefinery would guarantee a price that the feedstock would be sold to the biorefinery for (Covert et al. 2012). The production contract would essentially transfer the ownership of the expected yield from the farmers to the biorefinery. This would allow the biorefinery to make future predictions and calculations regarding ethanol output (Covert et al. 2012). Typically contract lengths have two levels. Producers are expected to require at least seven year contracts because switchgrass is a perennial that is planted once every ten years. If the producer continues to produce the switchgrass, then a contract of 16 years would be expected. Additional factors that may be included in a contract are: crop-insurance type instruments that may be purchased under the contract and the option for

biorefineries to personally harvest the biomass from the farmers land. Seed cost-share for establishment of the switchgrass may also be included in the contract (Fewell et al. 2011).

Long term leases between land owners and biorefineries would allow the biorefineries to reduce the expected variability of feedstock costs. Under such leases, the biorefinery would be able to control every aspect of the switchgrass production process such as, establishment, crop management, harvesting, storing, and transporting the switchgrass (Haque and Epplin 2012). Both contracts and long-term leases help to provide a continuous flow of feedstock to the biorefinery which may reduce risk and price variability (Haque and Epplin 2012).

2.1.3 Break-Even Price of Switchgrass

Two different pricing strategies for switchgrass were evaluated (Zhan et al. 2005). The first was a mixed pricing strategy in which one uniform price was paid to farmers regardless of transportation costs and the second was a discriminatory strategy where the price was based on farm-gate price plus the price of transportation to the biorefinery. The net present value and break-even approaches are also used in determining switchgrass price (Walsh et al. 2003; Mooney et al. 2009). Switchgrass is generally harvested once annually and has a relatively long lifespan; therefore, the net present value approach can be used to evaluate the value of switchgrass by discounting each year's value into the base year (Walsh et al. 2003). Because there is no market for switchgrass that can be used to determine the exact market value of switchgrass, the break-even price approach is a more common technique used in biomass pricing literature. The majority of the analysis for potential switchgrass markets has focused on estimating production costs (Jensen et al. 2007). Therefore, the break-even price is analyzed when evaluating the economic potential of switchgrass.

Farm-gate break-even prices for 5 year and 10 year production contracts were determined by calculating unit production costs from enterprise budgets that varied by input level and yield (Mooney et al. 2009). The well-drained upland location was found most suitable for row crops producing the largest yield (17.7 Mg ha^{-1}) and lowest break-even price (\$46 Mg^{-1}) for a 10 year period. However, the marginal flood plain location yielded lowest (8.5 Mg ha^{-1}) and had the highest break-even price (\$69 Mg^{-1}). Mooney et al. (2009) concluded, break-even prices were sensitive to yield, nitrogen price, and fuel price. Results suggest a lower break-even price for switchgrass in the Southeast U.S. as compared to other U.S. regions, mainly due to high yields for the Alamo variety (Mooney et al. 2009). Additionally, Wu et al. (2010) estimated the break-even price of switchgrass to be \$60 Mg^{-1}. The prorated cost of production per dry ton of switchgrass was \$39.48 for round bales; however, when transport, storage losses, loading and unloading costs were added the break-even cost of the feedstock ranged from \$52.92-\$60.81 per ton of switchgrass (Popp and Hogan 2007). Larson et al. (2010) estimated the break-even cost for a traditional round bale to be \$78.43 per dry ton of switchgrass.

2.2 Ethanol Production

2.2.1 Transportation

The transportation of switchgrass is an equipment intensive enterprise which accounts for the majority of the final delivered cost of switchgrass (Cundiff and Marsh 1996). The most important factors affecting the total delivered cost are: the bulk density of switchgrass, moisture content, and the distance the biomass is transported (Sokhansanj et al. 2006).

After switchgrass has been harvested and baled, the bales are placed along the edge of the farmers filed. This can be done by farmers with a tractor and bail fork. The bales are then collected, transported, and unloaded into a storage facility. Transportation costs include: loading, labor, fuel, and machinery. The transportation and handling study conducted by Iowa State showed that the total transportation cost per ton of switchgrass is $14.75 after being transported 30 miles. The cost of hauling switchgrass is minimized by maximizing the amount of dry matter in every truckload (Cundiff and Grisso 2008). One way that this can be accomplished is by maxing out the axle weight of each truck. Larson et al. (2010) indicates that the cost of transporting biomass to the biorefinery is assumed to be $11.95 per dry ton. The cost of loading, transporting, and unloading containerized loads of round switchgrass bales is estimated at $8-10 per dry ton (Cundiff and Grisso 2008). This assumes a certain size bale and truck load.

2.2.2 Storage and Dry Matter Loss

An enclosed building may maintain the quality of the switchgrass for ethanol production, but it is the most expensive type of storage. The exposure of bales to rain, ultraviolet rays, and fluctuations in temperature and humidity may result in increased dry matter storage losses (Sanderson et al., 1997). Differing storage methods and techniques affect how much ethanol can be produced from one ton of switchgrass (Covert et al. 2012). The most common methods of storing switchgrass are using square bales or round bales; both have advantages and disadvantages. Rectangular bales typically have cost advantages regarding handling, transportation, and storage because more tons can be placed in a given area (English et al. 2008). However, studies have indicated that dry matter loss from precipitation and weathering during

storage for covered square bales was greater than that of covered round bales. Additionally, stacks of large square bales, bailed too wet, may spontaneously combust.

According to Cundiff and Grisso (2008), round bales, baled at higher moisture contents, will store satisfactorily in single layer ambient storage. Large round bales are also designed to shed water and typically have an advantage over square bales when considering dry matter loss (Cundiff and Grisso 2008). This may be especially true in the Southeastern U.S. due to the typically higher precipitation year-round relative to other regions of the country (Larson et al.2012). The estimated costs for the storage of round switchgrass bales include the cost of: plastic tarps, gravel, and wooden pallets. Larson et al. (2010) estimated the storage cost for a round bale using a tarp and a pallet is $7.75 per dry ton when considering traditional round bales. Wang et al. (2009) determined that the cost of storage for a round bale is $3.83 per dry ton. Cundiff and Marsh (1996) determined that net wrapped round bales are not required to be stored under plastic tarps; therefore, the estimated costs for storing round switchgrass bales without a tarp is $3.20 per dry ton.

Most switchgrass storage is expected to occur outdoors due to its bulkiness (Popp and Hogan 2007). However, bales that are exposed to rain, ultraviolet rays, and fluctuation in temperature and humidity may experience dry matter storage losses (DML) (Sanderson et al. 1997). Total handling and storage dry matter loss for twine wrapped switchgrass bales stored for six months in Indiana was 13% (Johnson et al. 1991). Additionally, 13% storage dry matter loss for round switchgrass bales stored in Texas was reported by Wiselogel et al. (1996) and Sanderson et al. (1997). Data collected by Larson et al. (2010) suggested that storage dry matter losses generally increased at a decreasing rate with cumulative precipitation and time. Savoie et al. (2006) also indicated that dry matter losses for stored biomass tended to diminish over time

and eventually cease when there was no remaining organic matter to oxidize. Also, storage losses for bales were mainly influenced by whether the bales were covered with a plastic tarp or not (Larson et al. 2010).

2.2.3 Ethanol Production Process and the Biorefinery

Currently, the majority of ethanol in the United States is produced from corn (Petrulis et al. 1993). However, using corn as the only ethanol feedstock is unlikely to meet the growing demand for ethanol (McLaughlin et al. 1999). Developing the use of perennial forage crops such as switchgrass for ethanol production would assist in meeting the future demand for ethanol. There are two primary processes that can be used in switchgrass conversion to ethanol: enzymatic hydrolysis or thermochemical processes (Haque and Epplin 2012).

Enzymatic hydrolysis is a process that utilizes enzymes to break down cellulose, while gasification is a typical thermochemical process (Haque and Epplin 2012). For Fischer-Tropsch diesels and hydrogen production, thermochemical conversion processes are considered to be the most promising. However, biochemical (e.g. enzymatic) processing is viewed as the most suitable method for ethanol production. Biochemical processing begins with collection and transportation of the feedstock for pretreatment at the biorefinery. The pretreated biomass then undergoes a hydrolysis process which is used to depolymerize the cellulose and hemicellulose into their component sugars. Following, fermentation occurs in order to convert the sugars into ethanol and then the ethanol is recovered which yields the final product (Carolan et al. 2007).

Biorefineries optimum size involves tradeoffs between economies of scale with larger plants and increased costs of biomass transportation. Therefore, in order to achieve conversion

process economies research suggests large biorefineries capable of handling 5,000 to 10,000 tons of biomass per day will be necessary (Carolan et al. 2007). According to Aden et al. (2002), the optimal plant processes between 6,000 and 8,000 tons of biomass per day. Kaylen et al. (2000) analyzed the tradeoffs between transportation costs and scale economies and found the estimated net present value of a biorefinery maximized at capacity processes 4,360 tons of biomass per day. In an investment appraisal of a biorefinery, Tembo et al. (2003) assumed a biorefinery able to process 3,800 tons of biomass per day to be optimal. Hamelinck et al. (2005) assumed plant sizes of 2,000, 5,000 and 10,000 tons per day for their short-term, middle, and long-term analyses. Additionally, biorefineries with capacities to process 2,200 tons of biomass per day and 10,000 tons per day were modeled (Lynd et al. 2005). The studies listed suggest that in the future biorefineries will be large facilities able to process between 5,000-10,000 tons of biomass per day (Carolan et al. 2007).

The conversion rate is typically used to calculate the amount of ethanol (gallons) produced from processing one unit (tons) of switchgrass. Covert et al. (2012) utilized conversion rates of 75-100 gallons of ethanol per ton and listed the associated net revenue figures with each conversion rate. Perrin et al. (2008) used a conversion rate of 0.38 liter of ethanol per kilogram of switchgrass (91.07 gallons per ton). Schmer et al. (2008) also emphasized that the conversion rate of ethanol production is equal to 0.38 liter per kilogram of switchgrass.

2.2.4 Break-Even Price of Ethanol

Many studies have listed estimates of the cost to produce cellulosic ethanol. These cost estimates range from $0.21 per liter of ethanol to $1.25 per liter of ethanol when adjusted to 2010 dollars. Many assumptions have resulted due to the differing estimates. Such assumptions

include: differing ethanol conversion rates, varied biorefinery investment costs, a large range of switchgrass break-even costs, and differing ethanol conversion processes (Haque and Epplin 2012).

One study in the Midwest showed that switchgrass produced 540% more renewable energy than non-renewable energy consumed (Schmer et al. 2008). However, cellulosic ethanol production costs are two to three times higher than those of ethanol produced from corn (Sticklen 2008). Cellulosic ethanol production in the United States is expensive due to the high costs of pretreatment (da Costa Sousa et al. 2009).

Input costs and conversion costs are accounted for within a biofuels accounting system (Covert et al. 2012). The input costs result from purchasing the feedstock which may be driven by contracts or possibly the market. The conversion cost includes every cost that is incurred from converting the feedstock into ethanol (Peter 2002). The revenue that is generated from the sale of the ethanol will depend upon the market prices for the ethanol (Covert et al. 2012).

Haque and Epplin (2012) demonstrated a discounted cash flow modeling system that could be used to determine the necessary ethanol price in order for a biorefinery to break-even. Their model allowed for determination of optimal switchgrass production, harvest, investment in machinery, storage, transportation strategy, biorefinery size, and biorefinery location. They computed three different break-even prices due to the uncertainty regarding capital requirements and the number of liters of ethanol that could be produced per ton by a commercial sized facility. They concluded that for a capital requirements of $\$200\times 10^{6}$, $\$400\times 10^{6}$, and $\$600\times 10^{6}$ and a conversion rate of 250 L of ethanol Mg^{-1}, the break-even prices of ethanol would be \$0.48 L^{-1} (\$1.82 per gallon), \$0.56 L^{-1} (\$2.12 per gallon), and \$0.65 L^{-1} (\$2.46 per gallon).

The break-even price of ethanol produced by Haque and Epplin (2012) was much higher when compared to similar research. The Department of Energy estimates that the cost of producing ethanol will be $1.02 per gallon (Aden 2002; Glodemberg 2007; Tyner 2008). Wyman (2007) estimates the total cost per gallon of ethanol ranges between $0.64 and $0.52 where the variability in cost is credited to the changes in ethanol yield per ton of biomass. Tyner (2008) estimates the total cost of ethanol to be $1.12 per gallon. However, according to a sampling experiment of 4,825 monthly reports from 232 fueling stations in Minnesota between October 1997 and November 2006, the mean retail price of ethanol was $1.74 per gallon with the minimum price being $0.74 per gallon and the maximum price being $2.96 per gallon (Anderson 2010). The sampling result found by Anderson (2010) is closer to the results found by Haque and Epplin (2012).

CHAPTER III

CONCEPTUAL FRAMEWORK

Assume that the switchgrass feedstock purchased from farmers could potentially be transported and stored by the biorefinery at satellite facilities as opposed to leaving it on the farmer's land. By storing the feedstock in facilities near the biorefinery, the dry matter loss (DML) may be less than it would be if the feedstock was stored on farmer's land. The exposure of switchgrass bales to rain, ultraviolet rays, and fluctuations in temperature and humidity may result in dry matter storage losses including the sugar decomposition that occurs during storage (Sanderson et al. 1997). A model considering switchgrass procurement, transportation, storage, biorefinery construction costs, operating and maintenance costs, and ethanol production has been built to determine the break-even price of ethanol. All variable and parameter descriptions used in the model are shown in Tables 1 and 2.

3.1 Switchgrass Procurement and Ethanol Production

3.1.1 Switchgrass Transportation and Storage

The switchgrass feedstock that will be processed to produce ethanol during one year is harvested from the field and transported to the biorefinery at one time. We assume that the amount of feedstock harvested in year t, XT_t, is processed continuously throughout the year to produce ethanol at the biorefinery. Harvest is initiated in November following a hard frost and continues through February. Therefore, one third of the feedstock can be processed immediately within the first third of the 12 month period (e.g. November, December, January, and February).

The remaining two thirds of the feedstock that is purchased/transported from the farmers is placed into storage owned and maintained by the biorefinery. Therefore, the amount of feedstock stored in year t, XS_t, is equal to:

$$XS_t = \frac{2}{3} XT_t \quad (1)$$

which means the amount of switchgrass stored in year *t* is two thirds of the total amount of switchgrass purchased and transported by the biorefinery. The other one third of the switchgrass is processed continuously during the first four months of year *t.* The amount of switchgrass feedstock processed can be determined by dividing one year into three parts. The first third of the year, one third of the feedstock purchased is transported and then processed immediately by the biorefinery. The second third of the year, another one third of the feedstock that was transported and stored for the first third of the year is processed. The last third of the year, the remaining feedstock is processed by the biorefinery leaving no switchgrass in storage. However, during the months that the switchgrass is stored, dry matter loss occurs which includes some amount of sugar loss. The sugar within switchgrass is made up of cellulose and hemicellulose. The result of processing such sugars within a biorefinery yields ethanol. However, dry matter also includes ash, lignin, and extractives, which cannot be converted into ethanol. Therefore, the amount of sugar that is lost along with the total amount of sugar within the switchgrass being processed are the two key components in ethanol production.

3.1.2 Ethanol Production

All of the remaining sugar is assumed to be available for ethanol production during each period. Therefore, the amount of switchgrass stored during the second and third parts of the year must account for the dry matter loss which includes the sugar loss. The total amount of sugar processed in year t equals:

$$\text{Total Sugar Processed} = \frac{1}{3}XT_t * \gamma_0 + \frac{1}{3}XT_t * (1-\Delta) * \gamma_1 + \frac{1}{3}XT_t * (1-\Delta) * \gamma_2 \qquad (2)$$

where Δ is the total percentage of dry matter loss that has occurred after six months of storage, and we assume the dry matter loss in switchgrass stops increasing after about 200 days. However, the sugar may continue to decompose. The percentage of sugar within the switchgrass after the initial harvest is represented by, γ_0. The percentage of sugar within the switchgrass after being stored for 100 days is represented by, γ_1. The percentage of sugar within the switchgrass after being stored for 200 days is represented by, γ_2.

Through ethanol production processes, the sugar within switchgrass can be converted into ethanol. The conversion rate of sugar can be used to measure the amount of ethanol converted from one unit of sugar. Suppose the conversion rate of sugar to ethanol is λ, which remains constant. Multiplying the conversion rate, λ, by the total amount of the sugar processed from the switchgrass purchased and transported in year *t*, XT_t, yields the total amount of ethanol produced, Q_t, from the biorefinery in year t. Therefore, the biorefinery's ethanol production function in year t can be written as:

$$Q_t = \lambda * \left[\frac{1}{3} XT_t * \gamma_0 + \frac{1}{3} XT_t * (1 - \Delta) * \gamma_1 + \frac{1}{3} XT_t * (1 - \Delta) * \gamma_2\right] \quad (3)$$

The conversion rate of switchgrass to ethanol can also be used to determine ethanol production. We use α_0 to indicate the conversion rate of ethanol that can be produced from one ton of switchgrass. The α_0 can be determined through the experiment and there is existing literature regarding the α_0 as well. The conversion rate of ethanol that can be produced from one ton of switchgrass after being stored for 100 days is represented by α_1. The conversion rate of ethanol from one ton of switchgrass after being stored for 200 days is represented by α_2. Each of the three switchgrass conversion rates can be expressed as percentages of sugar contained within the switchgrass. Therefore, the switchgrass conversion rate is equal to the biomass conversion rate multiplied by the percentage of sugar contained within the switchgrass.

$$\alpha_0 = \lambda * \gamma_0;\ \alpha_1 = \lambda * \gamma_1;\ \alpha_2 = \lambda * \gamma_2 \quad (4)$$

Substituting equation (4) into equation (3), the ethanol production function can be rewritten as:

$$Q_t = \frac{1}{3} XT_t * \alpha_0 + \frac{1}{3} XT_t * (1 - \Delta) * \alpha_1 + \frac{1}{3} XT_t * (1 - \Delta) * \alpha_2 \quad (5)$$

Equation (5) means the ethanol production in year *t* is the summation of the ethanol produced in three processing periods. In each period, the ethanol production is calculated by multiplying the amount of switchgrass remaining (after the dry matter loss) and the switchgrass conversion rate. From equation (5) above, the total amount of switchgrass purchased/transported in year *t*, XT_t, is equal to:

$$XT_t = \frac{3Q_t}{\alpha_0 + (1-\Delta) * \alpha_1 + (1-\Delta) * \alpha_2} \tag{6}$$

Notice that the switchgrass conversion rate and dry matter loss are experimental parameters and are held constant. The total amount of switchgrass purchased/transported is a linear function of the total amount of ethanol produced. For each additional unit of ethanol produced, $\frac{3}{\alpha_0+(1-\Delta)*\alpha_1+(1-\Delta)*\alpha_2}$ more units of switchgrass must be purchased/transported. Substituting equation (6) into equation (1) yields the amount of switchgrass stored:

$$XS_t = \frac{2Q_t}{\alpha_0 + (1-\Delta) * \alpha_1 + (1-\Delta) * \alpha_2} \tag{7}$$

Similar to equation (6), the total amount of switchgrass stored in year *t* is also a linear function of the total amount of ethanol produced. In order to produce one additional unit of ethanol, $\frac{2}{\alpha_0+(1-\Delta)*\alpha_1+(1-\Delta)*\alpha_2}$ more units of switchgrass must be stored in that year.

3.2 Profitability of Biorefinery

3.2.1 Net Return of Ethanol Production in Year $\boldsymbol{t}$

Suppose the ethanol produced is sold in a perfectly competitive market. Therefore, the ethanol produced in one biorefinery will not affect the ethanol market price. The price of ethanol is represented by ρ_t in year t. Four different costs are considered variable in each year's

production: total transportation cost, total storage cost, switchgrass procurement cost, and operating and maintenance costs in processing and storage facilities. Assume that the rates for transportation and storage remain constant each year. The net revenue of ethanol production in year t can be written as:

$$NR_t = \left(\rho_t * Q_t - \tau * XT_t - \omega * XS_t - P_{switchgrass} * XT_t\right) - \sum_{f=1}^{F} OMC_f \qquad (8)$$

where $\rho_t * Q_t$ is the total revenue generated from ethanol production. The net revenue of ethanol production can be obtained by subtracting the four variable costs from the total revenue. The τ represents the average rate of transporting harvested switchgrass to a storage facility at the biorefinery. The average rate of storing switchgrass is represented by ω. The price of switchgrass is represented by $P_{switchgrass}$. That is the agreed upon contract price between the farmers and biorefinery or the spot market price of the switchgrass. The OMC_f indicates the operating and maintenance cost for facilities of type *f*, either processing facilities or storage facilities. In order to produce efficiently, the biorefinery will operate at full capacity every year; therefore, the amount of ethanol produced will change very little.

To simplify the model, assume the ethanol price, ρ_t, and the amount of ethanol produced, Q_t, remain constant every year:

$$\rho_t = \rho; \;\; Q_t = Q \qquad (9)$$

Therefore, the total amount of switchgrass purchased and stored remains constant when substituting equation (9) into equations (6) and (7):

$$XT_t = \frac{3Q}{\alpha_0 + (1-\Delta) * \alpha_1 + (1-\Delta) * \alpha_2} = XT; \qquad XS_t = \frac{2Q}{\alpha_0 + (1-\Delta) * \alpha_1 + (1-\Delta) * \alpha_2} = XS \tag{10}$$

When substituting equations (9) and (10) into equation (8), the net return can be rewritten as,

$$NR = \left(\rho * Q - \tau * XT - \omega * XS - P_{switchgrass} * XT\right) - \sum_{f=1}^{F} OMC_f \tag{11}$$

Therefore, the annual net revenue remains constant assuming the ethanol price and ethanol production remains constant each year.

*3.2.2 Present Value of Net Return in **T** Years*

Assume the biorefinery can operate for T years. Therefore, each year there will be a fixed amount of profit (net revenue) coming in. The biorefinery must compare the present value of the future profit with the biorefinery investment cost in order to decide whether to build the facilities (e.g. the processing and storage facilities) or not. After discounting the future profit back to the initial year (when $t = 0$), the present value can be written as:

$$\begin{aligned} PV_T &= \frac{NR_1}{1+r} + \frac{NR_2}{(1+r)^2} + \frac{NR_3}{(1+r)^3} + \cdots + \frac{NR_T}{(1+r)^T} \\ &= \frac{NR}{1+r} + \frac{NR}{(1+r)^2} + \frac{NR}{(1+r)^3} + \cdots + \frac{NR}{(1+r)^T} \\ &= NR * \left[\frac{1}{1+r} + \frac{1}{(1+r)^2} + \frac{1}{(1+r)^3} + \cdots + \frac{1}{(1+r)^T}\right] \end{aligned}$$

$$= NR * \frac{\frac{1}{1+r}\left[1-\left(\frac{1}{1+r}\right)^{T}\right]}{1-\left(\frac{1}{1+r}\right)}$$

$$= NR * \frac{(1+r)^{T}-1}{r(1+r)^{T}}$$

where r is the discount rate. Therefore, the present value of all future cash inflows will be a linear function of annual net revenue with a constant factor $\frac{(1+r)^{T}-1}{r(1+r)^{T}}$. When substituting the net revenue into the equation above, the present value can be rewritten as:

$$PV_T = \left\{\left(\rho * Q - \tau * XT - \omega * XS - P_{switchgrass} * XT\right) - \sum_{f=1}^{F} OMC_f\right\} * PVAF \tag{12}$$

Therefore, the present value of all the future profits in T years, PV_T, can be calculated by multiplying the annual net revenue and the present value annuity factor. The present value annuity factor is equal to:

$$PVAF = \frac{(1+r)^{T}-1}{r(1+r)^{T}} \tag{13}$$

When T increases, the $PVAF$ also increases. Therefore, the present value will also increase from equation (12).

3.2.3 Biorefinery Investment

Assume the biorefinery's down payment for building the plant in year zero is c_0. The remainder of the capital needed to construct the facility and storage facilities is financed through a bank at an interest rate r. Furthermore, assume that the debt will be completely paid off within ten years by making annual payments, PMT_t, in year t. Therefore, the total investment can be written as:

$$C = c_0 + \frac{PMT_1}{1+r} + \frac{PMT_2}{(1+r)^2} + \frac{PMT_3}{(1+r)^3} + \cdots + \frac{PMT_{10}}{(1+r)^{10}} \tag{14}$$

The total investment cost used to construct the ethanol processing and switchgrass storage facilities can be calculated by adding the down payment and the present value of every loan payment.

3.2.4 Net Present Value of Ethanol Production

According to capital budgeting theory, the net present value (NPV) and break-even price approaches are the most commonly used pricing techniques in previous similar literature (Walsh et al. 2003; Mooney et al. 2009). The NPV approach is preferable considering that the biorefinery has a lifespan of 10-20 years (Walsh et al. 2003). This method accounts for the time value of all future profits when evaluating the NPV of a biorefinery. Subtracting the biorefinery investment, c_0, from the present value of the future net revenue yields the biorefinery's NPV formula:

$$NPV = \left\{ \left(\rho * Q - \tau * XT - \omega * XS - P_{switchgrass} * XT \right) - \sum_{f=1}^{F} OMC_f \right\} * PVAF - \left(C_0 + \frac{PMT_1}{1+r} + \frac{PMT_2}{(1+r)^2} + \cdots + \frac{PMT_{10}}{(1+r)^{10}} \right) \quad (15)$$

By substituting equations (6) and (7) into equation (15) above, the NPV can be rewritten as:

$$NPV = \left\{ \left(\rho * Q - \tau * \frac{3Q}{\alpha_0 + (1-\Delta) * \alpha_1 + (1-\Delta) * \alpha_2} - \omega * \frac{2Q}{\alpha_0 + (1-\Delta) * \alpha_1 + (1-\Delta) * \alpha_2} - P_{switchgrass} * \frac{3Q}{\alpha_0 + (1-\Delta) * \alpha_1 + (1-\Delta) * \alpha_2} \right) - \sum_{f=1}^{F} OMC_f \right\} * PVAF - \left(C_0 + \frac{PMT_1}{1+r} + \frac{PMT_2}{(1+r)^2} + \cdots + \frac{PMT_{10}}{(1+r)^{10}} \right)$$

Then, the NPV formula can be simplified as:

$$NPV = \left\{ \left[\rho - \frac{3\tau + 2\omega + 3P_{switchgrass}}{\alpha_0 + (1-\Delta) * \alpha_1 + (1-\Delta) * \alpha_2} \right] * Q - \sum_{f=1}^{F} OMC_f \right\} * PVAF - \left(C_0 + \frac{PMT_1}{1+r} + \frac{PMT_2}{(1+r)^2} + \cdots + \frac{PMT_{10}}{(1+r)^{10}} \right) \quad (16)$$

The net present value of an operating biorefinery is affected by the ethanol production cost, transportation and storage cost, switchgrass procurement cost, ethanol production quantity, switchgrass conversion rate, switchgrass dry matter loss, biorefinery operating and maintenance costs, discount rate, and the biorefinery construction cost. From equation (10), ethanol price and production level have positive effects on the net present value, while transportation cost, storage cost, switchgrass procurement cost, biorefinery operating and maintenance costs, and biorefinery construction cost have negative effects on the net present value. Switchgrass conversion rates have positive effects on the net present value which indicates that additional production efficiency will cause the biorefinery to be more profitable. However, dry matter loss has a

negative effect on the net present value, which can be translated into an additional specific storage cost.

3.3 Break-Even Price of Ethanol

The break-even price of the ethanol produced by a biorefinery can be calculated by setting the $NPV = 0$:

$$NPV = \left\{\left[\rho - \frac{3\tau + 2\omega + 3P_{switchgrass}}{\alpha_0 + (1-\Delta) * \alpha_1 + (1-\Delta) * \alpha_2}\right] * Q - \sum_{f=1}^{F} OMC_f\right\} * PVAF - \left(C_0 + \frac{PMT_1}{1+r} + \frac{PMT_2}{(1+r)^2} + \cdots + \frac{PMT_{10}}{(1+r)^{10}}\right) = 0 \quad (17)$$

The break-even price of ethanol can then be calculated as:

$$\rho_{break-even} = \frac{\frac{C_0 + \sum_{i=1}^{10} \frac{PMT_i}{(1+r)^i}}{PVAF} + \sum_{f=1}^{F} OMC_f}{Q} + \frac{3\tau + 2\omega + 3P_{switchgrass}}{\alpha_0 + (1-\Delta) * \alpha_1 + (1-\Delta) * \alpha_2} \quad (18)$$

From equation (18), the breakeven price is positively affected by the biorefinery construction cost, operating and maintenance costs, transportation cost, storage cost, switchgrass procurement cost, and dry matter loss. However, the breakeven price of ethanol is negatively affected by the ethanol production level and switchgrass conversion rates.

The break-even price should be compared to the current market price of ethanol. This can be done in order to determine if the costs of a biorefinery are too high and if they need to be minimized in order for the biorefinery to make a profit from producing ethanol. If the break-even price is too high compared to the current spot market price of ethanol, then the cost of producing ethanol in the biorefinery is too high. This would leave little or no profit for the biorefinery. However, if the break-even price is low compared to the current spot market price of ethanol, then the biorefinery will be profitable when producing ethanol. As long as no additional biorefineries enter the market, then the biorefinery can keep the profit and earn more by increasing its ethanol production which will also improve the biorefinery's efficiency by achieving economies of scale within ethanol production.

CHAPTER IV

METHOD AND DATA

4.1 Plant Size and Switchgrass Conversion Rate

From the conceptual framework section above, it is apparent that the plant size greatly impacts the ethanol break-even price and the NPV of the biorefinery, according to equation (18). Also, the plant size will have an effect on the operating and maintenance costs of the biorefinery and the biorefinery construction cost, which will also affect the break-even price of ethanol and NPV of the biorefinery. The literature discusses varying hypothetical biorefinery plant sizes and biorefinery construction costs as shown in Table 4.

However, this study will evaluate three different plant sizes for the biorefinery, 50 million gallons of ethanol per year (189×10^6 L yr^{-1}), 75 million gallons of ethanol per year (284×10^6 L yr^{-1}), and 100 million gallons of ethanol per year (379×10^6 L yr^{-1}) (Haque and Epplin 2012). The data from Haque and Epplin (2012) is used because in addition to the plant size, the operating and maintenance costs and the biorefinery construction cost are provided. Therefore, three different break-even prices for ethanol will be determined based on the different plant sizes. Considering the switchgrass conversion rate between the production of ethanol and the amount of switchgrass processed, the amount of switchgrass processed can be derived with a conversion rate of 88.23 gallons of ethanol per dry ton of switchgrass (334 Liters Mg^{-1}) (Haque and Epplin 2012). When conducting the sensitivity analysis, a range of 66.04-110.16 gallons of ethanol per dry ton of switchgrass (250 – 417 Liters Mg^{-1}) will be used (Haque and Epplin 2012).

4.2 Costs

Currently, no biorefineries exist; therefore, several cost assumptions are needed. The operating and maintenance cost includes: labor, utilities, chemicals, other variable inputs, taxes, repairs, and insurance costs. This cost is estimated at \$0.20 L^{-1} of ethanol production (Haque and Epplin 2012). Assuming this cost, the total operating and maintenance cost (OMC_f) equals to \$19$\times 10^6$, \$37.8$\times 10^6$, and \$75.8$\times 10^6$ for each plant size. The cost of transporting the switchgrass to the biorefinery is \$11.95 Mg^{-1} for a traditional round bale and \$5.10 Mg^{-1} for a BaleTech bale (Larson et al. 2010). According to Larson et al. (2010), the storage cost for a round bale is \$7.75 Mg^{-1}.

The biorefinery construction costs (AFC) of the small, medium, and large plants are: \$190$\times 10^6$, \$275$\times 10^6$, and \$400$\times 10^6$ (Haque and Epplin 2012). However, an additional \$3$\times 10^6$, \$4.5$\times 10^6$, \$6$\times 10^6$construction costs are added to the small, medium, and large biorefineries yielding construction costs of \$193$\times 10^6$, \$279.5$\times 10^6$, and \$406$\times 10^6$. This is done to account for the additional land and capital costs incurred from adding storage facilities near the biorefinery which Haque and Epplin (2012) did not do (English 2012). Assume that the discount rate is equal to the interest rate. Therefore, the present value of all of the payments made is equal to the full loan amount borrowed. So, the biorefinery's construction cost includes the initial down-payment, c_0, plus the present value of every loan payment.

$$AFC = c_0 + \frac{PMT_1}{1+r} + \frac{PMT_2}{(1+r)^2} + \frac{PMT_3}{(1+r)^3} + \cdots + \frac{PMT_{10}}{(1+r)^{10}} \tag{19}$$

Substituting equation (19) into equations (16) and (18), simplifies the net present value formula and the break-even price formula:

$$NPV = \left\{\left[\rho - \frac{3\tau + 2\omega + 3P_{switchgrass}}{\alpha_0 + (1-\Delta)*\alpha_1 + (1-\Delta)*\alpha_2}\right] * Q - \sum_{f=1}^{F} OMC_f\right\} * PVAF - AFC \tag{20}$$

and

$$\rho_{break-even} = \frac{\frac{AFC}{PVAF} + \sum_{f=1}^{F} OMC_f}{Q} + \frac{3\tau + 2\omega + 3P_{switchgrass}}{\alpha_0 + (1-\Delta)*\alpha_1 + (1-\Delta)*\alpha_2} \tag{21}$$

Since there is no market for switchgrass as a fuel feedstock, it is assumed that the price of switchgrass is equal to the estimated break-even price of switchgrass, (i.e. \$78.43 Mg^{-1}) which is used as a rough estimate comparable to what a market price may be (Larson et al. 2010). According to Mooney et al. (2007), the range for the break-even price of switchgrass is \$43.93-\$78.88 Mg^{-1}. Table 4 also lists various feedstock costs shown in literature ranging from \$33.00-\$83.00 Mg^{-1}.

The discount rate base value is 10%. This base value was chosen because typically oil and gas companies discount their projected future revenue with a 10% rate (Covert et al. 2012). The 10% discount rate shows the time value of future net cash flows from the proven reserves (Board 1982). Biofuel companies wish to be treated with equal consideration by investors; therefore, the biofuel industry should discount its reserve values as well using the same 10%

discount rate (Covert et al. 2012). However, the discount rate range used for the sensitivity analysis is 8%-12% (Chen 2011).

4.3 Bale Study

The final data needed are dry matter loss and sugar content over time. In an experiment conducted at the University of Tennessee Biomass Innovation Park, switchgrass was packaged in different ways and stored under cover and not under cover. The various sample bales were evaluated over a 500 day storage experiment in order to determine the physical and chemical impacts experienced by each bale. About 200 acres of 2-year old Alamo switchgrass from fields near Tellico, Plains, TN, were mowed, harvested using a self-propelled forage chopper with a windrow pickup, and preprocessed using the BaleTech3® between November 20, 2011 and February 3, 2011 as shown in Figure 3-1. The BaleTech3®, traditionally used as a trash compactor, was used to bale chopped switchgrass into large bales using an air tight cellophane-like material illustrated in Figure 3-2. A traditional round baler was used for the remainder of the bales that utilized a variety of twine wrap, mesh wrap, and triple mesh wrap. Additionally, bales were covered by a plastic tarp. Bales were moved to the UT Biomass Innovation Park, Vonore, TN, and were randomly selected into six storage time treatments with five replications for storage time as shown in Figure 3-3 and 3-4.

Initial samples were taken of each bale. Subsequent samples were taken after 50, 100, 200, 300, 400, and 500 days of storage. Following procedures described in Mooney et al. (2011) for the Milan, TN, storage study, bales upon removal from storage were weighed, wrap materials removed, photographed, separated into two halves, and one of the halves photographed again. After each bale had been split open with either chain saws or a bale splitter, side profile

pictures were taken of every bale shown in Figure 3-5, Figure 3-6, and Figure 3-7. The picture was then evaluated to determine the different weathered areas within each bale. This was accomplished by evaluating areas that had differing physical appearances (i.e. color). The bales were then spray-painted to differentiate between each individual weathered area and biomass samples within each weathered area were collected by drilling into the bales with the Penn State sampler illustrated by Figure 3-8 and Figure 3-9. Several random plugs were taken for each area, and the number of weathered areas ranged from 1-4 per bale.

The percentage area of each weathered area was calculated using the profile picture and ArcMap software. It was determined that the best way to obtain a representative sample was to proportionately mix the weathered areas (based on the percentage area calculation) to obtain a representative sample for each bale. Then five bales were mixed in equal amounts to create one sample for compositional analysis. This resulted in 8 sample treatments per sampling time.

The Bioenergy Science and Technology Laboratory in the Center for Renewable Carbon followed the National Renewable Energy Laboratory (NREL) Standard Biomass Analytical Procedures to analyze the samples. The determination of the chemical composition of the switchgrass was achieved by the protocol developed by the US-DOE-NREL for the initial, 50, 100, 200,300,400, and 500 days samples in triplicate. The samples were first extracted using the laboratory analytical procedure developed by NREL to remove the non-structural material called extractives using both water and ethanol demonstrated in Figure 3-10. A total of eight primary components were measured: glucan, xylan, galactan, arabinan, mannan, extractives (sum of the water and ethanol soluble material), ash, and lignin. The glucan and xylan make up the cellulose portion of the switchgrass and the galactan, arabinan, and mannan make up the hemicellulose portion of the switchgrass. The cellulose and hemicellulose are the sugar components of the

switchgrass that are used to produce ethanol. Lignin is a byproduct that can be used to produce varying products and there is no known current use for the ash component of the switchgrass (English 2012).

Review of the data shows that in general, the cellulose and extractives content of the BaleTech bales decreases with time, while lignin and ash increase. The cellulose, lignin, ash, and extractives content within the traditional round bales appears to remain relatively constant. The cellulose content within the traditional round bales appears to remain constant up to 300 days; however, there is a greater amount of variability between the bales. The hemicellulose content appears to decrease within the first 50 days and then stabilizes for all samples. The ash content within the BaleTech bales is consistently higher compared to the traditional methods. Near infrared spectra were collected on each treatment sample and were analyzed for additional spectral characterization of biomass chemical composition. Total sugar (Cellulose and Hemicellulose) remaining in switchgrass bales from the experiment results is shown in Table 3.

Figure 1 illustrates the cellulose content of the switchgrass samples when comparing the triple mesh wrapped round bales compared to the BaleTech bales. The percentage dry basis is shown for the initial, 50, 100, 200, and 300 day samples. It is apparent that the percentage is variable within the triple mesh wrapped bales and exhibits a slight increase. However, the BaleTech bales show a reduction at a steady rate. Overall, it appears that the triple mesh wrapped bales show a higher percentage than the BaleTech bales.

Similar to Figure 1, Figure 2 shows the hemicellulose content of the switchgrass samples when comparing the BaleTech bales to the more traditional triple mesh wrapped round bales. The triple mesh wrapped round bales show some variability, but remain around the same general

percentage overall. The BaleTech bales substantially decrease within the first 50 days of storage, but then level off.

Additionally, Duncan's Multiple Range test was used to determine whether traditional round bales are significantly different from BaleTech bales considering the moisture content of the bales. The results indicated that the traditional round bales are statistically different from the BaleTech bales for weathered area one after 50, 100, 200, 300, 400, and 500 days of storage. However for weathered area two, the traditional round bales are only statistically different from the BaleTech bales after 100, 400, and 500 days of storage. Therefore, traditional round bales and BaleTech bales impact switchgrass differently after being stored.

The value used for dry matter loss is 13%. Additionally, the values used to calculate the change in sugar content within the bales were 63.4% for the initial November BaleTech samples, 60.8% for the 100 day November BaleTech samples, and 59.2% for the 200 day November BaleTech samples. The values used for the traditional triple mesh wrapped bales were 60.3% for the initial samples, 62.1% for the 100 day samples, and 58.5% for the 200 day samples.

CHAPTER V

RESULTS AND DISCUSSION

First a baseline is established for three plants, small, medium, and large similar to Haque and Epplin (2012). Following, a discussion of these base results, a sensitivity analysis is conducted for several variables including: conversion rate, switchgrass contract price, and discount rate.

5.1 Break-Even Price of Ethanol

The costs used as the baseline to determine the break-even price of ethanol are: $78.43 per ton of switchgrass purchased, $11.95 per ton of switchgrass transported for traditional round bales, $5.10 per ton of switchgrass transported for BaleTech bales, and $7.75 per ton of switchgrass stored. The assumed conversion rate was 88.23 gallons of ethanol per ton of switchgrass and the discount rate was 10%. Each of the base values listed above were held constant when determining the break-even prices of ethanol for the different biorefinery sizes as shown in Table 5.

5.1.1 Small Biorefinery

A small biorefinery will produce 50,000,000 gallons of ethanol per year. The construction cost is $193,000,000 and the annual operating and maintenance costs are $19,000,000. The amount of traditional switchgrass round bales purchased and transported to

the biorefinery was 620,475 tons and the amount stored was 413,650 tons; the break-even price of ethanol for a small biorefinery using traditional round bales is $2.02 per gallon.

Under the conditions listed above, the amount of switchgrass using the BaleTech bales purchased/transported was 683,787 tons and the amount of BaleTech bales stored was 455,858 tons. The resulting break-even price of ethanol using the BaleTech bales was $2.05 per gallon. The break-even price of ethanol using the BaleTech bales was higher than the break-even price of ethanol using the traditional round bales.

5.1.2 Medium Biorefinery

The medium biorefinery will produce 75,000,000 gallons of ethanol with a construction cost of $279,500,000 and an annual operating and maintenance cost of $37,800,000. The amount of switchgrass purchased/transported by the medium biorefinery using the traditional round bales was 930,713 tons. Additionally, the amount of switchgrass stored by the biorefinery was 620,475 tons. The break-even price for the traditional round bales in the medium biorefinery was $2.13 per gallon of ethanol. The amount of switchgrass BaleTech bales purchased by the medium biorefinery was 1,025,681 tons and the amount of BaleTech bales stored was 683,787 tons. Therefore, the medium biorefinery ethanol break-even price was $2.15 per gallon of ethanol using BaleTech bales.

5.1.3 Large Biorefinery

The construction cost of a large biorefinery was $406,000,000 with an annual operating and maintenance cost of $75,800,000. The amount of ethanol produced by a large biorefinery

was 100,000,000 gallons per year. The amount of traditional round switchgrass bales purchased and transported was 1,240,950 tons. Also, the amount of traditional round bales stored by the biorefinery was 827,300 tons. The break-even ethanol price of the large biorefinery using traditional round switchgrass bales was $2.42 per gallon. When considering switchgrass BaleTech bales, the amount purchased and transported to the large biorefinery was 1,367,574 tons. The amount of BaleTech bales stored was 911,716 tons. Therefore, the ethanol break-even price of the large biorefinery using BaleTech switchgrass bales was $2.45 per gallon.

5.1.4 Ethanol Break-Even Price Comparison with respect to Plant Sizes

When considering each plant size, the BaleTech ethanol break-even prices are higher than the traditional round bale break-even prices. The reason can be explained by the ethanol content in BaleTech bales compared to traditional round bales. The Bale Study experiment data shows a larger increase in sugar loss (ex. cellulose and hemicellulose) in BaleTech bales than in traditional round bales. The ethanol conversion rates of the BaleTech bales are lower than the conversion rates of the traditional round bales after being stored. It takes more switchgrass in the form of BaleTech bales to produce the same amount of ethanol compared to the traditional round bales. Therefore, the break-even ethanol price of BaleTech bales is higher than that of traditional round bales.

From Table 5, when the biorefinery size increases, the break-even price of ethanol increases as well regardless of bale type: ethanol prices increase from $2.02 to $2.42 using traditional round bales for storage, while the prices increase from $2.05 to $2.45 using BaleTech methods for storage. This occurs because the construction costs and operating and maintenance costs increase with size as well as the operating efficiency. When the biorefinery size increases,

more ethanol will be produced implying that more switchgrass will be processed. Therefore, the capacity of the machinery used in the ethanol production process will increase and the efficiency in producing ethanol will increase as well. However, operating and maintenance costs will increase due to the additional use of the machinery. Also, when the plant size increases, the biorefinery will build new and larger facilities; therefore, additional construction costs may be incurred. The tradeoff between the increases in cost and efficiency will yield the minimum efficient level of switchgrass processed. According to Kaylen et al. (2000), the minimum efficient level of switchgrass processed must be 1,569,600 tons per year. Carolan et al. (2007) suggests that biorefineries capable of handling 1,800,000 to 3,600,000 tons of switchgrass per year will be able to achieve production efficiency. The optimal level of switchgrass that should be processed annually is 2,160,000 to 2,880.000 tons in Aden et al. (2002). However, the amount of switchgrass processed in the large biorefinery shown in Table 4 is only 1,367,574 tons per year, which is significantly smaller than the minimum efficient switchgrass processing level. Therefore, the minimum efficient level was not achieved in this model, implying that the biorefinery is operating inefficiently. The increases in break-even prices are primarily due to the increases in biorefinery construction investment costs.

5.2 Sensitivity Analysis

Sensitivity analyses were conducted in order to determine the effects increasing/decreasing the ethanol conversion rate, switchgrass contract price, and discount rate had on the break-even prices of ethanol. These effects are illustrated in Figure 4 and in Tables 6 through 14.

5.2.1 Conversion Rate

For a small biorefinery using traditional round bales, when the conversion rate decreases to 66.04 gallons of ethanol per ton of switchgrass from the base value of 88.23 gallons of ethanol per ton of switchgrass, the break-even price of ethanol increases by 19.80% from $2.02 to $2.42 per gallon of ethanol. However, when the conversion rate increases from 88.23 gallons of ethanol per ton of switchgrass to 110.16 gallons of ethanol per ton, the ethanol break-even price decreases by 11.88% from $2.02 to $1.78 per gallon. The average elasticity of the conversion rate's influence on ethanol break-even price is -63.27%.

When the conversion rate decreases from the base value of 88.23 gallons of ethanol per ton of switchgrass to 66.04 gallons of ethanol per ton, for a small biorefinery using BaleTech bales, the ethanol break-even price increases by 19.51% from $2.05 to $2.45 per gallon. However, the breakeven price of ethanol decreases by 12.20% from $2.05 to $1.80 when the base conversion rate of 88.23 gallons of ethanol per ton of switchgrass increases to 110.16 gallons of ethanol per ton of switchgrass. Therefore, the average ethanol break-even price elasticity when considering the conversion rate is -63.32%. When comparing the impact that conversion rate has on the break-even ethanol prices of traditional round bales and Baletech bales, the BaleTech break-even prices are higher than the traditional round bales. However, both bale types show similar percentage price increases/decreases and price elasticities shown in Table 6.

Similarly, the conversion rate's impact on break-even ethanol prices for a medium biorefinery show comparable increases/decreases in price percentages and price elasticities to those of the small biorefinery (Table 7). The price elasticities of a medium biorefinery are

-38.53% and -60.37% for traditional round bales and BaleTech bales. However, the percentage increases /decreases are slightly less for the medium biorefinery compared to the small biorefinery. The impact of conversion rates on break-even ethanol prices for a large biorefinery are similar to the percentage changes in price and price elasticity of the medium biorefinery, but slightly less (Table 8). The price elasticity of a traditional round bale is -52.81% and -52.98% for BaleTech bales in a large biorefinery. Therefore, as biorefinery size increases, break-even prices become more insensitive to changes in switchgrass processing efficiency.

5.2.2 Switchgrass Contract Price

For a small biorefinery using traditional round bales, when the price of switchgrass decreases from the base value of $78.43 per ton of switchgrass to $43.93 per ton of switchgrass, the break-even price of ethanol decreases from $2.02 per gallon of ethanol to $1.59 per gallon (Table 9). Additionally, when the price of switchgrass increases from $78.43 per ton to $83.00, the break-even price of ethanol increases from $2.02 per gallon to $2.08 per gallon. However, when BaleTech bales are used in a small biorefinery, the break-even price of ethanol decreases from $2.05 per gallon to $1.57 per gallon when the price of switchgrass decreases from the base value of $78.43 per ton to $43.93 per ton. When the price of switchgrass increases from the base value of $78.43 per ton to $83.00 per ton, the break-even ethanol price increases from $2.05 to $2.11 per gallon. The average price elasticities of the small biorefinery using traditional round bales and BaleTech bales are 49.68% and 51.73%.

The elasticities of price based on the switchgrass prices for the medium biorefinery using traditional round bales and BaleTech bales are 43.09% and 52.79% (Table 10). Additionally, the price elasticities for the large biorefinery based on traditional round bales and BaleTech bales are

41.47% and 42.82% (Table 11). Therefore, similar to the impact of the conversion rate on ethanol break-even price, the break-even price becomes less sensitive as the size of the biorefinery increases.

5.2.3 Discount Rate

For a small biorefinery using traditional round bales, the break-even ethanol price decreases from $2.02 to $1.96 per gallon when decreasing the discount rate from the base value of 10% to 8% (Table 12). The break-even ethanol price increases from $2.02to $2.08 per gallon when increasing the discount rate from the base value of 10% to 12%. However, when using BaleTech bales in a small biorefinery and decreasing the discount rate from the base value 10% to 8%, the break-even ethanol price decreases from $2.05 to $1.99 per gallon. Also, increasing the discount rate from the base value 10% to 12% yields break-even ethanol prices of $2.05-$2.11 per gallon.

The price elasticities regarding discount rate for a small biorefinery using traditional round bales and BaleTech bales are 14.85% and 14.63% (Table 13). For a medium biorefinery, the price elasticities for traditional round bales and BaleTech bales are 14.08% and 13.95%. Finally for a large biorefinery, the price elasiticities for traditional round bales and BaleTech bales are 13.43% and 13.27% (Table 14). For each biorefinery size, as the discount rate increases, the break-even price of ethanol increases. Therefore, as the discount rate increases, the opportunity cost of the capital investment increases.

5.3 Ethanol Market Price Comparison

Figure 5 shows the market prices of ethanol from November 1, 2006 to August 1, 2012 in Iowa, Illinois, Nebraska, and South Dakota based data collected from the Agricultural Marketing Resource Center. Additionally, it shows the break-even ethanol prices from a small biorefinery using round bales and a large biorefinery using BaleTech bales calculated in this study. Analysis shows that it would be profitable for a small biorefinery to process traditional round bales at a break-even ethanol price of $2.02 per gallon. However, it would be less profitable for a large biorefinery to process BaleTech bales yielding a break-even ethanol price of $2.45 per gallon as shown in Figure 5.

CHAPTER VI

SUMMARY AND CONCLUSION

Ethanol produced from switchgrass is considered to be a promising future energy source. The economic feasibility of ethanol biorefineries using switchgrass as the only feedstock needs be examined further. The research conducted utilizes a model which considers switchgrass procurement, transportation, storage, biorefinery construction costs, operating and maintenance costs, and ethanol production in determining the break-even price of ethanol. Dry matter loss, including sugar (cellulose and hemicellulose) losses, were considered specific storage costs in this model.

The Bale Study experiment was used to determine sugar loss for this model. The Bale Study results revealed within traditional round bales, the cellulose content remained constant up to 300 days of storage. Additionally, the hemicellulose content decreased within the first 50 days of storage and then stabilized for all of the switchgrass samples. Additionally, the baseline costs used to determine the break-even price of ethanol were: $78.43 per ton of switchgrass, $11.95 per ton of switchgrass transported for traditional round bales, $5.10 per ton of switchgrass transported for BaleTech bales, and $7.75 per ton of switchgrass stored. The ethanol production is assumed to be a linear function of switchgrass processed after accounting for dry matter loss. The conversion rate used was 88.23 gallons of ethanol per ton of switchgrass and the discount rate was 10%. Based on the plant size and construction investment costs information obtained from Haque and Epplin (2012), the break-even price of ethanol produced ranges from $2.02 to $2.45 per gallon conditional upon three biorefinery sizes (small, medium, and large) and two bale types (traditional round bales and BaleTech bales). The results from the

model used are close to those calculated by Haque and Epplin (2012) ranging from $1.82 to $2.46 per gallon of ethanol.

The sensitivity analyses evaluated differing conversion rates, switchgrass contract prices, and discount rates. The results demonstrated that when the conversion rate increases from 66.04 to 110.16 gallons of ethanol per ton of switchgrass, the ethanol break-even price decreases. The more efficiently a biorefinery can process switchgrass, the average cost of ethanol production decreases, therefore, decreasing the ethanol break-even price because the biorefinery can use less switchgrass in order to produce a fixed amount of ethanol.

Additionally, switchgrass price has a positive impact on the ethanol break-even price. As the switchgrass procurement cost increases, the average cost of ethanol production increases also increasing the break-even price of ethanol. However, it becomes less sensitive as the biorefinery sizes increase. Discount rate also has a positive impact on the ethanol break-even price. This is due to the uncertainty regarding the future expectations and ethanol break-even prices. The biorefinery will require a higher price now in order to offset future risk. Among these factors, the ethanol conversion rate has the largest effect on the break-even price when considering the price elasticity. Using the ethanol market price data collected by the Agricultural Marketing Resource Center, the market price of ethanol ranges from $1.40-$3.02 per gallon with a mean value of $2.05 per gallon. Therefore, the small biorefinery would be the most profitable the majority of the time if traditional round bales are used yielding a break-even ethanol price of $2.02 per gallon.

Because there is no market for switchgrass, the market price of switchgrass cannot be used to calculate the break-even price of ethanol. Therefore, the break-even price of switchgrass must be used to estimate the costs associated with purchasing the switchgrass. Using such a

switchgrass procurement cost underestimates the real procurement cost because the biorefinery must provide a contract price higher than the break-even price of switchgrass in order to give farmers incentive to offset production and marketing risks. Also, due to the limitations of current technology, the ethanol production level is below the minimum efficient level required for the biorefinery to produce efficiently. If the biorefinery can reach economies of scale by increasing the switchgrass processing capacity, then the average cost of producing ethanol will decrease. Therefore, the break-even price of ethanol will be lower than the results obtained from this study. However, due to the limitations in accessing the information and data, the production conditions regarding the optimal switchgrass processing level cannot be analyzed accurately. These problems affect the results obtained from this analysis, and need to be researched further.

REFERENCES

Altman, I.J., D.R. Sanders, and C.R. Boessen. 2007. "Applying Transaction Cost Economics: A Note on Biomass Supply Chains." *Journal of Agribusiness* 25(1): 107-114.

Aden, M.R., K. Ibsen, J. Jechura, K. Neeves, J. Sheehan, B. Wallace, L. Montague, A. Slayton, and J. Lukas. 2002. "Lingnocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover." Golden, CO, Department of Energy: 154.

Adler, P.R., M.A. Sanderson, A.A. Boateng, P.J. Weimer, and H.G. Jung. 2006. "Biomass Yield and Biofuel Quality of Switchgrass Harvested in Fall or Spring." *Agronomy Journal* 98(6): 1518-1525.

Agricultural Marketing Resource Center, "Weekly Ethanol, Distillers Grain, & Corn Prices." Available online: http://www.google.com/url?sa=t&rct=j&q=agricultural%20marketing%20resource%20center%20weekly%20ethanol%20distillers%20grain%20corn%20prices&source=web&cd=1&ved=0CB8QFjAA&url=http%3A%2F%2Fwww.extension.iastate.edu%2Fagdm%2Fenergy%2Fxls%2Fagmrcethanolplantprices.xls&ei=b5h4UN3xCIK09gSwz4GgCg&usg=AFQjCNGfPTQjSYK6eLwvaMcqA2yDU_QzvQ (accessed September 12, 2012).

American Coalition for Ethanol. 2012. Federal Legislation. Available at: http://www.ethanol.org/index.php?id=78 (accessed March 26, 2012).

Anderson, S.T. 2010. "The Demand for Ethanol as a Gasoline Substitute." Working paper for National Bureau of Economic Research. Available at: http://www.nber.org/papers/w16371.

Bransby, D. 2008. "Switchgrass Profile." Department of Energy, Oak Ridge National Lab, Oak Ridge, TN. Available at: https://bioenergy.ornl.gov/papers/misc/switchgrass-profile.html (accessed September 4, 2012)

Board, F. A. S. 1982. "Statement on Financial Accounting Standard No. 69: Disclosures about Oil and Gas Producing Activities – An Amendment of FASB Statements 19, 25, 33, and 39." Norwark, CT: FASB.

Carolan, J.E., S.V. Joshi, and B.E. Dale. 2007. "Technical and Financial Feasibility Analysis of Distributed Bioprocessing Using Regional Biomass Pre-Processing Centers." *Journal of Agricultural & Food Industrial Organization* 5(2), Article 10.

Casler, M.D., K.P. Vogel, C.M. Taliaferro, and R.L. Wynia. 2004. "Latitude Adaptation of Switchgrass Populations." *Crop Science* 44: 293-303.

Chen, J. 2011. "Evaluation of Capital Investment and Cash Flows for Alternative Switchgrass Feedstock Supply Chain Configurations." MS Thesis, University of Tennessee, Knoxville.

Chen, F. and R.A. Dixon. 2007. "Lignin Modification Improves Fermentable Sugar Yields for Biofuel Production." *Nature and Biotechnology* 25(7): 759-761.

Covert, C. and B.C. English. 2012. "Biofuel Reserve Accounting." Working paper, Department of Agricultural and Resource Economics, University of Tennessee, Knoxville.

Cundiff, J.S. and L.S. Marsh. 1996. "Harvest and Storage Costs for Bales of Switchgrass in the Southeastern United States." *Bioresource Technology* 56: 95-101.

Cundiff, J.S. and R.D. Grisso. 2008. "Containerized Handling to Minimize Hauling Cost of Herbaceous Biomass." *Biomass and Bioenergy* 32: 308-313.

Da Costa Sousa, L., S. Chundawat, V. Balan, and B.E. Dale. 2009. "'Cradle-to-Grave' Assessment of Existing Lignocellulose Pretreatment Technologies." *Current Opinion in Biotechnology* 20: 339-347.

De La Torre Ugarte, D.G., B.C. English, and K. Jensen. 2007. "Sixty Billion Gallons by 2030: Economic and Agricultural Impacts of Ethanol and Biodiesel Expansion." Paper presented at Agricultural & Applied Economics Association, Annual Meeting, Portland, Oregon, July 29-August 1.

Duffy, M. 2007. "Estimated Costs for Production, Storage and Transportation of Switchgrass." University Extension, Iowa State University.

Duffy, M., and V. Nanhou. 2002. "Costs of Producing Switchgrass for Biomass in Southern Iowa." Reprinted from *Trends in New Crops and New Uses*: 267-275.

Eggeman, T., and R.T. Elander. 2005. "Process and Economic Analysis of Pretreatment Technologies." *Bioresource Technology* 96: 2019-2025.

English, B., Professor of Agricultural and Resource Economics. 2012. Personal communication, October 2012.

English, B.C., D. De La Torre Ugarte, K. Jensen, C. Hellwinckel, J. Menard, B. Wilson, R. Roberts, and M. Walsh. 2006. "25% Renewable Energy for the United States by 2025: Agricultural and Economic Impacts." *Report to the 25×25 Energy Work Group*. Biobased Energy Analysis Group, Department of Agricultural Economics, The University of Tennessee.

English, B.C., J.A. Larson and D. Mooney. 2008. "Switchgrass Harvest and Storage Costs and Bale Quality." Milan No-Till Field Day, July 24. Milan, Tennessee.

Esteghlalian, A., A.G. Hashimoto, J.J. Fenske, and M.H. Penner. 1997. "Modeling and Optimization of the Dilute-Sulfuric-Acid Pretreatment of Corn Stover, Poplar, and Switchgrass." *Bioresource Technology* 59: 129-136.

Epplin, F.M. C.D. Clark, R.K. Roberts, and S. Hwang. 2007. "Challenges to the Development of a Dedicated Energy Crop." *American Journal of Agricultural Economics* 89: 1296-1302.

Fewell, J. J. Bergtold, and J. Williams. 2011. "Farmers' Willingness to Grow Switchgrass as a Cellulosic Bioenergy Crop: A Stated Choice Approach." Paper presented at the 2011 Joint Annual Meeting of the Canadian Agricultural Economics Society and Western Agricultural Economics Association, Banff, Alberta, Canada, June 29-July 1.

Gallagher, P.W., H. Shapouri b, J. Price, G.Schamel, and H. Brubaker. 2003. "Some Long-Run Effects of Growing Markets and Renewable Fuel Standards on Additives Markets and the US Ethanol Industry." *Journal of Policy Modeling* 25: 585-608.

Goldemberg, J. 2007. "Ethanol for a Sustainable Energy Future." *Science* 315: 808-810.

Growth Energy. 2008. "Jobs, Environment and Energy Independence." Available at: http://www.growthenergy.org/images/reports/growth_energy_roadmaptogreeneramerica.pdf (accessed April 10, 2012).

Hamelinck, C., G. van Hooijdonk, and A. Faaij. 2005. "Ethanol from Lignocellulosic Biomass: Techno-Economic Performance in Short-, Middle- and Long-term." *Biomass and Bioenergy* 28: 384-410.

Haque, M. and F.M. Epplin. 2010. "Optimal Switchgrass Harvest Strategies Accounting for Yield and Nitrogen Requirement Differences by Month of Harvest." Paper presented at

the Southern Agricultural Economics Association Annual Meeting, Orlando, FL, February 6-9.

Haque, M. and F.M. Epplin. 2012. "Cost to Produce Switchgrass and Cost to Produce Ethanol from Switchgrass for Several Levels of Biorefinery Investment Cost and Biomass to Ethanol Conversion Rates." *Biomass and Bioenergy* XXX: 1-14.

Humbird, D., R. Davis, L. Tao, C. Kinchin, D. Hsu, A. Aden, P. Schoen, J. Lukas, B. Olthof, M. Worley, D. Sexton, and D. Dudgeon. 2011. "Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol: Delute-Acid Pretreatment and Enzymatic Hydrolysis of Corn Stover." U.S. Department of Energy, National Renewable Energy Laboratory, Golden, CO, Technical Report NREL/TP-5100-47764.

Jensen, K., C.D. Clark, P. Ellis, B. English, J Menard, M. Walsh, and D. De La Torre Ugarte. 2007. "Farmer Willingness to Grow Switchgrass for Energy Production." *Biomass and Bioenergy* 31: 773-781.

Johnson, K.D., J.H. Cherney, D.K. Greene, and J.J. Volence. 1991. "Evaluation of Switchgrass and Sorghum Biomass Potential." Report prepared under Subcontract 19X-27412C. Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Kaylen M., D. L. Van Dyne, Y. Choi, M. Blasé. 2000. "Economic Feasibility of Producing Ethanol from Lignocellulosic Feedstocks." *Bioresource Technology* 72: 19-32.

Keller, A., J. Froines, C. Koshland, J. Reuter, I. Suffett, and J. Last. 1998. "Health and Environmental Assessment of MTBE." Report to the Governor and Legislature of the State of California as Sponsored by SB 521.

Kazi, F.K., J.A. Fortman, R.P. Anex, D.D. Hsu, A. Aden, A. Dutta, G. Kothandaraman. 2010. "Techno-Economic Comparison of Process Technologies for Biochemical Ethanol Production from Corn Stover." *Fuel* 89: S20-S28.

Larson, J.A., B.C. English, and L. He. 2008. "Risk and Return for Bioenergy Crops Under Alternative Contracting Arrangements." Paper presented at the 2008 Annual Meeting of the Southern Agricultural Economics Association (SAEA), Dallas, TX, February 2-6.

Larson, J.A., B.C. English, C. Hellwinkel, D. De la Torre Ugarte, and M. Walsh. 2005. "A Farm-Level Evaluation of Conditions Under Which Farmers Will Supply Biomass Feedstocks for Energy Production." Paper presented at American Agricultural Economics Association Annual Meeting, Providence, RI, July 24-27.

Larson, J.A., D.F. Mooney, B.C. English, and D.D. Tyler. 2010a. "Cost Analysis of Alternative Harvest and Storage Methods for Switchgrass in the Southeastern U.S." Selected Paper presented at the Southern Agricultural Economics Association Meetings, Orlando, FL, Feb 6-9. Full conference paper published online by AgEcon Search at: http://purl.umn.edu/57623.

Larson, J.A., T. Yu, B.C. English, D.F. Mooney, and C. Wang. 2010b. "Cost Evaluation of Alternative Switchgrass Producing, Harvesting, Storing, and Transporting Systems and their Logistics in the Southeastern U.S." *Agricultural Finance Review* 70: 184-200.

Lehmann, J. 2007. "Bio-energy in the Black." *Frontiers in Ecology and the Environment* 5: 381-387.

Lynd, L. R., D. Wyman, D. Johnson, R. Landucci, and M. Laser. 2005. "Strategic Biorefinery Analysis: Analysis of Biorefineries." Subcontract Report NREL/SR-510-35578.

Mark, T., P. Darby, and M. Salassi. 2009. "A comparison of Pricing Strategies for Cellulosic Ethanol Processors: A Simulation Approach." Paper presented at the American Agricultural Economics Association Annual Meetings, Milwaukee, WI, July 26-28.

McLaughlin, S., J. Bouton, D. Bransby, B. Conger, W. Ocumpaugh, D. Parrish, C. Parrish, C. Taliaferro, K. Vogel, and S. Wullschleger. 1999. "Developing Switchgrass as a Bioenergy Crop." Reprinted from Perspectives On New Crops And New Uses: 282-299.

McLaughlin, S.B., D.G. De la Torre Ugarte , C.T. Jr Garten , L.R. Lynd , M.A. Sanderson , V.R. Tolbert , and D.D. Wolf . 2002. "High-Value Renewable Energy from Prairie Grasses." *Environmental Science and Technology* 36: 2122-2129.

Mooney, D.F., R.K. Roberts, B.C. English, D.D. Tyler, and J.A. Larson. 2008. "Switchgrass Production in Marginal Environments: A Comparative Economic Analysis across Four West Tennessee Landscapes." Paper presented at the American Agricultural Economics Association Annual Meeting, Orlando, FL, July 27-29.

Mooney, D.F., R.K. Roberts, B.C. English, D.D. Tyler, and J.A. Larson. 2009. "Yield and Breakeven Price of 'Alamo' Switchgrass for Biofuels in Tennessee." *Agronomy Journal* 101(5): 1234-1242.

Nicholson, W. 2005. *Microeconomic Theory: Basic Principles and Extensions, 9th edition.* South-Western.

Nguyen, Q.A., and J.N. Saddler. 1991. "An Integrated Model for the Technical and Economic Evaluation of an Enzymatic Biomass Conversion Process." *Bioresource Technology* 35: 275-282.

Organization of the Petroleum Exporting Countries. 2012. "OPEC Share of World Crude Oil

Reserve 2010." Available at: http://www.opec.org/opec_web/en/data_graphs/330.htm (accessed March 26, 2012).

Pacini, H., and S. Silveira. 2010. "Gasoline Pricing Systems and the Attractiveness of High-Ethanol Blends: The Cases of Brazil and Sweden." Work presented at the 3rd International Scientific Conference on Energy Systems with IT, part of the Swedish Energitinget, Stockholmsmässan, Älvsjö, Sweden, March 16-17, 2010.

Perrin, R., K. Vogel, M. Schmer, and R. Mitchell. 2008. "Farm-Scale Production Cost of Switchgrass for Biomass." *Bioenergy Resource* 1: 91-97.

Perrin, R.K., N.F. Fretes, and J.P. Sesmero. 2009. "Efficiency in Midwest US Corn Ethanol Plants: A Plant Survey." *Energy Policy* 37: 1309-1316.

Peter, M. 2002. "Energy Production from Biomass (Part 1): Overview of Biomass." *Bioresource Technology* 83(1): 37-46.

Peter, M. 2002. "Energy Production from Biomass (Part 2): Conversion Technologies." *Bioresource Technology* 83(1): 47-54.

Petrulis, M., J. Sommer, and F. Hines. 1993. "Ethanol Production and Employment." USDA Agricultural Resource Service. *Agricultural Information Bulletin*: 678.

Popp, M. and R. Horgan, Jr. 2007. "Assessment of Two Alternative Switchgrass Harvest and Transport Methods." Paper presented at Farm Foundation Conference, St Louis, MO, April 12-13.

Rathmann, R., A. Szklo, and R. Schaeffer. 2010. "Land Use Competition for Production of Food and Liquid Biofuels: An Analysis of the Arguments in the Current Debate." *Renewable Energy* 35(1): 14-22.

Renewable Fuels Reinvestment Act. 2010. H.R. 4940. 111th Congress 2d Session.

Rinehart, L. 2006. "Switchgrass as a Bioenergy Crop." National Sustainable Agriculture Information Service (ATTRA). Available at: http://www.uky.edu/Ag/Forage/switchgrass2.pdf (accessed at October 4, 2012).

Sanderson, M.A., R.P. Egg, and A.E. Wiselogel. 1997. "Biomass Losses during Harvest and Storage of Switchgrass." *Biomass and Bioenergy* 12(2): 107-114.

Savoie, P., L.D. Amours, A. Amyot, and R. Theriault. 2006. "Effect of Density, Cover, Depth, and Storage Time on Dry Matter Loss of Corn Silage." Paper presented at ASABE Meeting, Portland, Oregon, July 9-12.

Schemer, M.R., K.P. Vogel, R.B. Mitchell, and R.K. Perrin. 2007. "Net Energy of Cellulosic Ethanol from Switchgrass." *Proceedings of the National Academy of Sciences (PNAS)* 105(2): 464-469.

Sendich, E., M. Laser, S. Kim, H. Alizadeh, L. Laureano-Perez, B. Dale, L. Lynd. 2008. "Recent Process Improvements for the Ammonia Fiber Expansion (AFEX) Process and Resulting Reductions in Minimum Ethanol Selling Price." *Bioresource Technology* 99: 8429-8435.

Sokhansanj, S., P. Eng, and J. Fenton. 2006. "Cost Benefit of Biomass Supply and Pre-Processing." Synthesis paper, Biocap, Canada.

Solomon, B.D., J.R. Barnes, and K.E. Halvorsen. 2007. "Grain and Cellulosic Ethanol: History, Economics, and Energy Policy." *Biomass and Bioenergy* 31: 416-425.

Sticklen, M.B. 2008. "Plant Genetic Engineering for Biofuel Production: Towards Affordable Cellulosic Ethanol." *Nature Reviews Genetics* 9: 433-443.

Stroup, J.A., M.A. Sanderson, J.P. Muir, M.J. McFarland, and R.L. Reed. 2003. "Comparison of Growth and Performance in Upland and Lowland Switchgrass Types to Water and Nitrogen Stress." *Bioresource Technology* 86: 65-72.

Sun, Y., and J. Cheng. 2002. "Hydrolysis of Lignocellulosic Materials for Ethanol Production: A Review." *Bioresource Technology* 83(1): 1-11.

Tembo, G., F. Epplin, and R. Huhnke. 2003. "Integrative Investment Appraisal of a Lignocellulosic Biomass-to-Ethanol Industry." *Journal of Agricultural and Resource Economics* 28: 611-633.

Thorsell, S., F.M. Epplin, R.L. Huhnke, and C.M. Taliaferro. 2004. "Economics of a Coordinated Biorefinery Feedstock Harvest System: Lignocellulosic Biomass Harvest Cost." *Biomass Bioenergy* 27: 327-337.

Tyner, W.E. 2008. "The US Ethanol and Biofuels Boom: Its Origins, Current Status, and Future Prospects." *BioScience* 58(7): 646-653.

U.S. Energy Information Administration. 2011. "U.S. Imports by Country of Origin." Available at: http://www.eia.gov/dnav/pet/pet_move_impcus_a2_nus_ep00_im0_mbblpd_a.htm (accessed March 26, 2012).

U.S. Department of Energy. 2012. "Prices & Trends: Energy Prices 2000-2008." Available at: http://energy.gov/prices-trends (accessed April 9, 2012).

Walsh, M., D.G. De La Torre Ugarte, H. Shapouri, and S.P. Slinsky. 2003. "Bioenergy Crop Production in the United States." *Environmental and Resource Economics* 24: 313-333.

Wang, C. 2009. "Economic Analysis of Delivering Switchgrass to a Biorefinery from Both the Farmers' and Processor's Perspectives." MS thesis, University of Tennessee.

Wang, C., J.A. Larson, B.C. English, and K. Jensen. 2009. "Cost Analysis of Alternative Harvest, Storage, and Transportation Methods for Delivering Switchgrass to a Biorefinery from the Farmer's Perspective." Paper presented at Southern Agricultural Economics Association Annual Meeting, Atlanta, GA, January 31-February 3.

Wingren, A., M. Galbe, and G. Zacchi. 2003. "Techno-Economic Evaluation of Producing Ethanol From Softwood: Comparison of SSF and SHF and Identification of Bottlenecks." *Review. Biotechnol. Prog.* 19: 1109-1117.

Wingren, A., J. Soderstrom, M. Galbe, and G. Zacchi. 2004. "Process Considerations and Economic Evaluation of Two-Step Steam Pretreatment for Production of Fuel Ethanol from Softwood." *Biotechnol. Prog.* 20: 1421-1429.

Wiselogel, A.E., F.A. Agblevor, D.K. Johnson, S. Deutch, J.A. Fennell, and M.A. Sanderson. 1996. "Compositional Changes During Storage of Large Round Switchgrass Bales." *Bioresource Technology* 56: 103-109.

Wu, J., M. Sperow, and J. Wang. 2010. "Economic Feasibility of a Woody Biomass-Based Ethanol Plant in Central Appalachia." *Journal of Agricultural and Resource Economics* 35: 522-544.

Wyman, C.E. 2007. "What Is (and Is Not) Vital to Advancing Cellulosic Ethanol." *TRENDS in Biotechnology* 25(4): 153-157.

Wyman, C. E. 2008. "Cellulosic Ethanol: A Unique Sustainable Liquid Transportation Fuel." *MRS Bulletin* 33: 381-383.

Yu, E., J.A. Larsen, Y. Gao., and B. English. 2011. "Analyzing the Economics Values of An

Alternative Preprocessing Facility in the Biomass Feedstocks – Biorefinery Supply Chain." Paper presented at Agricultural & Applied Economics Association's 2011 AAEA & NAREA Joint Annual Meeting, Pittsburgh, Pennsylvania, July 24-26.

Zhan, F., X. Chen, C. Noon, and G. Wu. 2005. "A GIS-Enabled Comparison of Fixed and Discriminatory Pricing Strategies for Potential Switchgrass-to-Ethanol Conversion Facilities in Alabama." *Journal of Biomass and Bioenergy* 28: 295-306.

APPENDIX

Table 1 Parameter Description

Parameter	Description
α_0	Initial switchgrass conversion rate (gallons Mg^{-1})
α_1	Switchgrass conversion rate after 100 days of storage (gallons Mg^{-1})
α_2	Switchgrass conversion rate after 200 days of storage (gallons Mg^{-1})
γ_0	The percentage of sugar within the switchgrass after the initial harvest
γ_1	The percentage of sugar within the switchgrass after being stored for 100 days
γ_2	The percentage of sugar within the switchgrass after being stored for 200 days
τ	Cost of transporting biomass to the biorefinery (\$ Mg^{-1})
ω	Cost of storing biomass (\$ Mg^{-1})
λ	Conversion rate of sugar to ethanol (gallons Mg^{-1})
Δ	The total percentage of dry matter loss after six months of storage
$P_{switchgrass}$	Switchgrass contract price (\$ Mg^{-1})
f	Facilities: f ={processing, storage}
OMC_f	Biorefinery operating and maintenance cost for facility f (\$ yr^{-1})
r	Discount rate
$PVAF$	Present Value Annuity Factor
T	Maximum number of years the biorefinery will operate (e.g. 20 years)
C_0	Biorefinery's down payment for building the plant in year zero
PMT_t	Annual Payment for the debt borrowed for biorefinery construction
AFC	Biorefinery construction cost (\$)

Table 2 Variable Description

Variable	Description
NPV	Net Present Value of the system ($)
Q_t	Quantity of ethanol produced by a biorefinery (gallons)
XS_t	Biomass placed into storage in year *t* (Mg)
XT_t	Biomass transported to a biorefinery (Mg)
ρ_t	Break-even price of ethanol in year *t* ($)
NR_t	Biorefinery net revenue in year *t* ($)

Table 3 Total Sugar (Cellulose and Hemicellulose) Remaining in Switchgrass Bales from the Bale Study Experiment

Cellulose										
Sample\Days of Storage	**Initial**		**50**		**100**		**200**		**300**	
Twine (Round Bales)	**37.2**[a]	*2.2*[b]	**33.0**	*0.8*	**35.8**	*1.9*	**34.4**	*1.8*	**38.3**	*1.2*
Mesh (Round Bales)	**35.7**	*2.5*	**37.8**	*0.5*	**34.7**	*1.6*	**34.9**	*1.5*	**36.8**	*0.4*
Triple Mesh (Round Bales)	**33.7**	*0.3*	**36.0**	*0.1*	**36.8**	*0.4*	**34.7**	*0.3*	**38.8**	*0.1*
Plastic Tarp (Round Bales)	**36.8**	*0.7*	**35.7**	*0.1*	**37.2**	*0.1*	**34.9**	*1.0*	**34.4**	*0.7*
November (BaleTech)	**35.2**	*1.2*	**32.4**	*0.5*	**34.6**	*0.1*	**33.2**	*0.3*	**33.7**	*1.0*
December (BaleTech)	**36.1**	*1.1*	**34.0**	*0.6*	**36.1**	*0.4*	**32.8**	*0.3*	**35.0**	*0.9*
January (BaleTech)	**35.9**	*1.5*	**32.6**	*0.7*	**33.6**	*0.5*	**30.6**	*0.4*	**32.0**	*1.4*
February (BaleTech)	**37.4**	*1.9*	**34.7**	*1.3*	**33.8**	*0.1*	**32.2**	*0.4*	**30.4**	*1.0*

Hemicellulose										
Sample\Days of Storage	**Initial**		**50**		**100**		**200**		**300**	
Twine (Round Bales)	**28.6**	*0.2*	**25.6**	*0.7*	**23.9**	*1.4*	**25.5**	*0.8*	**25.2**	*0.5*
Mesh (Round Bales)	**27.5**	*0.2*	**24.8**	*0.6*	**24.9**	*0.8*	**25.6**	*0.5*	**27.5**	*0.2*
Triple Mesh (Round Bales)	**26.6**	*0.2*	**24.4**	*0.9*	**25.3**	*0.7*	**23.9**	*0.1*	**27.3**	*0.1*
Plastic Tarp (Round Bales)	**29.1**	*0.3*	**26.4**	*0.2*	**26.2**	*0.1*	**26.1**	*0.1*	**26.4**	*0.1*
November (BaleTech)	**28.2**	*0.2*	**24.1**	*0.4*	**26.2**	*0.3*	**25.9**	*0.5*	**27.6**	*0.1*
December (BaleTech)	**28.5**	*0.3*	**24.5**	*0.6*	**25.9**	*1.0*	**24.3**	*0.6*	**23.7**	*0.1*
January (BaleTech)	**29.0**	*0.2*	**24.2**	*0.9*	**24.7**	*0.9*	**25.1**	*0.7*	**24.6**	*0.4*
February (BaleTech)	**30.5**	*0.6*	**24.8**	*1.3*	**24.7**	*0.5*	**25.3**	*1.3*	**24.9**	*0.5*

Total Sugar										
Sample\Days of Storage	**Initial**		**50**		**100**		**200**		**300**	
Twine (Round Bales)	**65.8**	*1.6*	**58.5**	*0.8*	**59.7**	*2.1*	**59.8**	*1.2*	**63.5**	*0.9*
Mesh (Round Bales)	**63.3**	*1.8*	**62.6**	*0.6*	**59.6**	*1.3*	**60.4**	*1.1*	**64.2**	*0.3*
Triple Mesh (Round Bales)	**60.3**	*0.3*	**60.3**	*0.6*	**62.1**	*0.5*	**58.5**	*0.2*	**66.1**	*1.1*
Plastic Tarp (Round Bales)	**65.9**	*0.6*	**62.2**	*0.2*	**63.4**	*0.1*	**61.0**	*0.1*	**60.9**	*0.4*
November (BaleTech)	**63.4**	*0.8*	**56.5**	*0.4*	**60.8**	*0.2*	**59.2**	*0.4*	**61.3**	*0.6*
December (BaleTech)	**64.6**	*0.7*	**58.5**	*0.6*	**62.0**	*0.7*	**57.1**	*0.4*	**58.7**	*0.2*
January (BaleTech)	**64.9**	*1.2*	**56.8**	*0.8*	**58.3**	*0.7*	**55.7**	*0.5*	**56.6**	*0.9*
February (BaleTech)	**67.9**	*1.4*	**59.5**	*1.3*	**58.5**	*0.3*	**57.5**	*0.9*	**55.3**	*0.8*

a The percentage of cellulose contained within the switchgrass using the twine wrapped round bales at the initial time.

b The standard deviation of cellulose within the twine wrapped switchgrass round bales at the initial time.

Table 4 Feedstock Cost, Conversion Rate, Biorefinery Construction Cost, and Processing Capacity

Literature Source	Feedstock Cost ($\$ Mg^{-1}$)	Construction Cost (Million Dollars)	Processing Capacity (Million Gallons)	Conversion Rate (Gallon Mg^{-1})
Aden et al. (2002)	33	197	69	99
Eggemand and Elander (2005)	35	162	65	72
Sendich et al. (2008)	44	65	54	86
Sendich et al. (2008)	44	70	54	77
Wingren et al. (2003)	52	139	13	74
Wingren et al. (2003)	52	107	15	85
Wingren et al. (2004)	56	116	15	81
Nguyen and Saddler (1991)	60	80	14	78
Wu et al. (2010)	60	265	50	77
Humbird et al. (2011)	64	422	61	87
Kazi et al. (2010)	83	376	53	76

Source: Haque and Epplin (2012)

Table 5 Ethanol Break-Even Prices for Different Biorefinery Sizes

	Biorefinery Size		
	Small	Medium	Large
Ethanol Production Quantity (gallons)	50,000,000	75,000,000	100,000,000
Biorefinery Construction Cost ($)	$193,000,000	$279,500,000	$406,000,000
Biorefinery Annual Operating and Maintenance Costs ($)	$19,000,000	$37,800,000	$75,800,000
Switchgrass Purchased/Transported for Traditional Round Bales (Mg)	620,475	930,713	1,240,950
Switchgrass Purchased/Transported for BaleTech Bales (Mg)	683,787	1,025,681	1,367,574
Switchgrass Stored for Traditional Round Bales (Mg)	413,650	620,475	827,300
Switchgrass Stored for BaleTech Bales (Mg)	455,858	683,787	911,716
Switchgrass Transportation Cost for Traditional Round Bales ($)	$11.95	$11.95	$11.95
Switchgrass Transportation Cost for BaleTech Bales ($)	$5.10	$5.10	$5.10
Switchgrass Storage Cost ($)	$7.75	$7.75	$7.75
Conversion Rate (gallons Mg^{-1})	88.23	88.23	88.23
Switchgrass Contract Price ($)	$78.43	$78.43	$78.43
Discount Rate (%)	10%	10%	10%
Ethanol Break-Even Price for Traditional Round Bales ($)	**$2.02**	**$2.13**	**$2.42**
Ethanol Break-Even Price for BaleTech Bales ($)	**$2.05**	**$2.15**	**$2.45**

Note: The switchgrass dry matter loss is assumed to be 13% for both traditional round bales and BaleTech bales. The sugar percentages left in switchgrass for traditional round bales are: 60.3% (initial), 62.1% (after being stored for 100 days), and 58.5% (after being stored for 200 days). The sugar percentages remaining in the switchgrass from BaleTech bales are: 67.9% (initial), 58.5% (after being stored for 100 days), and 57.5% (after being stored for 200 days).

Table 6 Small Biorefinery Conversion Rate Sensitivity Analysis

	Conversion Rates (gallons Mg^{-1})		
	Base Value	Low	High
	88.23	66.04	110.16
Ethanol Break-Even Price for Traditional Round Bales ($)	$2.02	$2.42	$1.78
Ethanol Break-Even Price for BaleTech Bales ($)	$2.05	$2.45	$1.80
Switchgrass Purchased/Transported for Traditional Round Bales (Mg)	620,475	828,960	496,955
Switchgrass Purchased/Transported for BaleTech Bales (Mg)	683,787	913,545	547,663
Switchgrass Stored for Traditional Round Bales (Mg)	413,650	552,640	331,303
Switchgrass Stored for BaleTech Bales (Mg)	455,858	609,030	365,109
Ethanol Quantity (gallons)	50,000,000		
Biorefinery Construction Cost ($)	$193,000,000		
Biorefinery Annual Operating and Maintenance Costs ($)	$19,000,000		
Switchgrass Transportation Cost for Traditional Round Bales($)	$11.95		
Switchgrass Transportation Cost for BaleTech Bales ($)	$5.10		
Switchgrass Storage Cost ($)	$7.75		
Switchgrass Contract Price ($)	$78.43		
Discount Rate (%)	10%		

Table 7 Medium Biorefinery Conversion Rate Sensitivity Analysis

	Conversion Rates (gallons Mg^{-1})		
	Base Value	Low	High
	88.23	66.04	110.16
Ethanol Break-Even Price for Traditional Round Bales ($)	$2.13	$2.53	$1.89
Ethanol Break-Even Price for BaleTech Bales ($)	$2.15	$2.56	$1.91
Switchgrass Purchased/Transported for Traditional Round Bales (Mg)	930,713	1,243,440	745,432
Switchgrass Purchased/Transported for BaleTech Bales (Mg)	1,025,681	1,370,318	821,494
Switchgrass Stored for Traditional Round Bales (Mg)	620,475	828,960	496,955
Switchgrass Stored for BaleTech Bales (Mg)	683,787	913,545	547,663
Ethanol Quantity (gallons)	75,000,000		
Biorefinery Construction Cost ($)	$279,500,000		
Biorefinery Annual Operating and Maintenance Costs ($)	$37,800,000		
Switchgrass Transportation Cost for Traditional Round Bales ($)	$11.95		
Switchgrass Transportation Cost for BaleTech Bales ($)	$5.10		
Switchgrass Storage Cost ($)	$7.75		
Switchgrass Contract Price ($)	$78.43		
Discount Rate (%)	10%		

Table 8 Large Biorefinery Conversion Rate Sensitivity Analysis

	Conversion Rates (gallons Mg^{-1})		
	Base Value	Low	High
	88.23	66.04	110.16
Ethanol Break-Even Price for Traditional Round Bales ($)	$2.42	$2.82	$2.18
Ethanol Break-Even Price for BaleTech Bales ($)	$2.45	$2.86	$2.21
Switchgrass Purchased/Transported for Traditional Round Bales (Mg)	1,240,950	1,657,920	993,909
Switchgrass Purchased/Transported for BaleTech Bales (Mg)	1,367,574	1,827,091	1,095,326
Switchgrass Stored for Traditional Round Bales (Mg)	827,300	1,105,280	662,606
Switchgrass Stored for BaleTech Bales (Mg)	911,716	1,218,060	730,217
Ethanol Quantity (gallons)	100,000,000		
Biorefinery Construction Cost ($)	$406,000,000		
Biorefinery Annual Operating and Maintenance Costs ($)	$75,800,000		
Switchgrass Transportation Cost for Traditional Round Bales ($)	$11.95		
Switchgrass Transportation Cost for BaleTech Bales ($)	$5.10		
Switchgrass Storage Cost ($)	$7.75		
Switchgrass Contract Price ($)	$78.43		
Discount Rate (%)	10%		

Table 9 Small Biorefinery Switchgrass Contract Price Sensitivity Analysis

	Switchgrass Contract Price ($ Mg^{-1})		
	Base Value	Low	High
	$78.43	$43.93	$83.00
Ethanol Break-Even Price for Traditional Round Bales ($)	$2.02	$1.59	$2.08
Ethanol Break-Even Price for BaleTech Bales ($)	$2.05	$1.57	$2.11
Switchgrass Purchased/Transported for Traditional Round Bales (Mg)	620,475	620,475	620,475
Switchgrass Purchased/Transported for BaleTech Bales (Mg)	683,787	683,787	683,787
Switchgrass Stored for Traditional Round Bales (Mg)	413,650	413,650	413,650
Switchgrass Stored for BaleTech Bales (Mg)	455,858	455,858	455,858
Ethanol Quantity (gallons)	50,000,000		
Biorefinery Construction Cost ($)	$193,000,000		
Biorefinery Annual Operating and Maintenance Costs ($)	$19,000,000		
Switchgrass Transportation Cost for Traditional Round Bales ($)	$11.95		
Switchgrass Transportation Cost for BaleTech Bales($)	$5.10		
Switchgrass Storage Cost ($)	$7.75		
Conversion Rate (gallons Mg^{-1})	$78.43		
Discount Rate (%)	10%		

Table 10 Medium Biorefinery Switchgrass Contract Price Sensitivity Analysis

	Switchgrass Contract Price ($ Mg^{-1})		
	Base Value	Low	High
	$78.43	$43.93	$83.00
Ethanol Break-Even Price for Traditional Round Bales ($)	$2.13	$1.70	$2.18
Ethanol Break-Even Price for BaleTech Bales ($)	$2.15	$1.68	$2.22
Switchgrass Purchased/Transported for Traditional Round Bales (Mg)	930,713	930,713	930,713
Switchgrass Purchased/Transported for BaleTech Bales (Mg)	1,025,681	1,025,681	1,025,681
Switchgrass Stored for Traditional Round Bales (Mg)	620,475	620,475	620,475
Switchgrass Stored for BaleTech Bales (Mg)	683,787	683,787	683,787
Ethanol Quantity (gallons)	75,000,000		
Biorefinery Construction Cost ($)	$279,500,000		
Biorefinery Annual Operating and Maintenance Costs ($)	$37,800,000		
Switchgrass Transportation Cost for Traditional Round Bales ($)	$11.95		
Switchgrass Transportation Cost for BaleTech Bales ($)	$5.10		
Switchgrass Storage Cost ($)	$7.75		
Conversion Rate (gallons Mg^{-1})	$78.43		
Discount Rate (%)	10%		

Table 11 Large Biorefinery Switchgrass Contract Price Sensitivity Analysis

	Switchgrass Contract Price ($ Mg^{-1})		
	Base Value	Low	High
	$78.43	$43.93	$83.00
Ethanol Break-Even Price for Traditional Round Bales ($)	$2.42	$1.99	$2.48
Ethanol Break-Even Price for BaleTech Bales ($)	$2.45	$1.98	$2.51
Switchgrass Purchased/Transported for Traditional Round Bales (Mg)	1,240,950	1,240,950	1,240,950
Switchgrass Purchased/Transported for BaleTech Bales (Mg)	1,367,574	1,367,574	1,367,574
Switchgrass Stored for Traditional Round Bales (Mg)	827,300	827,300	827,300
Switchgrass Stored for BaleTech Bales (Mg)	911,716	911,716	911,716
Ethanol Quantity (gallons)	100,000,000		
Biorefinery Construction Cost ($)	$406,000,000		
Biorefinery Annual Operating and Maintenance Costs ($)	$75,800,000		
Switchgrass Transportation Cost for Traditional Round Bales ($)	$11.95		
Switchgrass Transportation Cost for BaleTech Bales ($)	$5.10		
Switchgrass Storage Cost ($)	$7.75		
Conversion Rate (gallons Mg^{-1})	$78.43		
Discount Rate (%)	10%		

Table 12 Small Biorefinery Discount Rate Sensitivity Analysis

	Discount Rate (%)		
	Base Value	Low	High
	10%	8%	12%
Ethanol Break-Even Price for Traditional Round Bales ($)	$2.02	$1.96	$2.08
Ethanol Break-Even Price for BaleTech Bales ($)	$2.05	$1.99	$2.11
Switchgrass Purchased/Transported for Traditional Round Bales (Mg)	620,475	620,475	620,475
Switchgrass Purchased/Transported for BaleTech Bales (Mg)	683,787	683,787	683,787
Switchgrass Stored for Traditional Round Bales (Mg)	413,650	413,650	413,650
Switchgrass Stored for BaleTech Bales (Mg)	455,858	455,858	455,858
Ethanol Quantity (gallons)	50,000,000		
Biorefinery Construction Cost ($)	$193,000,000		
Biorefinery Annual Operating and Maintenance Costs ($)	$19,000,000		
Switchgrass Transportation Cost for Traditional Round Bales ($)	$11.95		
Switchgrass Transportation Cost for BaleTech Bales ($)	$5.10		
Switchgrass Storage Cost ($)	$7.75		
Conversion Rate (gallons Mg^{-1})	88.23		
Switchgrass Contract Price ($ Mg^{-1})	$78.43		

Table 13 Medium Biorefinery Discount Rate Sensitivity Analysis

	Discount Rate (%)		
	Base Value	Low	High
	10%	8%	12%
Ethanol Break-Even Price for Traditional Round Bales ($)	$2.13	$2.07	$2.19
Ethanol Break-Even Price for BaleTech Bales ($)	$2.15	$2.10	$2.22
Switchgrass Purchased/Transported for Traditional Round Bales (Mg)	930,713	930,713	930,713
Switchgrass Purchased/Transported for BaleTech Bales (Mg)	1,025,681	1,025,681	1,025,681
Switchgrass Stored for Traditional Round Bales (Mg)	620,475	620,475	620,475
Switchgrass Stored for BaleTech Bales (Mg)	683,787	683,787	683,787
Ethanol Quantity (gallons)	75,000,000		
Biorefinery Construction Cost ($)	$279,500,000		
Biorefinery Annual Operating and Maintenance Costs ($)	$37,800,000		
Switchgrass Transportation Cost for Traditional Round Bales ($)	$11.95		
Switchgrass Transportation Cost for BaleTech Bales ($)	$5.10		
Switchgrass Storage Cost ($)	$7.75		
Conversion Rate (gallons Mg^{-1})	88.23		
Switchgrass Contract Price ($ Mg^{-1})	$78.43		

Table 14 Large Biorefinery Discount Rate Sensitivity Analysis

	Discount Rate (%)		
	Base Value	Low	High
	10%	8%	12%
Ethanol Break-Even Price for Traditional Round Bales ($)	$2.42	$2.36	$2.49
Ethanol Break-Even Price for BaleTech Bales ($)	$2.45	$2.38	$2.51
Switchgrass Purchased/Transported for Traditional Round Bales (Mg)	1,240,950	1,240,950	1,240,950
Switchgrass Purchased/Transported for BaleTech Bales (Mg)	1,367,574	1,367,574	1,367,574
Switchgrass Stored for Traditional Round Bales (Mg)	827,300	827,300	827,300
Switchgrass Stored for BaleTech Bales (Mg)	911,716	911,716	911,716
Ethanol Quantity (gallons)	100,000,000		
Biorefinery Construction Cost ($)	$406,000,000		
Biorefinery Annual Operating and Maintenance Costs ($)	$75,800,000		
Switchgrass Transportation Cost for Traditional Round Bales ($)	$11.95		
Switchgrass Transportation Cost for BaleTech Bales ($)	$5.10		
Switchgrass Storage Cost ($)	$7.75		
Conversion Rate (gallons Mg^{-1})	88.23		
Switchgrass Contract Price ($ Mg^{-1})	$78.43		

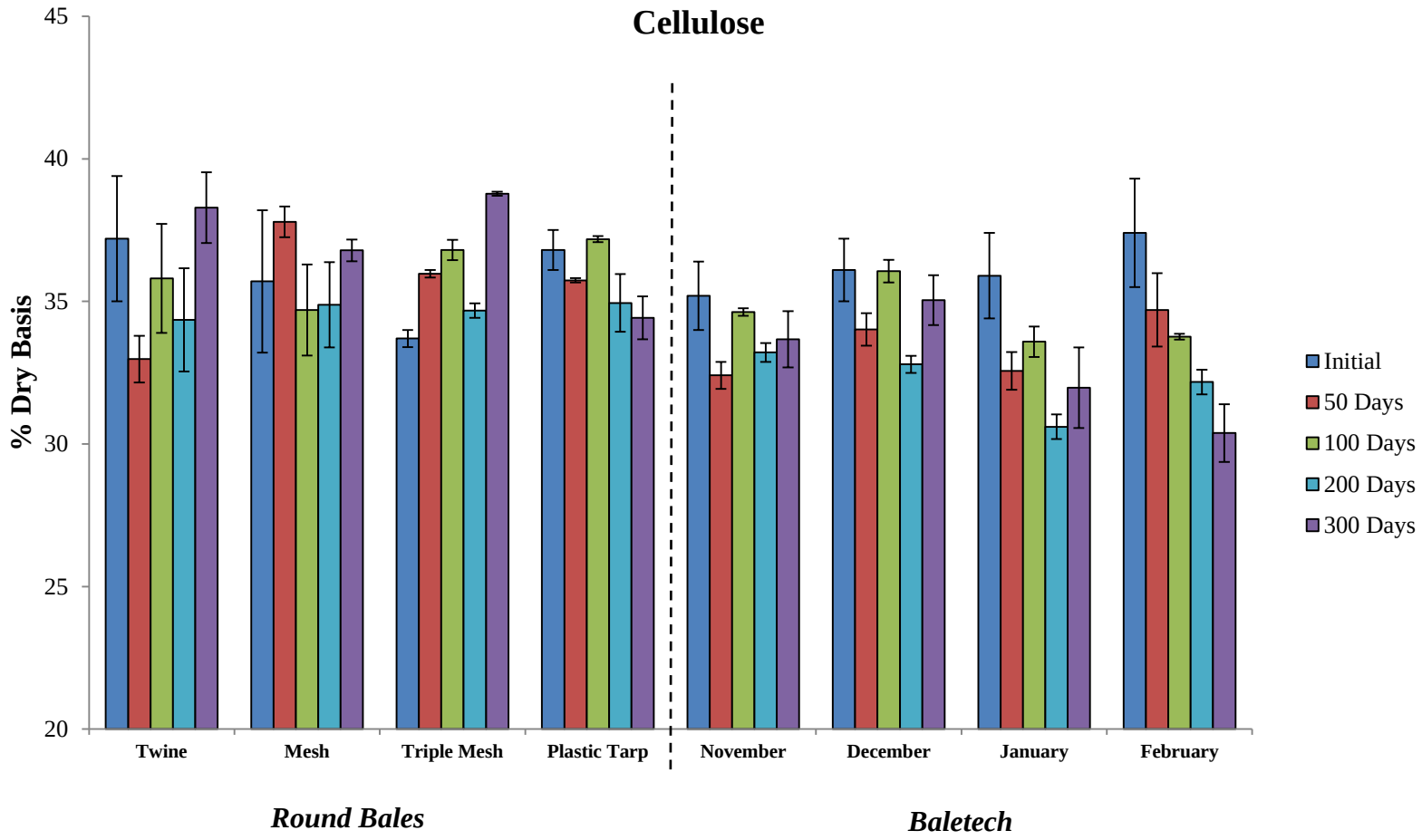

Figure 1 Cellulose Content of Switchgrass Bales

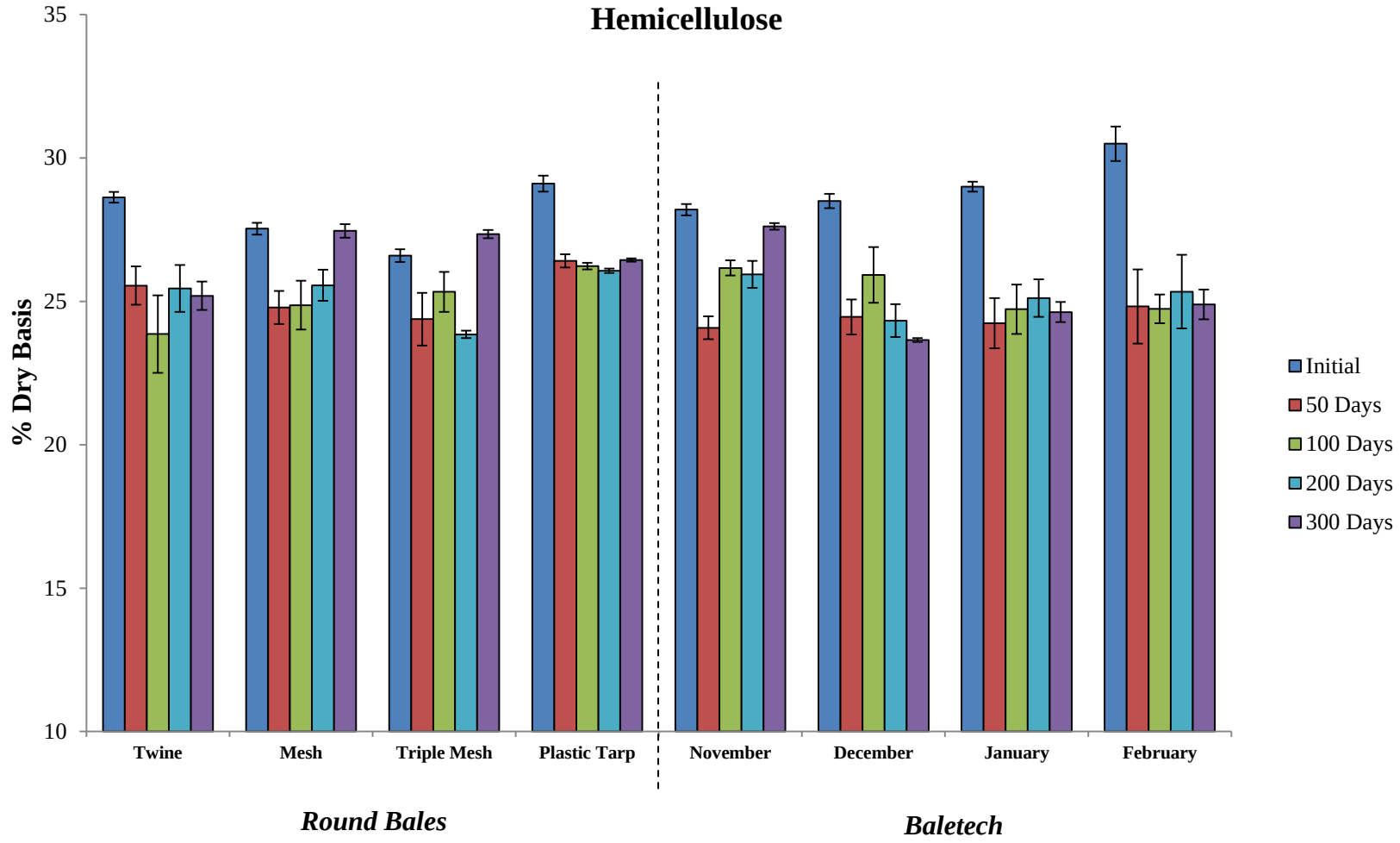

Figure 2 Hemicellulose Content of Switchgrass Bales

Figure 3-1 Switchgrass Being Harvested and Chopped

Figure 3-2 Switchgrass Being Baled With The BaleTech3®

Figure 3-3 Traditional Round Switchgrass Bales Being Stored

Figure 3-4 BaleTech Switchgrass Bales Being Stored

Figure 3-5 Switchgrass Bale Being Split With Bale Splitter

Figure 3-6 Switchgrass Bales Being Split With Chainsaw

Figure 3-7 Switchgrass Bale Profile

Figure 3-8 Switchgrass Profile Showing Weathered Areas

Figure 3-9 Switchgrass Bales Being Sampled With Penn State Sampler

Figure 3-10 Switchgrass Analysis Conducted In BEST Lab

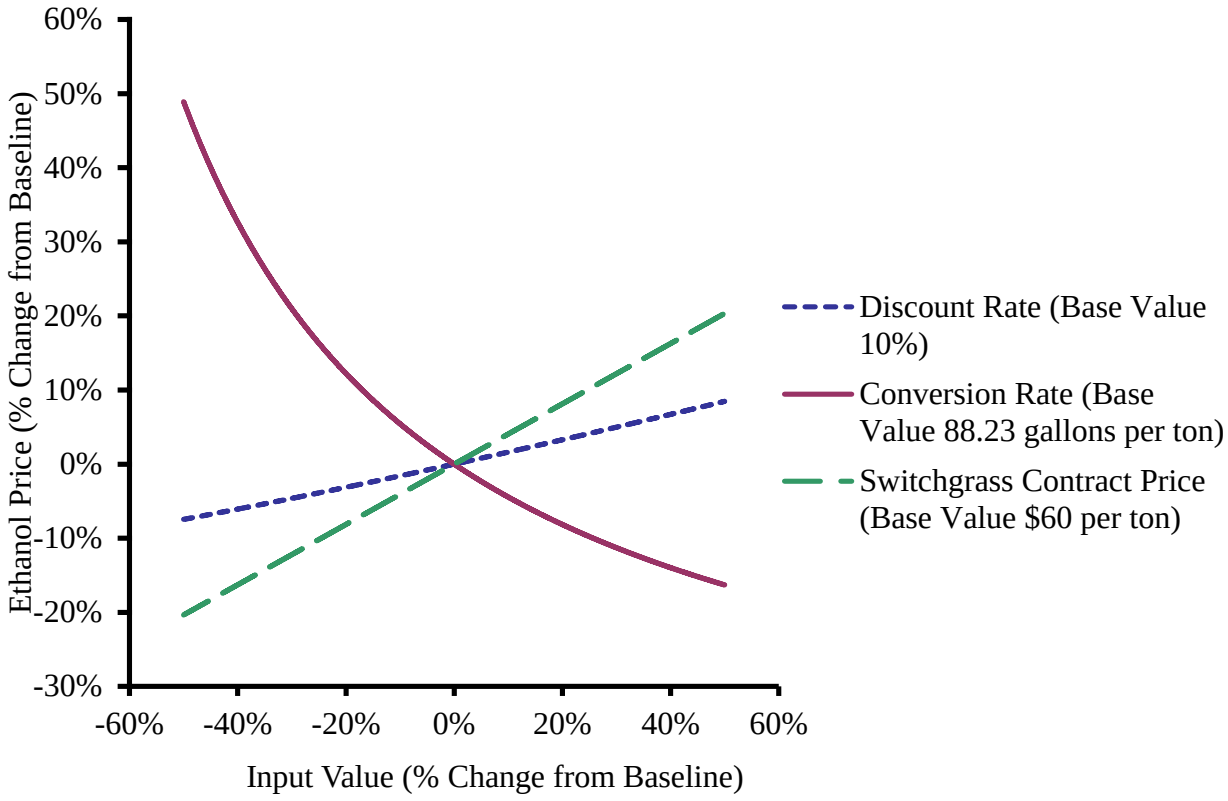

Figure 4 Sensitivity Analysis of Break-Even Price for a Medium Biorefinery Using Round Bales

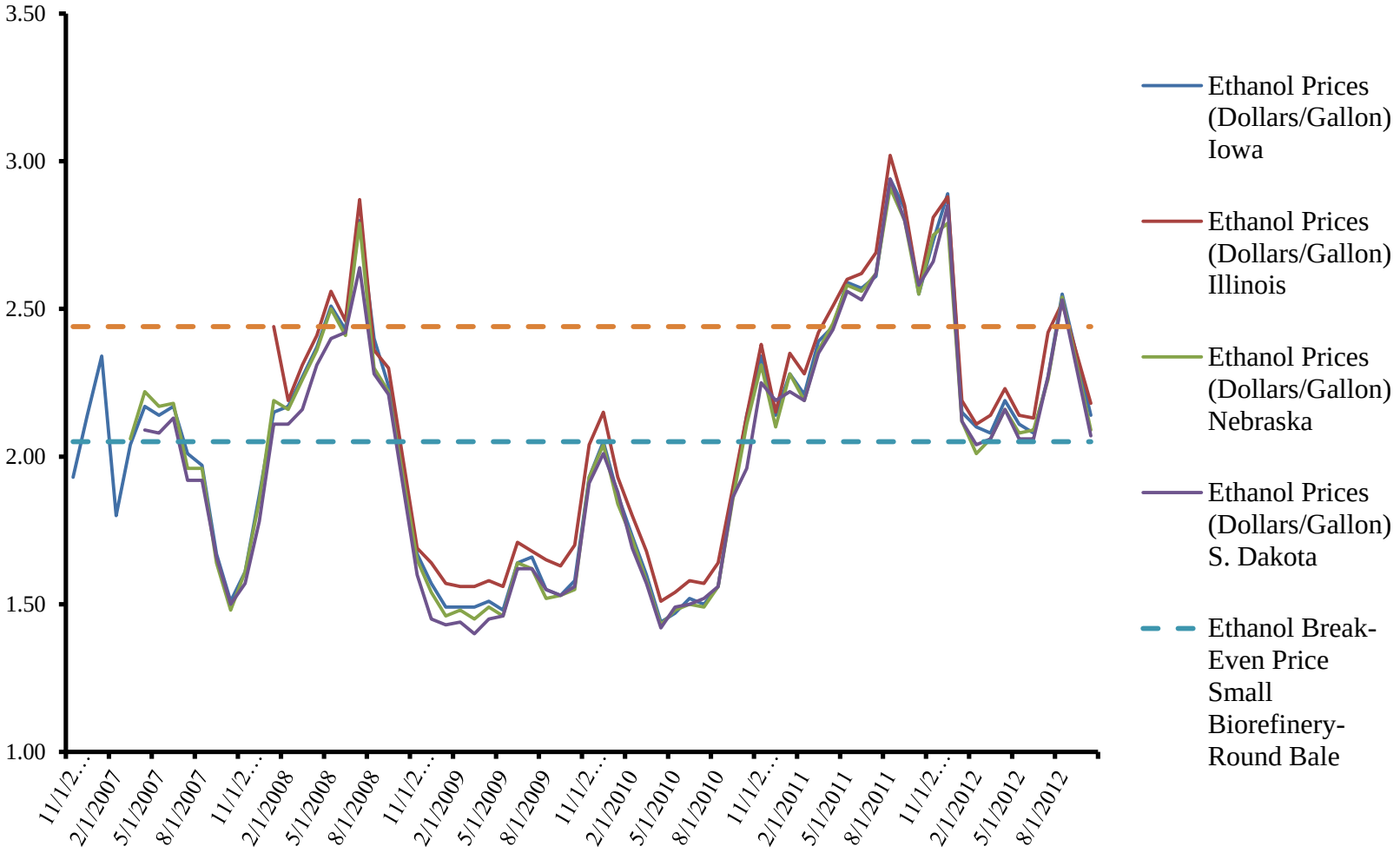

Figure 5 Comparison between Ethanol Break-Even Prices and Ethanol Spot Market Prices

Source: Agricultural Marketing Resource Center "Weekly Ethanol, Distillers Grain & Corn Prices"

VITA

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