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An ASABE – CSBE/ASABE Joint Meeting Presentation

Paper Number: 141910976

Techno-Economic Analysis (TEA) of Low-Moisture Anhydrous Ammonia (LMAA) Pretreatment Method for Corn Stover

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Written for presentation at the
2014 ASABE Annual International Meeting
Sponsored by ASABE
Montreal, Quebec Canada
July 13 – July 16, 2014

Abstract. *Techno-Economic Analysis (TEA) plays an important role in assessing economic performance and potential market acceptance for new technologies. Previous work has shown that the construction and operation of a cellulosic bioethanol plant can be very expensive. One of the largest cost categories is pretreatment processing. The purpose of this study was to conduct a detailed cost analysis to assess low moisture anhydrous ammonia (LMAA) pretreatment process at the commercial-scale, and to estimate the breakeven point in large-scale production. In this study, capital expenses, including annualized purchase and installation fees, and annual operating costs associated with each unit operation were determined. This research compared the unit cost per year between different scales of the LMAA process, and focused on exploring the optimal cost-effective point for this pretreatment method for bioethanol production.*

Keywords. Techno-Economic Analysis, LMAA, Commercial-scale

Introduction

With an increasing demand for energy, more and more researches have been focused on bioethanol production. Bioethanol, a promising replacement of fossil fuel, can be obtained from lignocellulosic biomass, such as energy crops and residues from arable land (Singh et al., 2010). Typically, ethanol production from lignocellulosic biomass follows several steps: pretreatment, enzymatic hydrolysis, fermentation of sugar, and ethanol recovery (Alvira et al., 2010). Among the ethanol production process, pretreatment is regarded as the critical step because it is required for efficient hydrolysis. Various pretreatment methods have been developed, such as dilute acid, hot water extraction, and ammonia fiber expansion (AFEX). Each method has its own advantages and disadvantages. Ammonia has been chosen because of its delignification effect (Kim & Lee, 2007) and swelling effect (Mosie et al., 2005). In 2011, a new method named low moisture anhydrous ammonia (LMAA) has been performed in lab scale (Yoo et al., 2011). In their study, LMAA process resulted in 89% of the maximum theoretical ethanol yield and showed the potential to decrease ammonia and water inputs compared with other pretreatment methods.

The technician report published by NREL in 2010 entitled *Techno-economic analysis of biochemical scenarios for production of cellulosic ethanol* compared four different models of pretreatment processing (dilute acid, two-stage dilute acid, hot water, and ammonia fiber expansion (AFEX)) (Kabir Kazi et al., 2010). It was concluded that without any downstream process variation, dilute acid process had the lowest product value (PV) of $ 3.40/gal of ethanol in 2007, which was equivalent to $5.15 / gal of gasoline. One year later, in 2011, the National Renewable Energy Laboratory (NREL) has published another technical report entitled *Process design and economics for biochemical conversion of lignocellulosic biomass to ethanol* (Humbird et al., 2011) focused on dilute acid pretreatment process. In that report, detailed bioethanol conversion design was built on eight specific areas. The minimum ethanol selling price reported from NREL was $2.15 / gal, which was equivalent to $3.27 /gal gasoline. When broke down into process sections, $0.74 / gal was contributed from the feedstock, enzyme and wastewater treatment each contributed $0.34 / gal, and the rest $0.73 / gal was contributed from the remaining conversion process areas. Even though the selling price was still higher than market price, the latter one was $0.13 / gal lower than previous.

With the recent development of pretreatment technology and updated cost estimation, an updated techno-economic analysis of biofuel production was required. As far as the authors know, cost analysis based on low-moisture anhydrous ammonia (LMAA) pretreatment has not been published in any journals yet. This research is focused on estimating unit costs of bioethanol production based on LMAA pretreatment process, and comparing it among three different production scales.

Methods

This study began by developing process flow diagrams (figure 1), and all the economic and environmental analysis were then calculated in an excel-based spreadsheet with an accuracy of ±30% (Coker, 2010). The whole process was divided into six sections: feedstock handling, ammoniation process, incubation process, simultaneous saccharification & co-fermentation (SSCF) process, evaporation process, and combustor /

burner. Waste water treatment, biomass and ethanol storage were not considered in this research.

This study was a derivative estimation from the NREL's report (Humbird et al., 2011). What's more, the calculation was based on a plant size of 2,000 metric tonne (MT) of corn stover per day; the other two scales were 100 MT/d and 800 MT/d, respectively. The following exponential expression was used for scaling, in which the exponent was assumed to be 0.6 (Aden, et al., 2002).

$$New\ cost = Original\ cost\ \left(\frac{New\ size}{Original\ size}\right)^{exp}$$

This bioethanol plant was assumed to work 24 hours per day, 7 days per week, and 45 weeks annually, which was 315 online processing day per year. The main product of the plant was ethanol, and electricity was generated as a by-product. Other major assumptions were listed in table 1 below.

Table 1. General assumptions.

Feedstock cost is $36.25 / dry tonne.[a]
The plant is located in the center of corn farmland in IOWA.
Electricity price is $0.0062/kWh.[b]
Water price is $0.027/ft^3.[c]
Power efficiency for equipment is assumed to be 85%.
Heat loss is not accounted for in the energy balance calculations.
Building cost is not considered in this report.
Construction time and start-up period are not considered.
Labor fee is not considered in this report.
No leakage happens during the whole process.
Insurance and tax are estimated to be 1.5% of the installed price.
Annual interest is 6.0% in US Bank.[d]
Equipment life expectancy is 10 years.
Plant life is 20 years.
Electrical wiring and controls fee is assumed to be 4% of the purchase price.
Equipment freight is assumed to be 1% of the purchase price.
Overhead fee is $0.16/ton.
Maintenance and repair cost are assumed to be 2% of the installation fee.
Enzyme price is $2 /kg.[e]

a. Available at: http://msue.anr.msu.edu/news/corn_stover_what_is_its_worth
b. Available at: http://www.cityofames.org/index.aspx?page=113
c. Available at: http://www.cityofames.org/index.aspx?page=355
d. Available at: https://www.usbank.com/calculators/jsp/MortgageCompare.jsp#3
e. Available at: http://www.alibaba.com/showroom/cellulase-enzyme.html

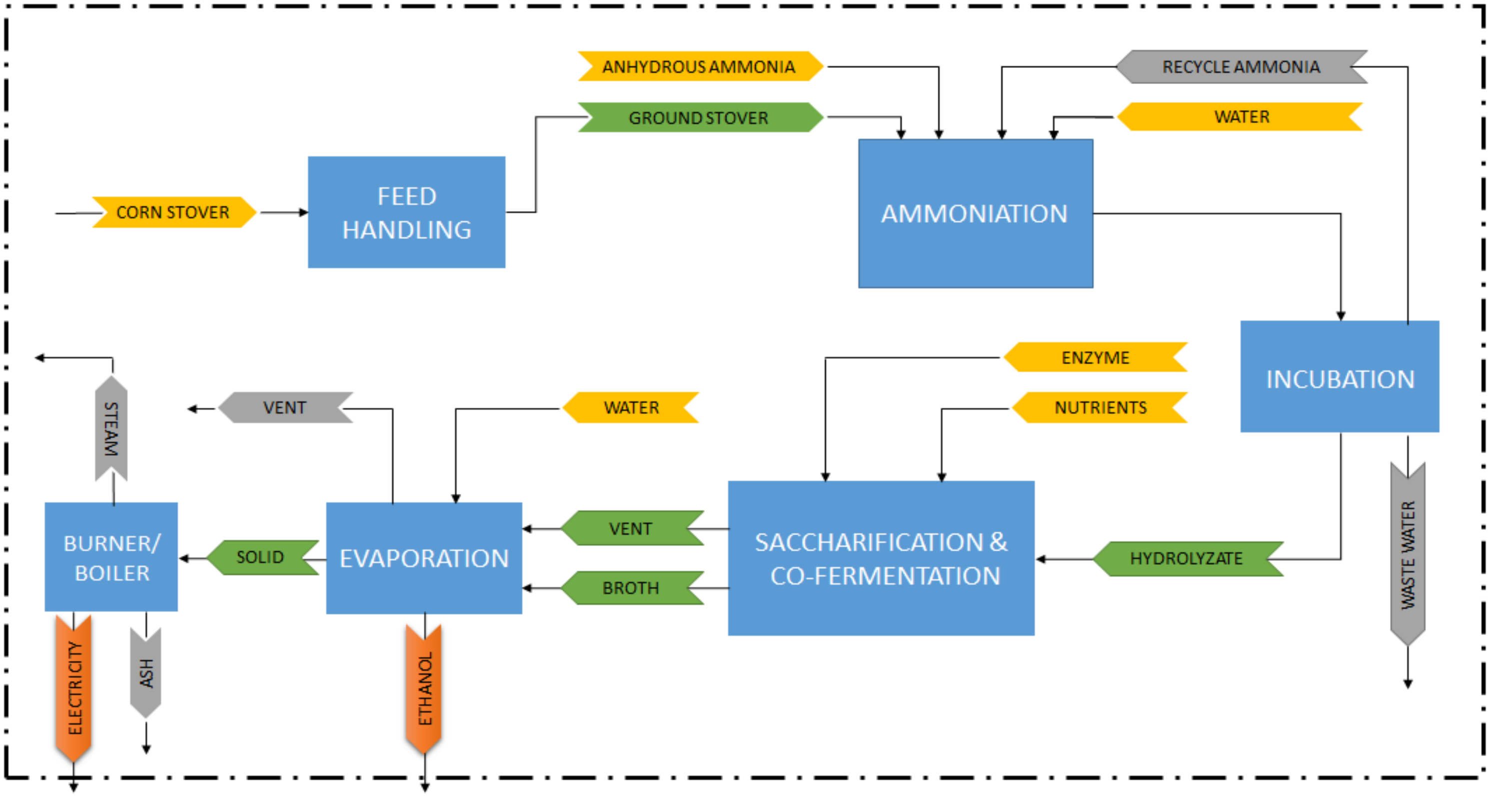

Figure 1. Overall process flow diagram.

Techno-Economic Analysis (TEA)

The TEA of the whole process was analyzed for each of the six sections mentioned in previous study. Equipment costs were obtained from industry quotations and previous NREL report (Aden et al., 2002).

Feedstock handling

The feedstock used in this study was corn stover. Table 2 showed the average composition (% dry basis) of corn stover based on NREL studies (Humbird et al., 2011). In this study, 89% of the glucose was converted into ethanol following the reaction: $Glucose \rightarrow 2Ethanol\ + 2CO_2$, which indicated that the yield of the ethanol was 0.45 g ethanol / g glucose. Corn stover was delivered in bales and the cost was $36.25 /dry ton (Pennington, 2013).

Table 2. Corn stover composition.

Components	Composition (%)
Extractives	14.65
Glucan	35.05
Xylan	19.53
Galactan	1.43
Arabinan	2.38
Mannan	0.60
Lignin	18.00
Ash	4.93
Acetate	1.81
Protein	3.10
Sucrose	0.77
Moisture	20.00

As figure 2 showed, corn stover bales were received by belt conveyors, including transport conveyors and unwrapping conveyors. Then the unwrapped feedstock is transport to hammer mill where the size of the material was reduced and became more homogeneous.

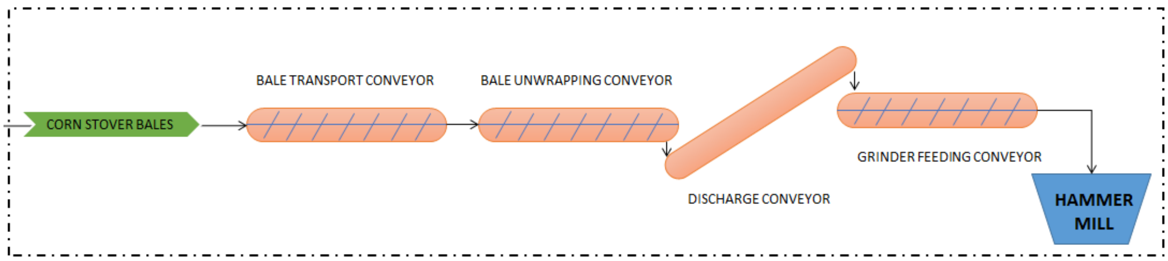

Figure 2. Feed handling process

Since the plant size was 2,000 MT/d, two lines of the transport conveyor and unwrapped conveyors with the capacity of 45 tons/hr were used to receive corn stover. Then the stover was introduced into the hammer mill with the capacity of 75 tons/hr. Water was sprayed on the biomass during transporting process to wash dirt, yet the amount was not considered here.

LMAA Pretreatment and incubation

Before ground corn stover was contacted with anhydrous ammonia, hydrolysate process was conducted in order to remove acetic acid and part of furfural, which may be toxic to downstream fermentation microorganisms (Aden, et al., 2002). Ammoniation was designed for 20 minutes of residence time, and ammonia loading was 0.1g ammonia / dry matter biomass. Ammoniated stover was then transferred into incubation tank for 3.5 days. After incubation, solids were used for saccharification and co-fermentation process. Other assumptions for pretreatment conditions were listed in table 3 below. Figure 3 and 4 were the flowcharts representing the ammoniation and incubation process. Surplus NH_3 from incubation tank was recycled to ammoniation tank.

Table 3. Pretreatment conditions.*

Ammonia loading	0.1g NH_3/ DM biomass
Water loading	1g /DM biomass
Residence time	20 minutes
Solids in the ammoniation	70%
Incubation temperature	80°C
Incubation time	3.5 days (84 hrs)

*Reference: Yoo et al., 2011.
Note: DM denotes dry matter.

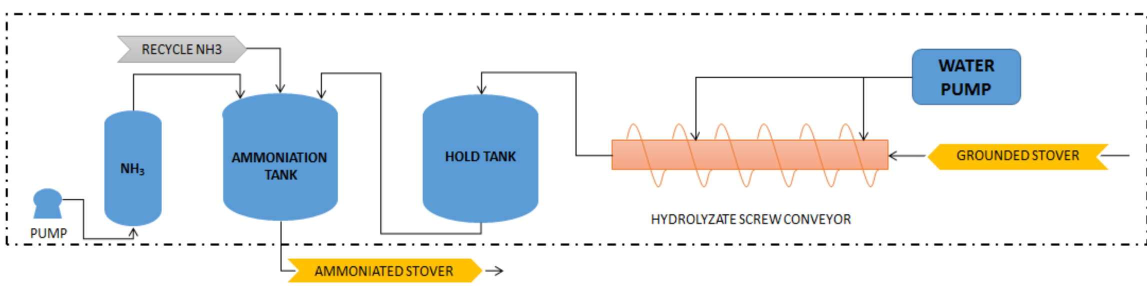

Figure 3. Ammoniation process flow diagram.

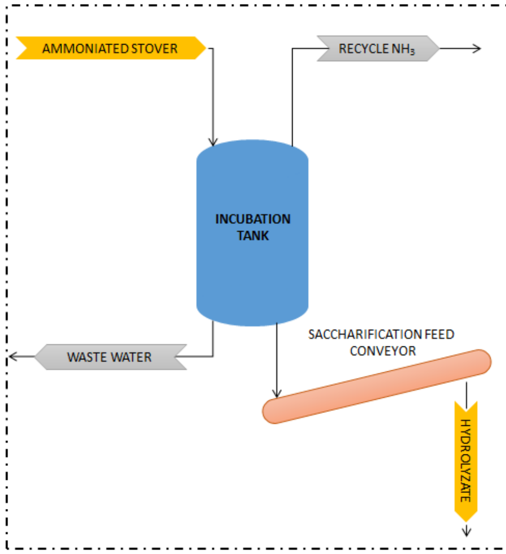

Figure 4. Incubation process flow diagram.

The washed and ground corn stover was fed to two screw conveyors with four water pumps for hydrolysis in this process. Then two hold tank with the capacity of 15,000 gal each were used because of ammoniation resistance time. For every half an hour, stover was fed to the ammoniation tank. Anhydrous ammonia was inlet into the tank by two pumps. After this, ammoniated corn stover was transferred into 10 incubation tanks with the capacity of 100,000 gal each. Hydrolysate from incubation was delivered to saccharification process by four belt conveyors. Waste water was collected and treated with both anaerobic and aerobic digester, which will not be discussed in this study.

Saccharification and co-fermentation process

Hydrolysate from pretreatment was fed to the saccharification tank along with enzymes. After saccharification, the microorganism *Z. mobilis,* grown in a seed tank (figure 5), was used as the biocatalyst in the fermentation process.

Then, the seed inoculum, nutrients, and saccharified slurry were added to the ethanol fermenter (figure 6).

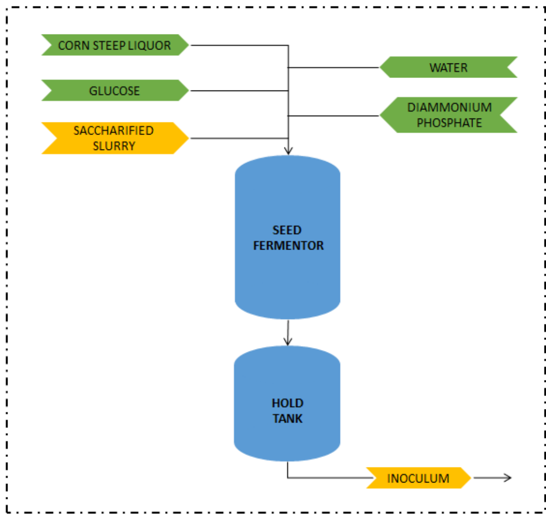

Figure 5. Seed production process flow diagram.

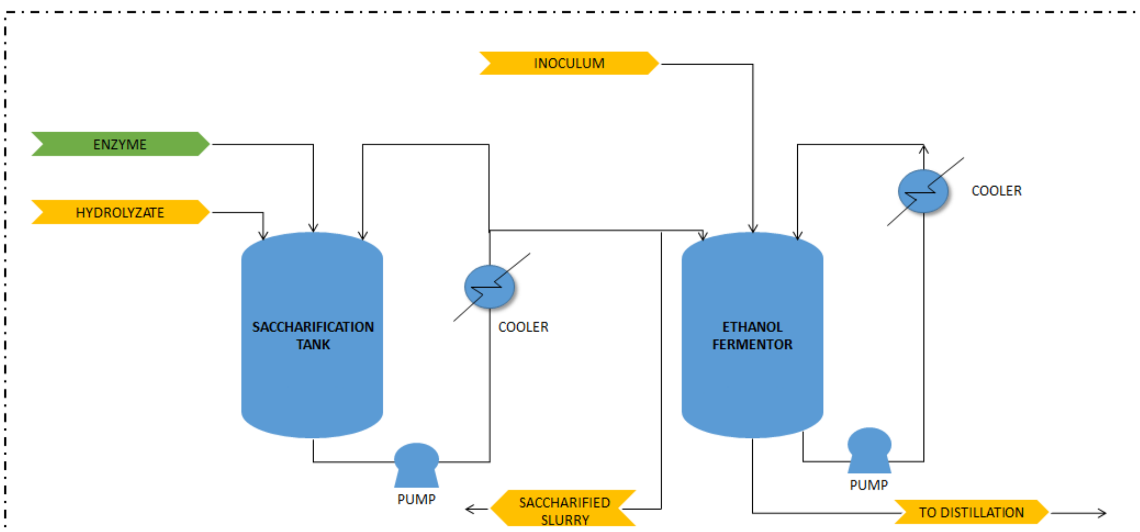

Figure 6. Saccharification and co-fermentation process flow diagram.

In the saccharification process, five 1,000,000-gallon tanks were used. The enzyme loading was calculated based on the cellulose content and target hydrolysis conversion level. A cooler was used for saccharified slurry. Other assumptions were listed in table 4 below.

Table 4. Saccharification conditions.*

Temperature	65°C
Residence time	2 days
Cellulose loading	12 FPU/g cellulose
Number of continuous trains	1

*Reference: Aden et al., 2002.

In terms of seed production process, 10% of the saccharified slurry was sent for seed production (Aden et al., 2002). Two trains were used for turn-around time for each seed fermenter for 12 hours; five fermenters were needed in each train. Other assumptions were listed in table 5 below.

Table 5. Seed production conditions.*

Number of trains	2
Number of fermenter	5 /train
Max fermenter volume	10,000L
Min fermenter volume	100L
Corn steep liquor level	0.5%
Diammonium phosphate level	0.67 g/L broth

* Reference: Aden et al., 2002.

Fermentation process was conducted in five 1,000,000-gal ethanol fermenters. The total residence time was assumed to be 36 hours. The fermenters were cooled before distillation and evaporation process. Table 6 listed the assumptions used in the fermentation process.

Table 6. Fermentation conditions.*

Microorganism	*Z. mobilis*
Residence time	36 hrs
Number of fermenter	5
Temperature	41°C
Corn steep liquor level	0.25%
Diammonium phosphate level	0.33 g/L broth

***** Reference: Aden et al., 2002.

Evaporation

During this process, molecular sieves and distillation were used for ethanol recovery. Figure 7 below represented this process.

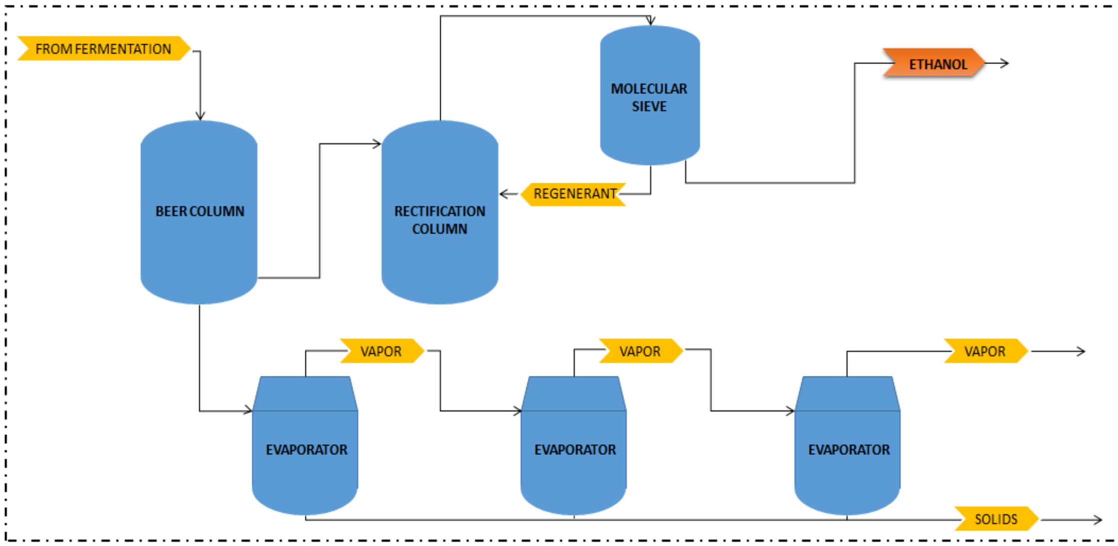

Figure 7. Distillation and evaporation process flow diagram.

Five beer columns with the capacity of 1,000L were used in distillation process to remove the dissolved CO_2 and most of the water. The ethanol was collected as vapor from the beer column and fed to rectification column. After rectification, overhead vapor of ethanol was given to molecular sieve adsorption unit. Nice pieces were contained in this unit, such as product cooler, condenser, and molecular sieve columns. The mixture was condensed and returned to the rectification column.

Liquids from beer column was sent to the 1st evaporator, about 24% of the water entering could be evaporated (Aden et al., 2002). Then the slurry was fed to the 2nd evaporator, about 44% of the water could be evaporated. The 3rd evaporator could evaporate nearly 76% of the water. The final vapor was condensed, and solids were sent to burner.

Combustor / burner

The purpose of this process was to burn solids or by-products downstream for electricity generation. All the remaining lignin and hemicellulose from the feedstock were burnt in the fluidized bed combustor. A generator was used to generate electricity. The flow diagram of this process was shown in figure 8.

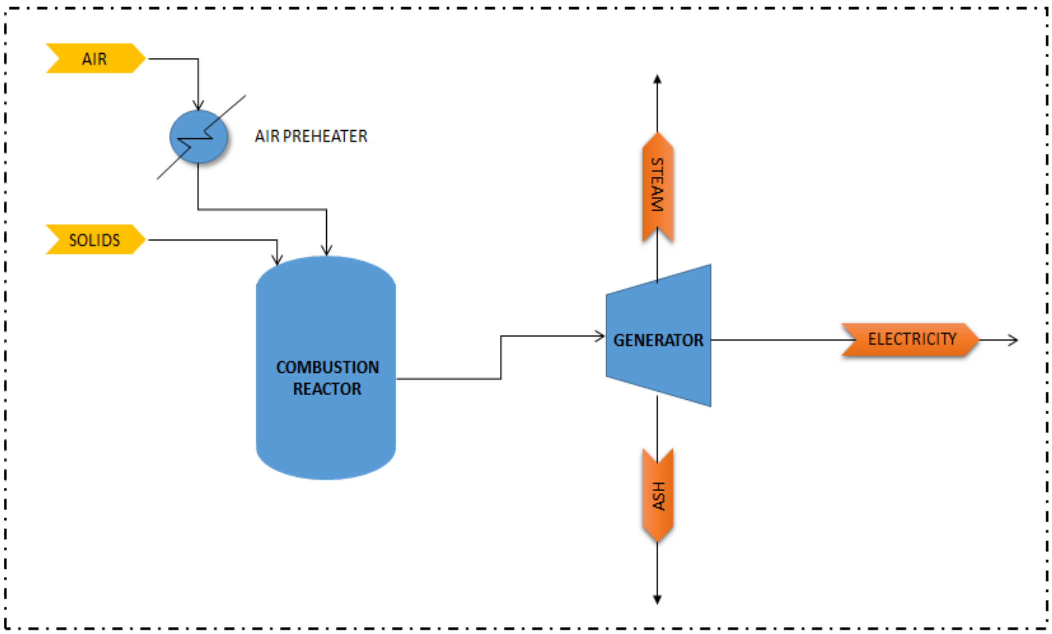

Figure 8. Burning process flow diagram.

Results and Discussion

The techno-economic analysis (TEA) of the cellulosic ethanol plant was conducted on three different scales based on corn stover capacity: 100 MT/d, 800 MT/d and 2,000 MT/d. Results showed that the larger the plant scale, the lower the product cost, which was illustrated in figure 9. The approximate ethanol yield per year in compatible with the corn stover capacity was 2.5 MMgal/y, 20 MMgal/y, and 50 MMgal/y, respectively. The lowest cost of ethanol was $3.86/gal for a commercial plant of 50 MMgal ethanol yield per year, which was still higher compared with market gasoline price ($3.704) (U.S. Energy Information Administration, 2014). However, this cost would be much higher in real commercial scale since the waste water treatment, storage cost, and utility cost were not considered in this study. In terms of the small scale ethanol plant (2.5 MMgal/y), the ethanol cost would be $5.08/gal; and $4.28/gal for medium scale ethanol plant (20 MM gal/y).

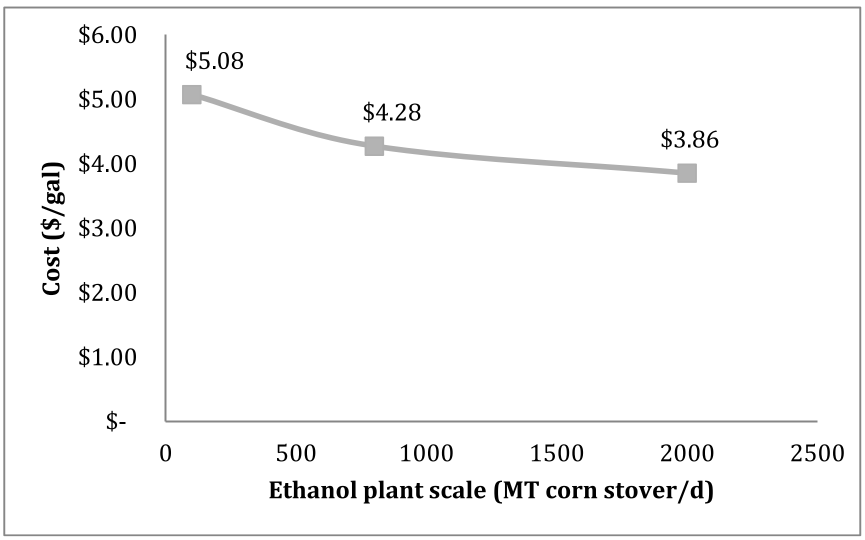

Figure 9. Cost per unit ethanol in different scales.

In terms of cost per ton of feedstock, as shown in figure 11, the larger the plant size, the lower the unit cost. For small scale, the cost per unit feedstock was $451.27; for medium scale, it decreased to $380.85; and $342.79/ton of corn stover for large scale ethanol production.

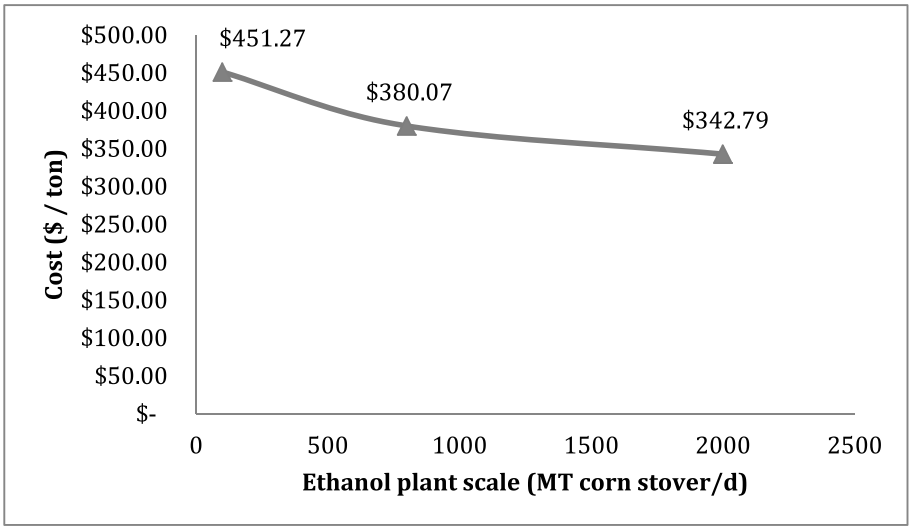

Figure 10. Cost per unit feedstock in different scales.

Detailed report for the 2000 MT corn stover/d plant with ethanol production of 50 MMgal/y was shown in table 7.

Table 7. TEA report of 50 MMgal/y ethanol production plant.

Large scale plant		
Capital Cost	**$**	**12,314,393.88**
1.Equipment initial cost	$	11,727,994.17
2. Engineering and design cost	$	586,399.71
Fixed Cost	**$**	**2,008,942.49**
1. Depreciation	$	687,503.11
2. Insurance	$	175,919.91
3. Interest	$	879,599.56
4. Overhead	$	90,000.00
5. Taxed	$	175,919.91
Variable Cost	**$**	**178,497,611.78**
1. Electricity cost	$	21,638.32
2.Maintenance & repair	$	234,559.88
3. Misc. supplies	$	148.13
4. Water cost	$	148,612.95
5. Materials cost	$	178,092,652.50
Annualized Benefit	**$**	**126,213,240.78**
Total cost	**$**	**192,820,948.15**
Cost ($/ton corn stover)	$	342.79
Cost ($/gal ethanol)	$	3.86

Detailed report for the 800 MT corn stover/d plant with ethanol production of 20 MMgal/y was shown in table 8.

Table 8. TEA report of 20 MMgal/y ethanol production plant.

Medium scale plant		
Capital Cost	**$**	**12,202,761.15**
1.Equipment initial cost	$	11,621,677.28
2. Engineering and design cost	$	581,083.86
Fixed Cost	**$**	**1,937,546.85**
1. Depreciation	$	681,270.74
2. Insurance	$	174,325.16
3. Interest	$	871,625.80
4. Overhead	$	36,000.00
5. Taxed	$	174,325.16
Variable Cost	**$**	**71,550,637.29**
1. Electricity cost	$	21,638.32
2.Maintenance & repair	$	232,433.55
3. Misc. supplies	$	59.25
4. Water cost	$	59,445.18
5. Materials cost	$	71,237,061.00
Annualized Benefit	**$**	**51,202,242.48**
Total cost	**$**	**85,690,945.29**
Cost ($/ton corn stover)	$	380.85
Cost ($/gal ethanol)	$	4.28

Detailed report for the 100 MT corn stover/d plant with ethanol production of 2.5 MMgal/y was shown in table 9.

Table 9. TEA report of 2.5 MMgal/y ethanol production plant.

Small scale plant		
Capital Cost	**$**	**3,123,018.88**
1.Equipment initial cost	$	2,974,303.70
2. Engineering and design cost	$	148,715.18
Fixed Cost	**$**	**576,657.62**
1. Depreciation	$	174,355.73
2. Insurance	$	44,614.56
3. Interest	$	223,072.78
4. Overhead	$	90,000.00
5. Taxed	$	44,614.56
Variable Cost	**$**	**8,992,367.92**
1. Electricity cost	$	20,811.17
2.Maintenance & repair	$	59,486.07
3. Misc. supplies	$	7.41
4. Water cost	$	7,430.65
5. Materials cost	$	8,904,632.63
Annualized Benefit	**$**	**6,557,686.59**
Total cost	**$**	**12,692,044.43**
Cost ($/ton corn stover)	$	451.27
Cost ($/gal ethanol)	$	5.08

Conclusions

In this study, the cellulosic bioethanol plant based on six major processing sections was built in three different scales: 100 MT corn stover/d, 800 MT corn stover/d, and 2,000 MT corn stover/d. After the techno-economic analysis, the result showed that the larger the ethanol plant, the lower the unit cost both in $/gal of ethanol and $/ton of feedstock. However, the minimum ethanol selling cost obtained from this study was still high compared with the current gasoline price. In order to further reduce the unit cost to make bioethanol more competitive, improvements in process design and ethanol conversion rate need to be made. As the development of biorenewable energy industry and the techno-economic analysis, lower price in bioethanol could be achieved in the near future.

Acknowledgements

This study was funded by the United States Department of Transportation, under contract DTOS59-07-G-00054.

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