Techno-economic Analysis of Co-located Corn Grain and Corn Stover Ethanol Plants

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Abstract

The goal of this paper is to evaluate the economic performance of co-located corn grain ethanol (Gen 1) and cellulosic ethanol (Gen 2) facilities. We present six scenarios to evaluate the impact of stover-to-grain mass (SGM) ratios on overall minimum ethanol selling price (MESP). For the Gen 1 plant, MESP is $3.18/ gasoline gallon equivalent (GGE) while for the Gen 2 plant it is $5.64/GGE. Co-located Gen 1 and Gen 2 plants operating at the lowest SGM ratio of 0.4 generates the lowest overall MESP of $3.73/GGE as well as the highest MESP for cellulosic ethanol of $7.85/GGE. Co-located plants operating at the highest SGM ratio of 1.0 achieve the highest overall MESP of $3.94/GGE as well as the lowest MESP for cellulosic ethanol of $5.47/GGE. Sensitivity analysis shows that the prices of feedstocks have the greatest impact on the overall MESP.

Keywords: Ethanol; corn grain; corn stover; cellulosic ethanol; co-located plants; techno-economic analysis

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1. Introduction

The goal of this paper is to evaluate the economic performance of co-located corn grain ethanol and cellulosic ethanol facilities, which has several advantages over separate facilities. Corn stover is the most abundant agricultural residue available in the U.S.,[1] and is expected to be one of the single largest sources of lignocellulosic biomass in the country by the end of the decade.[2] Corn production and stover production occur on the same land and its use effectively increases the amount of biofuel feedstock that can be sustainably harvested per acre of cropland by 30-51%.[3] Moreover, co-locating cellulosic ethanol and corn ethanol production plants has the potential to reduce the production costs of both pathways due to economies of scale, thus accelerating the commercialization of cellulosic ethanol and making corn ethanol more competitive with fossil fuels. Finally, co-locating the facilities increases the amount of bioenergy derived per acre of land, thereby decreasing the lifecycle emissions of both when measured on the same basis.[4] While such a reduction doesn't benefit the corn ethanol pathway under the revised Renewable Fuel Standard (RFS2) due to its explicit production cap of 15 billion gallons per year (BGY), it could improve public perceptions of the pathway.

Corn ethanol suffers from a number of drawbacks and has come under criticism in recent years. In 2011 nearly 46% of the U.S. corn crop, or 5 billion bushels, was used as corn ethanol feedstock.[5] Despite this high usage rate, fuel ethanol production for the same year equaled only 10% of gasoline production.[6] The diversion of such a large proportion of the U.S. corn crop to fuel ethanol production has driven fears that corn ethanol production causes chronic hunger in developing countries [7] and the destruction of rainforests in Brazil.[8] While more recent analyses have called into question the actual magnitude of these effects,[9, 10] the use of corn as a biofuel feedstock has remained controversial.

Cellulosic ethanol has several advantages over corn ethanol from energetic, environmental, and economic perspectives. Cellulosic ethanol can be derived from a variety of lignocellulosic feedstocks including corn stover, switchgrass, hybrid poplar, and wood residues.[11] Lignocellulosic biomass is not a source of human nutrition and can be grown on marginal cropland and forestland, allowing cellulosic ethanol to avoid controversies over “food vs. fuel” and indirect land-use change. Furthermore, cellulosic ethanol has a better net energy balance than corn ethanol and contributes less to direct-effect greenhouse gas (GHG) emissions than corn ethanol.[11, 12] Cellulosic ethanol has attracted significant attention in U.S. due to these advantages and, based on current construction, will account for nearly half of U.S. cellulosic biofuel capacity by the end of 2014.[13]

Co-locating a first generation (Gen 1) dry mill corn ethanol plant with a second generation (Gen 2) cellulosic ethanol plant is reported to be both technically feasible [14, 15] and capable of reducing cellulosic ethanol production costs.[15] However, the effects of different stover-to-grain mass (SGM) ratios on the economic feasibility of the co-located Gen 1+ Gen 2 plants have not been previously considered. The feedstock type mass ratio is linked to the sustainability of the pathway, since only a fraction of corn stover produced per acre can be sustainably removed for Gen 2 ethanol production, it is important to quantify the impact of changing SGM ratios on the technical and economic feasibility of a Gen 1+ Gen 2 plant as a result. This paper quantifies these feasibilities via a comparative techno-economic analysis of six different process scenarios:

a Gen 1 dry mill corn ethanol plant, a Gen 2 cellulosic ethanol plant using corn stover as feedstock, and a Gen 1+ Gen 2 plant under four SGM ratio scenarios of 0.4:1, 0.6:1, 0.8:1, and 1:1. Minimum ethanol selling prices (MESP) are calculated for each scenario.

2. Methods

2.1. Process modeling

The models for the stand-alone Gen 1 and Gen 2 ethanol plants are based on models previously described in the literature,[16-19] but with several important differences. First, the models used in the present study were constructed using ChemCAD™ rather than SuperPro Designer® and Aspen Plus™. Different compositions of corn grain and corn stover are assumed (see **Table 1** and **Table 2**). Moisture content of corn grain is assumed to be 15% while corn stover moisture is assumed to be 20%[17, 20] instead of 25% assumed in a previous National Renewable Energy Laboratory (NREL) model.[18]

[Insert Tables 1 and 2 here]

In this analysis, both kinds of ethanol plants are assumed to have 30-year lifetimes, consistent with the assumption of Humbird et al. [17] but longer than 10-20 year lifetimes assumed by several other studies.[16, 18, 19] Furthermore, a Lang factor of 5.03 is used for both plants, which is higher than those used in previous reports.

2.1.1 Gen 1 dry mill corn ethanol production

[Insert Fig. 1 here]

Fig. 1 is a schematic of the Gen 1 dry mill corn ethanol plant modeled in this study. Corn is received and cleaned using a blower and screens. The cleaned corn is fed to a hammer mill for size reduction. The ground corn is mixed with water, ammonia, lime and enzymes and undergoes liquefaction at 88 ^oC, where starch is broken down to oligosaccharides. The resulting oligosaccharides are then saccharified to glucose at 61 ^oC. Sulfuric acid is added to adjust pH in the tank and necessary enzymes are added. The glucose is then fermented to ethanol and carbon dioxide using yeast at 32 ^oC. Since the conversion of glucose to ethanol produces heat, cooling is necessary in the process of fermentation so that the temperature is maintained to ensure high yeast activity. After flashing off vapor, the effluent from fermentation goes to a beer column where most of ethanol produced is captured. Rectification is then used to separate water from ethanol. Distillate from the rectifier, which captures more than 99% of the ethanol, feeds the molecular sieves to remove the remaining water, producing 99.6% pure ethanol. The bottoms from the beer column are dewatered by centrifugation. The liquid product is split and used as backset, while the rest goes to an evaporator, where water is recovered. The concentrate from the evaporator is mixed with the solid product from the centrifuge. The mixture is dewatered and concentrated further. The product, known as distiller's dried grains with solubles (DDGS), is sold as an animal feed. Thermal energy for liquefaction of cornstarch, distillation of ethanol, and drying of DDGS in the Gen 1 plant is supplied by natural gas.

2.1.2 Gen 2 ethanol derived from corn stover

[Insert Fig. 2 here]

Fig. 2 is a schematic of a Gen 2 ethanol production plant. Corn stover bales are received and delivered to a feed handling area for impurity removal and size reduction. From here, the washed and milled stover is fed to a pre-steamer reactor. Low pressure (LP) steam is added to remove non-condensable gases and reduce the pre-hydrolysis reaction heat requirement. Acid and high pressure (HP) steam are added to hydrolyze most of the hemicellulose to soluble sugars such as xylose, mannose, arabinose and galactose. The liquid portion is overlimed after being separated from the solids. After pH adjustment it is mixed with hydrolyzate solids from the solid/liquid separation step. The conditioned slurry is then mixed with purchased cellulase enzymes to saccharify the cellulose to glucose. The resulting glucose together with the sugars released in the hydrolysis of hemicellulose are co-fermented to ethanol and carbon dioxide by the action of recombinant *Z. mobilis*, which is grown in a seed fermentation train of vessels in the process area. The beer from fermentation is fed into the beer column where almost all of the CO_2 and about 90% of water are removed. The vapor side draw from beer column then enters a rectifier to capture more than 99% of the ethanol. The distillate from the rectifier goes to molecular sieves to produce 99.5% pure ethanol by removing 95% of the water. The CO_2 produced in fermentation and the vent of the beer column pass through a water scrubber before venting the gas. The water effluent from the scrubber is fed to the beer column. The bottoms of the beer column, which contains insoluble solids, are sent to a multi-effect evaporator. Lignin is separated from the slurry from the first stage of the evaporator by solid-liquid separation. The liquid portion is then returned to the second stage of the evaporator. The concentrated syrup from the evaporator is mixed with lignin and sent to a boiler, which supplies all the thermal energy required in the Gen 2 plant for pretreatment of stover, saccharification of cellulose and hemicellulose, distillation of ethanol, and recovery of lignin and syrup from the distillation bottoms. The condensate from the evaporator is recycled to the process as relatively clean water.

2.2 Combined heat and power (CHP) plant design for co-located Gen 1 and Gen 2 plants

[Insert Fig. 3 here]

Thermal energy for the co-located Gen 1 and Gen 2 plants is provided by a CHP plant, illustrated in **Fig. 3**, co-fired by lignin and cornstover instead of natural gas, as is the case for a stand-alone Gen 1 plant. The fraction of corn stover that is combusted depends on the SGM ratio. The CHP plant also produces electricity in excess of plant requirements for power and is sold to the grid. Combustion occurs at 20% excess air to generate superheated steam at 60 atm and 454 ^{o}C. This steam is expanded through a turbine to 268 ^{o}C, 13 atm, which is split into three streams to meet the HP steam requirement of the Gen 2 plant, preheat boiler feed water to 177 ^{o}C, and supply the second stage of turbine expansion to 164 ^{o}C, 4.42 atm. The LP steam exiting this expansion stage supports thermal energy requirements of both the Gen 1 and Gen 2 plants. Excess LP steam is used to generate additional electricity. Efficiency of the turbine stages is assumed to be 0.85. Flue gas leaves the boiler at 278 ^{o}C and is used to preheat compressed air to 204 ^{o}C.

2.3 Economic analysis

The first step in performing economic analyses of the Gen 1 dry mill ethanol and Gen 2 cellulosic ethanol plants are to build process models using ChemCAD™. The process data implemented in ChemCAD™ are obtained from previously published papers.[16-19] The results from the ChemCAD™ simulations are then used to estimate purchased equipment costs. Purchased costs of some simple equipment such as pumps are obtained directly from ChemCAD™. Purchased costs of the remaining equipment are derived from previous reports and publications and scaled according to the sizing results of the ChemCAD™ simulations. The sum of purchased equipment costs are reported as total purchased equipment cost (TPEC). All prices are adjusted to 2012.

Total project investment (TPI) cost is calculated as a function of TPEC. A total Lang factor of 5.03 is recommended for estimating TPI based on TPEC.[21] **Table 3** presents the methodology employed to calculate plant TPI. Operating cost is calculated using the output data from ChemCAD™ and other available resources.[16-19] The results are imported into a Microsoft® Excel discounted cash flow rate of return (DCFROR) spreadsheet developed by NREL [22] in which MESP is calculated as a function of capital cost and operating cost. MESP is determined such that the net present value equals zero at a 10% internal rate of return (IRR). **Table 4** gives the main assumptions made to obtain the MESPs in this paper. **Table 5** gives the prices of the main pathway input and output commodities, which are used to calculate operating costs and revenue. Since 2011 the prices of corn grain and DDGS have ranged widely from $5/bu to $8/bu and $200/ton to $300/ton, respectively.[23] A corn grain price of $6/bu ($236/metric ton) and a DDGS price of $245/ton ($0.27/kg) are employed in this analysis. Electricity price have ranged from

$0.065/kwh to $0.074/kwh since 2011.[24] An electricity price of $0.070/kwh is employed. The purchased cellulase price is taken such that it contributes $0.50/gal to Gen 2 ethanol production cost.[17] Prices of sulfuric acid, alpha-amylase, glucoamylase, yeast from previous papers [18, 19] are adjusted to 2012 prices.

[Insert Tables 3, 4, and 5 here]

The mass ratio of corn stover to corn grain in the production of a corn crop is estimated to be 1:1.[25] Therefore, the maximum mass flow rate of corn stover available for ethanol production equals to the mass flow rate of corn if corn stover comes from the same location as corn. However, at least 40% of stover should be left on the field to ensure soil preservation by mitigating erosion.[26] Therefore at most 60% of stover can be sustainably harvested from the same location as the corn. In this paper, four SGM ratios are investigated: 0.4:1, 0.6:1, 0.8:1 and 1:1. Stover that exceeds 60% is either transported from other locations or from the same location on the occasion that it is demonstrated that more than 60% stover removal is agriculturally sustainable. The additional cost incurred either by transporting the exceeding part of stover or preservation of soil quality with more than 60% stover removal is dependent on plant location, feedstock availability and logistics and is difficult to account for. However, these addition costs can be treated as an increase in feedstock cost. Its impact on the overall MESP is discussed in sensitivity analysis.

Summarizing, six different scenarios are developed in the present study: a Gen 1 dry mill corn ethanol plant (Scenario A), a Gen 2 cellulosic ethanol plant using corn stover as feedstock

(Scenario B), and a co-located Gen 1+ Gen 2 ethanol plant with SGM ratios of 0.4:1, 0.6:1, 0.8:1, and 1:1 (Scenarios C, D, E and F). This analysis assumes that the two co-located plants have in common only utility-related equipment; that is, steam and electricity generated at the facility are shared by the Gen 1 and Gen 2 plants, making the overall facility self-sufficient in meeting energy demand, while the process streams are not co-mingled. Due to the fact that the dry mill corn ethanol plant is more energy intensive and requires a larger amount of steam than the Gen 2 plant, a fraction of the stover supply is combusted together with lignin co-product from processing corn stover in the Gen 2 plant to meet the overall steam demand.

In order to investigate the effect of SGM ratios on MESP, the capacity of the dry mill corn ethanol plant is fixed at 95.9 million gallons per year, which is a typical capacity of a modern dry mill plant,[27] while the mass flow rate of corn stover is varied to account for different SGM ratios. Not all of the harvested stover is converted to ethanol in the co-located plant since a fraction is combusted to provide process heat. The mass of stover combusted is calculated so that the co-located plant is self-sufficient in terms of steam and electricity. The capital costs of the Gen 2 ethanol plant in SGM ratio scenarios C, D, E and F are then scaled from the equipment cost of the stand-alone Gen 2 ethanol plant (Scenario B) based on the mass of stover combusted. The equipment scaling ratio is obtained from previous studies.[16-18] Finally, the capital costs and operating costs of the co-located plant is combined and the MESP for the co-located Gen 1 + Gen 2 facility is obtained. The MESP for cellulosic ethanol for the co-located plant is calculated via the following equation:[28]

$$MESP_{Gen\ 2} = \frac{MESP_{Gen\ 1+Gen\ 2} \cdot Y_{Gen\ 1+Gen\ 2} - MESP_{Gen\ 1} \cdot Y_{Gen\ 1}}{Y_{Gen\ 1+Gen\ 2} - Y_{Gen\ 1}} \qquad (1)$$

Where $MESP_{Gen\,1+Gen\,2}$ is the overall MESP, $MESP_{Gen\,1}$ is the MESP for corn grain ethanol

(Scenario A), $Y_{Gen\ 1+Gen\ 2}$ is the volume of Gen 1+ Gen 2 ethanol produced in the co-located plant, and $Y_{Gen\ 1}$ is the volume of ethanol produced in the Gen 1 process.

3. Results and discussion

3.1 Results

Table 6 shows TPEC and TIC of a 95.9 MMgal/yr stand-alone Gen 1 ethanol plant (Scenario A). Coproduct processing comprises the largest portion of installed cost of a Gen 1 ethanol plant, accounting for more than 40% of the total. The cost is mainly driven by the employment of a multi-effect evaporator, a rotary drum dryer and a centrifuge. Fermentation is the second largest contributor to the total installed cost, accounting for 20% of the total. These results accord with that of other publications.[19]

[Insert Table 6 here]

Table 7 shows TPEC and TIC of a 47.7 MMgal/yr stand-alone Gen 2 ethanol plant (Scenario B). Combustor, boiler, and turbogenerator contributes 38% of the total. It is the largest portion of total installed cost and is followed by pretreatment, recovery, saccharification and fermentation. These results also agree with other reports.[16, 18]

[Insert Table 7 here]

Table 8 shows the results of the six scenarios considered. MESPs of a stand-alone 95.9 million gallons per year Gen 1 plant and a stand-alone 47.7 million gallons per year Gen 2 plant are $3.18/ gasoline gallon equivalent (GGE) and $5.64/GGE, respectively. The high MESP of a Gen 2 plant is a major obstacle to its commercialization. It is also noticeable that a significant amount of surplus electricity is produced in a Gen 2 plant while a Gen 1 plant purchases electricity from the grid, making it possible to share the generated electricity in a co-located plant, thus decreasing the production cost.

[Insert Table 8 here]

In a co-located Gen 1 and Gen 2 plant, not all of the stover is used to produce cellulosic ethanol. Part of it is combusted to supply thermal energy to the plant, the amount depending upon the SGM ratio. By comparing scenarios C, D, E and F, it can be seen that for a SGM ratio of 0.4:1 (Scenario C), more than 40% of the corn stover is combusted in order to meet the steam and power demand of the co-located plants while only a small portion of stover is converted to ethanol, producing only 12.8 million gallons per year of cellulosic ethanol. As SGM ratio increases, the fraction of combusted corn stover decreases and cellulosic ethanol production increases. Co-located Gen 1 and Gen 2 plants with SGM ratios of 0.6:1 and 0.8:1 (Scenarios D and E) produce 24.4 and 36.0 million gallons of cellulosic ethanol per year, respectively. When the SGM ratio reaches 1:1 (Scenario F), about 16% of stover is combusted and cellulosic ethanol production reaches 47.7 million gallons per year, about 4 times of that of Scenario C. As a consequence of increased cellulosic ethanol production, the overall MESP of co-located plants goes up as the SGM ratio increases due to higher production cost of cellulosic ethanol. The overall MESP ranges from \$3.73/GGE to \$3.94/GGE as SGM ratio increases from 0.4:1 and 1:1. Although this value is higher than the MESP of a stand-alone Gen 1 plant, it is still significantly lower than the MESP for a stand-alone Gen 2 ethanol plant, demonstrating the advantage of co-locating a Gen 2 plant with a Gen 1 plant. In spite of the increasing overall MESP, MESP for cellulosic ethanol reduces from $7.85/GGE to $5.47/GGE as the SGM goes from 0.4:1 to 1:1, demonstrating the effect of economies of scale. This result indicates that higher SGM ratio favors production of price-competitive cellulosic ethanol. It also can be seen from **Table 8** that more surplus electricity is produced alongside the increase of Gen 2 ethanol yield when the SGM ratio increases since electricity is a main byproduct of Gen 2 ethanol.

By comparing the MESP of Scenario B with that of Scenario D, it is found that the co-located plants provide lower MESP for cellulosic ethanol than stand-alone Gen 2 ethanol plants with the same yield. It is expected that if corn price is reduced, the co-located plants will result in even lower MESP for cellulosic ethanol. However, as previously mentioned, around 40% percent of stover should be left in the field to prevent soil erosion; hence a higher SGM ratio may incur additional transportation costs, which are not considered in the calculation.

3.2 Sensitivity analysis

The overall MESP for a Gen 1+ Gen 2 facility is very sensitive to the price of the feedstocks (corn grain and corn stover) and to byproduct (DDGS and electricity) selling price; capital cost and yield also have significant impact on overall MESP; thus an analysis of impact of these variables on the overall MESP is performed for scenarios C, D, E, and F. The results are shown in **Fig. 4**. It should be noticed that as previously mentioned, the change in feedstock price may be a reflection of either change in real market price or an increase incurred by additional feedstock transportation cost or soil preservation cost.

[Insert Fig. 4 here]

The cost of purchasing corn grain accounts for a large proportion of the overall MESP for a Gen 1+ Gen 2 facility. In fact, with the rapid increase of corn price in recent years, corn accounts for a larger proportion of the MESP for grain ethanol than at any time in the past. Corn price has increased by more than 100% since 2010, from about $118/metric ton ($3/bu) to higher than $236/metric ton ($6/bu). Hence, it is expected that corn price has a significant impact on overall MESP for a Gen 1+ Gen 2 facility, as can be seen in **Fig. 4**(a). A decrease in corn price by 30% reduces the overall MESP by more than 15% in all scenarios. When corn price reaches a very high value (>$300/metric ton), the overall MESP gets very close in all mass ratio scenarios. The high corn price covers the difference of other variables in this case, thus resulting in a similar overall MESP.

Fig. 4(b) shows the impact of corn stover price on the overall MESP for a Gen 1 + Gen 2 facility. Despite the fact that the impact of corn stover price on the overall MESP is very similar to that of corn grain price in trend, the former has much less impact on the overall MESP than the latter does. A decrease in corn stover price by 30% reduces the overall MESP by less than 5%. If more cellulosic ethanol plants are built in the future, the price of corn stover is likely to increase with growing stover demand and overall MESP will go up for a Gen 1 + Gen 2 facility.

The impact of selling price of byproducts on the overall MESP is shown in **Fig. 4**(c) and (d). A decrease in DDGS selling price by 30% reduces the overall MESP by about 6% while a decrease in electricity selling price by 40% reduces the overall MESP by about 1%.

The impact of capital cost and yield on overall MESP is evaluated by assuming a ±20% change in these parameters from base case for each scenario. The results are shown in **Fig. 4**(e) and (f) respectively. A 20% increase (reduction) in capital cost leads to a 4% increase (reduction) in overall MESP. Overall MESP is more sensitive to yield by contrast. A 20% increase in ethanol yield results in approximately 17% reduction in overall MESP. If ethanol yield decreases by 20%, overall MESP would rise by 25%. It is not likely to increase the yield of Gen 1 ethanol plant due to relative maturity of technology; however, Gen 2 ethanol technology is still under development and it would be highly advantageous to employ new technologies such as 2-stage dilute acid pretreatment and separate C5 and C6 fermentation[18] if these technologies are proved to be able to increase Gen 2 ethanol yield.

4. Conclusions

Co-location of grain ethanol (Gen 1) and cellulosic ethanol (Gen 2) plants produces lower-cost cellulosic ethanol than stand-alone Gen 2 plants. In general, higher SGM ratio improves the competitiveness of cellulosic ethanol. An increase of SGM ratio from 0.4:1 to 1:1 reduces the MESP for cellulosic ethanol from \$7.85/GGE to \$5.47/GGE. Overall MESP for a Gen 1 + Gen 2 facility is most sensitive to the price of feedstocks.

With increasing corn price and Gen 1 ethanol production rate approaching the RFS2 capping, co-location of Gen 1 and Gen 2 plants may become even more appealing in the near future. However, MESP of co-located ethanol plants is still higher than ethanol market price.[29] This may be the main obstacle for commercialized co-located ethanol plants. The high MESP is mainly driven by high corn price and high conversion cost of Gen 2 stover ethanol plant. Sensitivity analysis indicates that increasing yield can lower MESP significantly. If new technologies are developed to increase the yield of Gen 2 ethanol plants, it is more likely to see co-located Gen 1 and Gen 2 ethanol plants emerge in the future.

Acknowledgements

The authors would like to acknowledge the financial support of the U.S. Department of Energy through the Bioenergy Technology Office.

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Figure Captions

Fig. 1. Schematic of a Gen 1 dry mill corn ethanol plant.

Fig. 2. Schematic of a Gen 2 cellulosic ethanol plant.

Fig. 3. Schematic of the CHP plant. Stream types: steam (dash), water (solid), air (dash dot), flue gas (dot).

Fig. 4. Influence of different variables on the overall MESP for a Gen 1 + Gen 2 ethanol facility.