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LCA and TEA of Corn Stover Size Reduction

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Abstract
Cost and environmental impacts are the two key issues related to the development of biofuels. The size reduction process of feedstock for the production of lignocellulosic ethanol, a second generation biofuel, is energy-intensive and costly. In this study, life cycle analyses and techno-economic analyses were conducted for six different scenarios of corn stover size reduction. Six grinding condition combinations of three different moisture content (5%, 10%, 20%, wet basis) and two different screens (2 mm, 6 mm) of a knife mill were each used for the six scenarios. The cost and environment impact was compared for each scenario on the basis of producing the same amount of fermentable sugars. A comparably cost-efficient and environmentally friendly corn stover size reduction scenario was concluded.

Keywords
biofuel, cellulosic ethanol, corn stover, size reduction, LCA, TEA

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LCA and TEA of Corn Stover Size Reduction

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ABSTRACT. *Cost and environmental impacts are the two key issues related to the development of biofuels. The size reduction process of feedstock for the production of lignocellulosic ethanol, a second generation biofuel, is energy-intensive and costly. In this study, life cycle analyses and techno-economic analyses were conducted for six different scenarios of corn stover size reduction. Six grinding condition combinations of three different moisture content (5%, 10%, 20%, wet basis) and two different screens (2mm, 6mm) of a knife mill were each used for the six scenarios. The cost and environment impact was compared for each scenario on the basis of producing the same amount of fermentable sugars. A comparably cost-efficient and environmentally friendly corn stover size reduction scenario was concluded.*

Keywords. *biofuel, cellulosic ethanol, corn stover, size reduction, LCA, TEA*

Introduction

Lignocellulosic ethanol is a promising second-generation biofuel, and it just started its commercialization in the US. The most recent one and the biggest one is the DuPont cellulosic ethanol plant in Nevada, Iowa. The claimed capacity is 30 million gallons a year. A bad news is that Abengoa Bioenergy shut down their cellulosic plant in Hugoton, Kansas due to some financial reasons. Thus, the cellulosic ethanol industry still needs some improvement before its blossom.

The CO_2 emissions and the cost are the most two important issues that is related to the commercialization of cellulosic ethanol. The impetus of producing cellulosic ethanol is to bring down the CO_2 emissions, which intends to be less than the CO_2 emission from fossil fuel and corn ethanol industry. The cost of the whole processing is the key issue to the financial feasibility of the plant. To analyze these two issues, life cycle assessment (LCA) and techno-economic analysis (TEA) are the best tools. for CO_2 emissions and cost, respectively.

The results in the corn stover grinding experiment showed that the specific energy increased as the moisture content increased and the screen size decreased. In commercial production, however, not only the cost of one specific processing should be considered, but the cost of the whole processing and the yield of final product are considered at the same time. There are some trade-offs between the drying cost the energy consumption of the size reduction. The dryer the feedstock, the higher the drying cost, but the grinding energy consumption will be lower. There are also trade-offs between the energy consumption of size reduction and the efficiency of the downstream processing, i.e., the yield of fermentable sugars. The larger the screen, the lower the grinding energy consumption, but there will be smaller sugar yield.

The objective of this study was to do a Life Cycle Assessment (LCA) and Techno-Economic Analysis (TEA) of corn stover size reduction to test the CO_2 emissions and cost for six different scenarios. Six grinding condition combinations of three different moisture content (5%, 10%, 20%, wet basis) and two different screens (2mm, 6mm) of a knife mill were each used for six scenarios. The cost and environment impact was compared for each scenario with or without the consideration of fermentable sugar yield in the hydrolysis processing. The results showed that when not considering the sugar yield, scenario 6 (grinding the corn stover of 5% moisture content with 6mm screen) has the lowest overall CO_2 emission and lowest overall cost. When considering the sugar yield, on the basis of same fermentable sugar production, however, scenario 5 (grinding the corn stover of 5% moisture content with 2mm screen) has both the lowest CO_2 emission and lowest cost. Hopefully this study will provide a good reference for biomass size reduction process optimization to reduce the environmental impacts and bring down the cost for cellulosic ethanol production.

Methods

Scope and system boundary

System boundary for this study is from the drying of the corn stover to the sugar products of hydrolysis. It is from corn stover to fermentable sugars. Corn stover of 3 different moisture contents was ground using a bench scale knife mill using two different-sized screens, i.e., a 6mm one and a 2mm one. Thus, six grinding scenarios were compared in this study:

- scenario 1: 20% moisture content, 2mm screen;
- scenario 2: 20% moisture content, 6mm screen;
- scenario 3: 10% moisture content, 2mm screen;
- scenario 4: 10% moisture content, 6mm screen;
- scenario 5: 5% moisture content, 2mm screen;
- scenario 6: 5% moisture content, 6mm screen.;

The CO_2 emission and cost of drying and grinding were calculated. The corresponding fermentable sugar yield were analyzed for each scenario. The total CO_2 emission and cost of drying and grinding were compared with or without the consideration of the sugar yield.

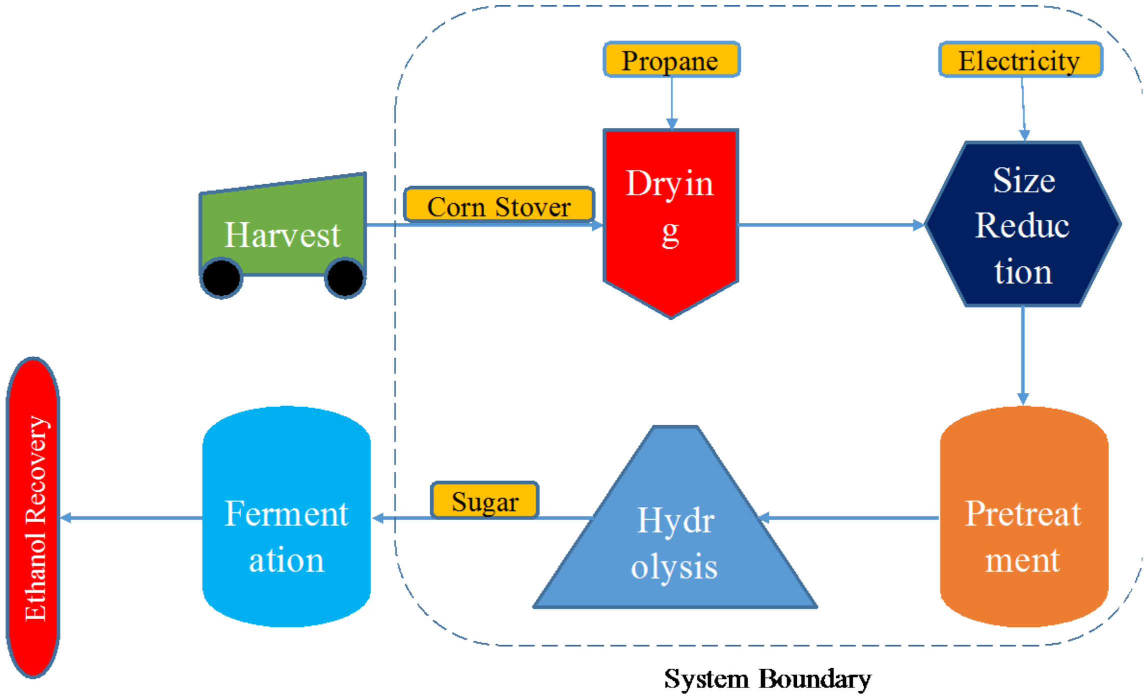

Fig. 3.1 Flowchart of Cellulosic Ethanol Production and System Boundary

Assumptions

All the assumptions used in this LCA and TEA are listed table 3.1. Propane was chosen for the heating media since it is stored in liquid form, easy to transport, relatively cheap, and it is the most widely used for grain drying. The sugar yield conversion factor were assumptions based on the results of the hydrolysis after Low Moisture Anhydrous Ammonia (LMAA) pretreatment. The moisture content settings of the corn stover was 20% wet basis initially. Part of it is dried to 10%, and another part is dried to 5%.

The pretreatment method was assumed to be low-moisture anhydrous ammonia (LMAA) pretreatment, a process that was evaluated by our group. The hydrolysis data for corn stover of different size also came from the LMAA experiment data.

CO2 emission equivalents was analyzed in the LCA part. Online tool EIO-LCA was used for the LCA in this study. CO2 emission equivalents for the manufacturing of each equipment, the producing of corn stover and enzymes were estimated using EIO-LCA. The CO2 emission equivalents for water usage was from oCOcarbon.com. Carbon footprint for ammonia was from TRACI LCA tool. The electricity CO2 equivalent data was obtained from EIA website. CO2 emissions on the basis of same fermentable sugar production were calculated.

Both the capital costs and the operational costs were analyzed in this part. The base costs refer to the fixed capital costs and the operational costs that were the same for each scenario. Similar to CO2 emissions, costs on the basis of same fermentable sugar produced were analyzed.

Table 3.1. Assumptions

Assumptions	Value	Unit	Source
Drying Energy Requirement	4000	kJ/kg water removed	NREL 1998
Heating Media	/	Propane	evergreen-fs.com
Propane Energy Density	90000	BTU/gallon	DOE 2014
Propane Price (Whole Sale, Midwest)	0.5	usd/gallon	eia
Propane CO_2 emission	5.76	kg CO_2/gallon	eia
Conversion Efficiency	85%	1	Maier 2002
Electricity CO_2 Emissions	0.5	kg CO_2/kWh	eia
Electricity Price (Industrial, Midwest)	0.06	usd/kWh	eia
Sugar Yield	40%	of dry mass for 6mm screen	Yang 2014
	85%	of dry mass for 2mm screen	
Corn Stover Initial Moisture Content	20%	wet basis	
Corn Stover Use	1	kg wet material	

Results and Discussion

The separate CO_2 emissions and cost for drying and grinding without the consideration of sugar yield is shown in table 3.2. Table 3.3 is for the emissions and cost for drying and grinding separately on the basis of same fermentable sugar yield. The total emission and cost of drying and grinding is shown in table 3.4.

Table 3.2 CO_2 Emissions and Cost for Drying and Grinding

Scenarios	Drying				Grinding		
	energy use (kJ/kg wet biomass)	**Propane Use (gallon)**	**CO2 emission (kg/kg)**	**cost (usd/kg)**	**electricity use (kWh/kg wet biomass)**	**CO2 emission (kg/kg)**	**cost (usd/kg)**
1 (20%, 2mm)	0	0	0	0	0.241	0.1205	0.0145
2 (20%, 6mm)	0	0	0	0	0.154	0.077	0.0092
3 (10%, 2mm)	400	0.0050	0.0285	0.0025	0.112	0.056	0.0067
4 (10%, 6mm)	400	0.0050	0.0285	0.0025	0.061	0.0305	0.0037
5 (5%, 2mm)	600	0.0074	0.0428	0.0037	0.052	0.026	0.0031
6 (5%, 6mm)	600	0.0074	0.0428	0.0037	0.032	0.016	0.0019

Table 3.3 CO_2 Emissions and Cost per Unit Sugar Yield

Scenarios	Drying				Grinding			sugar yield (kg/kg wet biomass)
	energy use (kJ/kg wet biomass)	Propane Use (gallon)	CO2 per unit sugar (kg/kg sugar yield)	cost per unit sugar (usd/kg sugar yield)	electricity use (kWh/kg wet biomass)	CO2 per unit sugar (kg/kg sugar yield)	cost per unit sugar (kg/kg sugar yield)	
1 (20%, 2mm)	0	0	0	0	0.241	0.1772	0.0213	0.68
2 (20%, 6mm)	0	0	0	0	0.154	0.2406	0.0289	0.32
3 (10%, 2mm)	400	0.0050	0.0420	0.0036	0.112	0.0824	0.0099	0.68
4 (10%, 6mm)	400	0.0050	0.0892	0.0077	0.061	0.0953	0.0114	0.32
5 (5%, 2mm)	600	0.0074	0.0630	0.0055	0.052	0.0382	0.0046	0.68
6 (5%, 6mm)	600	0.0074	0.1338	0.0116	0.032	0.0500	0.0060	0.32

Table 3.4 Total CO_2 Emissions and Cost

Scenarios	total CO2 (kg/kg)	total CO2 per unit sugar (kg/kg sugar yield)	total cost (usd/kg)	total cost per unit sugar (usd/kg sugar yield)
1 (20%, 2mm)	0.1205	0.1772	0.0145	0.0213
2 (20%, 6mm)	0.0770	0.2406	0.0092	0.0289
3 (10%, 2mm)	0.0845	0.1243	0.0092	0.0135
4 (10%, 6mm)	0.0590	0.1845	0.0061	0.0192
5 (5%, 2mm)	0.0688	0.1012	0.0068	0.0101
6 (5%, 6mm)	0.0588	0.1838	0.0056	0.0176

LCA

As can be seen in Figure 3.2, without considering sugar yields, the drying emission is increasing as the material goes drier; the grinding emission increases significantly as the moisture content goes up. The effect of the screen size is not as obvious as moisture content, but it is still noticeable. As is shown in figure 3.3, after taking the sugar production into consideration, the trend for different moisture content remains the same; However, for different screen size, the results become the opposite. That is to say, grinding with the screen of smaller size will have less emissions if the sugar yield is the same.

Even though no LCA study has been carried out specifically on the size reduction processing of lignocellulosic biofuel, some literature focusing on the LCA of biofuels can be found. The emission of different blend of wheat ethanol was analyzed in one of the studies (E. Gnansounou et al. 2009). According to Gnansounou et al., co-products, reference systems, functional unit, and the type of blend would all affect the final results. Another LCA study was conducted on lignocellulosic ethanol. It was said that optimizing the operation is key to reduce the CO_2 emissions (Spatari, Bagley, and MacLean 2010). Hopefully the LCA study in this part will provide some useful information for lignocellulosic ethanol production optimization.

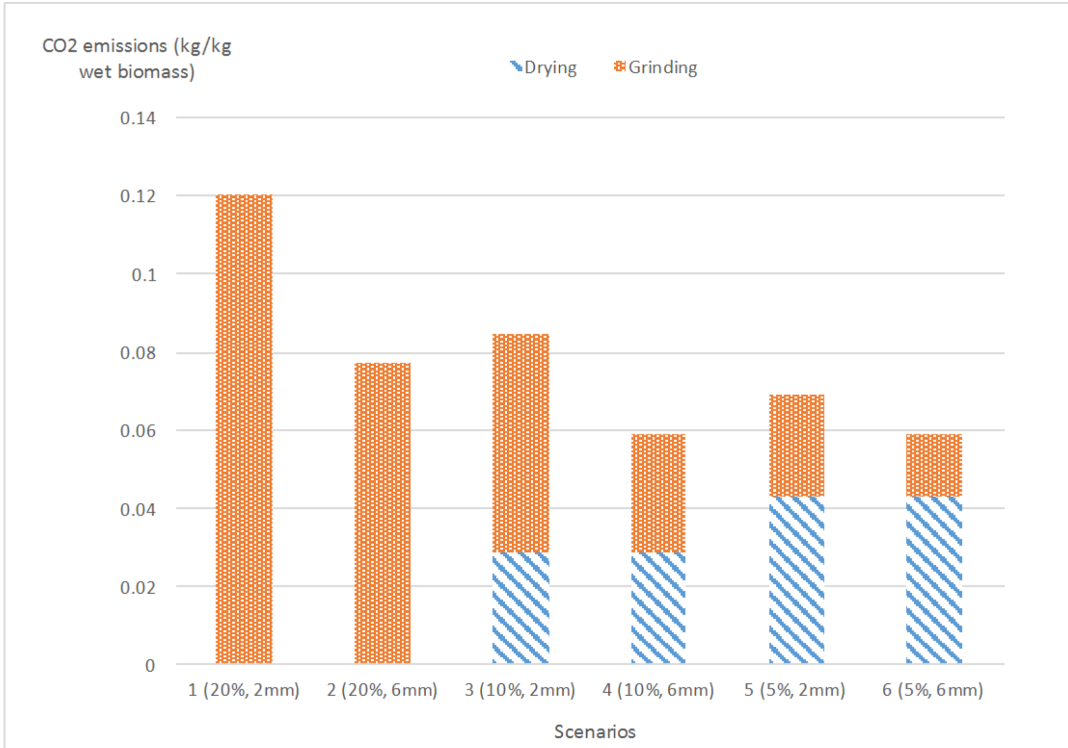

Fig. 3.2 CO_2 Emissions

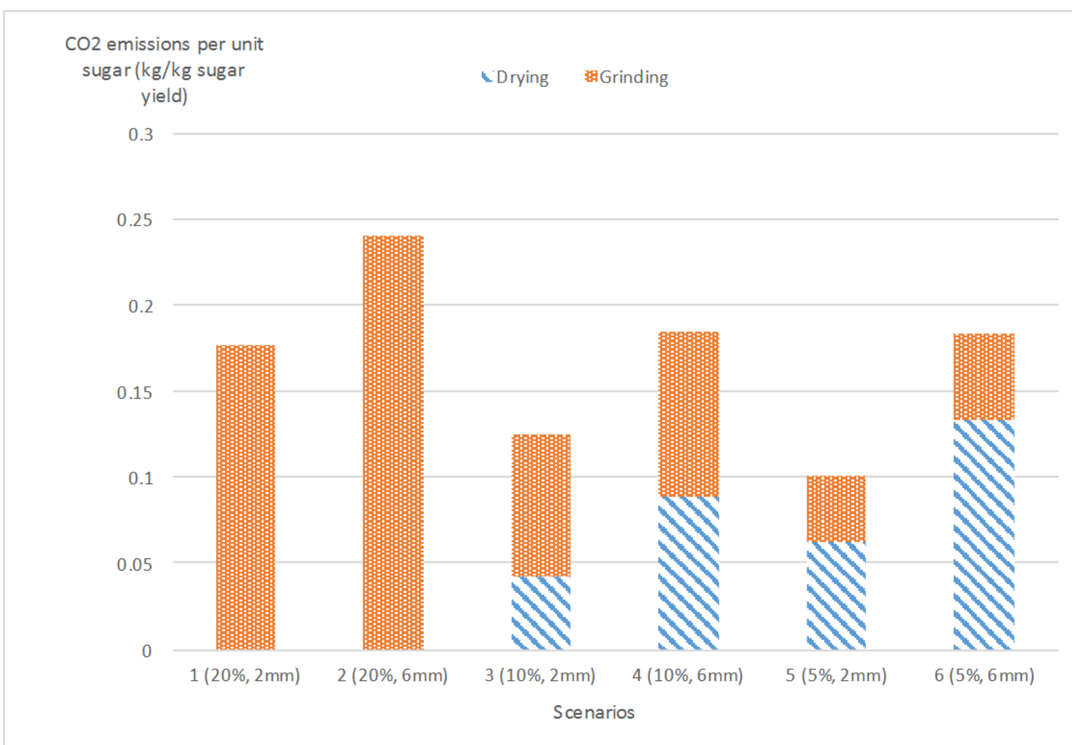

Fig. 3.3 CO_2 Emissions per Unit Sugar Yield

TEA

The costs and the emissions have the same trend in general. As is shown in figure 3.4 below, not considering the sugar yields, the drier the corn stover, the more the drying cost will cost. In terms of the grinding expense, the drier, the cheaper; the larger the screen size, the cheaper. As can be observed in figure 3.5, when sugar yield is considered, the drying cost trend is the same, so is the trend of grinding cost in term of moisture content, but the trend of the grinding cost regarding screen size reverses. Smaller screen tends to have smaller cost on the basis of same sugar production.

According to Yang and Rosentrater, in a commercial-scale plant with the productivity of 50 million gallons a year, the lowest cost of ethanol produced from corn stover using LMAA pretreatment was assumed to be 3.86 USD/US Gallon (Yang and Rosentrater 2015). This is higher than the average US gasoline price in 2012, which was 3.68, the highest in last 20 years (EIA, 2016). However, the result of TEA on lignocellulosic ethanol can be affected by the feedstock price and properties, conversion efficiency, and the use of energy (Edgard Gnansounou and Dauriat 2011). Thus, it is necessary to develop new processing methods and make the production, including size reduction operation, more efficient. The results in the TEA study will provide some reference for a more economical size reduction operation.

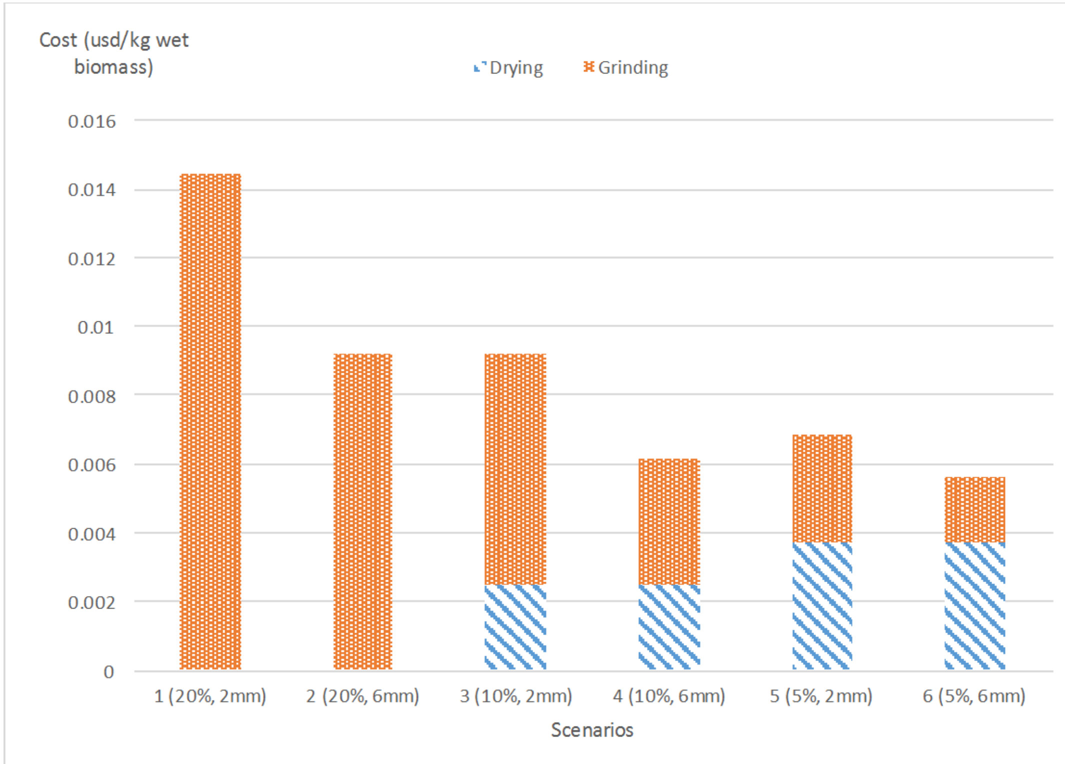

Fig. 3.4 Cost

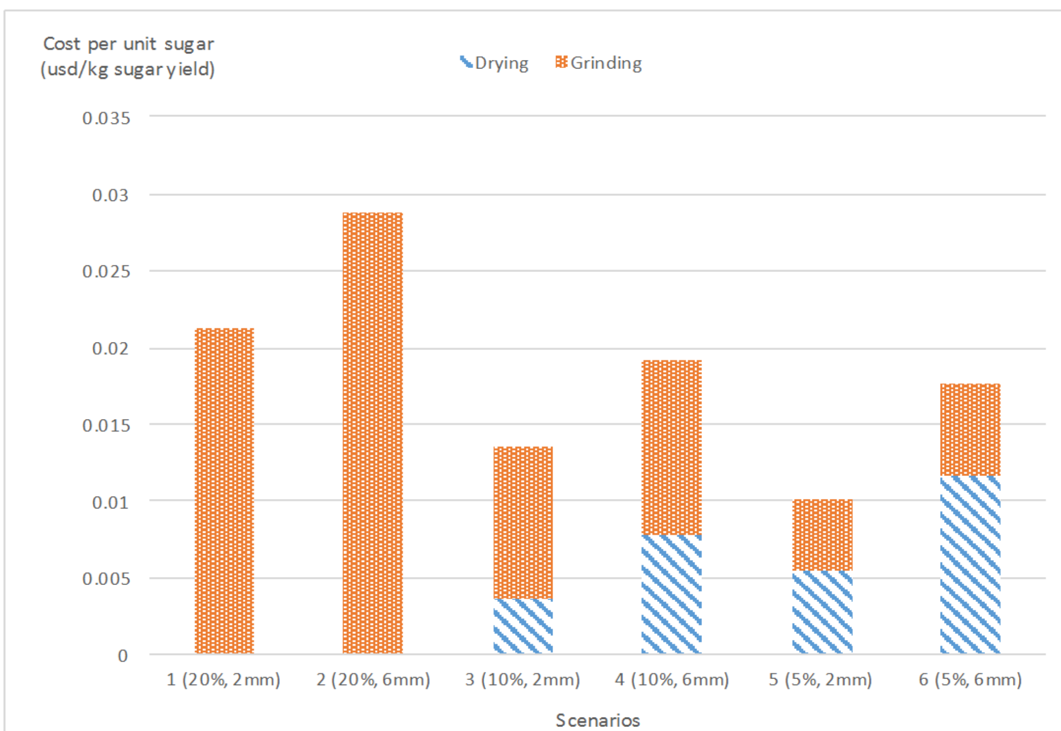

Fig. 3.5 Cost per Unit Sugar Yield

Conclusion

Equivalent CO_2 emissions and system costs were analyzed in this study. Six grinding scenarios are discussed in this study: scenario 1: 20% moisture content, 2mm screen, scenario 2: 20% moisture content, 6mm screen, scenario 3: 10% moisture content, 2mm screen, scenario 4: 10% moisture content, 6mm screen, scenario 5: 5% moisture content, 2mm screen, scenario 6: 5% moisture content, 6mm screen, 5% moisture content, 6mm screen.

When not considering the sugar yield, scenario 6 (5%, 6mm) has the lowest CO_2 emission and cost. On the basis of same fermentable sugar yields, scenario 5, which is grinding 5% moisture content corn stover using 2mm screen turns out to have the least CO_2 emission and to be cheapest in operation. The results were not intuitive.

This indicates that even though grinding the feedstock of higher moisture content might require more energy than that of low moisture, drying the moist material can cost more than the extra money spent on grinding the moist material. Thus, field drying of corn stover could be a better choice than drying after harvest.

Grinding with smaller screens may have higher energy consumption, but the more biofuel yield can make up for the additional cost compared to larger screens.

The LCA and TEA studies are the completion of the energy consumption of corn stover grinding study. Without them, the results were limited to the scope of grinding processing itself. By conducting the LCA and TEA studies, the scope was enlarged to reflect the whole processing cellulosic ethanol production, the results could be a good reference to cellulosic ethanol production operations.

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