Title: Comparing alternative cellulosic biomass biorefining systems: centralized versus distributed processing systems

Seungdo Kim^{1,2} and Bruce E. Dale^{1,2}

1 DOE Great Lakes Bioenergy Research Center, Michigan State University, 3815 Technology Boulevard, Lansing, MI 48910

2 Department of Chemical Engineering and Materials Science, Michigan State University, 3815 Technology Boulevard, Lansing, MI 48910

Corresponding author: Seungdo Kim

Telephone number: 517-355-4621, fax numbers: 517-336-4615, e-mail address:

kimseun@egr.msu.edu.

Abstract

This study explores how two different cellulosic ethanol production system configurations (distributed versus centralized processing) affect some aspects of the economic and environmental performance of cellulosic ethanol, measured as minimum ethanol selling price (MESP) and various environmental impact categories. The eco-efficiency indicator, which simultaneously accounts for economic and environmental features, is also calculated. The centralized configuration offers better economic performance for small-scale biorefineries, while the distributed configuration is economically superior for large-scale biorefineries. The MESP of the centralized configuration declines with increased biorefinery size up to a point and then rises due to the cost of trucking biomass to the biorefinery. In contrast, the MESP in the distributed configuration continuously declines with increasing biorefinery size due to the lower costs of

railroad transportation and the greater economies of scale achieved at much larger biorefinery sizes, including biorefineries that reach the size of an average oil refinery—about 30,000 tons per day of feedstock. The centralized system yields lower environmental impacts for most impact categories than does the distributed system regardless of the biorefinery size. Eco-efficiency analysis shows that the centralized configuration is more sustainable for small-scale biorefineries, while the distributed configuration with railroad transport is more sustainable for large-scale biorefineries. Compared with gasoline from petroleum, cellulosic ethanol fuel offers sustainability advantages for the following environmental impact categories: fossil energy consumption, global warming, human health impacts by particulate matter, ozone layer depletion, ecotoxicity, human health cancer, and human health non-cancer, depending somewhat on the biorefinery sizes and the system configurations.

KEYWORDS: Cellulosic ethanol, Corn stover, Distributed Biomass Processing, Life Cycle Assessment, Local Biomass Processing Depot, Minimum Ethanol Selling Price

ABBREVIATIONS

ACID: acidification; AFEX: ammonia fiber expansion; DCFROR: discounted cash flow rate of return; ECOT: ecotoxicity; EISA: Energy Independence and Security Act; EUTR: eutrophication; FSE: fossil energy consumption; GE: gasoline equivalent; GHG: greenhouse gas; GREET: greenhouse gases, regulated emissions, and energy use in transportation model; GWI: global warming; HHC: human health cancer; HHNC: human health non-cancer; HHP: Human health impacts are measured by particulate matter; IPCC: International Panel on Climate Change ; MESP: minimum ethanol selling price; NREL: National Renewable Energy Laboratory; OLD: ozone layer depletion; PDF: Potentially Disappeared Fraction; SMG: smog formation

44

45 **1. Introduction**

46 Ethanol is a renewable liquid transportation fuel. Global ethanol fuel production in 2013 is about
47 89 hm³ (23 billion gallon) [1]. Ethanol production in the United States accounts for about 57% of
48 global ethanol production and is almost completely derived from corn grain. The second largest
49 ethanol producing country is Brazil, accounting for 27% of global ethanol production. Sugar
50 from sugar cane is the major feedstock for ethanol fuel in Brazil. Ethanol fuel from cellulosic
51 biomass is also of great interest because of the potentially much larger volumes obtained with
52 little impact on the food system. Unlike corn or cane ethanol, however, the cellulosic ethanol
53 industry is in its infancy, and the preferred production systems are still being developed. This
54 paper analyzes two very different potential system configurations for cellulosic ethanol:
55 distributed versus centralized processing.

56 Feedstocks for cellulosic ethanol fuel include crop residues (e.g., corn stover, wheat straw, etc.),
57 energy crops (e.g., switchgrass, miscanthus, willow, etc.), wood residues and wastes. Unlike
58 starch (or sugar) based feedstocks (e.g., corn, cane sugar), cellulosic feedstocks require a
59 pretreatment process to help convert cellulose and hemicellulose to fermentable sugars. There
60 are numerous available pretreatment technologies – e.g., ammonia fiber expansion (AFEXTM),
61 dilute acid, hot water, steam explosion, and so on [2 – 5]. Despite the requirement for a
62 pretreatment process, cellulosic biofuels are very attractive in terms of potential sustainability
63 and economic features. A cellulosic biorefinery facility can operate without external energy

¹ AFEXTM is a registered trademark of MBI International, Lansing, MI USA.

sources [6 – 9]. In some projected cellulosic biorefinery system designs, excess electricity can be exported to the electric grid.

Under the Energy Independence and Security Act (EISA) of 2007, the United States will produce 61 hm³ (16 billion gallon) of cellulosic biofuel by 2022. Currently several commercial cellulosic biorefinery facilities are operating or under construction. The average size of the proposed commercial cellulosic biorefinery at this point is about 700 dry Mg of feedstock per day [10]. Larger biorefinery facilities are expected in the future.

However, cellulosic biomass is bulky, geographically dispersed and prone to decomposition and combustion - making it expensive and difficult to store and transport. Until now, the cost of transporting and storing cellulosic biomass has severely limited the size of biorefineries and prevented them from achieving the economies of scale necessary to significantly reduce biofuel prices. In particular, modeling studies have shown that biorefineries producing cellulosic ethanol from biomass sugars are limited to processing less than about 5000 dry Mg biomass per day because the cost of transporting the low density biomass outweighs the greater economies of scale for larger biorefineries. In addition to the logistics cost, the relative costs of contracts (“transaction costs”) with farmers/biomass producers will increase with the biorefinery size [11, 12]. A distributed biomass processing system might reduce these limitations [11 – 14]. Two types of distributed systems are conceptually available thus far: the Advanced Uniform Design system [14] and the Local Biomass Processing Depots system [11, 12].

The advanced uniform design system is located near feedstock production areas and processes biomass to a higher-density, aerobically stable, easily transportable formatted feedstock [14]. Due to these properties of pre-processed feedstock, the advanced uniform design system can

cost-effectively utilize biomass from isolated and low yield areas (so-called “stranded biomass”). For large-scale biorefineries, the advanced uniform design system can result in a Minimum Ethanol Selling Price (MESP) that is lower than those of the centralized system. Greenhouse gas (GHG) emissions of the advanced uniform design system are slightly higher than those of the centralized system due to the additional transportation requirements, but are still significantly less than the corresponding petroleum fuel system.

The local biomass processing depot (referred to in this study as a ‘depot’) is a facility that first pretreats cellulosic feedstock and then densifies (pelletizes) the pretreated feedstock. The pretreatment process is therefore geographically isolated from the biorefinery and is located near feedstock production areas. This local network system consists of a number of small depots which supply the much larger biorefinery. The depot system can also reduce the logistics and contracting costs of cellulosic biofuels [11, 12]. Egbendewe-Mondzozo *et al.* [15] show that the depot system has better environmental performance at a biorefinery size of 2000 dry Mg per day in terms of GHG emissions despite lower profitability at that scale.

Most previous analyses of biorefinery systems were restricted by either constant feedstock collection radius or constant biorefinery size or both. Obviously, the required feedstock collection radius increases with increased biorefinery size. This study therefore investigates the effects of different biorefinery system configurations and biorefinery size on economic performance and environmental impacts in order to determine better system configurations with respect to biorefinery size. To achieve the objectives of this study, the MESP and environmental impacts are quantified for different system configurations with respect to the biorefinery size. A discounted cash flow rate of return analysis is used to determine the MESP. The environmental impacts are estimated via life cycle assessment and quantified by the TRACI model version 2.1

that is specific to US conditions [16]. To balance economic performance and environmental impacts, eco-efficiency indicators, which simultaneously account for economic and environmental features of a given system, are also estimated. The eco-efficiency indicator may be useful in decision making processes, particularly for systems that exhibit trade-offs between economic values and environmental impacts. In general, the eco-efficiency indicator is defined as a ratio of product (or service) economic value to its environmental impact [17]. High eco-efficiency indicators are obviously preferred to lower ones.

2. Methods

2.1. System configuration

The system configurations are illustrated in Figure 1. The distributed and centralized configurations are referred to as DEPOT and CENTRAL, respectively. Corn stover is the cellulosic feedstock in this study as it is ubiquitous in the Midwest region in the United States. The ammonia fiber expansion (AFEXTM) technology [18] is used as the pretreatment technology in each configuration.

It is possible that pretreatments other than AFEX technology might also function well in the DEPOT configuration, but the fact that many pretreatments (e.g., dilute acid, ionic liquids, etc.) require large amounts of water to wash the pretreated biomass probably precludes their use in the DEPOT configuration. AFEX technology use in the DEPOT configuration is also advantageous because AFEX enables easy pelleting of the pretreated biomass. Lignin, a natural adhesive, is brought to the surface of the biomass particles by AFEX pretreatment and enables low temperature/low pressure pelleting without adding expensive binders. We hope other researchers

will study their own pretreatments in the DEPOT configuration to determine if they make economic and environmental sense in a distributed processing system.

In the DEPOT configuration, baled corn stover is always transported by truck from farms to the depot, where corn stover is AFEX pretreated and densified (pelletized). Pretreated and densified corn stover is transported by truck from a depot to a railroad loading station and then via railroad from the loading station to the biorefinery. Baled corn stover in the CENTRAL configuration is transported by truck directly from farms to the biorefinery. Railroad transportation requires additional unloading and loading processes, which would tend to damage baled corn stover and would probably lead to some loss of feedstock (“shrinkage”). In contrast, additional unloading and loading of pretreated and densified feedstock would likely have little effect on the feedstock and cause little loss of material. AFEX pellet durability exceeds 99.3% in standardized tests and is essentially equal to that of corn grain.

Figure 1

2.2. Feedstock production and transportation

Corn stover is assumed to be collected in twelve US states: Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, South Dakota, and Wisconsin. Corn stover collection in this study follows the collection practices assumed in the Renewable Fuel Standard Program [19], i.e., 50% collection of available stover in areas where corn is grown under no-tillage practices, 35% in conservation tillage areas and 0% when corn is grown under conventional tillage practices. State level tillage practices are obtained from the literature [20]. Corn stover price at the farm gate is estimated based on fuel costs for collecting and baling corn stover, field operating costs (e.g., farm machinery cost, labor, etc.), and costs for additional

nutrients in the subsequent growing season due to removing nutrients in corn stover (i.e., nitrogen, phosphorus, and potassium) [21]. Fuel consumption during collecting and baling corn stover and field operating costs are calculated based on the methods used in Morey *et al.* [22], in which the field operations for collecting and baling corn include stalk shredding, raking, baling and moving the bales from field to loading site. Nutrient values in corn stover are obtained from literature [22 – 24].

The transportation distance of baled corn stover from the farms to processing facilities (i.e., depots in DEPOT and biorefinery in CENTRAL), $\mathbf{d}_f$, depends on the facility size and is determined by Equation (1).

$$\mathbf{d}_f = \mathbf{w} \cdot \sqrt{\frac{\mathbf{f}_s \cdot \mathbf{h}_r / 24}{\mathbf{Y}_{\text{stover}} \cdot \mathbf{r}_{\%} \cdot \mathbf{f}_{\text{corn}} \cdot \pi \cdot \mathbf{f}_a \cdot (1 - \mathbf{f}_l)}} \quad (1)$$

Where $\mathbf{f}_s$ is the facility size (i.e., the depot in DEPOT and the biorefinery in CENTRAL, dry Mg per day), $\mathbf{h}_r$ is the annual operating hours, and $\mathbf{f}_a$ is the percentage of participating cornfields in collection radius, $\mathbf{w}$ is the road tortuosity factor, and $\mathbf{f}_l$ is the transportation and storage loss factor. $\mathbf{r}_{\%}$ is the fraction of corn stover collected. $\mathbf{f}_{\text{corn}}$ is the ratio of harvested corn area to the total land area. $\mathbf{Y}_{\text{stover}}$ is the dry corn stover yield (dry Mg per ha). The distance from depots to a biorefinery in the DEPOT configuration, $\mathbf{d}_d$, is assumed to be the difference between the collection radius of the biorefinery and the collection radius of the depot, determined by Equation (2).

$$\mathbf{d}_d = \mathbf{w} \cdot \left(\sqrt{\frac{\mathbf{f}_{s, \text{bioref}} \cdot \mathbf{h}_r / 24}{\mathbf{Y}_{\text{stover}} \cdot \mathbf{r}_{\%} \cdot \mathbf{f}_{\text{corn}} \cdot \pi \cdot \mathbf{f}_a \cdot (1 - \mathbf{f}_l)}} - \sqrt{\frac{\mathbf{f}_{s, \text{depot}} \cdot \mathbf{h}_r / 24}{\mathbf{Y}_{\text{stover}} \cdot \mathbf{r}_{\%} \cdot \mathbf{f}_{\text{corn}} \cdot \pi \cdot \mathbf{f}_a \cdot (1 - \mathbf{f}_l)}} \right) \quad (2)$$

Where $f_{s, \text{bioref}}$ and $f_{s, \text{depot}}$ are the size of biorefinery and depot (dry Mg per day), respectively. In the DEPOT configuration, it is assumed that the depots are located within an 8-km radius of rail service. The parameters for corn stover transportation are summarized in Table 1.

Table 1

2.3. Depot and biorefinery

Process information (e.g., mass and energy balances, etc.) is estimated using ASPEN PlusTM. Modeling the AFEXTM pretreatment technology is done based on literature [7, 29, 30], while modeling other processes (e.g., enzymatic hydrolysis, fermentation, distillation, cogeneration, wastewater treatment, etc.) is based on studies done by the National Renewable Energy Laboratory (NREL) [6, 9]. Enzymatic hydrolysis and fermentation efficiencies obtained from the NREL's studies [6, 9] are modified according to Bals [31]. The ethanol yield in the cellulosic biorefinery is estimated to be about 293 liter per dry Mg (70 gallon per dry short ton), consistent with experimental data [29]. Note that the ethanol yield does not include feedstock loss during transportation and storage and is based on stover delivered to be processed.

Process information for each configuration is summarized in Table 2. The quantity of corn stover in Table 2 includes feedstock loss during transportation and storage (~4.94%) [25]. The enzyme loading in each configuration is 17.5 mg protein per gram of cellulose [29]. Although most ammonia in the AFEXTM pretreatment process is recycled, make-up ammonia is needed due to ammonia remaining in the biomass following the pretreatment process. Water consumption in the DEPOT configuration is slightly higher than in the CENTRAL configuration because the densified feedstocks require additional water for enzymatic hydrolysis. Lime and ammonia are used to reduce SO_x and NO_x emissions, respectively, resulting from combusting fermentation

residues and biogas in the cogeneration facility. The depots consume external energy for pretreatment and densification (i.e., electricity and natural gas). Natural gas consumption in the depots is due to a dryer required in the pelleting/densification process.

The DEPOT configuration generates more excess electricity for sale to the grid than does the CENTRAL configuration. The primary reason that more electricity is produced in the DEPOT configuration is that the pretreatment process is decoupled from the biorefinery. Decoupling in the DEPOT configuration can reduce steam and electricity used in the biorefinery processes even though external energy (e.g., natural gas) for steam generation and grid electricity are consumed in the depots instead. Reducing steam requirements in the biorefinery yields a higher power-to-thermal energy ratio in the cogeneration facility. In other words, less steam consumption in the biorefinery processes leads to more electricity generated beyond the needs of the biorefinery. Consequently more electricity is exported in the DEPOT configuration than in the CENTRAL configuration.

Process emissions in Table 2 do not include emissions associated with combusting natural gas in the depots, which are estimated from the life cycle inventory database. Most ammonia emissions in the DEPOT configuration are released in the depots, while ammonia emissions in the CENTRAL configuration are released in the wastewater treatment facility. Methane and nitrous oxide emissions are from the wastewater treatment facility. Biogenic carbon dioxide emissions are released from the fermentation and the cogeneration facilities. Other air emissions (e.g., CO, NO_x, SO_x) are also released from the cogeneration facility.

Table 2

2.4. Minimum ethanol selling price

The discounted cash flow rate of return (DCFRROR) analysis estimates the MESP that satisfies the condition that the net present value of the project is zero [3, 6, 7, 9]. The important assumptions for the DCFRROR analysis are that (1) plant lifetime is 25 years, (2) the plant is 40% equity-financed, (3) working capital is 5% of fixed capital investment, (4) internal rate of return (IRR) is 10%, (5) construction times for the biorefinery and depot are three years and one year, respectively, (6) the federal corporate tax rate is 35%, and (7) the capital depreciation is estimated via the IRS Modified Accelerated Cost Recovery System. Details of the assumptions relevant to the DCFRROR analysis are found elsewhere [9]. All costs are indexed to 2014 dollars by extrapolating the Chemical Engineering Plant Cost Index (<http://www.che.com/pci/>) and the price indices (e.g., inorganic and organic chemicals, labor, transportation, etc.) [32]. The energy price projections by the US Department of Energy [33] are used as the energy prices in this study. The selling price of excess electricity is projected as 5.55 cents per kWh in the year 2014, which is equal to the cost of generation [33]. The costs for biomass transportation are estimated based on literature [25, 34].

2.5. Life cycle assessment

The functional unit is defined as one MJ of ethanol, while the MESP is presented as US\$ per liter of gasoline equivalent (referred to as 'GE'). The system boundary includes corn stover production, transportation, the depot, the biorefinery, upstream processes (e.g., fuels, chemicals, fertilizers, etc.) and avoided grid electricity. Indirect consequences due to diverting corn stover to biofuel production are not investigated in this study. Farm machinery, capital and infrastructure (road, rail, etc.) are not included in the system boundary for LCA because of their small contribution to the overall impacts [35].

The incremental approach ('system expansion') is used to allocate the environmental burdens between corn grain and corn stover. The environmental impacts allocated to corn stover include impacts associated with fuel consumption for collecting and baling corn stover, additional nutrient requirements, and related soil emissions (i.e., N_2O , NO_x , NH_3 , NO_3^- and P). Nitrogen losses are estimated by the IPCC Tier 1 method [36], and phosphorus losses from literature [37].

The US life cycle inventory database built by the National Renewable Energy Laboratory [38] is used in the inventory calculations. Life cycle inventory information on some input materials (e.g., cellulase enzymes, ammonia, fertilizers,) is obtained from the Greenhouse gases, Regulated Emissions, and Energy use in Transportation model (GREET) [23]. The electricity fuel mixes are updated to the 2009 fuel mixes [39]. The US electricity fuel mixes are used in calculating life cycle inventory data for fuels, chemicals, enzymes, and fertilizers, while the regional electricity fuel mixes are used in the depot and the biorefinery processes. It is assumed that excess electricity from the biorefinery displaces the regional grid electricity.

The environmental impacts are measured as fossil energy consumption (FSE), global warming (GWI), acidification (ACID), eutrophication (EUTR), smog formation (SMG), ozone layer depletion (OLD), and ecotoxicity (ECOT). Human health impacts are measured by particulate matter (HHP), human health cancer (HHC), and human health non-cancer (HHNC). The TRACI model version 2.1 [16] is used to quantify the environmental impacts.

2.6. Eco-efficiency analysis

Because ethanol is a liquid fuel replacement for gasoline, the product economic value in the eco-efficiency indicator is defined as the normalized difference between the MESP and the gasoline price per liter of gasoline equivalent energy. The environmental impact is defined as the

normalized difference between the respective ethanol and gasoline environmental impacts based on their energy content. Both parameters are normalized to values of gasoline to make them dimensionless and then converted to exponentials to avoid singularities. The eco-efficiency indicator for the i^{th} environmental impact can be thus be expressed as

$$\text{Eco-efficiency indicator (Eco}_i\text{)} = \frac{\exp\left[\frac{(P_g \cdot \text{MESP})}{P_g}\right]}{\exp\left[\frac{(\text{EI}_{i,e} - \text{EI}_{i,g})}{\text{EI}_{i,g}}\right]} \quad (3)$$

Where P_g is the gasoline fuel price. EI_i is the i^{th} environmental impact, and subscripts e and g are ethanol and gasoline, respectively. The projected 2014 gasoline fuel price, US\$ 0.88 per liter of GE (US\$ 3.32 per gallon), is used [33]. The numerator in the eco-efficiency indicator reflects price savings (if any) accrued by ethanol fuel compared to gasoline fuel. Lower MESP indicates larger price savings and makes the numerator larger. The denominator in the eco-efficiency indicator reflects the environmental impact. The reduced environmental impacts of ethanol fuel make the denominator smaller, and the eco-efficiency indicator increases. Therefore, systems with larger eco-efficiency indicators are more sustainable. It is assumed that the product value and the environmental impacts are equally weighted. The eco-efficiency indicator for gasoline fuel is defined as one.

2.7. Sensitivity analysis

The effects of the following five variables are investigated in the sensitivity analysis: (1) parameters used in the DCFROR analysis, (2) tillage practices (referred to as “tillage scenario”), (3) ethanol yield (referred to as “ethanol yield scenario”), (4) transportation mode for pretreated and densified corn stover in DEPOT (referred to as “DEPOT-TR scenario”), and (5) ownership of the depots in DEPOT (referred to as “DEPOT-OS scenario”). Most parameters used in the

DCFROR analysis are obtained from literature [3, 6, 7, 9]. In the sensitivity analysis, the effects of parameters used in the DCFROR analysis, particularly plant lifetime and IRR, are scrutinized. The recent NREL study [9] assumed that plant lifetime is 30 years, while the previous NREL study [6] assumed a plant lifetime of 20 years. In the calculations, a median value (25 years) is used, which is consistent with the plant lifetime in the Laser *et al.* study [7]. The IRR varies with the business characteristics. The rate of return in higher-risk and low-volume businesses would be greater than the 10% IRR, which is used in the calculations [9]. In the tillage scenario, the fraction of land under no-tillage practice in corn cultivation remains unchanged, and land currently farmed under conservation tillage and reduced tillage is converted to no-tillage practices and conservation tillage practices, respectively. In the ethanol yield scenario, the following ethanol yields are assumed: 372 liter per dry Mg for the DEPOT configuration and 369 liter per dry Mg for the CENTRAL configuration. In the DEPOT-TR scenario, pretreated and densified corn stover is transported by truck from a depot to the biorefinery.

Recent (unpublished) analysis of the depot system shows that a system of farmer-owned depots is more economically viable than a biorefining industry-owned system [31]. When farmers own depots, the delivered price of biomass to the depot can be lower because the farmers will receive a portion of the value added by processing at the depot. Furthermore, more farmers adjacent the depots participate in supplying corn stover to the depots and convert their tillage practices to be more favorable to corn stover collection. These efforts reduce the collection radius – lowering transportation costs. In the DEPOT-OS scenario, it is assumed that 100% of farmers in the collection radius participate in collection corn stover and convert their current tillage practices to no-tillage practices to maximize corn stover collection.

The distance from the depot at which rail service is assumed to be located was determined to be approximately 8 km. The upper bounds of the rail service distance in the DEPOT-OS scenario are estimated by satisfying the following constraints: 1) MESP in the DEPOT-OS scenario is equal to a minimum MESP in CENTRAL, and 2) cellulosic ethanol fuel yields 60% reduction in GHG emissions compared to baseline gasoline fuel, which is defined as gasoline in the year 2005 [19]. Effects of allocation between corn grain and corn stover are not investigated in this study. Those effects are well documented in the literature [40 – 42].

3. Results and Discussion

3.2. Minimum ethanol selling price

The MESP in the DEPOT configuration ranges from US\$ 1.33 to US\$ 1.72 per liter of GE (US\$ 5.04 – 6.53 per gallon of GE), while the MESP in the CENTRAL configuration ranges from US\$ 1.27 to US\$ 1.69 per liter of GE (US\$ 4.81 – 6.40 per gallon of GE). This is illustrated in Figure 2. For small-scale biorefineries, the CENTRAL configuration yields lower values of MESP than does the DEPOT configuration, while the DEPOT configuration yields lower MESP values than does the CENTRAL configuration for large-scale biorefineries.

The MESP in the CENTRAL configuration declines rapidly until it reaches a biorefinery size of about 3,000 dry Mg per day and then begins to rise as seen in Figure 2. The collection radius increases with the biorefinery size so that the increased transportation cost exceeds capital cost reductions at larger biorefinery sizes ($\geq 4,000$ dry Mg per day) in the CENTRAL configuration. In contrast, the MESP in the DEPOT configuration continuously declines with increased biorefinery size due to lower costs of railroad transportation, resulting in lower MESP for very large-scale biorefineries ($\geq 12,000$ dry Mg per day). However, for small-scale biorefineries, the

DEPOT configuration yields higher MESP values than does the CENTRAL configuration due to high costs of railroad transportation for short distances.

Figure 2

The cost of corn stover is a dominant cost in the MESP, accounting for 20 – 27% of the MESP (US\$ 0.34 per liter of GE). The transportation cost is the primary cost for large-scale biorefineries ($\geq 8,000$ dry Mg per day) in the CENTRAL configuration, accounting for over 35% of the MESP. The cost of cellulase enzymes is about US\$ 0.13 per liter of GE, which is much less than the enzyme cost estimated by Kazi *et al.* [3] because of lower enzyme loading (17.5 versus 31.3 mg protein per gram cellulose). The external energy cost in the DEPOT configuration is about US\$ 0.12 per liter of GE, and natural gas accounts for about 81% of the external energy cost. The credit for excess electricity in the DEPOT configuration is about US\$ 0.15 per liter of GE, while the corresponding credit in CENTRAL is US\$ 0.10 per liter of GE.

3.3. Environmental impacts

Life cycle environmental impacts associated with cellulosic ethanol fuel are illustrated in Figures 3 and 4, which also present the environmental impacts associated with gasoline fuel. Cellulosic ethanol fuel provides better environmental performance than gasoline fuel in terms of FSE, GWI, HHP, ODP, ECOT, HHC and HHNC, depending somewhat on the biorefinery sizes and the system configurations. Regarding other environmental impacts (i.e., ACID, EUTR, and SMG), cellulosic ethanol fuel causes more environmental impacts than does gasoline fuel. Nitrogen-related emissions, which are released mostly from nitrogen fertilizer in corn stover production, are the dominant environmental impact sources in ACID, EUTR, and SMG. External energy

consumption in the depots is the primary source of higher HHP and ECOT impacts in the DEPOT configuration.

Generally small-scale biorefineries yield lower environmental impacts than do large-scale biorefineries per unit of fuel because of the collection radius effect and its related emissions. The DEPOT configuration exhibits larger environmental impacts (except for ODP, SMG and HHC) than the CENTRAL configuration due to external energy consumption (i.e., electricity and natural gas) in the depots. Transportation of pretreated and densified corn stover in the DEPOT configuration causes much lower ODP and SMG impacts than transportation of baled corn stover in the CENTRAL configuration. Even though the environmental impacts in the DEPOT configuration increase slightly with increased biorefinery size, the increases are small compared to the increases observed in the CENTRAL configuration because of advantages of railroad transportation for pretreated and densified corn stover, as seen in Figures 3 and 4.

Figure 3

Figure 4

Key environmental impact sources are summarized in Table 3. Excess electricity in the biorefinery is a key positive environmental impact source (providing environmental credits) for FSE, GWI, HHP, SMG, HHC and HHNC in both the DEPOT and the CENTRAL configurations. Reductions in sulfur oxide and mercury emissions associated with coal-fired power plants in the grid electricity system due to excess electricity production in the biorefineries play important roles in the environmental credits for HHP, HHC and HHNC. Natural gas consumption in the DEPOT configuration is a primary contributor to FSE, GWI, HHP, ECOT, HHC and HHNC. Sulfur oxide emissions to air from natural gas “sweetening” processes are major pollutants for

HHP. Barium emissions to water released from natural gas extraction are major pollutants for ECOT and HHNC, while volatile aromatic compound emissions to air in natural gas sweetening processes (i.e., benzene, toluene, ethyl-benzene, and xylene) are the major pollutants causing HHC. In the CENTRAL configuration, transportation is also one of the primary contributors to FSE, GWI, ODP, SMG, ECOT and HHNC, while transportation in the DEPOT configuration is a primary source only for ODP. Corn stover production, particularly soil emissions associated with additional nutrient requirements in the next growing season (i.e., NH_3 , NO_x , NO_3^- , P) are the primary sources for ACID and EUTR. Process emissions (e.g. NH_3 emissions) are also major pollutants contributing to ACID and EUTR. Purchased cellulase in both the DEPOT and the CENTRAL configurations is a major source of ECOT because of agrochemicals consumption represented in the glucose (required to produce cellulase) production supply chain.

Table 3

3.4. Eco-efficiency analysis

Both configurations exhibit trade-offs between the MESP and the environmental impacts of ethanol fuel. Such trade-offs lead to uncertainties in decision-making. The eco-efficiency indicator can help mitigate those uncertainties. Due to biogenic carbon released during combusting cellulosic ethanol fuel, carbon dioxide emissions released during combusting gasoline fuel are added to GWI associated with gasoline fuel in the eco-efficiency analysis. Figure 5 shows the eco-efficiency indicators for each environmental impact category with respect to the biorefinery size. The eco-efficiency indicators for ACID and EUTR are not included because the denominators in the eco-efficiency indicators for ACID and EUTR are large enough so that the eco-efficiency indicators are close to zero. The eco-efficiency indicators

for ECOT, HHP and SMG are less than one, depending on the biorefinery sizes and the system configurations. In other words, cellulosic ethanol fuel does not offer any sustainability advantages over gasoline fuel in terms of ACID, EUTR, HHP, SMG and ECOT, depending somewhat on the biorefinery sizes and the system configurations.

In contrast, cellulosic ethanol fuel offers improved eco-efficiency indicators compared to gasoline for a number of environmental impact categories including FSE, GWI, HHP, ODP, HHC, and HHNC, depending on the biorefinery sizes and the system configurations. The eco-efficiency indicators for HHC and HHNC in both configurations are always greater than one regardless of the biorefinery size. The eco-efficiency indicators for FSE, GWI and ODP in the CENTRAL configuration are less than one for large-scale biorefineries. In contrast the DEPOT configuration has greater-than-one eco-efficiency indicators for FSE, GWI and ODP for large-scale biorefineries.

The eco-efficiency indicators for most environmental impact categories (except for SMG) in the CENTRAL configuration increase for small-scale biorefineries due to sharp declines in the MESP and then decrease as biorefinery size increases. In the DEPOT configuration, the eco-efficiency indicators increase with increasing biorefinery size for most environmental impact categories (except for SMG) and then approach a horizontal asymptote.

Figure 5

3.5. Sensitivity analysis

The effects of the plant lifetime on the MESP values are not significant in both the DEPOT and the CENTRAL configurations. Despite high MESP values at a higher internal rate of return, the

MESP trends in both the DEPOT and the CENTRAL configurations remain unchanged. Detailed results are presented in the Supplementary Material.

Increasing no-tillage and conservation tillage practices can reduce fuel costs for corn stover collection and transportation of baled corn stover, and can also reduce environmental impacts in both the DEPOT and the CENTRAL configurations. The influence of changes in the tillage practices is large for the following environmental impacts: FSE, GWI, HHP, ODP, SMOG and ECOT. Reductions in both cost and environmental impacts due to changes in the tillage practices are larger in the CENTRAL configuration than in the DEPOT configuration. For example, the cost reductions caused by changes in the tillage practices range from US\$ 0.07 to US\$ 0.31 per liter of GE in the CENTRAL configuration, while the cost reductions in the DEPOT configuration are from US\$ 0.04 to US\$ 0.07 per liter of GE.

Highly efficient pretreatment/enzyme systems would hydrolyze more cellulose and hemicellulose to form fermentable sugars and thereby increase ethanol yield but they would also reduce the amount of residual biomass available for the cogeneration power facility (fermentation residues and biogas). Thus, less excess electricity is exported at higher ethanol yields. For example, increasing ethanol yield from 293 to 369 liter per dry Mg reduces excess electricity by 52% (0.5 kWh/liter of ethanol) in the CENTRAL configuration. Excess electricity in the DEPOT configuration is reduced by 46% (0.9 kWh/liter of ethanol) when ethanol yield is increased from 293 to 372 liter per dry Mg. Despite the fact that less excess electricity is generated at higher ethanol yields, the MESP declines with increased ethanol yield. This is illustrated in Figure 6.

Figure 6

However, higher ethanol yields can increase some environmental impacts to which excess electricity is a large contributor (i.e., FSE, GWI, SMOG, HHP, HHC, and HHNC). Other environmental impacts decrease with increased ethanol yield. Even though some environmental impacts increase with ethanol yield, higher ethanol yield offers higher eco-efficiency for most environmental impact categories (except for HHP, HHC, and HHNC) than does lower ethanol yield. Results are summarized in Table 4. More details are presented in the Supplementary Material. The two configurations exhibit similar patterns in most environmental impacts except for ACID and SMOG. For large-scale biorefineries, ACID and SMOG in the CENTRAL configuration decrease with increased ethanol yield because the reductions in those two environmental impacts associated with baled corn stover transportation due to higher ethanol yield increase as biorefinery size increases.

Table 4

Figure 7 summarizes results for the DEPOT-TR and DEPOT-OS scenarios. In the DEPOT-TR scenario trucks are used to transport pretreated and densified corn stover from a depot to the biorefinery. Truck transportation between depots and the biorefinery in DEPOT can reduce the MESP for small-scale biorefineries compared to railroad transportation, while truck transportation yields higher MESP values than does railroad transportation for large-scale biorefineries. Patterns of the MESP behavior in the DEPOT-TR scenario are similar to those in the CENTRAL configuration, but the MESP increase is less rapid than is the corresponding increase in the CENTRAL configuration. The DEPOT-TR scenario offers lower MESP for sizes from 1,000 to 8,000 dry Mg per day than does the DEPOT scenario. However, the DEPOT-TR scenario produces the highest GWI impact among other configurations.

The MESP in the DEPOT-OS scenario ranges from US\$ 1.23 to US\$ 1.63 per liter of GE. The farmer-owned depot system can reduce the MESP values by up to 7.5%, compared to the MESP values estimated in the DEPOT system where the depots are owned by the biorefinery interests. Due to short collection radii in the DEPOT-OS scenario, the farmer-owned depot system can also reduce GHG emissions by 9 – 11% compared to the MESP in DEPOT. The farmer-owned system can yield lower MESP values for large-scale biorefinery sizes ($\geq 7,000$ dry Mg per day) than does the CENTRAL configuration due to lower delivered price to the depot. The MESP values at sizes larger than 15,000 dry Mg per day in the DEPOT-OS scenario are lower than the minimum MESP value in the CENTRAL configuration.

The upper bound of rail service radius at a size of 15,000 dry Mg per day is about 14 km to satisfy two constraints (i.e., MESP and GHG reduction). However, two constraints are not satisfied for biorefineries less than 15,000 dry Mg per day. The upper bound of rail service radius declines slightly with the biorefinery size. The major constraint is the requirement for 60% greenhouse gas (GHG) reduction. A depot supplying large-scale biorefineries ($\geq 15,000$ dry Mg per day) should be located within about 14 km of rail service to meet the MESP requirement and to comply with the 60% GHG reduction constraint.

Figure 7

4. Conclusions

The biorefinery size is a key factor in determining MESP and some environmental impacts. The MESP declines with increased biorefinery size when the capital cost reductions due to the size increases outweigh transportation cost increases. However, the environmental impacts always

increase with the biorefinery size (comparing the two configurations studied here) because of a larger feedstock collection radius.

This study also shows how the different system configurations affect ethanol price and environmental impacts. The centralized system offers better economic performance for small-scale biorefineries, while the distributed system (using depots) has economic advantages for large-scale biorefineries and gives decidedly lower MESP values for these large-scale biorefineries. The centralized system yields lower environmental impacts for most impact categories than does the distributed system regardless of the biorefinery size. Furthermore, the eco-efficiency analysis clearly shows that the distributed configuration with railroad transportation for large-scale biorefineries is more sustainable than the centralized configuration for many environmental impact categories. In contrast, a biorefinery of 3,000 dry Mg per day in the centralized system offers the highest eco-efficiency indicators for most environmental impact categories.

This analysis has been done based on a homogenous feedstock (corn stover) supply chain system. However, a heterogeneous (using multiple cellulosic biomass feedstocks) feedstock supply chain system will probably be more relevant in practice. In a heterogeneous feedstock system, the feedstock logistics would become an even more important factor in determining both the MESP and the environmental impacts because croplands would not be uniformly distributed and a larger collection radius would be expected. Based on results from the tillage scenario, the distributed configuration would likely perform better than the centralized configuration in the heterogeneous feedstock supply chain system. Furthermore, the decentralized systems can more easily adopt relevant technologies for particular depots (e.g., leaf protein concentrate extraction, pyrolysis, etc.) under heterogeneous feedstock supply chain conditions [12]. In addition,

densified feedstock in the distributed systems can be blended much more easily to produce a uniform feedstock for the biorefinery than can baled feedstock in the heterogeneous feedstock supply system.

Since specific locations for depot and biorefinery, which can provide more exact information (e.g., road, railroad, cornfield, etc.), are not given here, this study provides only general information on the biorefinery system configurations. When locations for actual facilities are specified, more detailed local analyses should be performed to determine the best biorefinery system configurations. Due to lack of information, local conditions for each area (e.g., variations of soil emissions with respect to farming sites, etc.) are not taken into account in this study. More efforts to determine the effects of such local factors are required to perform better analyses.

Acknowledgements

This work was funded in part by the DOE Great Lakes Bioenergy Research Center (DOE BER Office of Science DE-FC02-07ER64494) and DOE OBP Office of Energy Efficiency and Renewable Energy (DE-AC05-76RL01830)).

References

1. Renewable Fuels Association. World Fuel Ethanol Production. [Internet]. Washington, DC; 2015. [cited 2015 January 6] Available from <http://ethanolrfa.org/pages/World-Fuel-Ethanol-Production>.
2. Garlock RJ, Balan V, Dale BE, Pallapolu VR, Lee YY, Kim Y, Mosier NS et al. (2011) Comparative material balances around pretreatment technologies for the conversion of switchgrass to soluble sugars. *Bioresour Technol* 2011; 102(24): 11063–71.

- 520 3. Kazi FK, Fortman J, Anex R, Hsu DD, Aden A, Dutta A, Kothandaraman G. Techno-
521 economic comparison of process technologies for biochemical ethanol production from corn
522 stover. *Fuel* 2010; 89(Supplement 1): S20–S30.
- 523 4. Kumar D, Murthy G. Life cycle assessment of energy and GHG emissions during ethanol
524 production from grass straws using various pretreatment processes. *Int J LCA* 2012; 17(4):
525 388–401.
- 526 5. Tao L, Aden A, Elander RT, Pallapolu VR, Lee YY, Garlock RJ, Balan V et al. Process and
527 technoeconomic analysis of leading pretreatment technologies for lignocellulosic ethanol
528 production using switchgrass. *Bioresour Technol* 2011; 102(24): 11105–14.
- 529 6. Aden A, Ruth M, Ibsen K, Jechura J, Neeves K, Sheehan J, Wallace B et al. Lignocellulosic
530 biomass to ethanol process design and economics utilizing co-current dilute acid
531 prehydrolysis and enzymatic hydrolysis for corn stover. Colorado: National Renewable
532 Energy Laboratory; 2002.
- 533 7. Laser M, Haiming J, Kemantha J, Lynd LR. Coproduction of ethanol and power from
534 switchgrass. *Biofuels Bioprod Bioref* 2009; 3: 195–218.
- 535 8. Sheehan J, Aden A, Paustian K, Killian K, Brenner J, Walsh M, Nelson R. Energy and
536 environmental aspects of using corn stover for fuel ethanol. *J Ind Ecol* 2003; 7(3-4): 117–46.
- 537 9. Humbird D, Davis R, Tao L, Kinchin C, Hsu D, Aden A, Schoen P et al. Process design and
538 economics for biochemical conversion of lignocellulosic biomass to ethanol: Dilute-acid
539 pretreatment and enzymatic hydrolysis of corn stover. Colorado: National Renewable Energy
540 Laboratory; 2011.

- 541 10. Bioenergy Technologies Office. Integrated biorefineries. [Internet]. Washington, DC: US
542 Department of Energy; 2010. [cited 2014 October 27] Available from
543 <http://www.energy.gov/eere/bioenergy/integrated-biorefineries>.
- 544 11. Carolan JE, Joshi SV, Dale BE. Technical and financial feasibility analysis of distributed
545 bioprocessing using regional biomass pre-processing centers. *J Agric Food Ind Org* 2007; 5:
546 1–29.
- 547 12. Eranki PL, Bals B, Dale BE. Advanced regional biomass processing depots - A key to the
548 logistical challenges of the cellulosic biofuel industry. *Biofuels Bioprod Bioref* 2011; 5: 621–
549 30.
- 550 13. Richard TL, Challenges in scaling up biofuels infrastructure. *Science* 2010; 329: 793–96.
- 551 14. Argo AM, Tan ECD, Inman D, Langholtz MH, Eaton LM, Jacobson JJ, Wright CT et al.
552 Investigation of biochemical biorefinery sizing and environmental sustainability impacts for
553 conventional bale system and advanced uniform biomass logistics designs. *Biofuels Bioprod*
554 *Bioref* 2013; 7: 282–302.
- 555 15. Egbendewe-Mondzozo A, Swinton SM, Bals BD, Dale BE. Can dispersed biomass
556 processing protect the environment and cover the bottom line for biofuel? *Environ Sci*
557 *Technol* 2013; 47(3): 1695–703.
- 558 16. Bare JC. TRACI 2.0 - The tool for the reduction and assessment of chemical and other
559 environmental impacts. *Clean Technol Environ Pol* 2011; 13: 687–96.
- 560 17. Verfaillie HA, Bidwell R. Measuring eco-efficiency: A guide to reporting company
561 performance. [Internet]. Geneva: World Business Council for Sustainable Development;

2000. [cited 2014 March 17] Available from
<http://oldwww.wbcd.org/plugins/DocSearch/details.asp?type=DocDet&ObjectId=Mjgy>.

18. Teymouri F, Laureano-Perez E, Alizadeh H, Dale BE. Optimization of the ammonia fiber explosion (AFEX) Treatment Parameters for Enzymatic Hydrolysis of Corn Stover. *Bioresour Technol* 2005; 96(18): 2014–18.

19. US Environmental Protection Agency. Renewable fuel standard program (RFS2) regulatory impact analysis. [Internet]. Washington, DC: US Environmental Protection Agency; 2010. [updated 2009 May 26; cited 2014 March 17] Available from:
<http://www.epa.gov/otaq/renewablefuels/420r10006.pdf> .

20. Horowitz J, Ebel R, Ueda K. “No-Till“ farming is a growing practice. [Internet]. Washington, DC: US Department of Agriculture; 2010. [cited 2014 March 17] Available from
www.ers.usda.gov/media/135329/eib70.pdf.

21. Gallagher PW, Baumes H. Biomass Supply from corn residues: estimates and critical review of procedures. [Internet]. Washington, DC: US Department of Agriculture; 2012. [cited 2014 March 17] Available from <http://www.usda.gov/oce/reports/>.

22. Morey RV, Kaliyan N, Tiffany DG, Schmidt DR. Corn stover supply logistics system. *Appl Eng Agric* 2010; 26(3): 455–61.

23. Argonne National Laboratory. Greenhouse gases, regulated emissions, and energy use in transportation (GREET) computer model. [Internet]. Argonne, Illinois: Argonne National Laboratory; 2012. [cited 2014 March 17] Available from <https://greet.es.anl.gov/>.

- 582 24. Hoskinson RL, Karlen DL, Birrell SJ, Radtke CW, Wilhelm WW (2007) Engineering,
583 nutrient removal, and feedstock conversion evaluations of four corn stover harvest scenarios.
584 Biomass Bioenergy 2007; 31: 126–36.
- 585 25. Suh K, Suh S, Walseth B, Bae J, Barker R. Optimal corn stover logistics for biofuel
586 production: a case in Minnesota. Trans ASABE 2011; 54(1): 229–38.
- 587 26. National Agricultural Statistics Service. US & all states data – Crops. [Internet]. Washington,
588 DC: US Department of Agriculture; 2013. [cited 2014 March 17] Available from
589 <http://www.nass.usda.gov/>.
- 590 27. Tan Z, Liu S, Bliss N, Tieszen LL. Current and potential sustainable corn stover feedstock
591 for biofuel production in the United States. Biomass Bioenergy 2012; 47: 372–86.
- 592 28. US Census Bureau. State area measurements and internal point coordinates. [Internet].
593 Washington, DC: US Census Bureau; 2013. [cited 2014 March 17] Available from
594 <https://www.census.gov/geo/reference/state-area.html>.
- 595 29. da Costa Sousa L, Jin M, Uppugundla M, Bokade V, Humpala JF, Gunawan C, Foston MB
596 et al. Extractive AFEX™ (E-AFEX™) pretreatment: a unified approach for resolving
597 bottlenecks to efficient cellulosic bioethanol production. New Orleans, LA: 34th Symposium
598 on Biotechnology for Fuels and Chemicals; 2012.
- 599 30. Campbell TJ, Teymouri F, Bals B. A packed bed ammonia fiber expansion reactor system for
600 pretreatment of agricultural residues at regional depots. Biofuels 2013; 4: 23–34.
- 601 31. Bals B. personal communication. Michigan: Michigan Biotechnology Institute; 2014.

- 602 32. US Bureau of Labor Statistics. Subject area categories. [Internet]. Washington, DC: US
603 Bureau of Labor Statistics; 2013. [cited 2014 March 17] Available from
604 <http://www.bls.gov/bls/proghome.htm>.
- 605 33. US Energy Information Administration. Annual energy outlook 2013 with projections to
606 2040. [Internet]. Washington, DC: US Department of Energy; 2013. [cited 2014 March 17]
607 Available from <http://www.eia.gov/forecasts/archive/aeo13/>.
- 608 34. Gonzales D, Searcy EM, Ekşioğlu SD. Cost analysis for high-volume and long-haul
609 transportation of densified biomass feedstock. *Transportation Research Part A* 2013; 49: 48–
610 61.
- 611 35. Graboski MS. Fossil energy use in the manufacture of corn ethanol. Chesterfield, Missouri:
612 National Corn Grower Association; 2002.
- 613 36. Intergovernmental Panel on Climate Change. 2006 IPCC guidelines for national greenhouse
614 gas inventories. [Internet]. Paris: International Panel on Climate Change; 2006. [cited 2014
615 March 17] Available from <http://www.ipcc-nggip.iges.or.jp/public/2006gl/>.
- 616 37. Jungbluth N, Emmenegger MF, Dinkel F, Stettler C., Doka G, Chudacoff M, Dauriat A et al.
617 Life cycle inventories of bioenergy. Dübendorf, CH: Swiss Centre for Life Cycle Inventories;
618 2007.
- 619 38. National Renewable Energy Laboratory. US life cycle inventory database. [Internet].
620 Colorado: National Renewable Energy Laboratory; 2008. [cited 2014 March 17] Available
621 from <http://www.nrel.gov/lci/>.

- 622 39. US Environmental Protection Agency. eGRID2012 version 1.0. [Internet]. Washington, DC:
623 US Environmental Protection Agency; 2012. [cited 2014 March 17] Available from
624 <http://www.epa.gov/cleanenergy/energy-resources/egrid/index.html>.
- 625 40. Kaufman AS, Meier PJ, Sinistore JC, Reinemann DJ. Applying life-cycle assessment to low
626 carbon fuel standards—How allocation choices influence carbon intensity for renewable
627 transportation fuels. *Energy Pol* 2010; 38(9): 5229–41.
- 628 41. Kim S, Dale BE, Jenkins R. Life cycle assessment of corn grain and corn stover in the United
629 States. *Int J LCA* 2009; 14(2), 160–74.
- 630 42. Luo L, van der Voet E, Huppes G, Udo de Haes HA. Allocation issues in LCA methodology:
631 A case study of corn stover-based fuel ethanol. *Int J LCA* 2009; 14(6), 529–39.

Table caption

Table 1 Parameters for corn stover transportation

Table 2. Process information for the depot and the biorefinery resulting from the ASPEN Plus™ model

Table 3. Key environmental impact sources

Table 4. Effects of ethanol yield on the environmental impact and eco-efficiency indicators

Figure legends

Figure 1. System configurations

Figure 2. Minimum ethanol selling price (MESP)

Figure 3. Life cycle impacts associated with one MJ of ethanol [FSE: Fossil energy consumption, GWI: Global warming, ACID: Acidification, EUTR: Eutrophication, HHP: Human health impacts by particulate matter, ODP: Ozone layer depletion]

Figure 4. Life cycle impacts associated with one MJ of ethanol [SMG: Smog formation, ECOT: Ecotoxicity, HHC: Human health cancer, HHNC: Human health non-cancer]

Figure 5. Eco-efficiency indicators for different biorefinery configurations

Figure 6. Effects of ethanol yield on MESP: (a) DEPOT and (b) CENTRAL [Unit of ethanol yield: liter per dry Mg]

Figure 7. Results for the DEPOT-TR and the DEPOT-OS scenarios (a) MESP and (b) GWI

Table 1 Parameters for corn stover transportation

Parameters	Values	References
Geographical coverage	Twelve states in the United States: Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, South Dakota, and Wisconsin	Defined
$r_{\%}$: Fraction of corn stover collected	22% $r_{\%} = r_N * F_N + r_{Cs} * F_{Cs} + r_{Ct} * F_{Ct}$ r_N : 50% of corn stover in no-tillage r_{Cs} :35% in conservation tillage r_{Ct} :0% in conventional tillage No-tillage (F_N): 22.6% Conservation tillage (F_{Cs}): 29.9% Conventional tillage (F_{Ct}): 47.5%	[19, 20]
f_a : Percentage of participating cornfields within the collection radius	36.8% $= 0.7 * (F_N + F_{Cs})$	[20, 25]
f_l : Transportation and storage loss factor	4.94%	[25]
Y_{grain} : Corn yield	7.96 dry Mg per ha	[26]
Y_{stover} : Corn stover yield	725.8 dry Mg per km ² (7.26 dry Mg per ha [‡])	[26, 27]
f_{corn} : Ratio of harvested corn area	14.5% Harvest corn area: 287,712 [‡] km ² Total regional area: 1,984,882 km ²	[26, 28]
f_s : Facility size	Depots: 200 dry Mg per day Biorefinery: 1,000 – 30,000 dry Mg per day	Defined
h_r : Annual operating hours	8,410 hours	[9]
W : Road tortuosity factor	1.3 for truck 1.79 for railroad	[25]

[‡] Average value from 2009 to 2012

Table 2. Process information for the depot and the biorefinery resulting from the ASPEN Plus™ model

		Unit	DEPOT configuration			CENTRAL configuration
			Depot	Biorefinery	Total	Biorefinery
Input materials						
Corn stover	dry kg per liter	3.6			3.6	3.6
Pretreated and densified corn stover	dry kg per liter			3.6	3.6	
Ammonia	g per liter	31.3	0.7		32.0	32.0
Lime	g per liter		0.6		0.6	0.6
Makeup water	kg per liter	2.1	8.3		10	7.0
Purchased cellulase enzyme	g per liter		22		22	22
Energy						
Steam used	kg per liter	5.3	4.9		10.2	9.9
Natural gas used	MJ per liter	3.3			3.3	
Grid electricity used	kWh per liter	0.2			0.2	
Electricity used	kWh per liter		0.7		0.7	0.8
Electricity generated	kWh per liter		2.5		2.5	1.9
Products						
Ethanol	liter		1.0		1.0	1.0
Excess electricity	kWh per liter		1.8		1.8	1.1
Process emissions						
CH ₄	g/liter		0.3		0.3	0.3
CO	g/liter		3.2		3.2	3.3
Biogenic CO ₂	g/liter		4001		4001	4001
N ₂ O	g/liter		0.03		0.03	0.03
NH ₃	g/liter	11.1	0.03		11.1	3.9
NOx	g/liter		0.09		0.09	0.09
SOx	g/liter		0.07		0.07	0.07

Table 3. Key environmental impact sources

	Unit	DEPOT	CENTRAL
Fossil energy consumption (FSE)	MJ	Excess electricity, Natural gas consumption	Excess electricity, Transportation
Global Warming (GWI)	g CO ₂ eq	Excess electricity, Natural gas consumption	Excess electricity, Transportation
Acidification (ACID)	g SO ₂ eq	Corn stover production, Excess electricity, Process emissions	Corn stover production, Excess electricity, Process emissions
Eutrophication (EUTR)	g N eq	Corn stover production, Process emissions	Corn stover production, Process emissions
Human health impacts by particulate matter (HHP)	g PM _{2.5} eq	Excess electricity, Natural gas consumption	Corn stover production, Excess electricity
Ozone Depletion (ODP)	g CFC-11 eq	Transportation	Transportation
Smog Formation (SMG)	g O ₃ eq	Corn stover production, Excess electricity, Process emissions	Corn stover production, Excess electricity, Transportation
Ecotoxicity (ECOT)	CTUeco ^{¶¶}	Natural gas consumption, Purchased cellulase	Purchased cellulase, Transportation
Human Health Cancer (HHC)	CTUcancer [§]	Excess electricity, Natural gas consumption	Corn stover production, Excess electricity
Human health Non-cancer (HHNC)	CTUnoncancer [‡]	Excess electricity, Natural gas consumption	Excess electricity, Transportation

^{¶¶}CTUeco: PDF (Potentially Disappeared Fraction)*m²*yr

[§] CTUcancer: cancer case

[‡] CTUnoncancer: non-cancer case

Table 4. Effects of ethanol yield on the environmental impact and eco-efficiency indicators

	DEPOT	CENTRAL
Fossil energy consumption (FSE)	Increase	Increase
Eco-efficiency _{FSE}	Higher	Higher
Global Warming (GWI)	Increase	Increase
Eco-efficiency _{GWI}	Higher	Higher
Acidification (ACID)	Decrease	for < 15,000 dry Mg/day: Increase for ≥ 15,000 dry Mg/day: Decrease
Eco-efficiency _{ACID}	Higher	Higher
Eutrophication (EUTR)	Decrease	Decrease
Eco-efficiency _{EUTR}	Higher	Higher
Human Health by Particulate (HHP)	Increase	Increase
Eco-efficiency _{HHP}	Lower	Lower
Ozone Depletion (ODP)	Decrease	Decrease
Eco-efficiency _{ODP}	Higher	Higher
Smog Formation (SMG)	Increase	for < 9,000 dry Mg/day: Increase for ≥ 9,000 dry Mg/day: Decrease
Eco-efficiency _{SMOG}	Higher	Higher
Ecotoxicity (ECOT)	Decrease	Decrease
Eco-efficiency _{ECOT}	Higher	Higher
Human Health Cancer (HHC)	Increase	Increase
Eco-efficiency _{HHC}	Lower	Lower
Human health Non-cancer (HHNC)	Increase	Increase
Eco-efficiency _{HHNC}	Lower	Lower