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Effect of biomass species and plant size on cellulosic ethanol: A comparative process and economic analysis

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ARTICLE INFO

Article history:
Received 30 July 2006
Received in revised form
8 April 2008
Accepted 2 May 2008
Published online ■

Keywords:
Lignocelluloses-to-ethanol process
Biorefinery
Techno-economic modeling
Cost estimation
Plant size
Biomass species
Aspen wood
Hybrid poplar
Switchgrass
Corn stover

ABSTRACT

The effects of five different biomass species and their chemical composition on the overall process efficiency and economic performance considering feedstock availability and feedstock costs to manufacture ethanol from lignocellulose were studied. First is a comparison of ethanol production and excess electricity generated between different biomass species. Results show that, at the same feedstock rate of 2000 Mg day^{-1}, aspen wood has larger ethanol production than switchgrass, hybrid poplar and corn stover, while the excess electricity generated is as follows in increasing order: aspen < corn stover < hybrid poplar/switchgrass. Second, our results show that the ethanol production is largely linear with holocellulose (cellulose plus hemicellulose) composition of the various biomass species. However, the relationship between excess electricity generated and non-holocellulose combustible component is nonlinear. Last, on environmental performance, it is found that the water losses per unit ethanol production are in the following order: aspen wood < corn stover < hybrid poplar < switchgrass. While corn stover is a potential feedstock to produce cellulosic ethanol with the lowest ethanol production cost at the present time, hybrid poplar and switchgrass are the two promising future energy crops.

The effects of plant size analysis showed that the estimated feedstock delivered costs, ethanol production, excess electricity generated and solid and gaseous waste emissions all increase with plant size for the various biomass species. The ethanol production costs decrease with the increase in plant size with optimal plant sizes for corn stover in the range from 2000 dry Mg day^{-1} to 4000 dry Mg day^{-1}.

1. Introduction

There has been increasing interests in conversion of biomass to fuel grade ethanol for many years due to variety of reasons including alternative green energy sources, the rise in oil prices, minimizing greenhouse gas (GHG) emissions caused by the use of fossil oil [1] and others. A number of corn-to-ethanol plants have been commercially built and operating around the world for many years. Recently, a lignocellulose-based ethanol (or cellulosic ethanol) plant is operating on commercial scale [2], though there still exists technical, economical, and commercial barriers.

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doi:10.1016/j.biombioe.2008.05.007

Recently, the Berkeley researchers found that both corn-to-ethanol and cellulosic ethanol could produce positive net energy and thus ethanol is an effective substitute for fossil fuels for transportation [3]. However, corn ethanol would only slightly reduce GHG emissions, by about 13%, while cellulosic ethanol could greatly reduce GHG by 88% [3]. In addition, large amounts of corn required for large-scale ethanol production will occupy cropland suitable for food production competing with food and feed needs [4], whereas fast-growing cellulosic energy crops such as hybrid poplar and switchgrass can be planted and grown on different types of lands. And, there are still great opportunities for potential improvement in production of these kinds of energy crops thus lowering purchase cost of feedstocks [5]. In addition, cellulosic feedstocks have lower chemicals and energy inputs (process steam and electricity) needed for production [6,7,8]. Therefore, the future for the production of ethanol from cellulosic feedstock appears very bright [3].

There are various cellulosic biomass species that can be considered for producing ethanol: agricultural residues – corn stover, wheat straw, rice straw and bagasse, etc.; woody materials – hardwood (e.g., aspen, poplar) and softwood (e.g., pine) and their residues; herbaceous – switchgrass; wastes from pulp and paper industry, etc [9,10]. In general, different cellulosic feedstocks have different compositions, but they are primarily composed of cellulose, hemicellulose and lignin. The carbohydrate components, namely cellulose and hemicellulose can be converted into ethanol by chemical or biochemical reactions, whereas lignin is usually used for combustion/gasification in order to produce process steam and electricity or for producing biofuel oil or syngas by thermo-chemical conversion.

The process of cellulosic biomass to ethanol involves several steps including feedstock pretreatment, hydrolysis/saccharification, fermentation, product recovery, and wastewater treatment (Fig. 1). The pretreatment step is used for separating the biomass into its components of cellulose, hemicellulose and lignin. In this step, lignin can be removed and some hemicellulose can be converted by hydrolysis to soluble sugars – primarily xylose, arabinose, mannose and galactose. Then, the remaining cellulose is converted into sugars by hydrolysis or saccharification. The third step is fermentation of five-carbon sugars and six-carbon sugars into ethanol [10,11]. To date, the major problems still exist in the saccharification process where cellulose and hemicellulose need to be broken down into sugars. Besides, it is an important and yet unsolved challenge, to completely and efficiently convert the mixture of five- and six-carbon sugars into ethanol by fermentation [10].

In order to look at the potential overall benefits of the cellulosic ethanol process, it is very important to perform techno-economic modeling and analysis of the whole process. Four earlier attempts were identified in the literature [11–14]. Saddler and co-workers had set up a process model for techno-economic analysis of a wood-to-ethanol process with focus on comparing generic hardwood and softwood [13,14]. In 2000 and 2002, NREL (National Renewable Energy Laboratory) released two reports on the process models which involve using co-current dilute acid prehydrolysis of the lignocellulosic biomass with enzymatic saccharification of the remaining cellulose and co-fermentation of the resulting glucose and xylose to ethanol [11,12]. The feedstocks in NREL's two models are yellow poplar and corn stover, respectively. In this paper, we will analyze the effects of an array of cellulosic species (aspen, hybrid poplar, switchgrass and corn stover) and their compositions on the overall lignocellulose to ethanol process and its costs and benefits, and the effect of plant size on the overall process efficiency and economic performance. Environmental consideration is also taken into account. It should be noted that composition could vary considerably within species as a function of variety or clone and the geographic region where it is grown. In this article the composition data of only a single sample of a clone or variety for each species was used, as primary focus of this work is on developing a methodology of analysis.

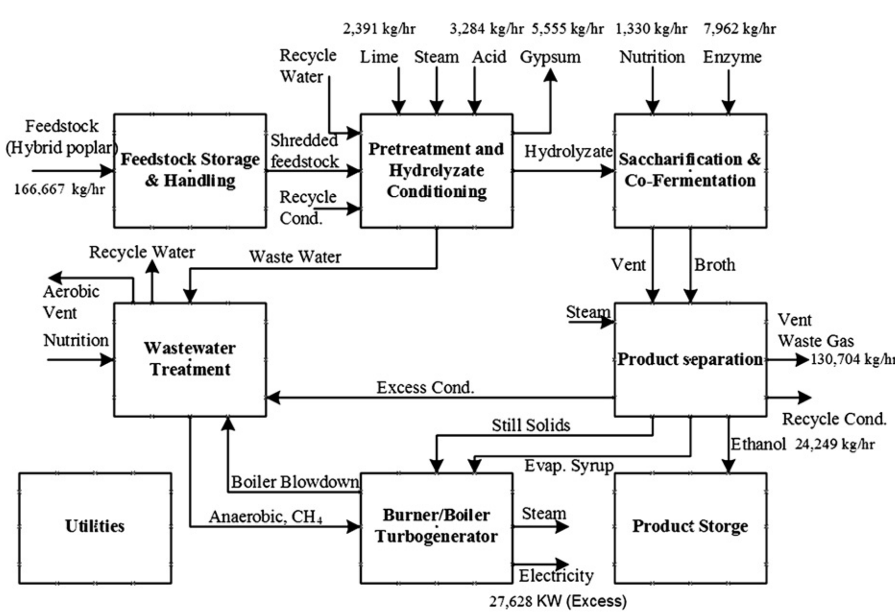

Fig. 1 – Overall process block diagram for a lignocellulose to ethanol biorefinery.

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2. Method for process design and economic analysis

2.1. Process description

The process for techno-economic analysis reported here is based on NREL's generic process model [11]. It mainly consists of eight areas: feedstock storage and handling, pretreatment and hydrolyzate conditioning, saccharification and co-fermentation, product separation and purification, wastewater treatment, product storage, lignin combustion for production of electricity and steam, and all other utilities (Fig. 1). There are many potential methods for feedstock pretreatment [15]: dilute acid hydrolysis, liquid hot water extraction, steam explosion, dilute acid-steam explosion, ammonia fiber explosion (AFEX) and lime pretreatment, etc. In NREL's process, dilute acid hydrolysis was adopted.

2.2. Process design basis

2.2.1. Biomass feedstock

Hardwood (aspen and hybrid poplar), switchgrass and corn stover are considered as biomass feedstocks in this techno-economic analysis. Aspen wood and hybrid poplar are delivered as chips, and switchgrass and corn stover as bales. The chemical and elementary compositions of a single clone, variety or sample of the various biomass species are listed in Tables 1 and 2. It is assumed, as per the common practice, that all the hardwoods contain 50% by weight moisture while switchgrass and corn stover contain 15% moisture.

As aspen wood and hybrid poplar are delivered as chips, which do not need to be unwrapped and shredded, the equipments such as bale unwrapping conveyor, shredder feed conveyor and shredder, etc. are excluded in process modeling and economic analysis for these two biomass species.

2.2.2. Operating conditions

Major process operating conditions for the lignocellulose to ethanol biorefinery are similar to the earlier conditions reported by NREL and given in Table 3 [11]. The operating conditions for the four biomass species are kept the same as in Table 3. The plant is assumed to operate 350 days per year. It should be noted that at the same conditions of cellulase loading (12 FPU g^{-1} cellulose), the amount of cellulase required for the four species at the same feedstock flowrates is different because of the different cellulose composition. Similarly, the amount of dilute acid required in the pretreatment processes is also different for the four biomass species since they have different compositions of hemicellulose and lignin.

Table 1 – Chemical compositions (WT% on dry basis)

Component	Aspen[a]	Hybrid poplar[b]	Switchgrass[b]	Corn stover[c]
Cellulose/glucan	53.02	43.67	33.75	37.4
Xylan	19.09	15.63	22.13	21.1
Arabinan	4.24	0.71	2.81	2.9
Mannan	2.12	2.27	0.19	1.6
Galactan	1.59	0.94	0.89	2.0
Lignin	19.09	27.23	16.82	18.0
Ash	0.85	1.35	5.96	5.2
Extractives	0	3.39	15.55	4.7
Acetate	0	0	0	2.9
Protein	0	0	0	3.1
Soluble solids	0	4.81	1.89	1.1

a Data from California Energy Commission [16] and normalized to 100% mass closure.
b Original data of hybrid poplar and switchgrass are from the biomass samples "19 Hybrid Poplar Caudina, DN-34" and "93 Switchgrass Alamo whole plant" in the biomass feedstock composition and property database [17] and normalized to 100% mass closure. The original components – uronic acids are taken as soluble solids for simplicity.
c Data from NREL's report [11].

2.3. Methods for process simulation and cost estimation

The rigorous mass and energy balance of the biorefinery process was calculated with Aspen Plus software (version 2004.1) produced by AspenTech Inc. The physical properties of common components such as ethanol and water are already available within Aspen Plus. The physical properties of many key components such as xylan, cellulose, lignin and cellulase, etc. included in the process model are developed by NREL [18]. One of the key outputs from the model is the amount of ethanol produced and thus the ethanol yield per unit biomass feedstock. The simulation results thus obtained are inputted into another AspenTech's software Icarus Process Evaluator to estimate the sizes and the costs of the common equipments

Table 2 – Elementary composition (WT% on dry basis)

	C	H	N	O	S	Ash	Heating value ($\times 10^4$ kJ kg^{-1})
Aspen[a]	48.8	6.00	0.5	44.7	0.01	0.5	2.001
Hybrid poplar[b]	50.02	6.28	0.19	42.17	0.02	1.32	1.953
Switchgrass[b]	46.77	5.57	0.54	41.10	0.07	5.95	1.851
Corn stover[c]	44.52	5.74	0.46	42.42	0.008	6.86	1.745

a Data from California Energy Commission [16] and normalized to 100% mass closure.
b Original data of hybrid poplar and switchgrass are from the biomass samples "19 Hybrid Poplar Caudina, DN-34" and "93 Switchgrass Alamo whole plant" in the biomass feedstock composition and property database [17] and normalized to 100% mass closure. The original components – uronic acids are taken as soluble solids for simplicity.
c Data from NREL's report [11].

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such as distillation columns, heat exchangers and vessels, etc. The costs of uncommon equipments such as pretreatment reactors were based on vendor quotations. When scaling of equipment, the new cost of the scaled equipment can be determined according to the following scaling expression:

$$C_{New} = C_o \left(\frac{S_{New}}{S_o}\right)^f$$

where C_{New} and C_o are the new cost and the original cost, respectively; S_{New} and S_o are the new size and the original size, respectively; f is the capital cost scaling factor or exponent. In this analysis $f = 0.7$.

In addition, a spreadsheet model was used to perform cost estimations with data loaded from Aspen plus simulation results [11].

2.4. Estimation of delivered cost of biomass feedstock

In order to observe the effect of plant size on the overall process efficiency and economic performance, one of the key elements is the feedstock cost. This is especially critical and somewhat different than petroleum based feedstock in the sense that the type of biomass species and the growth and availability are very much dependent on the geographical area and might significantly influence the economic performance.

Generally, biomass feedstock delivered costs are composed of farmer premium/land rent, fertilizer cost to compensate for the loss of nutrients removed with biomass, costs of production/farming, collection/harvest, storage, grinding/chipping, and transportation. The transportation cost consists of two parts: distance fixed cost (DFC) and distance variable cost (DVC) [19–21]. DFC includes costs of loading, uploading and stacking at biorefinery while DVC depends on hauling cost ($\$\,km^{-1}\,Mg^{-1}$) and hauling distance, etc. There are many potential methods for specific production/farming, harvest, handling, storage of biomass and transportation, which will influence the delivered cost of biomass feedstock. The following gives the details on the feedstock estimation method for various biomass species considering their availability, growth, geographic information, etc. Of the total feedstock delivered cost, cost components such as farmer premium/land rent, fertilizer cost, production/farming/stumpage, collection/harvest, storage, grinding/chipping and distance fixed cost (DFC) of transportation for four species will be described in Section 2.4.1, and the distance variable cost (DVC) of transportation will be described in Section 2.4.2.

Table 3 – Major operating conditions

Pretreatment	Acid concentration	1.1%
	Solids in the reactor	30%
	Temperature	463.15 K (190 °C)
	Pressure	1226.0 kPa (12.1 atm)
	Residence time	120 s
Saccharification	Cellulase loading	12 FPU g^{-1} cellulose
	Initial saccharification solids level	20% Total solids
	Temperature	338.15 K (65 °C)
	Total residence time	36 h
	Size of vessels	3596 m^3 each
	Number of vessels	5
	Number of continuous trains	1
Co-fermentation	Organism	Zymomonas mobilis strain
	Initial fermentation solids level	20% Total solids
	Inoculum level	10%
	Corn steep liquor (CSL) level	0.25%
	Diammonium phosphate (DAP) level	0.33 $kg\,m^{-3}$ fermentation broth
	Temperature	314.15 K (41 °C)
	Total residence time	36 h
	Size of vessels	3596 m^3 each
	Number of vessels	5
	Number of continuous trains	1

2.4.1. Cost components except transportation distance variable cost (DVC)

Corn stover. The total delivered corn stover costs include premium or payment to farmers, costs of collecting, storage, and transportation of stover from storage to conversion plant [22,23]. In this analysis, all the costs are in 2005 dollars except stated. The typical premium to farmers to compensate for lost nutrients and environmental benefits can vary between 11.02 $\$\,dry\,Mg^{-1}$ and 16.53 $\$\,dry\,Mg^{-1}$ (10–15 $\$\,dry\,US\,ton^{-1}$) [24]. In this analysis, the payment to farmers is assumed to be \$11 based on literature [11,24]. The costs for replacement of nutrients are assumed to be 8.0 $\$\,dry\,Mg^{-1}$ [11].

Estimation of corn stover collection cost has been reported by many researchers [24–30]. The stover collection cost is usually dependent on the collection system, sequence of operations, stover availability or yield collectable, baling method (the type of bale and bale density), operating hours, and storage format (covered or uncovered), etc [25,29]. Sokhansanj et al. [25] estimated baseline cost for collecting, baling, and transporting corn stover from the field to an intermediate storage 8 km away and stacking bales under a shed, using two existing stover harvest systems: one consisting of a combination of shredding–windrowing followed by large round baling and the other consisting of separate shredding and windrowing (raking) followed by large square baling. The calculated collection costs for these two systems are 21.60 $\$\,dry\,Mg^{-1}$ and 23.60 $\$\,dry\,Mg^{-1}$, respectively. More recently, Sokhansanj et al. [29] developed integrated biomass supply analysis and logistics model (IBSAL) to simulate a conventional baling system using a shredder, large square baler and automatic stacker for collecting corn stover at a yield of 5.7 $dry\,Mg\,ha^{-1}$. Graham et al. [30] estimated the corn stover collection costs using existing commercial equipment, considering erosion constraints to collection and the cost of fertilizer to replace nutrient removed.

In the analysis of Aden et al. [11], the corn stover yield was assumed 4.94 $dry\,Mg\,ha^{-1}\,year^{-1}$ (2 $dry\,Mg\,acre^{-1}\,year^{-1}$). In the Minnesota–Iowa region, the average corn stover yield during 1995–2000 is 7.59 $dry\,Mg\,ha^{-1}\,year^{-1}$, assuming a stover to grain mass ratio of 1:1 [30]. The yield of 5.7 $dry\,Mg\,ha^{-1}$ reported by Ref. [29] seems more reasonable for Minnesota

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in the near term. Thus, it is also used in this study. At this yield the collection cost for corn stover in square bales including costs of combine, shredding, baling and stacking was assumed as 21.12 $ dry Mg^{-1} based on the work of Sokhansanj et al. [29]. In addition, the cost of bales storage covered under a shed is assumed as 8 $ dry Mg^{-1} $year^{-1}$ for stover in square bales. This is necessary for a conversion facility to avoid bales being subjected to rain, snow and other severe weather conditions [25]. The distance fixed cost for corn stover in square bales including costs of loading, uploading and stacking at biorefinery is assumed to be 7.61 $ dry Mg^{-1} [29].

Switchgrass and hybrid poplar are the two fast-growing energy crops. Though these energy crops are not currently grown as biofuel feedstocks, it is suggested that they would be produced in suitable farm lands provided farmers could earn benefit equal to or more than that from traditional agricultural crops [22]. For switchgrass, its delivered costs are composed of costs of land (or farmer premium), production/farming, harvest, storage, and transportation costs. Based on Refs. [31,32], the rents for grasslands and croplands are assumed to be 124 $ ha^{-1} $year^{-1}$ and 185 $ ha^{-1} $year^{-1}$, respectively. Hence, the land rent per dry Mg switchgrass in this study is $11.27 and $16.82 for grasslands and croplands, respectively, assuming the same switchgrass production yield of 11 dry Mg ha^{-1} $year^{-1}$. This could represent a reasonable commercial yield today in Minnesota [20]. The production costs excluding the harvest and storage for switchgrass planted in croplands and grasslands are 44.24 $ dry Mg^{-1} and 36.83 $ dry Mg^{-1}, respectively, at the same yield of 9 dry Mg ha^{-1} $year^{-1}$ [33]. These production costs are then adjusted to be 36.17 $ dry Mg^{-1} and 30.10 $ dry Mg^{-1}, respectively, for the yield of 11 dry Mg ha^{-1} $year^{-1}$. Note that this is only for approximation because the costs are not exactly linear with production yield. As to the harvest cost, Kumar and Sokhansanj [20] simulated mowing and conditioning in a single operation and modeled five harvesting systems: round baling, square baling, loafing, wet chopping and dry chopping. Among these, round and square baling systems have been more commonly investigated [20,34,35], and since round baling late in the season is difficult because of toughness of the switchgrass [36], square baling system is selected in this analysis. Based on Kumar and Sokhansanj [20], the switchgrass harvest cost at the yield of 11 dry Mg ha^{-1} in square bales was assumed to be 24.10 $ dry Mg^{-1}. This includes mowing, raking, baling, transporting the bales to the edge of field and stacking, etc. The storage costs for switchgrass are considered the same as those of stover assuming that the switchgrass square bales can be made with the same density as the stover square bales. The distance fixed cost of transportation covering the costs of loading, unloading and stacking is 3.74 $ dry Mg^{-1} [20].

Hybrid poplar (HP) is another fast-growing energy crop. Costs for collecting and processing woody biomass vary with biomass production yield, tree size, harvest method, skid distance and transportation distance [37]. The yield of HP planted on croplands in Lake States of US was estimated to be in the range of 7.9–11.8 dry Mg ha^{-1} $year^{-1}$ [35]. In Minnesota, the yield of HP planted on poor corn lands was in the range of 7.7–9.0 dry Mg ha^{-1} $year^{-1}$ (3.0–3.5 cords $acre^{-1}$ $year^{-1}$, assuming 2.3 green US tons $cord^{-1}$), and the higher yield can be obtained in more productive croplands [38]. In this analysis the yield of 9.0 dry Mg ha^{-1} $year^{-1}$ was used. Given the cropland rent of 185 $ ha^{-1} $year^{-1}$ as described above, the land cost is 20.50 $ dry Mg^{-1}.

HP can be harvested with conventional forest harvest equipments. In Minnesota, the logging costs at the landing range from 15.43 $ dry Mg^{-1} to 30.86 $ dry Mg^{-1} for even-aged management, and the chipping costs range from 13.23 $ dry Mg^{-1} to 26.46 $ dry Mg^{-1} [37]. In our analysis, we assumed harvest costs of 16.0 $ dry Mg^{-1} and chipping costs of 14.0 $ dry Mg^{-1}. Besides, the transportation distance fixed cost of 4.55 $ dry Mg^{-1} was assumed [37].

Aspen wood grows naturally in forestlands. The stumpage price of aspen pulpwood in Minnesota is 57.22 $ dry Mg^{-1} (59.70 $ $cord^{-1}$) [39], assuming 2.3 green US tons $cord^{-1}$ and 50% moisture. The loading and uploading cost, the harvest costs and chipping costs for aspen wood are assumed to be the same as hybrid poplar. In Minnesota, the aspen woodland area is totally 1 958 924 ha (4 840 500 acres), and the total harvested amount of aspen wood is 1 962 710 dry Mg $year^{-1}$ (1 881 300 cords $year^{-1}$) [40]. So, the aspen wood yield is about 1.0 dry Mg ha^{-1} $year^{-1}$.

The total feedstock delivered costs excluding DVC of the four species are summarized in Table 4, in which corn stover and switchgrass are in square bales, and hybrid poplar (HP) and aspen wood are in the form of chips. Note that the fertilizer costs for switchgrass (croplands/grasslands) and HP are already hidden in their production/farming cost, and no storage costs are considered for HP and aspen wood since trees are in practice stored on the stump and used when needed [31]. In addition, the stumpage price of aspen wood already covers both farmer premium/land rent and fertilizer cost.

Table 4 – Total feedstock delivered costs excluding DVC ($ dry Mg^{-1})

Cost	Corn stover	Switchgrass (croplands)	Switchgrass (croplands)	HP (croplands)	Aspen wood
Farmer premium/land rent	11.0	16.82	11.27	20.50	–
Fertilizer cost	8.0	–	–	–	–
Production/farming/stumpage	–	36.17	30.10	38.64	57.22
Collection/harvest	21.12	24.10	24.10	16	16
Storage	8.0	8.0	8.0	–	–
Grinding/chipping	–	–	–	14	14
Distance fixed cost (DFC)	7.61	3.74	3.74	4.55	4.55
Total costs excluding DVC	55.73	88.82	77.21	93.69	91.77

2.4.2. *Estimation of transportation distance variable cost (DVC)*

2.4.2.1. Relationship between distance and annual feedstock demand by an ethanol plant. Assume that a biorefinery plant is located at the center of a circle of area A with a radius of R. So, the radius can be calculated for given production capacity of a biorefinery [41,42]:

$$R = \left(\frac{F}{\pi f_a f_{lc} Y}\right)^{1/2} \quad (1)$$

where F is annual feedstock demand by the ethanol plant (dry Mg $year^{-1}$), f_a is the fraction of total farmland from which feedstock (corn stover, switchgrass, hybrid poplar) can be collected or produced, f_{lc} is the fraction of surrounding farmland containing crops, and Y is the biomass yield, i.e., dry Mg feedstock collected/harvested per unit area per year (dry Mg km^{-2} $year^{-1}$). As described above, Y = 5.7, 11, 11, 9.0 and 1.0 dry Mg ha^{-1} $year^{-1}$ for corn stover, switchgrass in grasslands, switchgrass in croplands, hybrid poplar and aspen wood, respectively.

It is assumed that corn is planted as a crop of choice in 75% of the farmland area surrounding the plant ($f_{lc} = 0.75$) and that only 10% of the suitable corn acreage is available to collect the corn stover ($f_a = 0.1$), which is closer to reality in the near term [11]. Similar to corn stover, we assume that 75% of the land area surrounding the plant is actually farmland ($f_{lc} = 0.75$), and only 10% of this actual farmland acreage is used for switchgrass production ($f_a = 0.1$) [12]. The same assumption goes to hybrid poplar. Note that the assumption of $f_a = 0.1$ is conservative.

In the whole state of Minnesota, 29% of the total land area is timberland [40]. However, this is the average percentage. In reality the biorefinery is more likely to be constructed in a specific circular area with a radius of R where timberland takes up much more than 29% of that area. According to Berguson et al. [43], for example, the Minnesota timberland acreage is around 70% of the total Minnesota acreage lying with 75 miles of Hibbing. Here we assume 70% of the land area surrounding the plant is actual timberland ($f_{lc} = 0.70$) for aspen wood. In addition, 32% of this timberland acreage is actually aspen wood acres ($f_a = 0.32$) [40].

2.4.2.2. Average transportation cost per dry Mg feedstock. The average transportation cost per dry Mg feedstock is as follows [41,42,44]:

$$\overline{C} = \frac{2C_1 R f_w}{3(1-m)} \quad [\$ \text{ dry Mg}^{-1}] \quad (2)$$

where f_w is the road-winding factor, m is the biomass moisture in weight percent (wt%), C_1 is the hauling cost per unit weight-distance ($ dry Mg^{-1} km^{-1}).

In this paper, we assumed $f_w = 1.3$ [25] for all species, and m = 15% for corn stover and switchgrass, m = 50% for hybrid poplar and aspen wood as mentioned above. The hauling costs for transportation of biomass by truck depend on biomass moisture, bale density, road quality, etc., so the hauling costs for different biomass should be different. Kumar et al. [19] summarized the hauling costs for transportation of different biomass by truck in North America [19]. The hauling costs per dry ton-km for corn stover, wood chips (long-term supply) and switchgrass are 0.12 $ dry Mg^{-1} km^{-1} [11], 0.11 $ dry Mg^{-1} km^{-1} [45] and 0.11 $ dry Mg^{-1} km^{-1} [20], respectively. For simplicity, the average hauling costs for all the biomass studied was assumed to be 0.11 $ dry Mg^{-1} km^{-1}.

3. Results and discussion

3.1. *Effects of biomass species and chemical composition on process and economic analysis*

3.1.1. *Effect of different species on ethanol production and excess electricity generated*

The effect of different species on ethanol production at the feedstock rate of 2000 dry Mg day^{-1} is shown in Fig. 2. From this figure, it can be observed that aspen wood can produce the largest ethanol production per unit biomass, followed by switchgrass, hybrid poplar and corn stover. This is due to higher combined cellulose and hemicellulose (holocellulose) content in aspen compared to other species.

Similarly comparison of excess electrical energy generated indicates that aspen wood produces the least, followed in increasing order by corn stover, hybrid poplar, and switchgrass (hybrid poplar and switchgrass almost the same) (Fig. 3). This is probably because some of the ‘‘extractives’’ component along with lignin can be burnt for producing electricity and according to Table 1, the total combined amount (%) of lignin, acetate, protein and extractives of aspen, hybrid poplar, switchgrass and corn stover are 19.09, 30.62, 32.37 and 28.70, respectively (please refer to next section).

3.1.2. *Effect of chemical composition of biomass on ethanol production and excess electricity generated*

The relationship between the ethanol production and holocellulose (cellulose and hemicellulose) composition of specific varieties or clones of the different species is shown in Fig. 4. As expected, it is found that the ethanol production increases linearly with the increase in holocellulose composition, and the

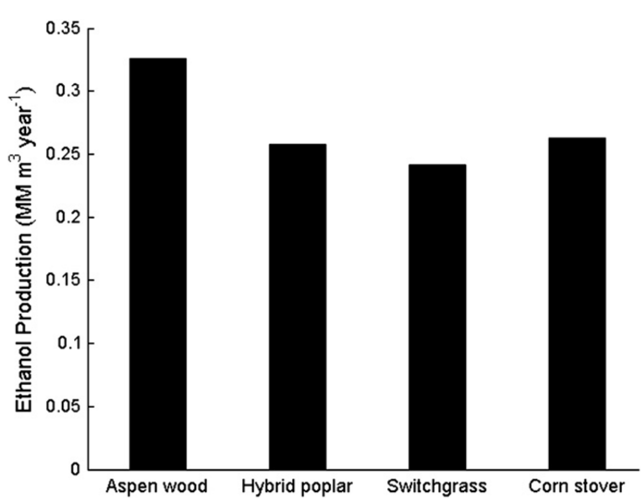

Fig. 2 – Comparison of ethanol production between aspen, hybrid poplar, switchgrass and corn stover.

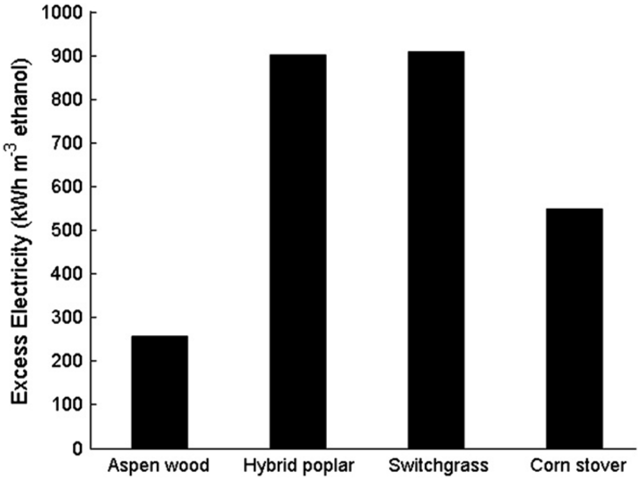

Fig. 3 – Comparison of excess electricity generated between aspen, hybrid poplar, switchgrass and corn stover.

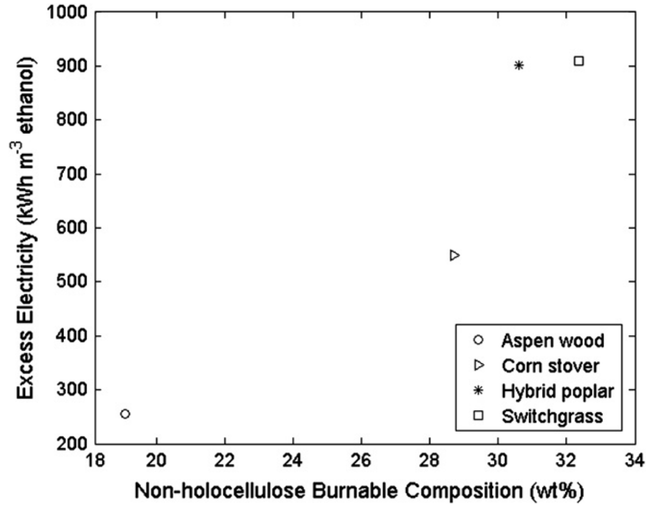

Fig. 5 – Effect of non-holocellulose combustible composition of aspen wood, hybrid poplar, switchgrass and corn stover on excess electricity generated.

ethanol production and the amount of holocellulose is in the same order: (low) switchgrass < hybrid poplar < corn stover < aspen wood (high). This is because, among the compositions listed in Table 1, holocellulose are the major components converted into ethanol and the same operating conditions are assumed here. Fig. 5 shows the effect of non-holocellulose combustible composition of aspen wood, hybrid poplar, switchgrass and corn stover on excess electricity generated. It is shown that the excess electricity generated increases with the increase in non-holocellulose combustible composition, and in the following order:

(Low) aspen wood < corn stover < hybrid poplar
< switchgrass (high)

Unlike the linear relationship between holocellulose composition and ethanol production (Fig. 4), the relationship between excess electricity generated and non-holocellulose combustible composition is nonlinear (Fig. 5). This is due to the fact that in addition to varying composition among the biomass species, the distribution and the specific heating value of the components are also different and they influence the net electricity generated.

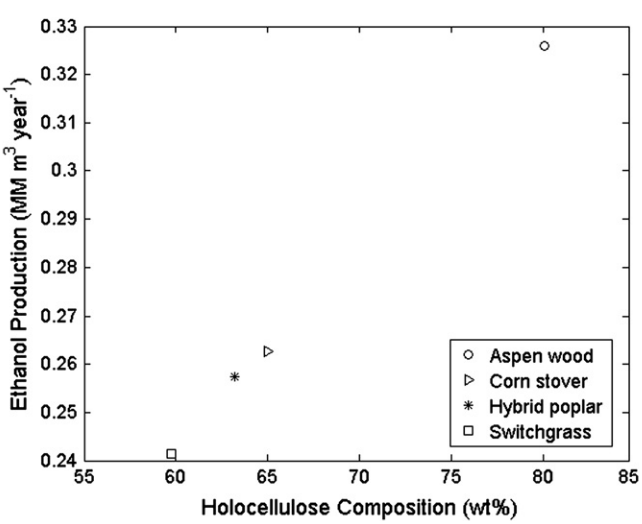

Fig. 4 – Effect of holocellulose composition of aspen wood, hybrid poplar, switchgrass and corn stover on ethanol production.

3.1.3. *Effect of species on major waste streams and total water losses*

Using again the 2000 dry Mg day^{-1} feedsstock as the basis, the major waste streams from the lignocellulose to ethanol biorefinery for aspen, hybrid poplar, switchgrass and corn stover are shown in Table 5. From this table it can be seen that the amount of major wastes streams for various biomass species is in the following order:

Gypsum : (low) Aspen < Hybrid poplar/Corn stover
< Switchgrass (high)

Ash : (low) Aspen < Hybrid poplar < Cornstover
< Switchgrass (high)

$CO_2/CO/NO_2/SO_2$: (low) Aspen < Corn stover
< Hybrid poplar < Switchgrass (high)

Table 5 – Major waste streams (unit: kg m^{-3} ethanol)

	Aspen wood	Hybrid poplar	Switchgrass	Corn stover
Gypsum	142.70	181.34	199.23	181.34
ASH	18.26	36.72	172.96	139.65
CO_2	2438.57	3376.16	3413.53	2856.43
CO	1.37	2.45	2.52	1.96
NO_2	1.37	2.45	2.52	1.96
SO_2	2.36	4.15	6.99	3.21

Considering all of the waste streams (zero discharge of liquid waste to a municipal treatment plant is designed in this analysis), aspen wood shows the lowest amount of waste streams, switchgrass the highest, hybrid poplar and corn stover are in between. In addition, hybrid poplar has the same amount of gypsum as corn stover, and has smaller amount of ash but larger amount of $CO_2/CO/NO_2/SO_2$ than corn stover. CO_2 mainly comes from oxidation of carbon source (e.g., lignin) in combustor and from fermentation gas. CO, NO_2 and SO_2 also come from combustor. Sulfur source is from wastewater treatment (hydrogen sulfide), neutralization of sulfuric acid, and is present in biomass, etc [11]. Nitrogen source is mainly from air. Though operating at the same conditions, due to the different feedstock compositions, the amount of the waste gas produced is different.

The total water losses including water evaporated and vented to atmosphere and water entrained in solid waste from the biorefining processes are 226.7 Mg h^{-1}, 254.7 Mg h^{-1}, 249.4 Mg h^{-1} and 208.1 Mg h^{-1}, corresponding to water losses to ethanol ratio (Mg H_2O m^{-3} ethanol) of 7.25, 8.86, 8.14 and 5.36, for corn stover, switchgrass, hybrid poplar and aspen wood, respectively, showing that the water losses are in the rank: aspen wood < corn stover < hybrid poplar < switchgrass. It is assumed that make-up water is used for making up the water losses.

3.2. *Effect of plant size on process and economic analysis*

3.2.1. Collection radius and feedstock delivered cost estimated
The collection radius and the delivered costs estimated as a function of plant size for various biomass species are plotted in Figs. 6 and 7, respectively. It is clearly seen from Fig. 6 that the collection radius increases nonlinearly with the plant size. Thus, transportation DVC varies nonlinearly with plant size, and since DVC is a part of delivered cost, the delivered cost also varies nonlinearly with plant size. Note that the curves of delivered costs in Fig. 7 are only slightly nonlinear with plant size due to the fact that DVC (distance variable cost) values are only a small fraction of the total costs in current estimations. For corn stover-to-ethanol plant at the capacity of 5000 dry Mg day^{-1}, the stover collection radius is about 114 km. Fig. 7 shows that the delivered costs of aspen wood, hybrid poplar, switchgrass in grasslands and croplands, and corn stover increase with the plant size. By comparison of these three species, it is found that the delivered costs decrease in the following order for various biomass species: (high) aspen wood > hybrid poplar > switchgrass in croplands > switchgrass in grasslands > corn stover (low). It is necessary to note, however, that this relative order of the biomass species could change with the change in the feedstock cost and there are many factors that could change the relative delivered cost of the various feedstocks.

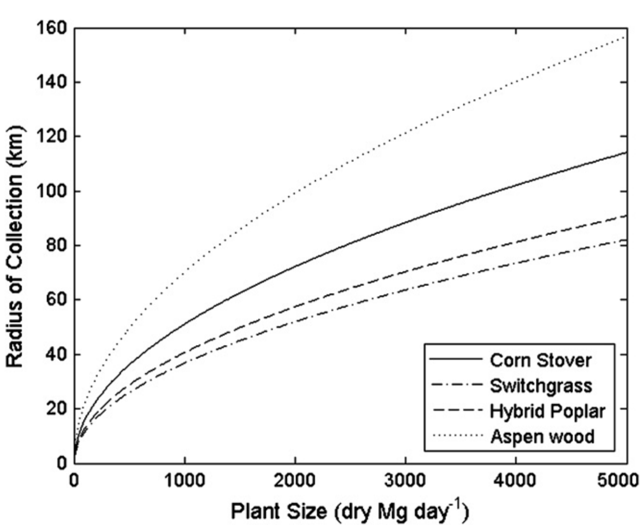

Fig. 6 – The radius of biomass collection as a function of plant size. (Yield = 5.7, 11.0, 9.0, 0.41 dry Mg ha^{-1} $year^{-1}$ for corn stover, switchgrass (grasslands/croplands), hybrid poplar and aspen wood, respectively).

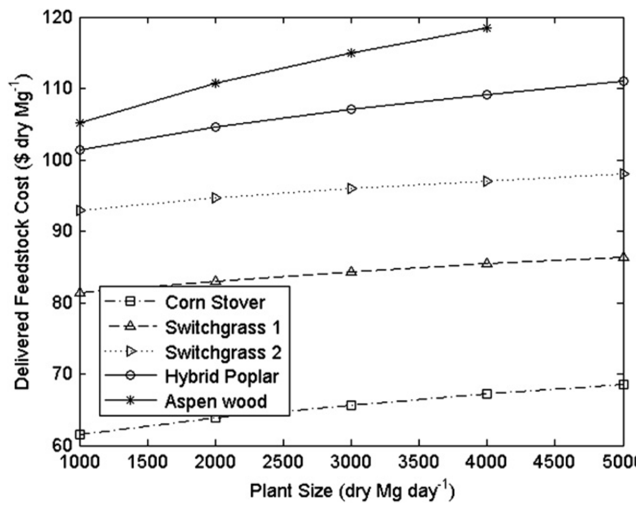

Fig. 7 – Effect of plant size on delivered feedstock cost (switchgrass 1 and 2 represent switchgrass planted in grasslands and croplands, respectively).

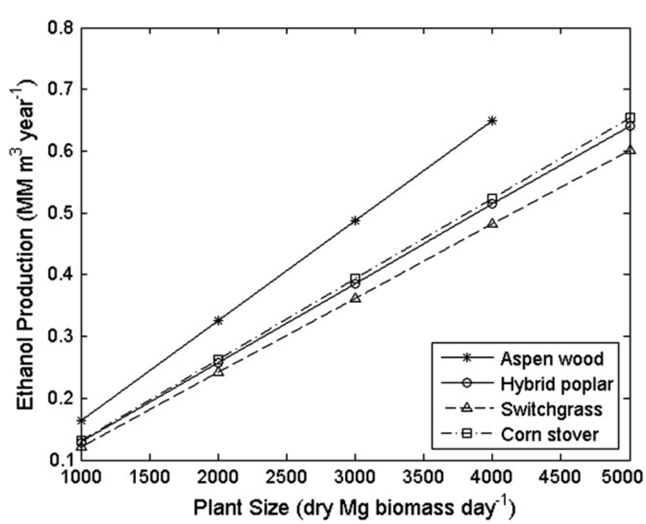

Fig. 8 – Effect of plant size on ethanol production for various biomass species.

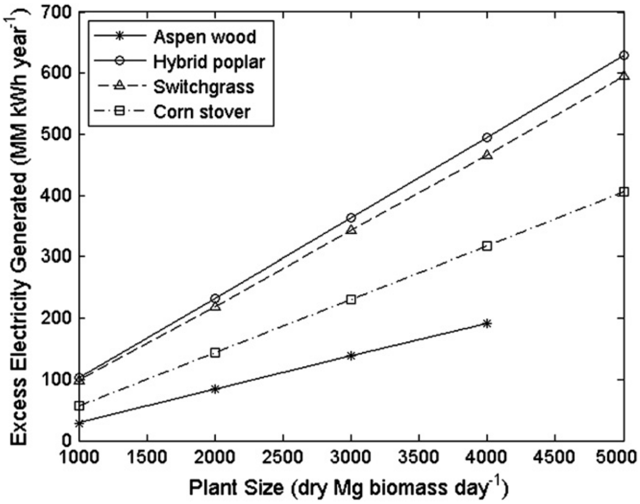

Fig. 9 – Effect of plant size on excess electricity generated for various biomass species.

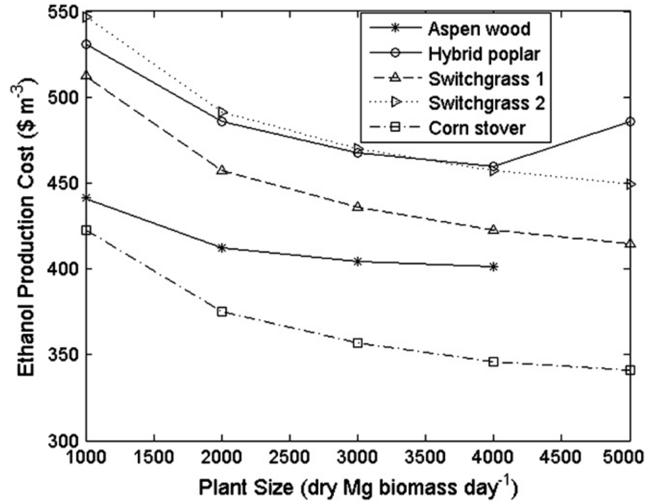

Fig. 10 – Effect of plant size on ethanol production cost.

3.2.2. *Effect of different plant sizes on ethanol production and excess electricity generated*

The effects of different plant size on the ethanol production and the excess electricity generated for various biomass species are shown in Figs. 8 and 9, respectively. From Fig. 8, it is observed that the ethanol production (MM m^3 volume per year) increases linearly with the increase in plant size, and the ethanol production is in the following order: (high) aspen wood > corn stover > hybrid poplar > switchgrass (low). As noted earlier (Fig. 2), this is due to the varying holocellulose content of the biomass species, and the total amount increases with the plant size. As shown earlier, this follows the same order as amounts of combined holocellulose content: (high) aspen wood > corn stover > hybrid poplar > switchgrass (low), as mentioned in Section 3.1.2. Fig. 9 shows the linear increase of the excess electricity generated with the plant size, in the same order as non-holocellulose combustible component-compositions: (low) aspen wood < corn stover < switchgrass < hybrid poplar (high). As described in Section 3.1.2, the reason for this is that the non-holocellulose combustible components contribute to the production of electricity.

3.2.3. *Effect of plant size on ethanol production cost*

Fig. 10 shows the effect of plant size on the ethanol production cost (total operating cost or minimum ethanol selling price), which is composed of feedstock cost and non-feedstock cost. It is shown that in the plant sizes ranging from 1000 dry Mg day^{-1} to 4000 dry Mg day^{-1} the ethanol production costs decrease with the increase in plant size owing to the economies of scale. It can also be seen that ethanol production costs decrease significantly from the plant size of 1000 dry Mg day^{-1} to 2000 dry Mg day^{-1}, and then with further increase in plant size the ethanol production costs decrease at a slower rate. For corn stover and switchgrass in grasslands and croplands, over 4000 dry Mg day^{-1} of plant size further increase in plant size does not appear to contribute to significant change in ethanol production costs. For hybrid poplar, however, above a plant size of 4000 dry Mg day^{-1} ethanol production costs increase with further increase in plant size. This is because ethanol production cost is composed of feedstock cost and non-feedstock cost, and for HP over 4000 dry Mg day^{-1} of plant size, the feedstock cost increases faster, while the non-feedstock cost decreases slower (figure not shown here). We also observed similar minima for other biomass species at a different point at the plant size of over 5000 (not shown in Fig. 10). HP makes this minimum happen sooner due to different biomass density, availability (or yield) and farming cost, and hence different delivered cost. Therefore, the relatively more suitable plant sizes are in the range from 2000 dry Mg day^{-1} to 4000 dry Mg day^{-1}, at which the ethanol production costs are relatively low. These results are consistent with the report of Aden et al. [11].

Comparing the four biomass species studied, it is observed that the ethanol production costs are the lowest for corn stover followed by aspen wood, switchgrass in grasslands, switchgrass in croplands or hybrid poplar. Comparing

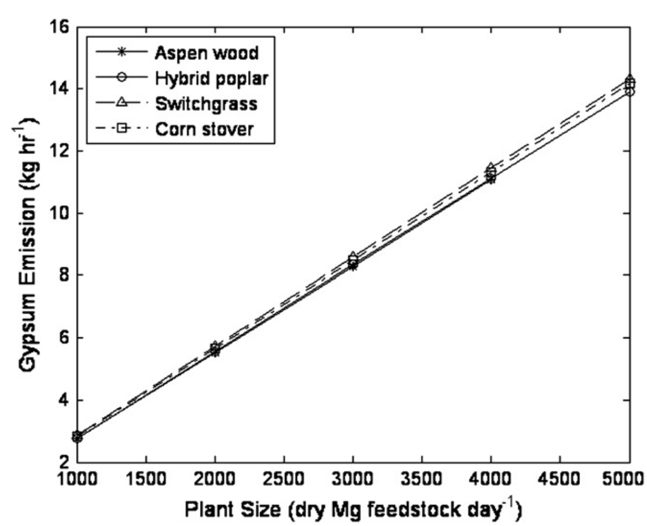

Fig. 11 – Effect of plant size on gypsum emission.

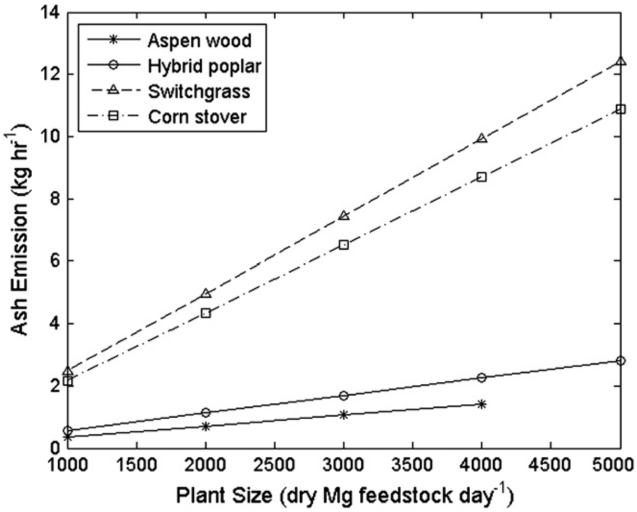

Fig. 12 – Effect of plant size on ash emission.

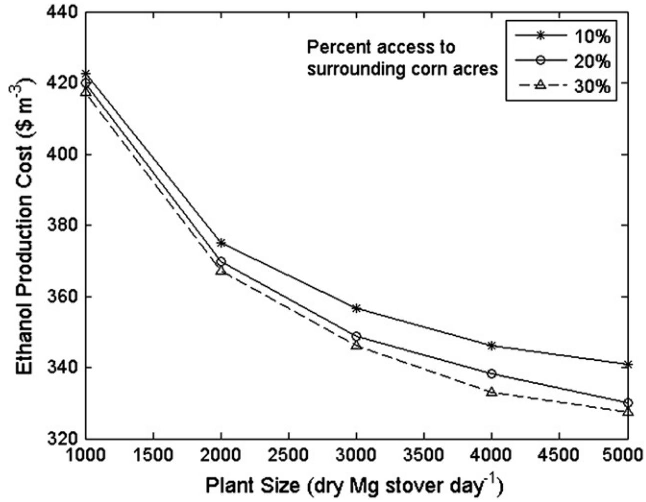

Fig. 14 – Effect of feedstock availability and plant size on ethanol production costs.

switchgrass in croplands and hybrid poplar, it is found that below the plant size of 3000 dry Mg day^{-1}, switchgrass in croplands has slight higher ethanol production cost than hybrid poplar, and between 3000 dry Mg day^{-1} and 4000 dry Mg day^{-1} both have very similar ethanol production costs, while over the plant size of 4000 dry Mg day^{-1} hybrid poplar has the highest ethanol production cost with similar reason as above.

3.2.4. *Effect of plant size on major waste effluents*

The effects of different plant sizes on the major waste effluents, i.e., gypsum, ash and total gas emission are shown in Figs. 11–13, respectively. As expected, the amount of gypsum, ash and the total gas emission increases linearly with the increase in plant size. Fig. 11 shows similar gypsum emissions for aspen wood, hybrid poplar, switchgrass and corn stover probably owing to assuming the same operating conditions. Fig. 12 shows the order of ash emissions: (high) switchgrass > corn stover > hybrid poplar > aspen wood (low). In addition, from Fig. 13, it is clear that the emissions of total gas (CO_2, CO, NO_2, SO_2 and CH_4) are in the sequence: (high) hybrid poplar > switchgrass > aspen wood > corn stover (low). The differences in emission of total gas are due to the different biomass compositions at the same operating conditions, similar to that described in Section 3.1.3. However, as seen in Fig. 8, owing to the differences in ethanol production (MM m^3 $year^{-1}$) among the various biomass species at a fixed feedstock rate, the overall waste streams as a function of ethanol production for various biomass species will be different.

3.2.5. *Effect of feedstock availability on ethanol production cost*

Feed stock availability is one of the important factors to be considered in any renewable resource based biorefinery. Considering corn stover as an example, as shown in Fig. 14, the ethanol production cost decreases with the

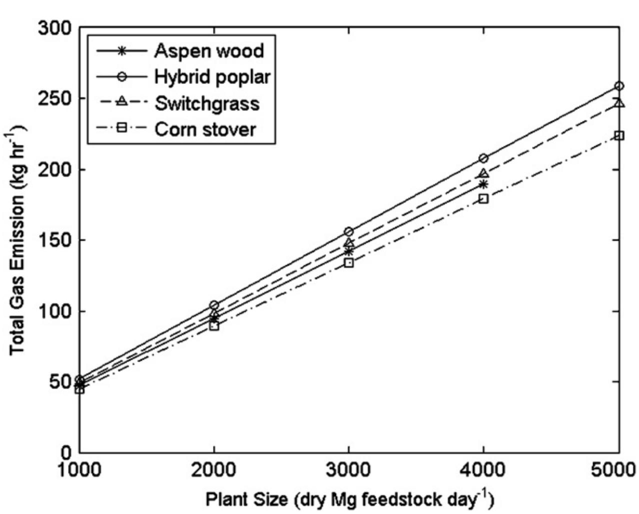

Fig. 13 – Effect of plant size on total gas (CO_2, CO, NO_2, SO_2, CH_4) emission.

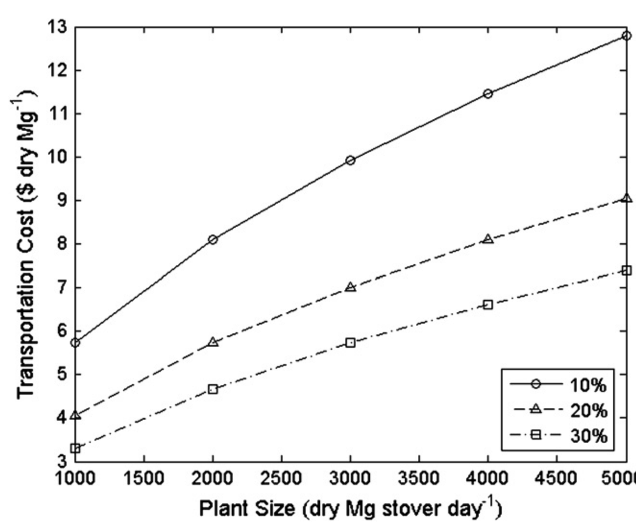

Fig. 15 – Transportation cost as a function of plant size and availability for corn stover.

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Table 6 – Effects of different biomass species on the total project investment, operating and ethanol yield (2000 dry Mg biomass day^{-1} basis)

	Corn stover	Switchgrass (croplands)	Switchgrass (grasslands)	HP (croplands)	Aspen wood
Estimated feedstock cost ($ dry Mg^{-1})	63.83	83.04	94.65	104.65	110.67
Total project investment (MM $)	202.2	212.1	212.1	203.3	187.0
Total operating costs (MM $ $year^{-1}$)	98.7	110.7	118.9	125.1	134.2
Total operating costs ($ m^{-3} ethanol)	375.7	458.1	492.2	485.8	411.6
Ethanol yield (m^3 dry Mg^{-1} feedstock)	0.375	0.345	0.345	0.368	0.465

increase in percent access to surrounding corn acreages (availability). It is interesting to note, however, that the ethanol production costs decrease faster as the crops availability was increased from 10% to 20%, and then decreases more slowly from 20% to 30%. The reason for this is that the transportation distance and hence the transportation cost decrease faster as the crops availability increases from 10% to 20%, and then decreases more slowly from 20% to 30% (Fig. 15). This can also be explained directly by Eq. (1), which shows that $R \propto (1/f_a)^{1/2}$ and the value of $(1/f_a)^{1/2}$ at $f_a = 10\%$, 20% and 30% are 3.16, 2.24 and 1.83, respectively. It appears from this study that it may be beneficial to increase the stover availability to at least 20% for optimum ethanol production cost and hence higher profitability and better economic performance.

3.3. *Comparison of four species in terms of total project investment, operating costs and ethanol yields*

Using the same feedstock rate of 2000 Mg day^{-1}, the total project investment, operating costs and ethanol yield of different biomass species are reported in Table 6. It is found that with aspen as feedstock the largest ethanol yield (m^3 dry Mg^{-1} feedstock) is obtained with the lowest total project investment. Corn stover requires the second lowest capital investment cost with the median ethanol yield.

3.4. *Overall comparison of the four biomass species*

On the basis of lowest cost of ethanol produced, corn stover can be considered as a biomass feedstock of choice. Aspen wood has the next lower cost of ethanol, and it has the largest ethanol yield, the lowest total investment, and the least water losses. However, in order for aspen to become the preferred choice of biomass feed stock, it will certainly depend on local availability and competition with other markets such as pulp and paper and forest products. This also suggests that it is very important to develop a modified species with high production yield and high holocellulose content possibly by genetic modification and hybridization. On the other hand, hybrid poplar and switchgrass as dedicated energy crops are not yet available in large quantities, but they are predicted to be very promising in the future because they have potentially much lower feedstock delivered costs. Considering the above and the fact that corn stover is very abundant in much of the corn-belt areas of the mid-west, corn stover is possibly a potential preferred feedstock for producing ethanol at the present time.

4. Conclusions

There are apparent effects of feedstock composition and feedstock costs on the overall lignocellulose to ethanol process efficiency and economics. Assuming representative average composition of each species, the effect of different biomass species in terms of their suitability as a feedstock for biofuels can be identified.

It is found that, based on the same feedstock rate of 2000 Mg day^{-1}, aspen wood can produce more ethanol than switchgrass, hybrid poplar and corn stover due to its higher content of combined cellulose and hemicellulose (holocellulose), and the ethanol production increases with holocellulose composition of various species. Given that variation in composition within species can be broad and that genetic selection or transformation can change composition, the ''species'' differences observed are only an indicator of the importance of composition, rather than a clear identifier of the ''best'' feedstock species for ethanol production. This is also dependent on optimizing the conversion process specific to each biomass species. In addition, the excess electricity generated for the various biomass species are in the following order: (low) aspen < corn stover < hybrid poplar/switchgrass (high), but the relationship between excess electricity generated and non-holocellulose combustible composition is nonlinear.

On the basis of lowest cost of ethanol produced, corn stover is the preferred biomass species to produce ethanol among the four species considered. Also the costs of hybrid poplar, switchgrass, and corn stover can be more variable than indicated depending on the geographic region, and handling and storage requirements. While the costs and effects on ethanol production are not conclusive based on this analysis, the results are sufficiently suggestive to indicate that all three feedstocks can be considered for cellulosic ethanol production. Given the current availability of corn stover and feed stock costs, it would naturally be the most logical immediate choice, with hybrid poplar and switchgrass being brought into the feedstock supply as the biorefinery industry develops.

Considering all of the waste streams, aspen wood shows the lowest amount of waste streams, switchgrass the highest, hybrid poplar and corn stover are in between. In addition, hybrid poplar has the same amount of gypsum as corn stover, and has smaller mount of ash but larger amount of CO_2/CO/NO_2/SO_2 than corn stover. The total water losses from the

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processes are in the rank: aspen wood < corn stover < hybrid poplar < switchgrass.

In summary, our result predicts that at the present time all biomass species can be used to produce cellulosic ethanol, however, at higher cost compared with gasoline based on equivalent energy content (for example, the ethanol production cost for corn stover is 375.7 $ m^{-3} ethanol, i.e., $563.6 per gasoline-equivalent cubic meter in comparison with the gasoline production cost of $208.7 per cubic meter in $2002 [10], noting that gallons of ethanol with the energy of 1 gal of gasoline is about 1.5). Corn stover shows the feasibility for the lowest cost and the lowest waste effluents than the other biomass species considered. While corn stover is a potential feedstock to produce ethanol with the lowest ethanol production cost among the species studied at the present time, hybrid poplar and switchgrass are the two promising future energy crops.

Unlike a petroleum refinery, the economies of scale or the effect of plant size on process efficiency and economic performance is a complicated function of biomass availability, growth rate, geographic area, etc. Hence, it is highly important to conduct a more thorough detailed economic and performance analysis considering all of the factors, as reported here.

Considering various aspects of biomass availability, crop density etc. and using a simplified method for estimating feed stock delivered costs to the biorefinery, the delivered costs of hybrid poplar, switchgrass and corn stover increase nonlinearly with the increase in plant size and can be ranked in the following order: aspen wood > hybrid poplar > switchgrass in croplands > switchgrass in grasslands > corn stover.

Both ethanol annual production and excess electricity generated increase linearly with the plant size, for various biomass species as follows: ethanol annual production: aspen wood > corn stover > hybrid poplar > switchgrass, and the excess electricity: (low) aspen wood < corn stover < switchgrass < hybrid poplar (high).

The ethanol production costs decrease with the increase in plant size because of the economies of scale. However, the rate of change in production costs as a function of plant size is nonlinear and is a function of the biomass species. For the four species, the relatively more suitable plant sizes, based on lower ethanol production costs, are found to be in the range of 2000–4000 dry Mg day^{-1}. It is also observed that the ethanol production costs are in the following order for the various species considered: (low) corn stover < aspen wood < switchgrass in grasslands < switchgrass in croplands or hybrid poplar (high).

The amount of gypsum, ash and the total gas (CO_2, CO, NO_2, SO_2 and CH_4) emissions increases linearly with the increase in plant size. The four species have similar amounts of gypsum emissions, but different ash emissions in the order: (high) switchgrass > corn stover > hybrid poplar > aspen wood (low), and different total gas emissions: hybrid poplar > switchgrass > aspen wood > corn stover.

Finally, as expected, ethanol production costs are dependent on the feedstock delivered price. However, this dependency is a unique function, characteristic of each of the biomass species. Feed stock availability is one of the important factors to be considered in any renewable resource based biorefinery. Ethanol production cost decreases with the increase in crops availability. It is interesting to note, however, that the ethanol production costs decrease faster as the crops availability was increased from 10% to 20%, and then decreases more slowly from 20% to 30%. This is because the transportation distance and hence the transportation cost decrease faster as the crops availability increase from 10% to 20%, and then decreases more slowly from 20% to 30%. It is shown from this study, for the first time, that it may be beneficial to increase the stover availability to at least 20% for optimum ethanol production cost and hence higher profitability and better economic performance.

Acknowledgments

This work was carried out with support from the University of Minnesota's Initiative on Renewable Energy and the Environment (IREE) (www.iree.umn.edu). We would like to thank NREL for their support and cooperation. We also thank Prof. Harlan Petersen, Department of Bioproducts and Biosystems Engineering and Mr. Keith Jacobson, Minnesota Department of Natural Resources for much of the information on wood feedstock and delivered hardwood chip price.

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Please cite this article in press as: Huang H-J et al., Effect of biomass species and plant size on cellulosic ethanol: A comparative process and economic analysis, Biomass and Bioenergy (2008), doi:10.1016/j.biombioe.2008.05.007