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Optimization and economic evaluation of industrial gas production and combined heat and power generation from gasification of corn stover and distillers grains

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ABSTRACT

Thermochemical gasification is one of the most promising technologies for converting biomass into power, fuels and chemicals. The objectives of this study were to maximize the net energy efficiency for biomass gasification, and to estimate the cost of producing industrial gas and combined heat and power (CHP) at a feedrate of 2000 kg/h. Aspen Plus-based model for gasification was combined with a CHP generation model, and optimized using corn stover and dried distillers grains with solubles (DDGS) as the biomass feedstocks. The cold gas efficiencies for gas production were 57% and 52%, respectively, for corn stover and DDGS. The selling price of gas was estimated to be \$11.49 and \$13.08/GJ, respectively, for corn stover and DDGS. For CHP generation, the electrical and net efficiencies were as high as 37% and 88%, respectively, for corn stover and 34% and 78%, respectively, for DDGS. The selling price of electricity was estimated to be \$0.1351 and \$0.1287/kW h for corn stover and DDGS, respectively. Overall, high net energy efficiencies for gas and CHP production from biomass gasification can be achieved with optimized processing conditions. However, the economical feasibility of these conversion processes will depend on the relative local prices of fossil fuels.

1. Introduction

Thermochemical gasification converts feedstock primarily into gas containing CO, H_2, CH_4, CO_2, and/or N_2 at high temperature and in presence of catalysts and oxidizing agents. Versatility, in terms of the feedstock, and many potential usages of products gases for producing energy and a wide range of chemicals and fuels provide enormous opportunities for biomass thermochemical gasification.

Combined heat and power (CHP) generation through biomass gasification is a direct route to extract energy from renewable resources efficiently. Use of biomass reduces the CO_2 emission as biomass production consumes CO_2 and completes the recycling of CO_2 in a shorter cycle. Since biomass is locally available, it can be used to produce heat and electricity in developing and underdeveloped countries where infrastructure for electricity is not available. However, for the rural applications of biomass gasification, the cost of production and technical expertise needed for operation must be reduced (Wu et al., 2002; Siemens, 2001; Abe et al., 2007). The use of biomass also promotes rural economies by creating new markets for these agricultural byproducts. In developed countries, it can reduce the consumption of fossil fuels for CHP generation. The byproducts from bioprocessing facilities such as rice husk, distillers grains and food processing wastes, can be used to displace the demands for electricity and natural gas. Since these byproducts are localized at the facilities, reduction in transportation cost may improve its financial attractiveness. At the same time, the use of byproducts for energy and fuel production will decrease the landfill requirements (Maniatis and Millich, 1998; Prasertsan et al., 2001; Bakos et al., 2008; Morey et al., 2006; Hussain et al., 2003; De Kam et al., 2007; Kinoshita et al., 1997).

Combustion and gasification are two processes for CHP generation from biomass. Combustion of biomass to produce heat and electricity is the most conventional and direct use of biomass for producing heat. Gasification of biomass and subsequent combustion to generate CHP has some advantages. First, the conversion of biomass to gas enables the removal of the nitrogen and sulfur containing compounds from the product gas which generate SO_x and NO_x during combustion. Hence, gasification can reduce

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harmful emissions. Second, a combined cycle with gas and steam turbines, for producing power from product gas, increases the net efficiency of the process as compared to using a steam turbine for combustion (Rentizelas et al., 2009; Faaij et al., 1997; Stiegel and Maxwell, 2001). Third, combustion of a gaseous fuel is easier to control and mix with the oxygen as compared to a solid fuel (e.g., biomass). However, additional operations for gasification increase the capital and operating costs of CHP generation by gasification as compared to direct combustion (Kinoshita et al., 1997). In this study, we have estimated the cost of producing units of heat and power, and gas from biomass.

Corn stover and distillers grains were used as the biomass feedstocks in our study. It is estimated that 204 Mt year^{-1} (dry basis) of corn stover is available annually in the US (Kadam and McMillan, 2003). Perlack et al. (2005) estimated that annually, 998 million dry tons of agricultural residue and 368 million dry tons of forestry residue are available in US. Dried distillers grains with solubles (DDGS) are the unfermented portion of the corn during conversion of corn to ethanol process. Since, distillers grains are the byproduct of the process, they are available at the site of the ethanol processing facility and can supply the heat and electricity needs of the plant, displacing the use of fossil fuels (Tiffany et al., 2007).

We developed and validated an Aspen Plus-based gasification model in our previous study. Here, the gasification model was integrated with a CHP generation model. Therefore, the objectives of this study were to simulate CHP generation from biomass (corn stover and DDGS) using our previously developed gasifier model, to optimize the operating conditions to obtain maximum energy efficiency, and to conduct an economic evaluation of the optimized process to determine the cost of production of product gas or CHP by biomass gasification.

2. Methods

Corn stover and DDGS were used a the biomass feedstocks. The properties of corn stover and DDGS were described in Kumar et al. (2008) and Wang et al. (2009), respectively. The moisture contents of the corn stover and distillers grains were 6.2% and 12.16%, respectively, on a wet basis.

2.1. Aspen Plus model

The Aspen Plus-based model for gasification was developed and validated previously at a biomass feedrate of approximately 1 kg/h. The model has been described in detail by Kumar et al. (2009b). The underlying assumption of this gasifier model was that tar and char yields are known. The gasifier was represented by a combination of two reactors (called DECOMP and G-REACTR) and a separator (called C-SEP), shown in Fig. 1. The purpose of the DECOMP rector was to breakdown the biomass into conventional compounds so the reaction, with oxidizing agents, could be simulated in a subsequent Gibbs reactor (G-REACTR). The input to the DECOMP reactor was only biomass. Knowing yields of tar, balancing the mass of each element and ash of biomass, and assuming a ratio of CO and CO_2, mass yields of DECOMP products were calculated. After separating known amount of char from the DECOMP products by a separator (called C-SEP), a heterogeneous reaction took place in a Gibbs reactor (called G-REACTR, shown in Fig. 1) to determine final product composition by minimization of the products' Gibbs free energy.

Yields of char and tar were assumed to be known. For corn stover, mass yields of H_2O, ash, carbon, H_2, NH_3, O_2, S, CO, CH_4, CO_2 and tar from the DECOMP reactor were provided as 0.05, 0.08, 0.16, 0.004, 0.009, 0, 0.003, 0.088, 0.168, 0.415 and 0.023 kg/kg corn stover, respectively. For DDGS, mass yields of H_2O, ash, carbon, H_2, NH_3, O_2, S, CO, CH_4, CO_2 and tar from the DECOMP reactor were provided as 0.1216, 0.051, 0.16, 0.012, 0.053, 0, 0.008, 0.073, 0.154, 0.345 and 0.022 kg/kg DDGS, respectively. These mass yields correspond to mass yields for the most efficient experimental conditions of biomass.

The components for CHP generation were added to the gasifier model and biomass feed rate was increased to 2000 kg/h. The main components added to the CHP model were a gas turbine, steam turbine, air compressor, combustor, boiler, and condenser. The parameters for gasifier and turbines (Table 1) are similar to the parameters described by Sudiro et al. (2008), Xinag and Wang (2008), Faaij et al. (1997), and Ståhl and Neergaard (1998).

Two scenarios were evaluated in this study. One scenario was to produce industrial gas from the biomass at optimum gasification conditions. The second scenario was to convert the product gas at the optimum gasification conditions to combined heat and power (CHP) with a combined cycle using gas and steam turbines.

For the first scenario, gasification temperature, equivalence ratio and steam to biomass ratio were varied from 700 to 850 °C, 0.05 to 0.25 °C, and 0 to 3.0 °C, respectively. The gasification model was optimized to achieve maximal energy efficiency by varying the previously described operating conditions. The total energy input to the system was the sum of the energy in the biomass, and energy needed to obtain air at 400 °C and steam at 400 °C at 1 atm. The total energy output from the system was the sum of the sensible and chemical energy contents of the product gas. For energy evaluations, heat losses for operations were assumed to be negligible because the objective was to evaluate maximal theoretical efficiency. Depending on the heat loss for specific equipment, the factor for heat loss needs to be incorporated for determining energy efficiency for a particular system. It should be noted that heat is required to breakdown biomass into gaseous compounds. In case of gasification, supplying a limited quantity of oxidizing agent generated heat from oxidation reactions which provided the heat for the endothermic reactions to take place.

For the second scenario, the product gas from the optimized gasification conditions was supplied to the CHP generation system (Fig. 1). The CHP system generated electricity using gas and steam turbines, and the residual sensible heat was recovered using a heat exchanger. The properties of gas and steam turbines are given in Table 1. The total energy input, in this scenario, was the sum of the energy contents of the biomass, air and steam and the energy supplied to the air compressor. The total energy output from the system was the sum of the electrical energy generated from the gas and steam turbines, and the sensible energy of the hot water produced by the condensing waste steam and by cooling the product gas.

The cold gas efficiency of this system was defined as the percentage of total energy input available in the form of chemical energy of the producer gas at standard temperature and pressure. The net gas efficiency was defined as the percentage of total energy input available in the form of chemical and heat energies of producer gas and electricity produced in case of CHP system.

2.2. Economical evaluation

The economics for producing either gas or combined heat and electricity were evaluated at a biomass feedrate of a 2000 kg/h. The economic evaluations were performed based on the empirical estimation of capital cost with an Excel-based software called CAPCOST version 2.0 from Turton et al. (2002). Chemical engineering plant cost index (CEPCI) of 525.4 for year 2007 was used for the estimation of capital costs (Anonymous, 2009).

The major equipment for gas production was a steam boiler, an air-heater, a cooler and a gasifier. The additional major equipments for the CHP generation system were an air compressor, two heat

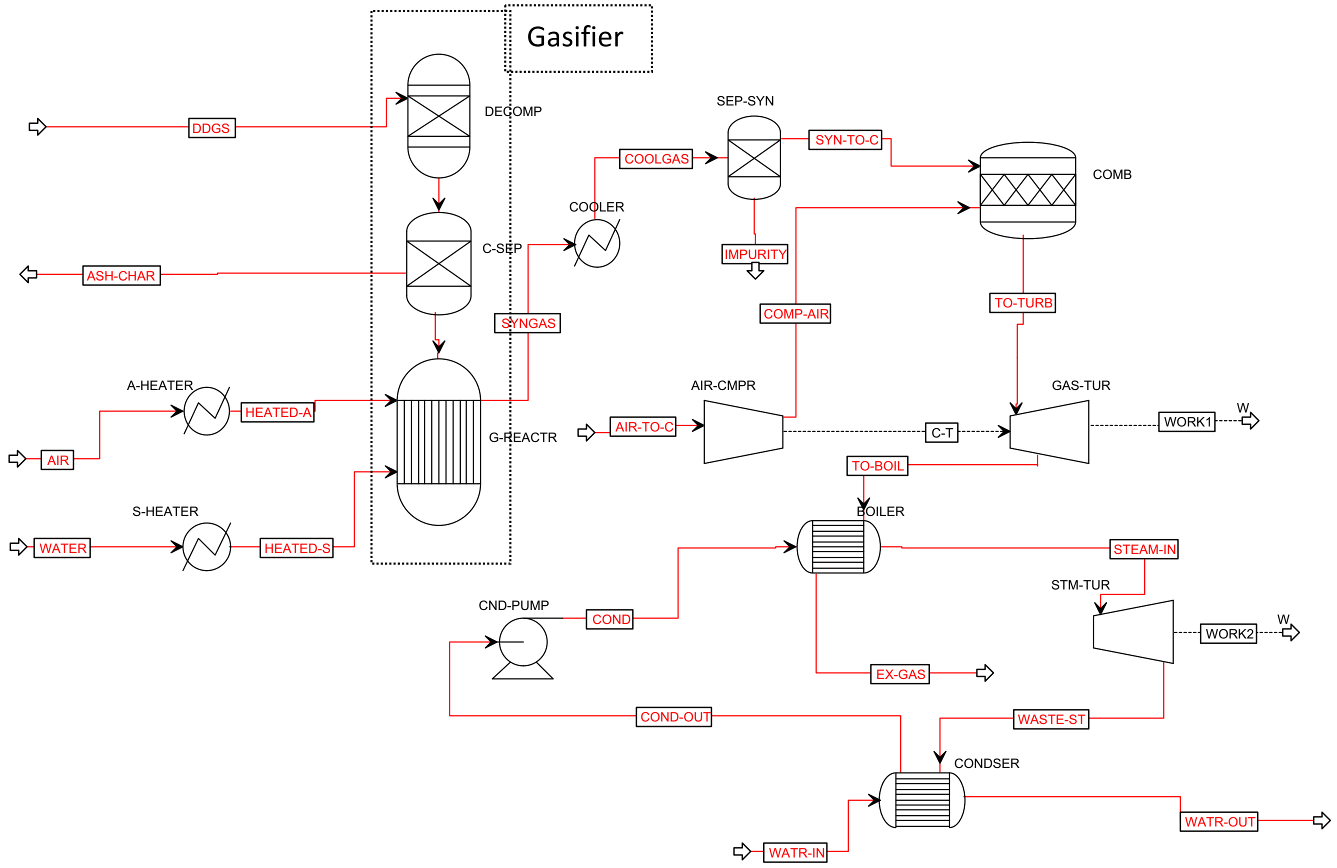

Fig. 1. Process flow diagram of CHP generation from biomass gasification.

Table 1
Parameters of the main equipments for CHP generation.

Equipment	Conditions
Gasifier	Atmospheric pressure, temperature – 850 °C, cold gas efficiency of 58% for corn stover and 52% for DDGS gasification
Gas turbine	Isentropic/mechanic efficiency – 92/99%, discharge pressure of 1.4 bar
Steam turbine	40 bar, 450 °C, isentropic/mechanic efficiency – 88/97.5%, discharge pressure 1.4 bar

exchangers, a gas turbine and a steam turbine. The grass root values of the capital costs were considered for this analysis. The grass root value was the cost associated with building the facility on essentially undeveloped land, which includes costs for contingency, fees and auxiliary facilities (Turton et al., 2002). A modified accelerated cost recovery system (MACRS) method for 7 years was applied for determining depreciation of equipment. Water and electricity, as utilities, were estimated to cost \$0.544/m^3 and \$0.12/kW h, respectively. The cost for water was adopted from Wei et al. (2008). The high temperature heat needed for producing hot air and superheated steam was assumed to cost \$7.5/GJ. Costs of corn stover (including the cost of delivering and grinding) and DDGS (including the cost of delivering), as raw materials, were estimated to be \$60.15/dry Mg (Sokhansanj and Turhollow, 2004), and \$132/Mg with 10% moisture, wet basis (National Weekly Ethanol Summary, 2009), respectively.

The periods for construction and operation were assumed to be 1 and 15 years, respectively. The plant was assumed to operate 350 days per year. Rate of taxation and interest were set as 42% and 6%, respectively. The cost of land and operating labor were assumed to cost \$150,000 and \$250,000 each, for the productions of gas and CHP, respectively. Working capital was assumed to be 15% of the total grass root value. The salvage value was assumed to be 10% of the capital cost. Since the cost of the main product (electricity or gas) was to be evaluated in this study, the revenue from process heat was assumed to be \$6/GJ, which is comparable to the price of natural gas.

Three criteria were satisfied to determine the selling price of a unit of electricity or gas. The net present value of the project should be close to or above zero; the payback period should be less than the project life (15 years); and the rate of return should be equal to or higher than the interest rate (6%). For estimating capital costs on per unit basis, the total capital cost was divided by the units of power produced.

3. Results and discussion

The technical and economical assessments of producing either industrial gas or CHP were performed in the following sequence. The operating conditions of the gasification were optimized using our previously developed model to achieve maximal energy efficiency. The economical evaluation was performed subsequently on the optimized model condition to estimate the cost of producing a unit amount of product gas. The CHP generation system was then added to the gasification model. The operating conditions of turbines were varied to obtain maximal electric power from the integrated model. The economical analyses were performed on the optimized and integrated model to estimate the cost of producing a unit amount of electricity.

Table 2
Operating conditions and energy balance for the corn stover gasification.

Condition #	Air (kg/kg biomass)	Steam (kg/kg biomass)	QAir* (kW)	QSteam* (kW)	QCooler* (kW)	Qgas* (kW)
1	0.64	0.00	136	0	1080	7578
2	0.64	0.74	136	1367	2601	7337
3	0.64	1.04	136	1935	3285	7284
4	0.64	1.47	136	2734	4270	7231
5	1.27	0.00	272	0	1489	6240
6	1.27	0.74	272	1367	3055	6030
7	1.27	1.04	272	1935	3748	5986
8	1.27	1.47	272	2734	4742	5942

QAir* and QSteam* are energy required to generate air, and steam at 400 °C, respectively.
QCooler* and Qgas* are energy available in the product gas as sensible and chemical energy, respectively.

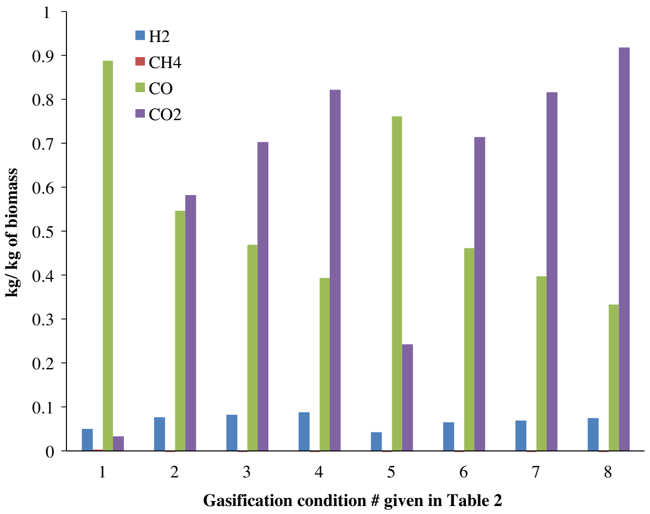

Fig. 2. Energy conversion efficiency with varying flowrates of air and steam at 850 °C for corn stover gasification.

3.1. Optimization of operating condition for maximal energy efficiency

It was observed that with increasing the temperature of the gasifier from 700 to 850 °C, the net energy efficiency increased from 81% to 86% for corn stover and 77% to 82% for DDGS, when heat loss were not accounted for. Hence, the gasifier temperature of 850 °C was selected for further technical and economical analyses. However, it should be mentioned that the model assumed that the gasification reactor maintained a constant temperature of 850 °C. The variable temperature along gasifier may affect the composition of the product gas (Kumar et al., 2009a). Ståhl et al. (2004) reported that, at the scale of 6 MW_e, combustion of char was able to maintain the temperature of biomass gasifier. The air flowrate also may affect gasification temperature. The air and steam flow rates affected the gas composition and overall energy efficiency (Table 2 and Fig. 2, and Kumar et al., 2009a). The desired gas composition will vary depending on the utilization of the product gas. So, the corresponding optimized gasification condition is dependent on how the product gas is utilized. For example, for corn stover gasification, CO was maximal for condition #1 with zero steam flow and an equivalence ratio (ER) of 0.056 (air flow of 0.64 kg/kg corn stover). Hydrogen yield increased with increasing steam to biomass ratio. Net energy efficiency was maximal (cold gas efficiency of 58%) at condition #4. With an assumption of 5% heat loss from process heat, the net energy efficiency for gas production was 90%. In this study, since the objective of this study was to perform economic evaluation at the maximal net energy efficiency, condition #4 was selected as the optimum gasification conditions with an ER of 0.11 and steam to biomass ratio of 1.47 kg/kg for corn stover. For DDGS, the net energy efficiency reached 94.2% at the ER and steam to biomass ratio of 0.073 and 2.95, respectively. The net efficiency of this system was comparable to the 83% net efficiency reported at the scale of 6 MW_e by Ståhl et al. (2004), 81% net efficiency by Rentizelas et al. (2009), 93% fuel to gas efficiency at the scale of 75 kW input by Ahrenfeldt et al. (2006). The optimum operating conditions will change with incorporating factors for heat losses for particular system. For CHP generation from corn stover, optimum flowrates of air to compressor and steam to steam turbine were 7676 kg/h and 7580 kg/h, respectively, with a total electricity generation of 4.6 kW from both turbines. For CHP generation from DDGS, optimum flowrates of air to compressor and steam to steam turbine were 7944 kg/h and 10,810 kg/h, respectively, with a total electricity generation of 6.38 kW from both turbines.

3.2. Energy balance at the optimized condition

Since it was assumed that partial combustion of the biomass would maintain the gasification temperature, the energy flow during the gasification reactions was not taken into consideration for energy balance. As expected, with increasing air and steam flowrates, the energy required by the heaters and boilers increased. However, for corn stover gasification, supplying steam up to 1.47 kg steam/kg biomass also resulted in increased total energy content of the product gas. The sensible heat of the product gas ranged from 11% to 40% of the total energy content in product gas (Table 2). Hence, to maximize the net energy efficiency, the sensible heat of the product gas must be recovered effectively. For gas production at the optimized conditions, the energy input to the system from biomass, hot air and superheated steam were 77%, 1.1%, and 21.9%, respectively, of total energy input. The sensible and chemical energy contents of the product gas were 36% and 64% of the total energy of the product gas, respectively (Table 2). For DDGS gasification, supplying steam of 2.95 kg/kg of biomass resulted in increased net efficiency. The optimum steam to biomass ratio will change if the sensible heat from unreacted steam cannot be recovered. At the optimum condition of gas production, 44.7% of total output energy was available as sensible energy of product gas. The energy supplied by the hot air, superheated steam and biomass were 0.65%, 29% and 70% of total energy input, respectively.

For CHP production, additional energy was required by the air compressor. Since the compressor was driven by the gas turbine, the energy required by the compressor was subtracted from the electrical energy of the gas turbine. For corn stover gasification, the gas and steam turbines generated electrical power of 3.27 and 1.36 kW at the optimum conditions. The total process heat from condensate and cooling of product gas was 6.12 kW. The electrical and thermal efficiencies of the system were 37% and 49%, respectively. For DDGS gasification, gas and steam turbines generated 4.4 and 1.9 kW of electricity. In this case, the electrical and

Table 3
Economical results for gas production and CHP generation from corn stover and DDGS gasification.

Item	Gas production from corn stover	CHP generation from corn stover	Gas production from DDGS	CHP generation from DDGS
Fixed capital investment ($)	3,170,000	12,400,000	3,170,000	12,400,000
Cost of land ($)	150,000	250,000	150,000	250,000
Cost of Labor ($/year)	150,000	250,000	150,000	250,000
Cost of utility ($/year)	664,355	664,355	1,298,860	1,298,860
Cost of raw material ($/year)	889,089	889,089	1,901,160	1,901,160
Selling price for heat ($/GJ)	6	6	6	6
Revenue from heat ($)	774,749	1,168,474	1,429,566	1,513,210
Revenue from gas or electricity ($)	2,512,431	5,249,770	3,854,530	6,897,290
Selling price for gas ($/GJ)	11.49		13.08	
Selling price for electricity ($/kW h)		0.1351		0.1287

thermal efficiencies were 34% and 44%, respectively. The results were similar to the 35.4–40.3% electrical efficiency reported by Faaij et al. (1997), 32% electrical efficiency reported by Ståhl et al. (2004), and 35–40% electrical efficiency reported by Craig and Mann (1996).

3.3. Economical analysis of the optimized conditions

With the optimized conditions, the product gas flowrate was 72.3 N m^3/s with energy content (HHV) of 6.00 MJ/Nm^3 for corn stover. For DDGS, product gas flow rate was 64.4 N m^3/s with an energy content of 8.78 MJ/Nm^3. The energy content of the product gas from DDGS gasification was higher because of the higher energy content in the DDGS as compared to the corn stover. Since the product gas can be used as chemical feedstocks to produce valuable fuels and chemicals such as hydrogen, ammonia, methanol, the price of product at the commercial scale are dependent on the composition of the product gas. However, additional process operations are needed to provide the acceptable gas composition for use as chemical feedstocks. For simplicity, we estimated the selling price of the product gas based on its energy content rather than its composition.

For gas production, the total grass root capital cost for gas production for both feedstocks was estimated to be $3.17 million (Table 3). For corn stover, with a selling price of product gas was $11.49/GJ with a discounted payback period and rate of return of 12.9 years and 6%, respectively. For DDGS, the selling price of product gas was $13.08/GJ with a discounted payback period and rate of return of 12.9 years and 6%, respectively. Seventy-six and seventy-three percent of total revenues were generated from product gas for corn stover and DDGS, respectively. The selling price of gas was higher from DDGS as compared to corn stover gasification. At the scale of 60 N m^3 h^{-1}, Wei et al. (2008) estimated the cost of producing syngas to be $0.009 MJ^{-1}. Their estimation was based on the cost of wood feedstock at $25/ton.

For CHP generation, the total grass root capital cost was estimated to be $12.4 million for both feedstocks. The capital cost for the part of CHP generation, such as turbines and boiler, was approximately three times more than the capital costs for gasification only. The revenue, in this scenario, was generated from the electricity and process heat. For corn stover, the cost of electricity (coE) was $0.1351/kW h with discounted rate of return at 6% and payback period of 12.7 years. For DDGS, the coE was estimated to be $0.1287/kW h with discounted rate of return at 6% and payback period of 12.7 years. Eighty-two percent of the total revenue generated was from electricity for both feedstocks. The coE for DDGS gasification was lower than that of corn stover gasification. The per unit capital costs were $2681 and $1944/kW for corn stover and DDGS, respectively.

Although the capital cost for CHP generation was much higher than that of gas production only, the revenue was proportionally higher due to the revenue generated from cost of electricity (Rentizelas et al., 2009). These estimates for coE were closer to the estimates reported in the literature. Brammer and Bridgwater (2002) reported that the coE for the optimum condition was 8.67 Euro c/kW h with feedrate of 2 dt/h at a cost of 30 Euro/dt. They concluded that drying should be done as far as possible before gasifier, to increase the net energy efficiency and decrease the coE. Kinoshita et al. (1997) reported the capital cost estimate to be from 1400 to 2750 $/kW for smaller scale biomass combined heat and power generation systems (less than 20 MW). However, at a scale of more than 50 MW, Craig and Mann (1996) estimated the capital cost and coE to be 1108–1696 $/kW h and 0.066–0.082 $/kW h, respectively. They also observed that with increase in scale, the capital cost for the CHP generation lowers. However, biomass based gasification system is unlikely to be of such large scale because biomass generally is not available at one centralized location. The comparatively lower capital cost of 1200 $/kW, reported by Wu et al. (2008) at a scale of 5.5 MW_e, may be because of the use of gas engines as compares the turbines.

The gasification and CHP generation equipment may need to be modified as the particle and energy densities of the biomass and biomass generated gas are lower than those of fossil resources such as coal and natural gas. Hence, the estimated capital cost may change accordingly. Ståhl et al. (2004) observed that after some modification, a gas turbine was suitable for generating electricity from the low energy content product gas (up to 3.9 MJ/Nm^3) from biomass gasifier. The energy contents of the product gases, at our optimum conditions, were 5.86 and 8.78 MJ/Nm^3 for corn stover and DDGS, respectively. This energy content was similar to the 5.8 MJ/Nm^3 obtained from dry wood chips by Kramreiter et al. (2008). The production of valuable chemicals from product gas may be more economically attractive than CHP generation. Currently syngas (a mixture of CO, CO_2 and H_2) is produced from natural gas using an energy-intensive steam reforming process. The syngas is then used as a feedstock to produce chemicals such as hydrogen, ammonia and methanol. Hence, based on energy efficiency and economics, product gas from biomass gasifier may be more competitive with syngas to produce fuels and chemicals than with natural gas for CHP generation.

4. Conclusions

An Aspen Plus-based model of gasification was optimized to obtain maximum energy efficiency by varying gasification temperature and flowrates of air and steam. Higher temperature increased the efficiency. Assuming that the gasification temperature was maintained at 850 °C by the air supplied, maximal net energy efficiency was 92% and 94% when no heat loss was considered for corn stover and DDGS, respectively. The economical evaluation of optimum model revealed that the minimum selling price of gasifier product gas was $11.49 and $13.08/GJ, for corn stover and

DDGS as the biomass feedstocks, respectively. The cost of electricity (selling price) for the combined heat and power generation was estimated to be $0.1351 and $0.1287/kW h from corn stover and DDGS, respectively. However, these estimates may vary because some equipment may need to be customized for lower mass and energy density of biomass feedstock as well as low energy density of product gas compared to commercially available equipments for CHP generation from coal and natural gas.

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