BIOMASS FOR ELECTRICITY AND PROCESS HEAT AT ETHANOL PLANTS

R. V. Morey, D. G. Tiffany, D. L. Hatfield

ABSTRACT. *Biomass can provide electricity and process heat at dry-grind ethanol plants to both reduce costs and improve the net energy value of ethanol production. Distillers dried grains with solubles (DDGS), which are coproducts of ethanol production, can potentially be used for energy. Corn stover is another potential biomass energy source for ethanol plants. Biomass (DDGS and corn stover) alternatives to provide process heat and electricity at corn dry mill ethanol plants are evaluated. Corn dry grind ethanol production using biomass (DDGS or corn stover) to meet process energy needs and generate electricity achieves net energy values in the range of 20 to 30 MJ/L (72,000 to 108,000 Btu/gal) of ethanol, which equals or exceeds previous estimates for biomass ethanol production. There are significant annual energy cost savings/returns for a 150 million L (40 million gal) per year plant capacity over a range of natural gas and biomass prices to apply to additional capital and operating costs required for a biomass energy system. Electricity generation is potentially an important contributor to the annual energy cost savings/returns because of the ability to effectively use waste heat from electricity generation to meet process energy needs. Important next steps are to evaluate capital and operating costs of biomass combustion/gasification, emission control, biomass fuel handling, and electricity generation technologies to determine overall economic feasibility.*

Keywords. *Biomass, Process heat, Ethanol production, Electricity, Combined heat and power.*

Energy, particularly natural gas for process heat, is one of the major costs in operating an ethanol plant. Although the energy balance for producing ethanol is positive, ethanol conversion (distillation, evaporation, drying) at either dry mill or wet mill plants requires the largest amount of energy in the overall process (Shapouri et al., 2002). Under current technology for ethanol conversion, the process heat is usually supplied by natural gas and the electricity is generated with coal or natural gas. Substituting biomass sources for the electricity and process heat has the potential to significantly improve the renewable energy balance for ethanol production.

Distillers dried grains with solubles (DDGS) are coproducts of the dry-grind ethanol production process and are normally sold for livestock feed. Expanded ethanol production has increased the supply of DDGS, which has in turn, reduced the price. At the same time, natural gas prices have increased resulting in a situation where DDGS may be more valuable as a fuel to replace natural gas than as a feed. Concentrated wet stillage or "syrup" is already being converted to meet process energy needs in a fluidized-bed combustor in at least one dry-grind ethanol plant.

Corn stover is another potential biomass energy source for ethanol plants. Corn stover is available in the vicinity of most ethanol plants. Also, many ethanol plants are owned by farmers who produce the corn and corn stover; therefore, the process of procuring the material is potentially simplified if collection, storage, and transportation issues can be solved.

Several researchers have evaluated the net energy value for producing ethanol from corn and biomass (table 1). Net energy value is the sum of all energy outputs including energy in the ethanol plus credits for coproducts (DDGS) and, if applicable, electricity delivered to the grid minus all fossil energy inputs. Shapouri et al. (2002) found a positive energy balance for ethanol production from corn for both wet mill and dry mill plants. They reported an energy ratio (energy out versus energy in) of 1.30 for wet mill plants and 1.37 for dry mill plants, or a weighted average of 1.34. Shapouri et al. (2003 and 2004) updated their results using improved data and methodology, resulting in revised energy ratios of 1.77 and 1.57 for dry and wet mills, respectively. The major factors contributing to an improved energy balance were increased corn yields and a new approach to estimating coproduct energy credits. Kim and Dale (2005) evaluated nonrenewable energy consumption in production of ethanol derived from corn and found a positive energy balance over a range of conditions.

A few studies have reported negative energy values for corn ethanol production; however, Farrell et al. (2006) reviewed six corn ethanol studies, including two that reported negative energy balances (Patzek, 2004; Pimentel and Patzek, 2005). Farrell et al. (2006) concluded that the two studies reporting negative energy balances stood apart from other studies because they incorrectly assumed that ethanol coproducts should not be credited with any of the input energy and included some input data that were old and unrepresentative of current processes. Farrell et al. (2006)

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Table 1. Summary of net energy value and energy ratio for several ethanol processes.

Source	Material/Process	Net Energy Value[a], MJ/L (Btu/gal)	Energy Ratio[b]
Shapouri et al. (2002)	Corn wet mill ethanol	5.37 (19,262) HHV[c]	1.30
	Corn dry mill ethanol	6.31 (22,629) HHV	1.37
	Corn wet/dry ethanol	5.88 (21,105) HHV	1.34
Shapouri et al. (2003)	Corn wet mill ethanol	7.54 (27,054) HHV	1.48
	Corn dry mill ethanol	8.47 (30,391) HHV	1.57
	Corn wet/dry ethanol	8.09 (29,028) HHV	1.53
Shapouri et al. (2004)	Corn wet mill ethanol	7.73 (27,729) LHV	1.57
	Corn dry mill ethanol	9.25 (33,196) LHV	1.77
	Corn wet/dry ethanol	8.51 (30,528) LHV	1.67
Kim and Dale (2005)	Corn ethanol (several scenarios)	3.64 (13,060) LHV to 10.1 (39,100) LHV	
Farrell et al. (2006)	Corn ethanol today	4.5 (16,500) LHV	
	Cellulosic ethanol	23 (84,340) LHV	
Wang et al. (1999)	Corn wet mill ethanol	7.44 (26,700) LHV	
	Corn dry mill ethanol	6.80 (24,400) LHV	
	Herbaceous biomass ethanol	17.6 (63,300) LHV	
	Woody biomass ethanol	20.7 (74,400) LHV	
Sheehan et al. (2004)	Corn ethanol	4.9 (17,580) LHV	1.27
	Corn stover ethanol	17.6 (63,150) LHV	4.39

[a] Net energy value is the sum of all energy outputs including energy in the ethanol plus credits for coproducts (DDGS) and, if applicable, electricity delivered to the grid minus all fossil energy inputs.

[b] Ratio of energy outputs to energy inputs.

[c] HHV – higher heating value; LHV – lower heating value.

used a model to apply consistent conditions to each of the six studies for comparison. They used their model to estimate a net energy value for "corn ethanol today" of 4.5 MJ/L (table 1).

Wang et al. (1999) and Sheehan et al. (2004) evaluated ethanol production from corn as well as biomass sources (table 1). Their net energy values for corn ethanol production were within the range (4 to 10 MJ/L of ethanol) found by most researchers. The net energy values they found for biomass (corn stover, other herbaceous biomass, woody biomass) ethanol production were 17 to 21 MJ/L. Farrell et al. (2006) estimated a net energy value of 23 MJ/L for "cellulosic ethanol" (table 1). Several factors contribute to the higher net energy values for biomass (cellulosic) ethanol. Less fertilizer is required to produce biomass than corn grain, or in the case of corn stover most of the energy in the fertilizer was assigned to the grain rather than the stover, leading to higher net energy values for biomass ethanol production. Perhaps more importantly, process energy, and in some cases electricity generation, were assumed to be provided by the residue from the biomass ethanol process. Use of renewable energy in the conversion process significantly increases the net energy value for biomass ethanol.

McAloon et al. (2000) compared costs of producing ethanol from corn starch and lignocellulosic feedstocks. They found the cost of ethanol from lignocellulosic processes to be about 70% higher than from starch-based processes, with depreciation of capital the largest contributor to cost for lignocellulose processes and corn the largest contributor to cost for starch processes. Wallace et al. (2005) studied the feasibility of co-locating and integrating ethanol production plants from corn starch and lignocellulosic feedstocks. They found potential savings for some co-location scenarios compared to a stand-alone corn stover to ethanol process. Tiffany and Eidman (2003) evaluated factors associated with the success of corn-based ethanol production. Major factors affecting net return were price of ethanol, price of coproduct (DDGS), cost of feedstock (corn), and cost of natural gas.

OBJECTIVES

The objectives of this article are to: 1) evaluate the net energy value for ethanol derived from corn when biomass (DDGS or corn stover) is used to generate electricity and provide process heat, and 2) calculate potential energy cost savings or returns (excluding increased capital and labor costs) that could be applied to technology to utilize biomass sources for process heat and electricity.

METHODOLOGY

We will evaluate four options or alternatives for the conversion process.

- Current technology – natural gas for process heat and electricity from coal or natural gas.
- Biomass (DDGS, corn stover, or combination) to provide process heat (PH) only by combustion or gasification.
- Biomass (DDGS, corn stover, or combination) to provide process heat and plant electricity (CHP) – waste heat from electric generation at temperatures sufficient to produce process steam.
- Biomass (DDGS, corn stover, or combination) to provide process heat, plant electricity, and electricity to grid (CHPG) – amount based on using all waste heat for process steam.

The technical assumptions or values for the analysis are summarized in table 2. Net energy value is the sum of all energy outputs minus all energy inputs. The important elements are described in the equation:

$$\text{Net energy value} = \text{energy in ethanol} + \text{coproduct energy} + \text{electricity to grid energy} - \text{fossil energy input}$$

In the case of conventional corn-based ethanol production, outputs include the energy in the ethanol and the coproduct (DDGS) energy credit. There is no electricity to the grid energy. The energy inputs are energy for production and conversion, all assumed to be from fossil sources. Shapouri et al. (2004) summarize these estimates and they are presented in table 2.

For alternatives involving biomass to provide process heat and electricity for the plant, the energy in the ethanol remains the same. If a portion of the coproduct (DDGS) is used to provide the input energy, the coproduct energy output is reduced accordingly. If corn stover is used to provide energy input, the coproduct energy credit for DDGS remains in the energy balance.

The fossil energy inputs are reduced if biomass energy is used for conversion processes at the plant. If only process heat is generated from biomass, the fossil contribution for process heat (table 2), but not electricity is removed from the fossil energy input. If both process heat and electricity are generated, both fossil contributions (table 2) are removed from the input. The energy for production of corn always remains in the fossil energy input. When corn stover is used as the energy source, a small amount of additional energy (table 2) for harvest, transport, and fertilizer replacement is added to the fossil energy input. Most of the energy in the fertilizer has already been attributed to the corn production.

The amount of biomass (DDGS or corn stover) required to meet process energy needs is based on the heating value (LHV) for the corresponding material (table 2). Biomass energy required to generate electricity is based on a generation efficiency defined in terms of lower heating value. The amount of biomass thermal energy required to generate electricity is estimated using a generation efficiency of 10% to meet plant needs, and 20% or 30% for applications where electricity is also delivered to the grid. Biomass steam-electric plants may operate in the range of 20% efficiency, while biomass integrated-gasification combined-cycle (BIGCC) plants have the potential to operate at generation efficiencies in the range of 30% (Williams and Larson, 1996; Larson and Williams; 2001). Results are presented at both generation efficiencies to provide an indication of the potential range for electricity production in this application.

When electricity is generated for the grid, energy output (electricity to grid energy) is added to the net energy value in an amount equivalent to the fossil energy (thermal) that would have been required to generate the electricity replaced. An electricity generation efficiency of 35% based on lower heating value is used to estimate the equivalent fossil thermal energy replaced (table 2).

Shapouri et al. (2002, 2003, 2004) also defined a net energy ratio. The numerator was the energy in the ethanol and the denominator was the energy input (fossil) minus the co-product energy credit. Farrell et al. (2006) summarize the problems in using net energy ratio for comparing alternatives especially when renewable biomass energy is used to replace process energy inputs and to generate electricity. If energy credits, either for coproducts or electricity generation, are subtracted from fossil energy input in the denominator, the denominator can approach zero and eventually become negative, which is meaningless. To address that issue, we defined the energy ratio for our comparisons as shown below.

Table 2. Technical assumptions for corn dry-mill ethanol production using biomass energy.

Quantity	Value	Source/Comments
Ethanol yield per unit of corn	0.41L/kg (2.75 gal/ bushel)	Current technology
Co-product (DDGS) amount per unit of corn	0.313 kg/kg (17.5 lb/bushel)	Current technology
Energy (LHV[a]) in ethanol	21.3 MJ/L (76,330 Btu/gal)	Shapouri et al. (2004)
Energy (LHV) for corn production	6.27 MJ/L (22,500 Btu/gal)	Shapouri et al. (2004)
Co-product energy (LHV) credit – dry mill	7.38 MJ/L (26,482 Btu/gal)	Shapouri et al. (2004)
Total energy (LHV) for ethanol conversion – dry mill (current)	13.1 MJ/L (47,116 Btu/gal)	Shapouri et al. (2004)
Process heat (LHV) for ethanol conversion – dry mill; (distillation, evaporation, drying)	9.67 MJ/L (34,700 Btu/gal)	Shapouri et al. (2004)
Electricity for ethanol conversion – dry mill	3.43 MJ/L (12,416 Btu/gal) 0.288 kWh/L (1.09 kWh/gal)	Shapouri et al. (2004)
DDGS heat content (LHV) per unit of dry matter	20.9 MJ/kg (8978 Btu/lb)	Estimated from higher heating value data in AURI (2005)
DDGS moisture content	13% wet basis	
Corn stover heat content (LHV) per unit of dry matter	16.5 MJ/kg (7078 Btu/lb)	Morey and Thimsen (1981) Pordesimo et al. (2005)
Corn stover moisture content	13% wet basis	
Fossil energy (LHV) to produce and process corn stover	0.82 MJ/kg (354 Btu/lb)	Assumed at 5% of heat content
On-site electricity generation efficiency	10%, 20%, or 30% defined on a lower heating value basis	Discharge temperature high enough to meet process needs
Grid electricity generation & distribution efficiency	35% defined on a lower heating value basis	Used for calculating fossil energy replaced for electricity supplied to grid

[a] LHV – lower heating value.

$$\text{Renewable energy ratio} = \\ (\text{energy in ethanol} + \text{coproduct energy} \\ + \text{electricity to grid energy}) \div \text{fossil energy input}$$

The coproduct energy credit is included in the numerator as a positive term and, if applicable, the energy credit associated with generating electricity for the grid is also included as a positive term in the numerator. The denominator contains only fossil energy inputs. With this definition all of the outputs in the numerator are considered renewable, while all of the inputs in the denominator represent fossil sources. Thus, the renewable energy ratio represents the units of renewable energy output for each unit of fossil energy input. Shapouri (2004) calculated an energy ratio of 1.77 for dry mill ethanol production. Our revised definition yields a renewable energy ratio of 1.48 for the same conditions.

RESULTS

The amount of biomass required, net energy values, and renewable energy ratio for five alternatives are compared in table 3. Less DDGS per unit of corn processed (or ethanol produced) are required than corn stover at each technology level because the heating value for DDGS is greater than for corn stover. The net energy values and renewable energy ratios are somewhat higher for corn stover because the DDGS are used as livestock feed so the coproduct energy credit applies. For both biomass materials, net energy values increase as increasing amounts of the material are used in the technology alternatives. Electrical generation efficiency has a significant impact on electricity produced per unit of ethanol produced; and therefore on the potential increase in net energy values. Even at 20% generation efficiency, net energy values are in the range of those reported by Wang et al. (1999) for biomass ethanol, Sheehan et al. (2004) for corn stover ethanol, or Farrell et al. (2006) for cellulosic ethanol.

The percent of available DDGS required for the four biomass technology alternatives is 70, 77, 87, and 100, respectively. The ratio of corn stover to corn required for the four biomass technology alternatives is 0.28, 0.31, 0.35, and 0.39 kg/kg, respectively. Since the mass of above ground residue (corn stover) per unit area is approximately equal to the mass of the grain (corn), this ratio corresponds to the portion of corn stover that would need to be removed per unit area. Sheehan et al. (2004) estimated for Iowa conditions that approximately 40% of the residue could be removed for continuous corn using mulch till compared to 70% removal for no-till production methods. Thus, these removal rates appear to be within sustainable levels.

Application of biomass to produce process heat and electricity could include a mix of DDGS and corn stover. Also, processes to improve ethanol yield, plant efficiency, and capture other value-added products from the material that remains are currently being developed. They involve removing products such as fiber and germ in advance of enzymatic processing and fermentation. These processes are expected to reduce the value of the residue (modified DDGS) as feed, but the energy contained in this material will still be available for electricity generation and process heat. It may be necessary to supplement this residue with corn stover to have enough material (total energy content) to achieve the full electricity generating capacity of the ethanol plant. Mixtures of DDGS or modified DDGS and corn stover should provide net energy values and renewable energy ratios between the estimates for using 100% of either of the materials.

While the biomass technology alternatives provide significant improvements in net energy values for corn dry mill ethanol production, the key question is under what conditions would they be economically feasible. All of the alternatives involve substitution of solid fuel handling and combustion or gasification equipment for natural gas technology, which is well established and much simpler to implement; therefore less costly. In addition, alternatives involving combined heat and power require electricity generation capacity, which involves additional capital and management costs.

We calculated the potential annual energy cost savings/returns (excluding increased capital and labor costs) for the biomass technology alternatives for a 150 million L (40 million gal) per year plant (a typical nominal size) for a range of natural gas, biomass (DDGS or corn stover), and electricity

Table 3. The amount of biomass required, net energy values, and renewable energy ratios for five alternatives.

		100% DDGS			100% Corn Stover		
Technology	Elect. Energy Prod. kW_eh/L (kW_eh/gal)	Amount[a] kg/kg (lb/bu)	Net Energy Value[b] MJ/L (Btu/gal)	Energy Ratio[c]	Amount[d] kg/kg (lb/bu)	Net Energy Value[b] MJ/L (Btu/gal)	Energy Ratio[c]
Current – Natural gas & coal	0	0	9.25 (33,196)	1.48	0	9.25 (33,196)	1.48
Biomass – Process heat only (PH)	0	0.22 (12.2)	13.8 (49,408)	2.42	0.28 (15.5)	18.4 (65,902)	2.79
Biomass – CHP–10%[e]	0.29 (1.09)	0.24 (13.5)	16.7 (59,841)	3.66	0.31 (17.2)	21.8 (78,104)	4.16
Biomass – CHPG–20%[f]	0.67 (2.54)	0.27 (15.3)	19.9 (71,358)	4.17	0.35 (19.4)	25.6 (91,976)	4.68
Biomass – CHPG–30%[g]	1.15 (4.36)	0.31 (17.5)	23.9 (85,761)	4.81	0.39 (22.1)	30.5 (109,324)	5.31

[a] Amount of DDGS required: kg DDGS/kg corn or lb DDGS/bushel of corn (56 lb/bushel); percent of available DDGS required: 0%, 70%, 77%, 87%, and 100%, respectively, for the five technology alternatives.

[b] Net energy value is the sum of all energy outputs including energy in the ethanol plus credits for coproducts (DDGS) and, if applicable, electricity delivered to the grid minus all fossil energy inputs.

[c] Renewable energy ratio = renewable energy outputs/fossil energy inputs.

[d] Amount of cornstover required: kg corn stover/kg corn or lb corn stover/bushel of corn (56 lb/bushel).

[e] CHP–10% generation efficiency (LHV) required – Process heat and plant electricity biomass technology alternative.

[f] CHPG–20% generation efficiency (LHV) – Process heat, plant electricity and electricity to grid biomass technology alternative. Electricity sold: 0.38 kW_eh/L (1.45 kW_eh/gal).

[g] CHPG–30% generation efficiency (LHV) – Process heat, plant electricity and electricity to grid biomass technology alternative. Electricity sold: 0.86 kW_eh/L (3.27 kW_eh/gal).

sale price to the grid combinations. A 150 million L per year plant requires approximately 5 MW$_e$ for its own needs, and can generate another 6.6 MW$_e$ to the grid at 20% generation efficiency or 14.9 MW$_e$ to the grid at 30% efficiency, or totals of 11.6 or 19.9 MW$_e$, respectively, under conditions in which all waste heat is used for process needs.

The results for process heat only (PH), combined process heat plus plant electric power (CHP-10%), and combined process heat plus plant electricity and electricity to the grid (CHPG-20% or CHPG-30%) are shown in table 4. Clearly, the annual energy cost savings/returns (excluding increased capital and labor costs) are very sensitive to natural gas and biomass prices. High natural gas and relatively low biomass costs generate significant annual savings to be applied toward increased capital and operating costs associated with biomass fuel technologies. The price received for DDGS at some Minnesota dry mill plants is currently in the range of \$80/t (\$73/ton) [t - metric ton (1000 kg); ton - English ton (2000 lb)]. These results suggest advantages for generating electricity for the plant and also to the grid even at an electricity sale price of 3 cents per kW$_e$h. The ability to effectively use waste heat from electricity generation to meet process needs explains the apparent significant advantage for including generation in the mix. A renewable energy credit of 1.5 cents per kW$_e$h added to the sale price to the grid increases revenue by about \$2 million per year for the 30% generation efficiency case.

The Public Utilities Regulatory Act of 1978 (PURPA) and the Federal Energy Regulatory Commission (FERC) establish regulations for electricity producing companies called qualifying facilities (QF), which provide power to the grid (EIA, 1998). “Firm” power from a QF is defined as 65% or greater availability during on-peak hours. “Firm” power produced with renewable energy sources must be purchased by the utility at avoided cost (MPUC, 2005). Thus, electric power produced with biomass fuels at ethanol plants should meet the criteria of being both “firm” and renewable.

The corresponding prices for corn stover in table 4 range from \$63 to \$79/t (\$58 to \$72/ton). Sokhansanj and Turhollow (2004) evaluated costs for delivering dry corn stover in several forms to an end user. They estimated the cost for corn stover bales including final grinding at \$60/t (\$55/ton) and the cost for corn stover cubes at \$72/t (\$65/ton). Both of these costs included \$11/t (\$10/ton) payment to the farmer. They suggested that opportunities existed to reduce the cost of delivering cubes to the level of bales. Sufficient corn stover should be available to provide energy for heat and power at most dry-grind ethanol plants within closer transport distances than the 64 km (40 miles) assumed in their analysis.

There are significant potential for energy cost savings/returns over a range of conditions. However, we need to evaluate capital and operating costs of biomass combustion/gasification, emission control, biomass fuel handling, and electric generation technologies to determine overall economic feasibility. That is the next step in the evaluation process.

The high cost of natural gas has already caused some new dry mill ethanol plants to design for coal as a fuel to meet process needs. At \$2 to \$3 per GJ (\$2.11 to \$3.17 per million Btu), coal can be competitive if air emission standards can be met. Even if mercury and particulate criteria are met, use of coal will result in greater release of carbon dioxide and other greenhouse gases (GHG) to the environment than with natural gas. The net energy values and renewable energy ratios for coal-powered dry mills will be the same as with current technology using natural gas because both are using fossil fuels. However, since coal is a solid fuel, some of the technology and equipment employed may be adaptable to renewable biomass fuels in the future.

Summary and Conclusions

Biomass (DDGS and corn stover) alternatives to provide process heat and electricity at corn dry-grind ethanol plants were evaluated. Net energy values and renewable energy ratios were compared to previous estimates for both corn and biomass ethanol production. Annual energy cost savings/returns (\$ millions), excluding increased capital and labor costs, for a 150 million L (40 million gal) per year plant were estimated.

Table 4. Estimated annual energy cost savings/returns (\$ millions) for a 150 million L (40 million gal) per year plant for four biomass technology alternatives at several natural gas, DDGS (or corn stover), and electricity sale to the grid price combinations – electricity purchase price from the grid assumed to be 5¢/kW$_e$h (excluding increased capital and labor costs for biomass systems).

	DDGS[a] Prices, \$/t (\$/ton)											
	\$80/t (\$73/ton)						\$100/t (\$91/ton)					
			CHPG–20%[d]		CHPG–30%[e]				CHPG–20%		CHPG–30%	
Natural Gas, \$/GJ (\$/MM Btu)	PH[b]	CHP–10%[c]	3¢/ kW$_e$h	4.5¢/ kW$_e$h	3¢/ kW$_e$h	4.5¢/ kW$_e$h	PH	CHP–10%	3¢/ kW$_e$h	4.5¢/ kW$_e$h	3¢/ kW$_e$h	4.5¢/ kW$_e$h
\$6 (\$6.33)	\$3.3	\$4.8	\$5.6	\$6.4	\$6.6	\$8.6	\$1.7	\$3.0	\$3.6	\$4.4	\$4.3	\$6.3
\$7 (\$7.39)	\$4.9	\$6.4	\$7.2	\$8.1	\$8.2	\$10.2	\$3.3	\$4.4	\$5.2	\$6.1	\$5.9	\$7.9
\$8 (\$8.44)	\$6.5	\$8.0	\$8.8	\$9.7	\$9.9	\$11.8	\$4.9	\$6.2	\$6.8	\$7.7	\$7.6	\$9.5
\$9 (\$9.50)	\$8.2	\$9.6	\$10.5	\$11.3	\$11.5	\$13.4	\$6.6	\$7.9	\$8.5	\$9.3	\$9.2	\$11.2
\$10 (\$10.55)	\$9.8	\$11.3	\$12.1	\$13.0	\$13.1	\$15.1	\$8.2	\$9.5	\$10.1	\$11.0	\$10.8	\$12.8

[a] The corresponding prices for corn stover are \$63/t (\$58/ton) and \$79/t (\$72ton), respectively, based on the difference in heat content for DDGS (20.9 MJ/kg) versus corn stover (16.5 MJ/kg).

[b] PH – Process heat only biomass technology alternative.

[c] CHP–10% generation efficiency (LHV) required – Process heat and plant electricity (5 MW$_e$) biomass technology alternative.

[d] CHPG–20% generation efficiency (LHV) – Process heat, plant electricity and electricity to grid (6.6 MW$_e$ to grid, 11.6 MW$_e$ total electric power generation) biomass technology alternative at 3¢/kW$_e$h and 4.5¢/kW$_e$h electricity sale prices.

[e] CHPG–30% generation efficiency (LHV) – Process heat, plant electricity and electricity to grid (14.9 MW$_e$ to grid, 19.9 MW$_e$ total electric power generation) biomass technology alternative at 3¢/kW$_e$h and 4.5¢/kW$_e$h electricity sale prices.

The following conclusions are drawn:

- Corn dry-grind ethanol production using biomass (DDGS or cornstover) to meet process energy needs and generate electricity achieves net energy values in the range of 20 to 30 MJ/L (72,000 to 108,000 Btu/gal), which equals or exceeds previous estimates for biomass ethanol production.
- There is significant annual energy cost savings/returns for a 150 million L (40 million gal) per year plant capacity over a range of natural gas and biomass prices to apply to additional capital and operating costs required for a biomass energy system.
- Electric generation is an important contributor to the annual energy cost savings/returns because of the ability to effectively use waste heat to meet process energy needs.
- Electric power produced by ethanol plants using either DDGS or cornstover will result in ”firm” (65% or greater availability) and renewable power. Under PURPA and FERC regulations, power produced in this fashion must be purchased by local utilities.
- An important next step is to evaluate capital and operating costs of biomass combustion/gasification, emission control, biomass fuel handling, and electric generation technologies to determine overall economic feasibility.

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