Corn Grain Drying Using Corn Stover Combustion and CHP Systems

A. S. Bennett, C. J. Bern, T. L. Richard, R. P. Anex

Abstract. *Post-harvest drying of shelled corn grain requires large amounts of fossil fuel energy. In 2004, it was estimated that the upper Midwest consumed more than $1.4 billion of fossil fuels to dry $19.7 billion of corn grain. Over the long term, drying corn with fossil fuels may become cost prohibitive due to limited fuel reserves. To address future energy concerns for grain dryers, this study evaluated the potential use of combined heat and power (CHP) systems that use the combustion of corn stover both to produce heat for drying and to generate electricity for fans, augers, and control components. Net present value (NPV) cost estimates were determined for two continuous-flow dryers: a relatively small on-farm dryer (8.9 Mg h^{-1}), and a larger dryer more common to grain elevators (73 Mg h^{-1}). For each dryer, three levels of assumed stover price were used: $15, $25, and $35 per dry Mg for the small dryer, and $30, $45, and $60 per dry Mg for the larger dryer (includes payments to farmer and off-farm transport costs). Compared to equivalently sized fossil fuel-fired dryers, both the small and large CHP dryers were found to be more economical over the long term. Twenty-year NPV cost savings and breakeven points were estimated to be $63,523 and 14.3 years for the small CHP dryer ($25 Mg^{-1} stover) and $1,804,482 and 7.5 years for the large dryer ($45 Mg^{-1} stover). Sharing CHP infrastructure with other processes requiring heat that extend seasonal use can reduce payback periods significantly and provide broader efficiency benefits. Sensitivity analysis found cost savings to be most sensitive to fluctuations in fossil fuel costs, followed by annual use of dryer equipment.*

Keywords. *Bioenergy, Biomass, Biorenewable, CHP, Combined heat and power, Continuous grain driers, Corn drying, Cost analysis, Steam, Stover.*

For many corn producers, post-harvest drying of shelled corn grain provides considerable flexibility in harvesting schedules and conditions. Compared to natural in-field drying, benefits of heated-air drying include earlier harvest, a larger harvest window, reduced field losses, reduced harvest damage, and less labor. The benefits associated with post-harvest drying, however, require significant energy input, of which the majority comes from fossil fuels. Due to ever increasing demands on limited natural gas and petroleum reserves, drying costs are likely to increase significantly.

Between 1992 and 1995, approximately 87% of the 38.8×10^6 Mg (1.52×10^9 bu) of the Iowa shelled corn crop (15 wt% moisture) was artificially dried (Bern, 1998). The energy consumption for drying was estimated to be 15.8×10^6 GJ (15.0×10^6 MMBtu), with energy from fossil fuel combustion, largely propane, providing approximately 80%. The remaining 20% came from electricity generated mostly by centralized fossil fuel-fired power stations (Bern, 1998).

By assuming the same 80/20 relationship, commercial electrical power cost of $18.9 GJ^{-1} ($0.068 kWh^{-1}), and propane valued at $11.9 GJ^{-1} ($1.15 gal^{-1}), it can be estimated that $300 million in fossil fuel-derived energy was required in 2004 to dry Iowa's 57.0×10^6 Mg (2.24×10^9 bu) corn grain production (EIA, 2006, 2007b; USDA-NASS, 2005). Even more significant is the estimated $1.4 billion drying cost for the entire upper Midwest corn belt (Illinois, Iowa, Indiana, Kansas, Michigan, Minnesota, Montana, Nebraska, North Dakota, Ohio, South Dakota, and Wisconsin), which in 2004 was reported to produce a combined 263×10^6 Mg (10.4×10^9 bu) of corn grain valued at $19.7 billion (USDA-NASS, 2005).

Sustainable and Renewable Alternative Energy Sources

There is a growing global awareness that the sustainability and long-term success of society depend on reducing our reliance on fossil fuels as a primary energy source. As concerns for the environment, national security, and fossil fuel costs continue to grow, biorenewable energy resources, including dedicated energy crops and agricultural residues, are increasingly viewed as attractive options and essential components for the future conversion to more sustainable, bio-based economies. Significant constraints, however, currently limit the practical application of these alternative biorenewable energy resources. Most power generation facilities in the developed world are large-scale centralized power stations, which rely on energy-dense and/or easily transported fossil

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The authors are **Albert S. Bennett, ASABE Member Engineer,** Graduate Student, and **Carl J. Bern, ASABE Fellow,** Professor, Department of Agricultural and Biosystems Engineering, Iowa State University, Ames, Iowa; **Thomas L. Richard, ASABE Member Engineer,** Associate Professor, Department of Agricultural and Biosystems Engineering, Pennsylvania State University, University Park, Pennsylvania (formerly with Department of Agricultural and Biosystems Engineering, Iowa State University, Ames, Iowa); and **Robert P. Anex, ASABE Member Engineer,** Associate Professor, Department of Agricultural and Biosystems Engineering, Iowa State University, Ames, Iowa. **Corresponding author:** Albert S. Bennett, 3144 NSRIC Bldg., Iowa State University, Ames, IA 50011; phone: 515-294-4330; fax: 515-294-4250; e-mail: asbnntt@iastate.edu.

fuels such as coal, petroleum, and natural gas. In contrast, biomass-based fuel sources are generally highly dispersed in nature and have relatively high moisture contents, low bulk densities, and low heating values. Because of these constraints, it is economically prohibitive and inefficient (both in time and energy), in most cases, to transport large quantities of low-density biomass to large centralized power stations.

Apart from the operational and construction benefits associated with economies of scale, there are also limitations to the maximum efficiencies attainable by large-scale, fossil fuel-fired power generating facilities, which typically operate at energy efficiencies that range from 35% to 45%. Greater efficiencies are possible. For example, very large-scale, combined-cycle power stations are the trend in U.S. power generation research efforts and are projected to achieve up to 60% efficiencies (Brown, 2003). The most advanced systems under consideration are combinations of gas turbines, fuel cells, and steam turbines. Existing large-scale, combined-cycle systems typically employ high-temperature gas turbines followed by lower-temperature steam turbines and operate at efficiencies approaching 47% (Brown, 2003). Further increases in energy efficiencies, however, will be much more difficult to attain. This is because large, centralized systems are not able to economically utilize the vast quantities of low-grade waste heat that they generate. In addition, the nominal operating efficiencies of fossil fuel-dependent power stations do not reflect the energy consumed in fossil fuel exploration, extraction, processing, transport, power transmission, and grid maintenance, nor do they reflect the negative environmental impacts associated with fossil fuel-fired power plants.

Small-Scale, Localized Power Generation

In contrast to large-scale power generation, smaller decentralized power stations located in agricultural communities can take advantage of their close proximity to highly dispersed biomass resources. More importantly, they can incorporate multi-process designs that are able to recover and utilize the low-grade heat energy that is otherwise typically wasted, leading to greater energy use efficiencies. There are currently combined heat and power (CHP) plants operating in Europe that are able to achieve energy efficiencies greater than 85% (Nikolaisen et al., 1998). Some of the processes that can be incorporated into these alternative decentralized power plants include systems for distillation, food processing, electrical energy generation, absorption-based refrigeration, and hot water and space heating for buildings, greenhouses, and aquaculture.

One of the possible areas where decentralized CHP scenarios can be applied is in continuous-flow corn grain drying applications. Instead of natural gas or propane, these CHP systems use corn stover to fuel a steam boiler to power a steam engine or turbine and electrical generator. These engines in turn drive a grain dryer's fan motors, auger motors, and electronic controls. Low-pressure steam engine exhaust can also be readily condensed to provide part of the process heat required by the dryers. Additional high-pressure steam can be used to provide the remaining process heat required to dry corn grain. In addition to the costs associated with the purchase and operation of a boiler, steam engine, and generator, only minor modifications to the actual grain drying equipment would be necessary. These include the installation of steam condensers inside the dryer to replace gas burners and fuel systems.

Corn stover, comprised of corn stalks, leaves, and cobs, represents an ideal biomass feedstock for decentralized CHP drying applications. It is widely available across the Midwestern U.S., and a recent study conducted by the USDA and DOE (Perlack et al., 2005) estimates that over 68 million dry Mg (75 million tons) can be sustainably harvested each year in the U.S.

Study Objective

Currently, grain driers are heated by the direct use of relatively "clean" combustion products from natural gas or propane. Due to stover's relatively high chlorine and ash content, combustion products from biomass, such as corn stover, would preferably be used indirectly; for this study, indirect use is accomplished with a steam condenser (Brown, 2003). When used directly in a grain dryer, these materials are corrosive and can lead to the deposition of unwanted or harmful particulates in the grain. In addition, a direct-fired, fossil fuel-heated grain dryer is not nearly as capital intensive as a hypothetical grain dryer with an additional steam boiler, engine/turbine, generator, and condenser.

Since the annual cost of drying U.S. corn grain production using fossil fuel-heated dryers is significant, the objective of this study was to evaluate the economic feasibility and sensitivities of drying corn with corn stover as a possible fuel alternative in both small (8.9 Mg h^{-1}) and large (73 Mg h^{-1}) capacity continuous-flow grain dryers. Potential benefits to converting to CHP stover-fired dryers include more environmentally friendly systems that may ultimately promote greater energy independence for rural communities.

Economic feasibility was determined by comparing the difference in the net present value (NPV) in operating costs of traditional fossil fuel-fired dryers and CHP-configured stover-fired dryers over a 20-year period. Sensitivities were tested by varying likely values for annual dryer use, CHP capital investments, labor wages, interest rates, and fossil fuel costs.

Methods

Corn Stover Collection Costs, Transport Costs, and Pricing Assumptions

From 2000 to 2005, the average U.S. corn grain yield (dry weight) was reported to be 220 million Mg $year^{-1}$, which averages to be approximately 7.56 Mg ha^{-1} $year^{-1}$ (USDA-NASS, 2005). According to Perlack et al. (2005), it is reasonable to assume a 1:1 dry grain to dry stover ratio; therefore, the U.S. also likely produced an average of 220 million Mg $year^{-1}$ of dry corn stover during the same period. However, although a very large mass of corn stover is produced annually, soil conservation concerns limit how much of it can be removed for bio-energy related applications. Recommendations for sustainable collection rates of stover depend on the type of soil, topography, crop rotation, tillage practices, and other environmental constraints. Some stover residues should be left in the field, and a minimum of 30% surface coverage by residue is required to comply with USDA guidelines for erosion protection (Glassner et al., 1999). Residue removal has the greatest potential on mildly sloping, no-till fields, with recommended collection values of up to 58%

(Wayman and Parekh, 1990). Hasche et al. (2003) estimated the impact of stover removal on soil erosion for various combinations of corn and soybean rotations. Their study indicated that soil erosion is largely dependent on tillage practices and slope, with biomass removal of secondary importance and soil type having a relatively minor effect. No biomass removal was recommended for land slopes greater than 11.5% or when intensive tillage practices (fall moldboard plowing) are employed on slopes greater than 2.5%. In comparison, 40% removal rates are possible when no-till practices are used on rapidly regenerating soils with slopes up to 7%, or when no-till is used on slowly regenerating soils with slopes below 2.5%.

Potential feedstock costs delivered to the plant (adjusted to 2007 dollars) for agricultural residues were reported to range from $18.10 per dry Mg for low-cost sources up to $66.50 per dry Mg for high-cost sources (Lynd, 1996). Recently, more detailed cost estimates have been developed specifically for the collection of corn stover. Sokhansanj and Turhollow (2002) estimated baling costs associated with the more common large round bales (0.580 dry Mg bale^{-1}) and compared them with large rectangular baling systems (0.770 dry Mg bale^{-1}). In their study, stover was assumed to be collected after completion of the grain harvest and delivered to an intermediate storage facility. Stover harvest rates were assumed to be 3.8 dry Mg ha^{-1} (42% of available residues). Cost estimates, adjusted to 2007 dollars, for both options were similar at $25.00 per dry Mg for round bales and $27.30 per dry Mg for rectangular bales. These estimates provide no payments to farmers for stover or storage. They are also impractically low for centralized processing facilities because they do not include costs related to reloading and delivery of bales from intermediate storage areas.

For very large farming operations and grain elevators, transportation will play a more significant role in determining final stover collection costs. Transportation costs for distances greater than 8 km were considered by Perlack and Turhollow (2002) and included cost estimates for corn stover collection and delivery to hypothetical ethanol processing facilities using large 580 kg round bales and large 590 kg rectangular bales. Collection procedures were very similar to those described by Sokhansanj and Turhollow (2002). Results from Perlack and Turhollow (2002) (adjusted to 2007 dollars) indicated that round bale collection and delivery costs (dry basis) to an intermediate storage area ranged from $30.20 Mg^{-1} for small ethanol processing facilities (450 Mg d^{-1}) to $31.60 Mg^{-1} for large facilities (3,630 Mg d^{-1}). Large rectangular bales were slightly more expensive, with costs ranging from $30.60 Mg^{-1} to $32.90 Mg^{-1}. Hauling distances from intermediate storage to processing facilities ranged from 35 km for small facilities to close to 100 km for very large facilities and typically added another $11.80 Mg^{-1} to $16.40 Mg^{-1} for large round and rectangular baling systems. When combining baling and off-farm transport, the total costs of large baling systems were found to range from $42.00 to $49.40.

There are other possible options for the collection and transport of stover based on one-pass, whole-plant harvest schemes. These alternative harvest systems have the potential to be much more economical than current baling systems (Quick, 2000; Shinners et al., 2003; Tuetken, 2002).

In this study, potential variability of on-farm stover collection costs, off-farm transportation costs, demand for alternative biofuels, and payments to farmers were simulated by using three price scenarios for small on-farm dryers and a second set of price scenarios for a large dryer typical of what an independent grain elevator might use. The dry basis stover price scenarios are $15, $25, and $35 Mg^{-1} for the smaller on-farm dryer and $30, $45, and $60 Mg^{-1} for the large dryer. Price scenarios for the large dryer are higher to account for off-farm transportation costs and payments made to farmers for purchasing stover.

Corn Stover as an Alternative Energy Source

An annual sustainable production of 68 million dry Mg of corn stover (Perlack et al., 2005) represents a very significant source of biomass. If that same biomass is completely converted to thermal energy (e.g., as steam) with a process efficiency of 80% and lower heating value of 16.5 MJ kg^{-1} (Morey et al., 2006), then the U.S. would be able to annually generate an additional 0.90 EJ (0.85 quadrillion Btu) of energy. In comparison, the U.S. currently uses more than 100 EJ of energy per year throughout its entire economy (Brown, 2003). Although 0.90 EJ is slightly less than 0.9% of the U.S. energy economy, it still represents a significant economic resource. For example, approximately 35×10^9 L of propane worth $13 billion is required to generate 0.90 EJ of heat energy. There are significant challenges to utilizing low energy dense, highly dispersed biomass resources such as corn stover. However, when compared to current prices for propane and natural gas, the potential for economic savings is considerable. This is clearly indicated by the values shown in table 1, which compare this study's simulated costs of stover energy, on a per GJ basis, to U.S. commercial market prices for both natural gas and propane between August 2005 and July 2007 (EIA, 2007a, 2007b). The values shown for costs of stover energy do not include capital costs associated with stover-to-energy conversion equipment.

Limited Direct Application of Corn Stover Combustion Products

One of the primary limiting factors in utilizing corn stover as an energy source for drying grain is its relatively high concentration of chlorine. Chlorine becomes highly corrosive, forming hydrochloric acid, when allowed to condense on metal surfaces. Fortunately, this corrosion problem can be readily overcome by indirect firing or by using stover combustion gases to generate steam instead of sending them directly into a grain dryer. Unfortunately, a significant efficiency penalty is associated with the indirect application of condensing steam to provide process heat for grain drying. Part of this penalty can be compensated by the low cost of corn stover, and by incorporating CHP generation schemes into the grain drying system.

In steam-fired power plants, high chlorine concentrations in combustion products can also cause significant boiler tube corrosion problems for high-pressure steam (>6.0 MPa) at temperatures greater than 450°C (Nikolaisen et al., 1998; Bryers, 1996). Fortunately, in grain drying applications, less expensive boilers that operate at lower pressures (<2.3 MPa) and below 220°C can be used, with which the very high temperature corrosion of boiler tubes from chlorine is not considered to be a significant problem. Other maintenance issues associated with tube fouling from ash and particle depositions are assumed to be important, but manageable. This is especially true for corn grain drying applications, which are

Table 1. Comparative energy costs for stover, natural gas, and propane.

	Units	Small Dryer				Large Dryer		
Corn stover combustion								
Stover feedstock cost (d.b.)	$ Mg^{-1}	15.00	25.00	35.00		30.00	45.00	60.00
Stover lower heating value	GJ Mg^{-1}	16.5	16.5	16.5		16.5	16.5	16.5
Combustion efficiency	%	80	80	80		80	80	80
Stover energy cost	$ GJ^{-1}	1.14	1.89	2.65		2.27	3.41	4.55
Natural gas combustion				Natural gas is not available on most farms				
Natural gas cost	$ GJ^{-1}			9.01	10.82	13.57		
	$ MMBtu^{-1}			9.50	11.40	14.30		
Combustion efficiency	%			97	97	97		
Natural gas energy cost	$ GJ^{-1}			9.78	11.74	13.69		
Propane combustion								
Propane cost	$ m^{-3}			383	423	462		
	$ gal^{-1}			1.45	1.60	1.75		
Combustion efficiency	%			97	97	97		
Propane energy cost[a]	$ GJ^{-1}			15.43	17.02	18.62		

[a] Propane energy content: 25.6 GJ m^{-3} (92,000 BTU gal^{-1}).

typically operated for only a few months each year. As a result, considerable downtime is available for maintaining boiler tubes.

Fossil Fuel-Fired Continuous-Flow Grain Dryers

Performance data for two continuous-flow grain dryers fabricated by Delux Manufacturing Company (Delux, 2005) located in Kearney, Nebraska, provided the basis for the analytical comparisons. Both units considered for this study are modified, cross-flow designs that improve drying efficiencies by using heat recovery from the grain cooling section to preheat air entering the heated section. According to the manufacturer, heat recovered from the cooling section can increase the air temperature from 17°C to 28°C (30°F to 50°F). This study assumes the minimum 17°C. The first unit considered is a relatively small continuous dryer typical of what a moderate to large (e.g., 300 to 600 ha) family farming operation might use and where propane would be the fuel of choice. The second dryer is much larger and represents what a typical grain elevator might use, and where natural gas or propane might be the fuel of choice. Table 2 shows dryer capacities, electrical loads, and heating loads applied in this study. Boiler sizing is based on estimated heat load requirements for an ambient air temperature of 4.4°C. Heat loads at 20°C are based on the manufacturer's performance data (Delux, 2005).

Table 2. Continuous dryer capacity, and electrical and heating loads.

Dryer Size	Dryer Capacity, Mg h^{-1} (bu h^{-1})	Electrical Load,[a] kW (hp)	Ambient Temp., °C (°F)	Heating Load,[b] GJ h^{-1} (BTU h^{-1})
Small	8.9 (350)	16.4 (22)	21 (70)	2.2 (2.1 × 10^{6})
			4.4 (40)	2.8 (2.7 × 10^{6})
Large	73 (2880)	160 (214)	21 (70)	19.9 (18.9 × 10^{6})
			4.4 (40)	25.5 (24.2 × 10^{6})

[a] Electrical loads include fans, augers, and control systems.
Heating loads for a 5% moisture removal (20% to 15%, wet basis).

Components and Capital Investments for CHP Modified Continuous-Flow Grain Dryers

To convert from a traditional fossil fuel, direct-fired, continuous-flow grain dryer to a system capable of using corn stover as its primary fuel, the addition of a stover-fired steam boiler, steam engine or turbine with a generator, and steam condensers, which replace a natural gas or propane burner, is necessary. Table 3 shows component sizing and capital cost estimates for the small and large dryer CHP systems.

Prices for the grain dryers were obtained from Delux Manufacturing Company (Delux, 2005). Costs for stover-fired steam boilers were obtained from Hurst Boiler and Welding Co. (Zebley, 2005). It was calculated that the smaller dryer would require slightly less than 735 kW (2.5 MMBtu h^{-1}). Due to limited availability of solid fuel-fired systems under 980 kW (3.3 MMBtu h^{-1}), the sizing and cost protocol described by Ulrich and Vasudevan (2004) was used to the

Table 3. Component sizing and capital investments for fossil fuel and stover-fired dryer systems.

Concept	Units	Small Dryer Installation: Size	Small Dryer Installation: Fossil Fuel Costs ($)	Small Dryer Installation: Stover Costs ($)	Large Dryer Installation: Size	Large Dryer Installation: Fossil Fuel Costs ($)	Large Dryer Installation: Stover Costs ($)
Continuous dryer	Mg h^{-1}	8.9	35,000	35,000	73	175,000	175,000
Propane tanks	m^{3}	7.6	4,000	--	--	--	--
Steam engine	kW	24	--	13,050	--	--	--
Steam turbine	kW	--	--	--	239	--	65,000
Generator	kW	19	--	5,000	185	--	235,000
Boiler system	kW (MPa)	735 (1.0)	--	232,000	6870 (1.7)	--	1,250,000
Condenser	m^{2}	17.7	--	43,520	162	--	139,350
Stover storage	m^{2}	153	--	12,000	3860	--	302,000
Utility tractor	kW	--	--	--	56	--	34,000
Total capital			$39,000	$374,570		$175,000	$2,200,350

estimate the cost for the 735 kW system. The basic formula for this sizing and cost protocol relation is as follows:

$$C_v = C_u \cdot (v/u)^a \tag{1}$$

where

C_v = estimated equipment purchase cost
v = capacity associated with estimated purchase cost
C_u = known equipment cost
u = capacity associated with known equipment cost
a = sizing exponent.

The larger dryer was calculated to require a maximum of 6870 kW (23.0 MMBtu h^{-1}). The larger boiler system also includes costs associated with federally mandated pollution control systems. Installation costs along with additional equipment for material handling and buildings structures are included in estimates for both the small and larger dryer CHP systems. Based on manufacturer price quotes (Zebley, 2005), the sizing exponent used to estimate the cost of the 735 kW solid-fuel boiler was calculated to be approximately 0.65.

Because of difficulties in obtaining small-scale steam turbines (less than 100 kW), this study assumed the use of a steam engine coupled to a commercially available PTO-driven generator for the small dryer CHP system. A steam engine performance model was used to estimate power output and steam requirements. The model was developed using methods and actual engine performance data (Stumpf, 1912). Small engine and generator costs were estimated from similarly sized components available from internet sources (Brown, 2005; Grainger, 2005) and by employing sizing protocols, described in equation 1, and installation factors (Ulrich and Vasudevan, 2004). A more traditional steam turbine and generator was assumed for the large dryer CHP system, with prices obtained from a manufacturer (Nick, 2005). To minimize capital investments and take advantage of steam engine designs, which typically operate at these lower pressures, a maximum operating pressure of 1.0 MPa (150 psig) was assumed for the small dryer CHP boiler system. The large dryer CHP system was assumed to use a boiler operating at a pressure of 1.7 MPa (250 psig). This will better accommodate commercial steam turbines that are capable of operating at relatively low pressures.

The condenser installation was assumed to be comprised of two stages: a lower-pressure condenser that receives low-pressure exhaust from the steam engine or turbine, followed by a higher-pressure condenser that applies most of the heat energy needed to raise temperatures in the grain dryer to just under 95°C. Figure 1 shows a schematic of the small (8.9 Mg h^{-1}) and large (73 Mg h^{-1}) dryer systems, including hypothetical condenser placement, airflow rates, and general dimensions. Condenser capacity was determined using the maximum heat and air temperature requirements for each dryer and the following formula (Ulrich and Vasudevan, 2004):

$$A = Q/(U \cdot \Delta T_m) \tag{2}$$

where

A = exterior bare tube exchanger surface area, excluding fins (m^2)
Q = heat transfer rate (W)
U = overall heat transfer coefficient (J m^{-2} s^{-1} K^{-1})
ΔT_m = log-mean of hot-end and cold-end "approach" temperatures (K).

Typical overall heat transfer coefficient (U) values for condensing steam in air-cooled (fin-fan) heat exchangers range from 790 to 850 J m^{-2} s^{-1} K^{-1}, where fin area is approximately 15 to 20 times that of the bare tube area (Ulrich and Vasudevan, 2004). For this study, a more conservative value of 500 J m^{-2} s^{-1} K^{-1} was used to calculate heat exchanger bare tube area. Condenser capital costs were also estimated (Milligan, 2005). Installation costs were estimated by applying multipliers typically used by the chemical processing industry (Ulrich and Vasudevan, 2004).

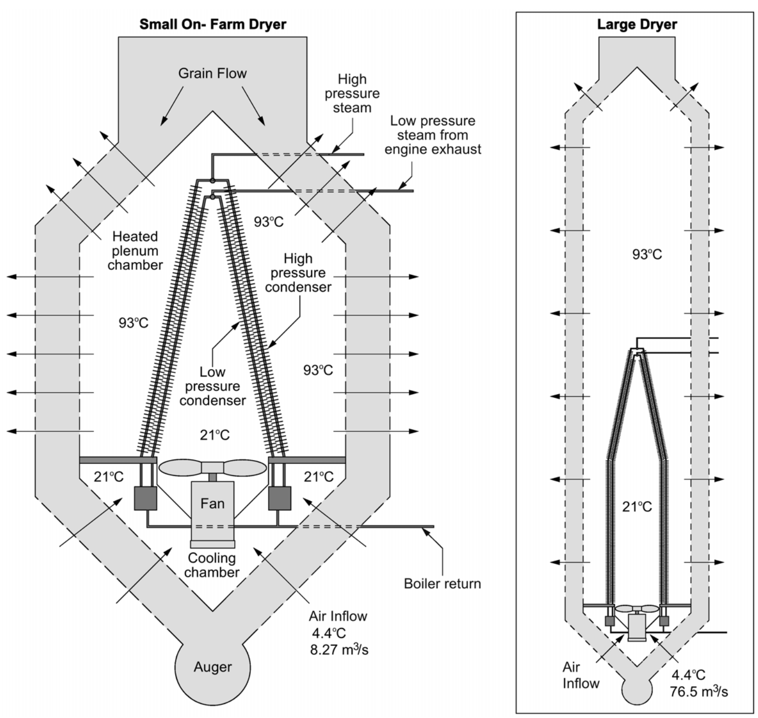

Figure 1. Modified, continuous CHP cross-flow grain dryers.

Although not necessary in many regions, stover storage costs, assuming the use of a totally enclosed hay barn, are also included (House and Stone, 1988; Taylor, 1995). The purchase cost of a dedicated utility tractor for transporting stover bales between storage and materials processing is included in capital cost estimates for the large dryer system.

Financial Analysis

A 20-year financial analysis was used to predict the potential for cost savings generated by converting from traditional fossil fuel-fired grain dryers to stover-fired CHP grain dryer systems. The analysis included initial capital costs, equipment and structures depreciation, and operational costs associated with the additional labor needed to handle stover.

Depreciation was assumed to follow a 20-year straight-line relation for capital investments. Annual interest and inflation rates were assumed to be 7% and 1%, respectively, and were combined to establish a discount rate (i) of 5.94%. The following formula was used to calculate the discount rate:

$$i = [(\text{interest rate} + 1) / (\text{inflation rate} + 1)] - 1 \quad (3)$$

Discounted annual cash flow (DACF) was calculated by the following formula:

$$\text{DACF} = \text{ACF} / (1 + i)^n \quad (4)$$

where ACF is the annual cash flow, which includes the sum of energy and equipment costs minus depreciation, and n is the year.

For each analysis, the net present value (NPV) cost was subsequently calculated by summing the discounted annual cash flow. Differences between the NPV of operational costs for stover and fossil fuel systems were subsequently used to compare and evaluate the potential for medium- to long-term cost savings of stover-fired CHP systems. Operational costs for both fossil fuel and stover-fired CHP systems include fuel costs, depreciation, and an annual maintenance cost equal to 2% of the initial capital invested (Brown, 2003). Financial costs for each system assume 60% financing of initial capital using a 7-year loan compounded monthly. While fossil fuel systems include electrical power costs, stover-fired CHP systems include additional stover handling and labor costs.

The small dryer is assumed to operate 6 weeks per year and 14 h per day, while the large dryer system is assumed to operate 10 weeks per year and 24 h per day. Labor to move stover between the bale storage building and processing equipment is assumed to be \$12 h^{-1}. This value is based on actual surveys conducted by Iowa State University Extension Service and Occupational Employment Statistics, which reported farm machinery operators earning approximately \$10 h^{-1}; an additional 20% is included to account for benefits and other employer expenses (BLS, 2007; Edwards and Smith, 2006). It is also assumed that approximately 10% of the labor is associated with operating a tractor to move bales. The cost to operate the small utility tractor (labor excluded) is taken to be \$21 h^{-1} (Edwards, 2007).

Fossil Fuel and Electricity Cost Assumptions

According to the U.S. Energy Information Administration (EIA), between January 2005 and December 2006, the average U.S. commercial prices for natural gas and propane were approximately \$10.10 GJ^{-1} (\$10.65 $MMBtu^{-1}$) and \$16.50 GJ^{-1} (\$1.60 gal^{-1}), respectively (EIA, 2007a, 2007b). These same values are used for comparisons. The cost of electrical energy is assumed to be \$18.9 GJ^{-1} (\$0.068 kWh^{-1}) (EIA, 2006).

Results and Discussion

Twenty-Year Cost Comparisons

The potential cost savings resulting from the use of stover CHP dryer systems are shown in figures 2 and 3. Savings for both the large and small dryer systems are represented as net present values (NPV). Details regarding each of the six scenarios shown in figure 2 and 3 are provided in table 4, including three scenarios where 100% of the CHP-related capital investments and financial costs are charged to the dryer systems and three scenarios where only 25% of the capital and financial costs associated with the solid-fuel boiler, steam turbine/engine, and generator are charged to the dryer analysis. Included are values used for annual dryer use, capital investments, depreciation, fossil fuel cost, stover cost, each scenario's accumulated DACF at year 20, and savings breakeven point (i.e., where accumulated DACF values for CHP systems are equal to fossil fuel-fired systems). The large capital investments associated with a CHP dryer systems and the limited operation time (1 to 3 months) support the rationale for sharing capital and financial expenses; for example, the CHP unit can supply winter heat to a greenhouse structure.

During the early years of the investment, fossil fuel-fired dryers are less expensive to operate due to the CHP stover system's high capital investment requirements. With time, however, all of the modeled alternative CHP systems become the more economical investment, as is clearly indicated in figures 2 and 3. This especially true for shared CHP configurations.

Other processes that might share a CHP system include winter greenhouses, aquaculture operations, and residential heat and electricity. Low-cost locally grown biomass fuels could make these types of enterprises attractive for many farming communities, which are now searching for means of improving farm profitability and promoting rural development. In addition, it is not uncommon to find grain elevators near the center of small rural towns in the Midwest corn belt. This would allow a large CHP dryer system to sell waste heat to nearby residents during winter months, and selling electrical power to a local grid may be an attractive and profitable option for reducing fossil fuel dependence.

The potential savings in fossil fuel use can be significant when converting to a CHP dryer configuration. For example, the small 8.9 Mg h^{-1} (350 bu h^{-1}) dryer modeled in this study could save 33,000 GJ in fossil fuel use, which for propane valued at \$16.5 GJ^{-1} (\$1.60 gal^{-1}) is worth approximately \$545,000. In comparison, over 20 years, a single large stover-fired 73 Mg h^{-1} (2880 bu h^{-1}) dryer can avoid the use of approximately 855,000 GJ of propane worth \$14.1 million.

Sensitivity Analysis

Model sensitivities were tested and compared to the corresponding base case scenarios L-2, L-5, S-2, and S-5

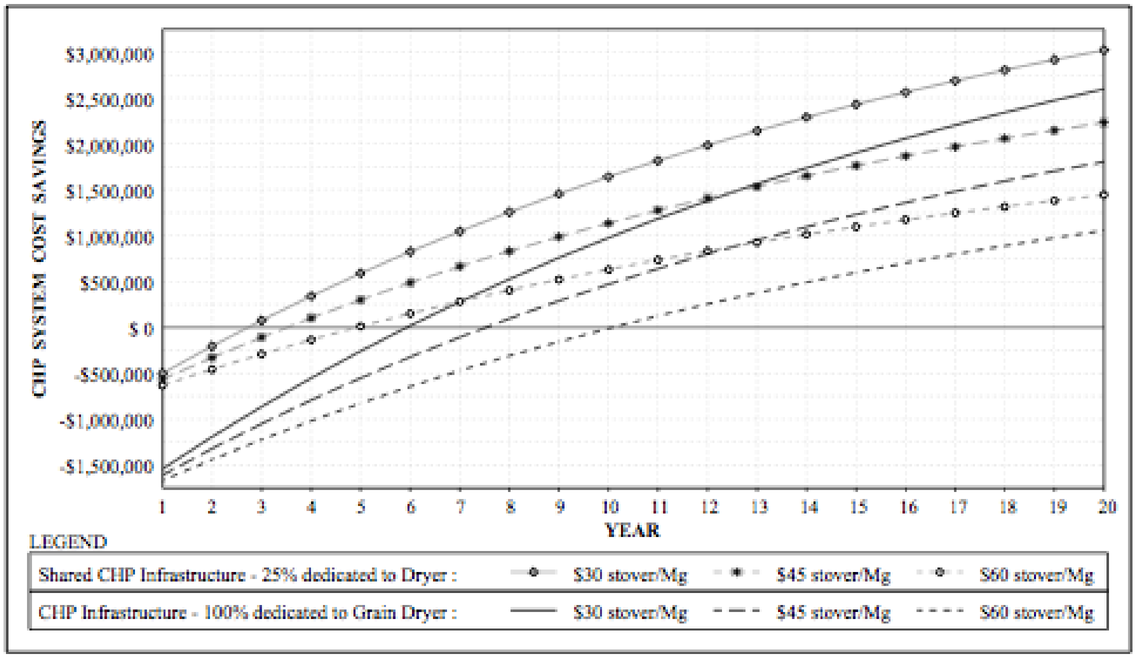

Figure 2. Large dryer (73 Mg h^{-1}): net present value cost of stover-fired combined heat and power dryer "minus" net present value cost of the natural gas-fired dryer.

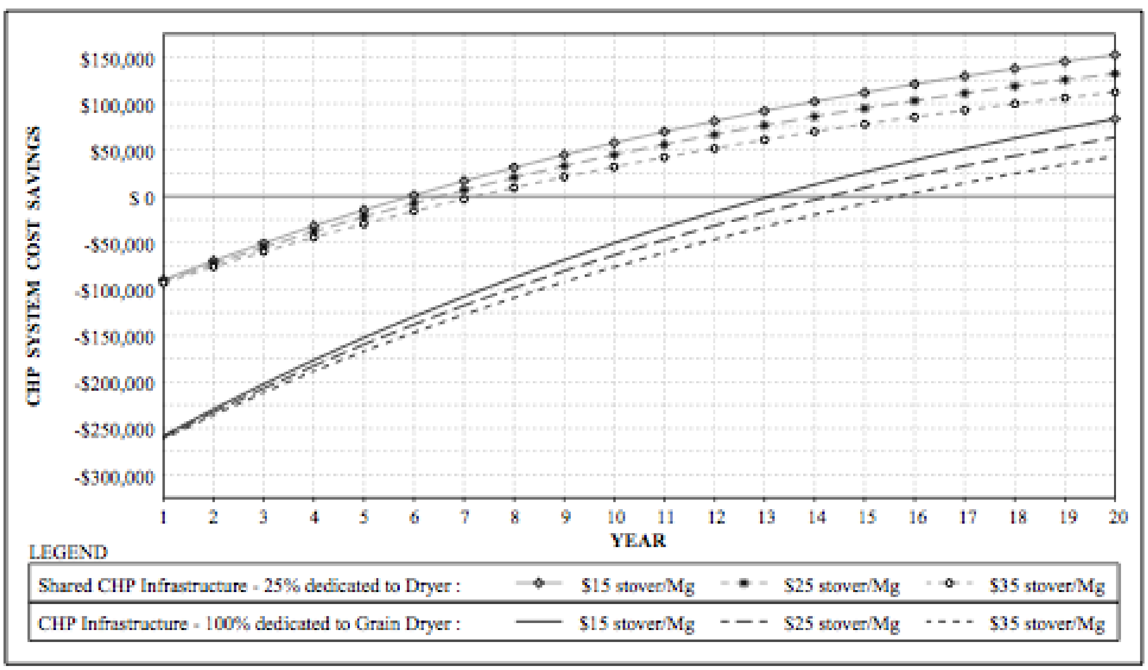

Figure 3. Small dryer (8.9 Mg h^{-1}): net present value cost of stover-fired combined heat and power dryer "minus" net present value cost of propane-fired dryer.

Table 4. Modeled scenarios corresponding to figures 2 and 3.

Scenario	Annual Dryer Use (h)	Fossil Fuel-Fired Dryer[a] Fuel Cost ($ GJ^{-1})	Dryer Capital ($)	Annual Deprec. ($)	Stover-Fired CHP Dryer[b] Stover Cost ($ Mg^{-1})	CHP Capital ($)	CHP Equipment Use	Annual Deprec. ($)	CHP Savings 20-Year Accumulated Savings ($)[c]	Breakeven Point (years)
Large dryer (fig. 2)										
L-1	1680	10.10	175,000	-8,750	30	2,200,350	Dedicated	-110,018	2,593,296	5.9
L-2	1680	10.10	175,000	-8,750	45	2,200,350	Dedicated	-110,018	1,804,482	7.5
L-3	1680	10.10	175,000	-8,750	60	2,200,350	Dedicated	-110,018	1,015,668	10.3
L-4	1680	10.10	175,000	-8,750	30	1,037,850	Shared	-51,893	3,020,693	2.7
L-5	1680	10.10	175,000	-8,750	45	1,037,850	Shared	-51,893	2,231,879	3.5
L-6	1680	10.10	175,000	-8,750	60	1,037,850	Shared	-51,893	1,443,065	4.9
Small dryer (fig. 3)										
S-1	588	16.50	39,000	-1,750	15	374,570	Dedicated	-17,029	83,616	13.1
S-2	588	16.50	39,000	-1,750	25	374,570	Dedicated	-17,029	63,523	14.3
S-3	588	16.50	39,000	-1,750	35	374,570	Dedicated	-17,029	43,430	15.7
S-4	588	16.50	39,000	-1,750	15	187,033	Shared	-7,652	152,565	5.9
S-5	588	16.50	39,000	-1,750	25	187,033	Shared	-7,652	132,472	6.5
S-6	588	16.50	39,000	-1,750	35	187,033	Shared	-7,652	112,379	7.2

[a] Electrical power: $0.068 kWh^{-1}.
[b] Labor to handle stover: $12 h^{-1}.
[c] 7% interest rate.

Table 5. Sensitivity analysis: 20-year CHP savings for dedicated and shared CHP infrastructure.

Variable	Unit	Base Value	Adjusted Value -10%	Adjusted Value +10%	Accumulated Savings ($) -10%	Accumulated Savings ($) +10%	% Difference -10%	% Difference +10%	Breakeven (years) -10%	Breakeven (years) +10%
Large Dryer										
Dedicated CHP - Base case (scenario L-2)										
Annual dryer use	h	1,680	1,512	1,848	1,549,571	2,059,393	-14.1	14.1	8.2	6.9
CHP capital[a]	$	1,689,350	1,520,415	1,858,285	1,878,945	1,730,020	4.1	-4.1	6.9	8.2
Hourly wages	$ h^{-1}	12.0	10.8	13.2	1,827,718	1,781,247	1.3	-1.3	7.5	7.6
Interest rate	%	7.0	6.3	7.7	2,010,931	1,616,039	11.4	-10.4	7.4	7.7
Fossil fuel costs	$ GJ^{-1}	10.10	9.09	11.11	1,306,692	2,302,272	-27.6	27.6	9.0	6.5
Shared CHP - Base case (scenario L-5)										
Annual dryer use	h	1,680	1,512	1,848	1,976,968	2,486,790	-11.4	11.4	3.9	3.2
CHP capital[a]	$	422,338	380,104	464,571	2,263,602	2,200,156	1.4	-1.4	3.2	3.8
Hourly wages	$ h^{-1}	12	10.8	13.2	2,255,114	2,208,644	1.0	-1.0	3.5	3.5
Interest rate	%	7	6.3	7.7	2,406,069	2,072,514	7.8	-7.1	3.5	3.5
Fossil fuel costs	$ GJ^{-1}	10.10	9.09	11.11	1,734,089	2,729,669	-22.3	22.3	4.3	3.0
Small Dryer										
Dedicated CHP - Base case (scenario S-2)										
Annual dryer use	h	588	529	647	45,936	81,110	-27.7	27.7	15.5	13.3
CHP capital[a]	$	293,570	264,213	322,927	74,757	52,289	17.7	-17.7	13.1	15.4
Hourly wages	$ h^{-1}	12.0	10.8	13.2	71,655	55,391	12.8	-12.8	13.8	14.8
Interest rate	%	7.0	6.3	7.7	82,368	46,374	29.7	-27.0	13.5	15.2
Fossil fuel costs	$ GJ^{-1}	16.50	14.85	18.15	32,113	94,933	-49.4	49.4	16.6	12.6
Shared CHP - Base case (scenario S-5)										
Annual dryer use	h	588	529	647	114,885	150,058	-13.3	13.3	7.1	6.0
CHP capital[a]	$	73,393	66,053	80,732	136,811	128,132	3.3	-3.3	5.9	7.1
Hourly wages	$ h^{-1}	12.0	10.8	13.2	140,604	124,339	6.1	-6.1	6.3	6.8
Interest rate	%	7.0	6.3	7.7	146,113	120,014	10.3	-9.4	6.4	6.6
Fossil fuel costs	$ GJ^{-1}	16.50	14.85	18.15	101,062	163,881	-23.7	23.7	7.7	5.6

[a] Includes CHP steam turbine/engine, generator, solid-fuel boiler, and condenser.

(table 4) by varying annual dryer use, CHP capital investments, labor wages, interest rates, and fossil fuel costs by ±10%. For each of the tested variables, table 5 shows the 20-year saving, corresponding percent difference from base case conditions, and breakeven point. The models show the greatest sensitivity to changes in fossil fuel costs, followed by annual dryer use.

CONCLUSIONS

This study illustrates that corn stover can provide an economically viable fuel for grain drying systems for both small and large CHP systems. Sensitivity analysis indicates that the economics of CHP-driven grain dryers resist significant variation in capital, fuel, and labor costs; interest rates; and annual use of CHP equipment. However, some significant challenges must be met before CHP dryers can be considered practical for commercial applications. Prominent constraints include the high cost of relatively small turbine and generator systems, and the unavailability of large steam engines (or small turbines) and commercial dryers fitted with steam condensers. The capital investments required for boiler systems capable of handling agricultural residues are also significant (nearly ten times the cost of package fossil fuel boilers). High boiler and CHP equipment costs, however, can be mitigated by sharing the CHP infrastructure with other heat-requiring processes and, with time, can benefit from competition and wider applications of biomass-based CHP systems. This cost reduction is especially important for small to medium-sized farming operations, where the high initial capital investments and longer payback, combined with additional labor and maintenance requirements, will limit the practical application of farm-scale CHP systems.

Farm-based and local micro-, small-, and medium-scale CHP facilities offer considerable potential. With the right focus, these CHP systems will be able to take advantage of the large supplies of local, carbon dioxide neutral, agricultural and forestry residues, and dedicated energy crops, which will ultimately provide greater national security, and an environmentally friendly and more sustainable energy base.

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