Biomass gasification for farm-based power generation applications

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Abstract

Willow biomass crops have been shown to be a good fuel for farm-based power production using advanced gasification technology. The fuel gas can be used for generating electricity, using microturbines modified to operate on low-BTU gas, or for other farm energy needs. Willow biomass was found to make an excellent fuel for ash-rejection gasifiers with a predicted net gasification efficiency of about 85 percent. The main drivers to the cost-of-electricity were found to be associated with the harvesting, handling, and transporting of the willow biomass, accounting for 40 to 50 percent of the annual operating cost. In the present study, analysis showed that developing a method to co-gasify willow with various amounts of low-cost wastes, such as dairy farm animal waste, can be an excellent way to reduce the fuel cost, to increase the overall fuel availability and help work around problems resulting from seasonal availability of bioenergy crops. Co-gasification of dairy farm wastes along with willow offers an economical way to dispose of the wastes and manage nutrient flows on a dairy farm. The power generated from the animal waste can be used on the farm or sold to offset the cost of waste treatment.
Keywords: willow biomass, Salix, dairy-farm animal wastes, co-gasification, air-blow gasification, farm-based power system.

1 Introduction

A study was recently carried out to investigate the feasibility of using an advanced gasifier to convert willow biomass crops into a fuel gas that could be

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used for farm-based power production [1]. In the proposed power system, the gasifier product gas can be either utilized in microturbines for generating electricity or used for other farm energy needs. This paper reports on the extension of the original willow biomass study to include the co-gasification of willow with dairy-farm animal wastes as a way to lower the cost of energy production, increase the overall fuel availability, and to manage nutrient flows on a farm.

Willow is one of the more promising short-rotation woody crops for energy use in the near future in the northeastern and north-central United States. In New York, the federal and state governments have made a concerted effort to develop willow crops as an alternative renewable energy source. The cultiva-tion and use of willow for the production of bioenergy or bioproducts provide numerous potential environmental and rural development benefits. These benefits include reduction and replacement of fossil fuel usage, reduced imports of fuel and export of dollars, new uses for agricultural lands currently out of production, and creation of jobs in rural New York [2]. The near term use for willow biomass crops is co-firing with coal in existing utility power plants and direct-fired biomass facilities. Co-firing results in consistently reduced SO_x emissions, and reduced NO_x emissions under certain operating conditions. Gasification offers an alternate method of converting willow biomass to energy that should produce substantially less net CO_2 emission, more fuel flexibility and provide opportunities for distributed power generation.

Study results indicate that willow biomass makes an excellent gasifier fuel because of its low ash content and high ash-fusion temperature. The predicted gasification efficiency of the willow-fueled gasifier is about 85 percent [1]. Although willow would make an excellent gasifier fuel, it is still a relatively expensive fuel because it is a cultivated crop. In order for willow to be a commercially viable bioenergy fuel, it must be able to compete in a market where there is already an abundance of low-cost and negative-cost waste fuels. In the willow gasification system, the fuel cost accounts for 40 to 50 percent of the annual operating costs. For this reason, continuous efforts have been made to reduce the cost of willow biomass crops by improving yields and reducing production costs; and adding value to the multiple environmental and rural development benefits associated with the crop through programs such as the Conservation Reserve Program, federal biomass tax credits, green pricing premiums, renewable portfolio standards, and agricultural tax assessments on land used for growing willow crops.

Another issue with the willow fuel is its seasonal availability. Willow biomass crops are typically harvested in late fall and during the winter. Storage and scheduling of fuel will be needed in order to use willow for year-round power generation. Co-gasifying willow along with agricultural wastes can be a way to increase the overall fuel availability, ease the effects of seasonal variability of willow supply, and lower the cost-of-electricity (COE) of the power system.

Dairy farm animal waste is a possible fuel for co-gasification with willow biomass. In a previous study, we demonstrated that dairy farm wastes can be an excellent biomass fuel for our advanced gasifier [3]. A major problem facing the dairy industry is the proper disposal/utilization of livestock waste. Dairy farms have historically imported three times more nutrients than they export. Field spreading of manure, to recycle the nutrients to the crop fields, can cause soil to become saturated with some nutrients resulting in non-point source pollution. As stricter environmental regulations are applied, farms need a way to reduce the amount of manure they spread in a cost effective manner. Gasification offers an economical way to dispose of the wastes and to remove the nutrients from the farm. The power generated from the animal waste can be used on the farm or sold to offset the cost of waste treatment.

In the proposed co-gasification scheme, shown in Fig. 1, willow biomass will be made available to the dairy farm operator for use as animal bedding. In exchange, the liquid portion of the animal manure will be transported to the willow farm for use as fertilizer. The solid portion of the manure and the soiled bedding from the dairy farm are used to augment the willow biomass fuel for the gasifier. The nutrients that are concentrated in the combustion wastes of the gasifier are in forms that can easily be transported off the farms and sold as fertilizers. The export of nutrients from the dairy farm, in the form of liquid manure to the willow fields and solid manure to the gasifier/power system, will help reduce or eliminate field spreading of manure, which currently cost New York state dairy farms an averaged of about \$50/cow/year in labor and equipment. The proposed arrangement will eliminate the need for dairy farms to purchase wood chips and sawdust for beddings, resulting in additional saving of approximately \$50-100/animal/year [4]. In order for this scheme to be feasible, the willow production fields will need to be in close proximity to the dairy farms to minimize transportation costs, or strategically located on the dairy farms and integrated directly into the dairy farm operations to further reduce non-point source pollution.

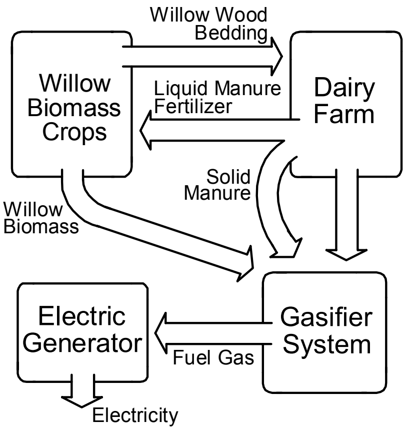

Figure 1: Proposed willow/dairy farm-based power system.

The particular gasification system we have selected for our application was originally developed using high-temperature preheated air to convert coal and waste-derived fuels into synthetic fuel gas and value-added byproducts. This advanced gasifier system, known as MEET (Multi-staged Enthalpy Extraction Technology), has several unique attributes that are advantageous for biomass power generation. The gasification technology and its attributes are described in Section 2. The gasifier performance and cost analysis results, as well as implementation issues associated with the willow-biomass/manure-waste co-gasification scheme, are reported in Section 3.

2 Description of gasification system

The basic scheme of the gasification system is shown in Fig. 2. Solid fuel is gasified using high-temperature, preheated air in a reactor vessel to produce a flammable raw synthetic gas. The inorganic ash residue from the gasification reactions is extracted from the gasifier either as a molten slag (slagging mode of operation) or as ash (non-slagging or dried-bottom operation), depending on the selected operating temperature of the gasifier. Upon exiting the gasifier, the fuel gas is cooled in a heat recovery boiler and then cleaned, using conventional gas cleanup technology. A small fraction of the product gas is diverted to the preheater where it is used for heating the gasification air. Depending on the intended application of the plant, the rest of the cleaned fuel gas is utilized for a variety of possible downstream processes.

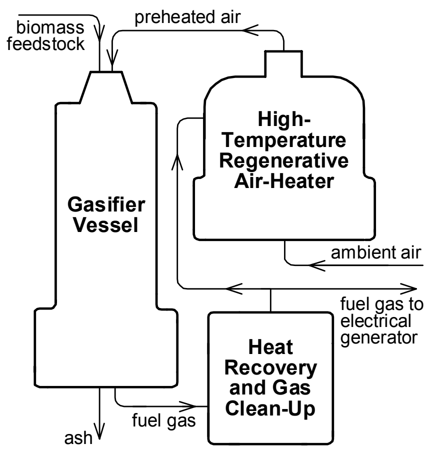

Figure 2: Basic scheme of the MEET gasification system.

The gasifier vessel consists of an entrained-flow section, followed by a particulate-removal section. In the slagging MEET gasifier, the gasification temperature is maintained above the fluid temperature (FT) of the ash and a high-temperature ceramic pebble-bed filter is used for particulate removal.

When the gasifier is configured in the dried-bottom mode, the operating temperature is maintained at a value below the ash's initial deformation temperature (IDT) and an aerodynamic particulate removal device is used for ash rejection. Gasifier operations in the temperature range between the IDT and FT are avoided to prevent ash agglomeration and fouling problems. A compact regenerative heater supplies the high-temperature air for the gasifier. As mentioned previously, the source of heat for this preheater comes from the combustion of a small amount of the fuel gas produced by the gasifier.

The use of high-temperature air in the MEET process increases the yield of the gasification process over those of conventional air-blown gasifiers [5]. This is because preheated air increases the heating rate of the incoming fuel and the volatile yield from the fuel particles is greatly enhanced under these high-temperature, rapid-heating conditions. Another reason for the increased yield is that higher caloric-valued syngas can be obtained using preheated air as the gasifying agent. The gasifier can be operated at substantially more fuel-rich conditions to achieve the given gasification temperature, leading to higher caloric-valued product gas.

In addition to higher gasification yields, the MEET gasification system has several other features that are advantageous for biomass power generation applications. These attributes include fuel flexibility, compact size, ability to operate on low-rank solid feedstock and transportability. The MEET gasifier technology and the current status of its development are described in Pian and Yoshikawa [5].

3 Performance and COE estimates of the willow/manure gasification system

The ultimate and ash analyses of the biomass feedstock used in this study are shown in Table I. The willow wood data are based on the averages of a large group of SUNY College of Environmental Science & Forestry (ESF) crops harvested in the winter of 1999 [1]. The variations in composition between the different wood samples were small, on a dried basis. However, large variations in moisture content were typical due to differences in harvesting and storage conditions of the test samples.

The manure samples were collected from Sun Rich Farms, located in Albian, New York [3]. The ultimate and ash analyses of the manure waste are similar to those for grass and hay, except for the higher ash and SiO_2 contents, which presumably are caused by the soil that was picked up during manure collection or ingested by the cow while feeding.

The solid fuel's ash IDT and FT temperatures are important parameters needed for configuring our gasifier and for determining its operating condition. The values of these temperatures, under both oxidizing and reducing conditions, were determined using a hot-stage microscopic (HSM) technique [6]. Measured results of these temperatures are shown in Fig. 3 for varying mass fractions of willow biomass in the overall gasifier feedstock. The ash fusion temperature of the fuel decreases with increasing fractions of manure. This trend is due to the higher concentrations of phosphorus, potassium and sodium in the manure ash, which act as fluxing agents, as well as higher concentration of SiO_2, which can form a eutectic with CaO that lowers the fusion temper-ature. Comparison of ash fusion temperature measurements made in reducing and oxidizing conditions also showed minimum differences between the values. This behavior for the willow/manure ash, which has very low ferric concentrations, is similar to that measured for low-iron coal ashes [7]. Based on the HSM results one can conclude that the ash-rejection MEET gasifier should not encounter any ash fouling problems when operating at 900°C for any mixture ratios of willow and manure.

Table 1: Analyses of SUNY-ESF willow biomass crops and Sun Rich Farms manure wastes.

Ultimate Analysis of Willow*		Ash Analysis	
Carbon (mass %)	49.71	Al_2O_3 (mass %)	0.20
Hydrogen	5.97	CaO	41.92
Oxygen	42.16	Fe_2O_3	0.73
Nitrogen	0.50	MgO	3.52
Sulfur	0.03	ZnO	0.35
Ash	1.62	P_2O_5	9.05
		K_2O	13.22
		SiO_2	3.65
HHV (cal/g)	4,798	Na_2O	0.28
		SO_3	2.40
Ultimate Analysis of Manure**		Ash Analysis	
Carbon (mass %)	44.65	Al_2O_3 (mass %)	1.51
Hydrogen	5.85	CaO	32.13
Oxygen	38.18	Fe_2O_3	0.93
Nitrogen	2.05	MgO	9.84
Sulfur	0.31	MnO	0.17
Ash	8.96	P_2O_5	13.04
		K_2O	9.41
		SiO_2	19.83
HHV (cal/g)	4,352	Na_2O	5.95
		SO_3	5.57
		TiO_2	0.11

* Dried basis.

** Dried basis. The as-received manure, after separation of liquid fertilizer by mechanical press, contained 69.57 mass % moisture.

The gasifier performances were estimated using a previously developed gasifier model [5]. The model assumes chemical equilibrium conditions and uses the minimization of Gibb's free energy method to determine the thermodynamic properties at the state points. Validation of model results was carried out previously by comparisons with coal-fired gasifier test data.

Figure 4 shows the estimated net gasifier conversion efficiencies and costs-of-electricity for the co-gasification of willow with various amounts of manure wastes. An air-preheat temperature of 1230°C and a fuel moisture content of 10% are assumed. The gasifier is configured in the non-slagging mode with an operating temperature of 900°C to minimize ash fouling problems. The net gasifier conversion efficiency is defined as the higher heat value of the product fuel gas, after subtracting that portion of the fuel gas used to fire the air preheater, divided by the thermal input of the solid fuel. The net conversion efficiency for the gasifier operating on willow is 85 percent and on manure is 80 percent [1]. For co-gasification operations, the gasifier performance decreases with increasing mass fraction of manure waste in the total fuel. This behavior can be attributed to several factors. The heating value of the manure waste is approximately 10% lower than that of the willow biomass. Consequently, as the mass fraction of manure waste increases, the gasifier must operate at a less fuel-rich condition to maintain the 900°C gasification temperature; larger fractions of the incoming fuel must be used to raise the gas temperature, resulting in a lower caloric-valued product gas. With increasing manure mass fraction, greater amount of the product fuel gas is used in the air preheater, also contributing to lowering the net gasifier efficiency.

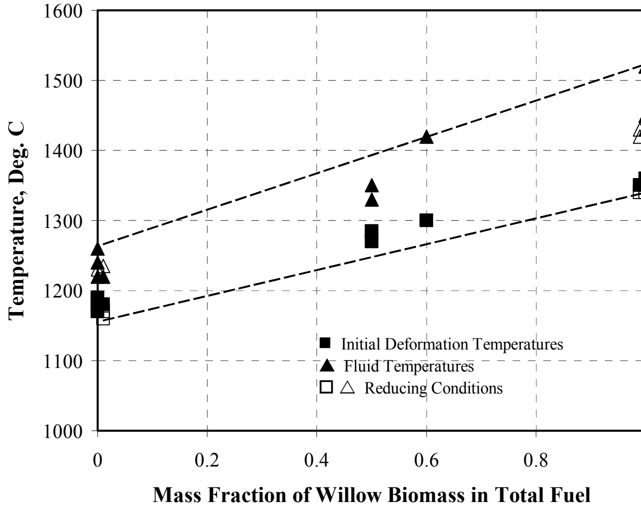

Figure 3: Fusion temperatures of willow/manure ash determined from hot-stage microscope data.

For our cost analysis, we selected a gasifier system with a capacity for processing approximately 160 kg of dried willow biomass and/or manure wastes per hour. For a gasifier of this scale, one reactor vessel can process the yearly crop yield of a 106-ha willow farm or the animal wastes produced yearly by a

400-animal dairy farm. For larger applications, multiple units of this reactor will be used. A MEET gasifier of this size has been previously built and tested at the Mississippi State University by Pian and Yoshikawa [5]. This refractory-lined vessel, with exterior dimensions of approximately 1-m diameter and 3-m length, can be mounted on a flatbed truck for mobile applications.

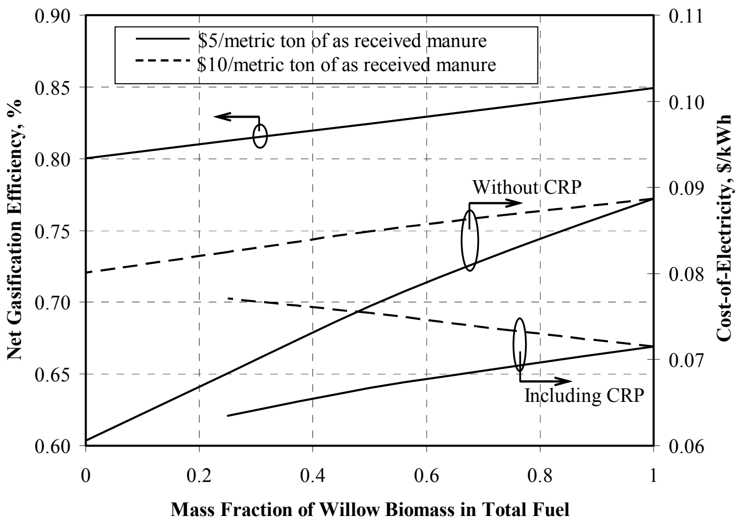

Figure 4: Net efficiency and cost-of-electricity vs. mass fraction of willow biomass.

Microturbines, modified to operate on low-calorific fuel gas, will be used to generate electrical power for our small on-farm applications. FlexEnergy developed these 30-kW microturbine units in partnership with Capstone Turbine Company. Conversion efficiencies (fuel gas-to-electricity) of the order of 22% have been achieved during initial demonstration tests using low-calorific fuel gas [1]. If one assumes all the fuel gas available from the biomass gasification are used to generate electricity, then five microturbine units are required to support each gasifier unit.

The COE for the willow-fueled power system was estimated previously to be $0.09/kW-hr and a capital cost of about $2,833/kW [1]. The system consisted of a MEET gasifier operating in the dried-bottom mode and five microturbines. The COE estimate assumed a 25-year lifespan for the capital equipment, an annual 6% interest rate, an averaged 85% availability, and a willow delivered cost of $49.6/metric ton of dry wood. The COE also included an operation and maintenance cost of $0.012/kWh. The willow delivery cost was determined from actual field experiences accumulated by SUNY-ESF [8]. When the contributions from the Conservation Reserve Program (CRP) are included as part of producing the willow biomass, then the delivered price was reduced to $31.7

per metric ton of dry wood and the COE would decrease to $0.073/kWh. The CRP program contributes funding through the US Department of Agriculture, which partially pays for the site preparation and planting costs, as well as an annual rent payment to the farm landowner. Possible economic benefits from the sale of process heat, recovered solids/nutrients, or other "green energy" price premiums or tax incentives were not factored into the cost analysis.

Figure 4 shows the potential to lower COE by co-gasifying willow with various amounts of dairy-farm manure. Also shown are the sensitivities of estimated COE's to the assumed manure costs and the impacts of CRP contributions. Variations in the assumed manure cost can be used to account for project specific factors such as manure preparation, handling or transportation costs. The contribution of co-gasification to lower COE increases with increasing willow-fuel cost and decreases with increasing manure cost. Also, co-gasification can be a viable method to keep the willow-gasification power system commercially competitive after the various tax incentives have expired.

Usage of willow as bedding for dairy cows shows no evidence of being very different than any other wood bedding, assuming similar particle size and moisture content. However, dairy operators are reluctant to switch to willow for bedding in place of their current practice unless they can be convinced the practice is safe and beneficial to them. The willow must be proved acceptable by demonstration of use and the cost must be shown to be substantially lower than the $50/cow/year price of current wood bedding. Several New York-based dairy farms have agreed to be involved with trial demonstration tests, using willow bedding in heifer pens. Initial test results indicated the willow would need to be chipped finer, to the consistency of sawdust, and dried to a moisture content of 20 to 45%. Both requirements can be easily met. The particle size can be changed by new forage harvester systems that are being developed for willow biomass crops. Lower moisture content is obtainable by using the waste heat of the gasifier system to dry the willow or letting the willow sit on the field or in storage for a longer period of time. The benefits to the dairy farms are numerous. In addition to lower cost for bedding, and environmental and financial benefits from better nutrient management, the energy produced from the manure waste can contribute to lower farm operating cost; and in many cases become another source of revenue for the farms. In an earlier manure-gasification case study, we have found that the production of fuel gas from gasification of farm animal waste from a particular upstate NY dairy farm can generate almost four times the amount of energy necessary for energy self-sufficiency [3].

4 Summary

Willow biomass makes an excellent fuel for ash-rejection gasifiers because of its low ash content and high ash-softening temperature. The predicted gasification efficiency of the willow-fueled gasifier is about 85 percent. Higher fuel costs and seasonal variation in availabilities are some of the drawbacks associated with using willow wood for energy production. Co-gasifying willow wood with biomass wastes in a flex-fuel gasifier can be an effective way to lower the net cost of the fuel and ease the effects of seasonal variability in the willow supply.

The performance and operating characteristics of the MEET gasifier running on various ratios of willow biomass and dairy-farm livestock waste were investigated. The gasification efficiency decreased slightly, from 85 to 80 percent, with increasing amount of manure in the fuel mix. The contribution of co-gasification to lower COE increases with increasing willow-fuel cost and decreases with increasing manure cost.

Co-gasification of willow with manure waste also benefits the dairy farm operators, by offering an economical way to manage nutrient flows on the farm and reduce non-point source pollution. The power generated from the animal waste can be used on the farm or sold to offset the cost of waste treatment. In order for this scheme to be feasible, the willow production fields will need to be in close proximity to the dairy farms to minimize transportation costs, or strategically located on the dairy farms and integrated directly into the dairy farm operations.

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