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OPPORTUNITIES FOR HYDROGEN: AN ANALYSIS OF THE APPLICATION OF BIOMASS GASIFICATION TO FARMING OPERATIONS USING MICROTURBINES AND FUEL CELLS

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Abstract

This paper examines the concept of using biomass gasification in conjunction with microturbines or fuel cells to generate electricity for on-farm installations. The biomass farm feedstock would be either switchgrass or wood. Various levels of hydrogen purity required relative to the prime mover are discussed. In general, individual on-farm electricity demand is relatively low (12 kW). Commercial stationary power generation fuel cells are currently available in the 200-kW size range, and many nonstationary power generation proton-exchange membrane fuel cells are being produced at lower power levels. Commercial microturbines are available as 30-kW units. Approximately 250 acres of land would be required to produce biomass in the form of switchgrass or willow for a 200-kW power plant. It is expected that higher-value crop production will most likely be the primary focus for U.S. farmers and that power production will remain a secondary interest. The primary factors holding back the interest in power production are low electric rates, high system capital costs, and operating costs. Gasification to fuel cells or microturbines could compete if capital costs approached < $1000/kW and systems could be completely automated. The results of a study comparing the costs of gasifiers coupled to various fuel cells and a Flex-Microturbine™ are presented. The capital cost of the systems studied ranged from $1300 to $4450/kW, with the Flex-Microturbine™ and molten carbonate fuel cell systems having the lowest capital and operating costs.

Introduction

The U.S. Department of Energy's (DOE's) Hydrogen Program mission is to enhance and support the development of cost-competitive hydrogen technologies and systems that will reduce the environmental impacts of energy use and enable the penetration of renewable energy into the U.S. energy mix. To achieve this mission, the Hydrogen Program has four strategies, which include 1) expanding the use of hydrogen, 2) developing storage and generation technologies, 3) demonstrating hydrogen vehicles and fueling systems, and 4) lowering the cost of technologies that produce hydrogen directly from sunlight. The project described here was supported by DOE's Hydrogen Program to complete systems analysis for information dissemination and outreach.

Hydrogen is one of the most promising energy carriers for the future. It is an energy-efficient, low-polluting fuel. When hydrogen is used in a fuel cell to generate electricity or is combusted with air, the only products are water and a small amount of NO_x. Hydrogen is renewable and found in many compounds such as water, fossil fuels, and biomass. Hydrogen typically makes up about 6% by weight of dry biomass. Using biomass for energy results in lower emissions than using fossil fuels. Carbon dioxide is continuously recycled as biomass in the form of trees and other plants that use it to regenerate, and lower emissions of sulfur and NO_x can be expected when converting woody biomass in comparison to coal. To obtain hydrogen from biomass, pyrolysis or gasification must be applied, which typically produces a gas containing 20% hydrogen by volume, which can be further steam-reformed to make higher-purity streams for various fuel cells. The challenge is to overcome the economic barriers that current technology presents for converting biomass to hydrogen for use in clean, efficient energy conversion devices. The following analysis compares technologies, approaches, and costs for near-term small biomass gasification power technologies.

Design Criteria and Discussion

This analysis examines the concept of using biomass gasification in conjunction with microturbines or fuel cells to generate electricity for on-farm installations. The biomass farm feedstock would be either switchgrass or wood. The project decisions involve selecting size range, gasifiers, gas preparation equipment, and prime movers to analyze and compare. The purpose of the comparison is to identify challenges for technologies in this area.

The following are the basic drivers in the decision-making process:

- Resource availability
- On-farm energy use
- Technology status
- Cost

Information was collected to assess resource availability for small farming operations. It was assumed that dairy farms would most likely be the highest users of electricity, since refrigeration equipment is required to be operated around the clock for most of the year. Large dairy farms may house 2000 head of cattle, and small farms have lately trended toward about 500 milking head; however, the average is approximately 250 head. Resource availability is based on the number of cattle. Land ownership for dairy farms is typically an acreage 4 times the amount of cattle. The expected electrical use of a dairy farm is about 440 kWh/cow (University of Vermont Extension Service 1999). This equates to a 12.6-kW average annual load. According to Vogel and Masters (1998) the most productive switchgrass species can yield 12,500 lb/acre/year of product. Similar production rates have also been found for fast-growing willow species. A typical small biomass gasification power plant will consume 2 lb/hr/kW_e (Schmidt et al. 1998). Table 1 shows the various land area requirements of a dedicated biomass energy crop relative to total farm acreage and cattle population.

Table 1. Resource Availability for Energy Crop Power Production

No. of Cows	Total Land Area (acres)	Annual Electricity Use (kWh)	Average Load (kW)	Land Required for Biomass Energy Crop (acres)
250	1000	110,000	12.6	17.6
500	2000	220,000	25.1	35.2
1000	4000	440,000	50.2	70.4
2000	8000	880,000	100.5	140.8

In general, individual on-farm electricity demand is relatively low (12 kW). Although the data in Table 1 suggest using very small power plants, commercial stationary power generation fuel cells are typically only available in the 200-kW size range. Proton-exchange membrane (PEM) fuel cells are being developed at smaller power levels for residential markets and the automotive industry, and may become good options; however, they require a higher level of gas purity. Commercial microturbines are available as 30-kW units. Given the status of current technology, the authors chose to compare all technologies at the 200-kW size. Some additional cases are also presented to show the potential of PEM technology in the smaller size ranges. In order to supply a 200-kW power plant, approximately 250 acres of land would be required.

Flex-Microturbine™

In the past, the primary technology focus for conversion of hydrogen to electricity has been the fuel cell. Fuel cells are promising, but currently expensive. They require extremely high-purity hydrogen, which is also expensive to produce. According to Prabhu et al. (1998), an innovative new approach is to use the Flex-Microturbine™ that will accept low-pressure fuel of significantly lower purity and concentration, would require much less capital, is closer to commercialization, and could stimulate hydrogen use in a shorter time frame than fuel cell technology. This investigation looks at whether the increased efficiency of fuel cells can offset the capital investment in the required gas-cleaning equipment.

Microturbines are already available commercially, with prices expected to drop sharply. They are currently designed to work on natural gas, not hydrogen. With key modifications, including a catalytic combustor, the microturbine could be converted into a Flex-Microturbine™, which is much more fuel flexible and capable of running on a whole range of hydrogen fuel gases with much lower purity than required by fuel cells. Figure 1 illustrates the Flex-Microturbine™ concept.

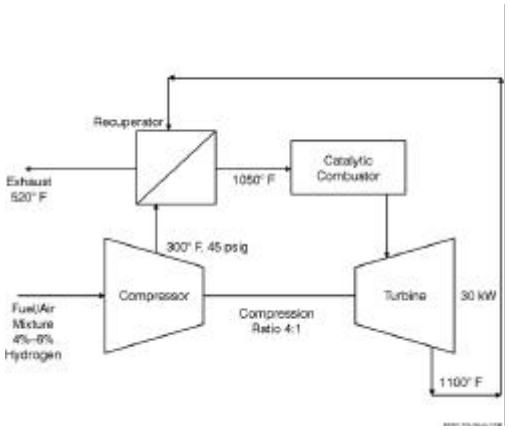

Figure 1 – Flex-Microturbine™

Fuel Cell Technology

Currently there are four basic types of fuel cells that can or have potential use with biomass gasification. They are characterized in terms of their electrolyte component and include PEMs, (also referred to as polymer electrolyte fuel cells), phosphoric acid fuel cells (PAFCs), molten carbonate fuel cells (MCFCs), and solid oxide fuel cells (SOFCs).

The PEM fuel cell electrolyte is a thin polymer. This semipermeable membrane allows protons to pass, but insulates the electrical contacts. The cell operates at a low temperature, approximately 80°C (175°F). A PEM fuel cell's output can vary quickly, making it well-suited for automobile applications and residential and commercial buildings. PEM technology is commercially available in the smaller size ranges, typically under 10 kW. Efficiency is 30%–35%. The costs of PEM fuel cells are expected to decrease sharply as applications occur in the automotive industry. Daimler Chrysler's NECAR fuel cell engine costs $30,000 or approximately $600/kW. Mass-produced automotive internal combustion engines typically sell for $3000. Ballard is developing a 250-kW stationary unit currently in field trials. The capital cost target is $1000–$2000/kW.

PAFC technology is available commercially and being used in many applications, including buses and stationary power. Reliability averages over 96%. Electrical generation efficiency is typically 36%. Stationary units can be provided at 200 kW that operate on natural gas. A typical unit installation cost is $850,000, and a $1,000/kW federal rebate can be obtained. Costs are approaching $2000/kW. The PAFC operates at 200°C (392°F), and uses a phosphoric acid electrolyte. ONSI corporation has sold over 200 units.

MCFCs technically offer the best potential to be coupled with large coal and biomass gasification processes. MCFCs can be built from stainless steel and less exotic materials than their SOFC counterpart. The cell can accept carbon monoxide and tolerate carbon dioxide. Carbon dioxide is used in the cathode reaction and obtained from the output of the anode reaction. The fuel cell operates at 650°C (1200°F), and offers the highest efficiency capability of all fuel cell types (45%–55%). MCFCs have been installed in several demonstration projects around the world, but are not commercially available products. Fuel Cell Energy is developing its Model 9000 fuel cell and demonstrating 250-kW stationary fuel cell stacks. A current MCFC would cost as high as $8000/kW.

SOFCs also show good promise for high efficiencies. The cell operates at 1000°C (1800°F), and uses a solid yttria-stabilized zirconia electrolyte. This allows for the hard ceramic electrolyte to be formed in a tubular arrangement rather than a flat plate, which is difficult to seal at the ends. The SOFC is fuel-flexible, much like the MCFC, but will probably be geared toward large generation applications to be economically attractive because of the relative cost of the high-temperature materials. A lower-temperature 660°C (1220°F) SOFC is also under development. Siemens Westinghouse has demonstrated 100-kW stacks; however, costs remain high and proven operational time has been minimal.

All of the technologies mentioned above are essentially the same in several respects. They are all electrochemical devices that convert the chemical energy of reaction directly into electrical energy. They consist of an anode, cathode, and electrolyte. They continuously use fuel, primarily hydrogen, and air (oxygen) in a reverse electrolysis manner to produce electricity. These technologies differ in their electrochemical reactions, materials of construction, tolerance to contaminants, fuel flexibility, and operational characteristics. These characteristics, briefly described above, vary the application of the technologies and cost. Tables 2–4 below delineate the different characteristics of PEM, PAFC, MCFC, and SOFC technologies.

Table 2. Various Fuel Cell Technologies and Characteristics

Fuel Cell Technology	Electrolyte	Anode	Cathode	Operating Temperature	Electrical Efficiency
PEM	Ion-exchange membrane, hydrated organic polymer	Platinum	Platinum	175°F	30%–35%
PAFC	Phosphoric acid	Platinum	Platinum	392°F	35%
MCFC	Molten Li/Na/K carbonate	Nickel	Nickel oxide	1200°F	45%–55%
SOFC	Yttria-doped zirconia	Nickel	Sr-doped lanthanum manganite	1800°F	45%–47%

Table 3. Electrode Reactions for Various Fuel Cells

Fuel Cell	Anode Reaction	Cathode Reaction
PEM	$H_2 \rightarrow 2H^+ + 2e^-$	$½\ O_2 + 2H^+ + 2e^- \rightarrow H_2O$
PAFC	$H_2 \rightarrow 2H^+ + 2e^-$	$½\ O_2 + 2H^+ + 2e^- \rightarrow H_2O$
MCFC	$H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^-$ $CO + CO_3^{2-} \rightarrow 2CO_2 + 2e^-$	$½\ O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-}$
SOFC	$H_2 + O^{2-} \rightarrow H_2O + 2e^-$ $CO + O^{2-} \rightarrow CO_2 + 2e^-$ $CH_4 + 4O^{2-} \rightarrow 2\ H_2O + CO_2 + 8e^-$	$½\ O_2 + 2e^- \rightarrow O^{2-}$

Table 4. Contaminants and Poisons for Various Fuel Cells (Hirschenhofer et al. 1998)

Gas Species	PEMFC	PAFC	MCFC	SOFC
H_2	Fuel	Fuel	Fuel	Fuel
CO	Poison (>10ppm)	Poison (>0.5%)	Fuel	Fuel
CH_4	Diluent	Diluent	Diluent	Fuel
CO_2 and H_20	Diluent	Diluent	Diluent	Diluent
S as (H_2S and COS)	No studies to date	Poison (>50 ppm)	Poison (>0.5 ppm)	Poison (>1.0 ppm)

Approach

Various methods were analyzed for producing power from biomass gasification. Four prime mover technologies were compared, including the Flex-Microturbine™, PEM fuel cell, PAFC, and MCFC. Two gasification technologies were also used in the analysis. Considering the various purity requirements, it appears that the Flex-Microturbine™, PAFC, and MCFC would couple well to a small downdraft gasifier. Downdraft gasifiers are relatively simple, low-cost, low-pressure devices, which produce relatively clean gas suitable for power generation. Figure 2 is a schematic of a downdraft gasifier system, and Table 5 compares gasification technologies and gas contaminant levels.

PEM fuel cells have the advantage of becoming the first mass-produced low-cost fuel cells in the marketplace, a good reason for considering this technology. In order to link a gasifier to PEM fuel cell technology, the fuel gas must be high-purity hydrogen. The Battelle indirectly heated biomass gasifier applies well to PEM technology. As compared to direct gasification, which produces a high-nitrogen-content gas stream, the indirect process enables production of a gas stream consisting primarily of carbon monoxide, hydrogen, methane, and carbon dioxide. This gas can be steam-reformed and catalyzed to produce a 62% hydrogen-rich gas. This gas is then run through a pressure swing absorption unit to separate the hydrogen.

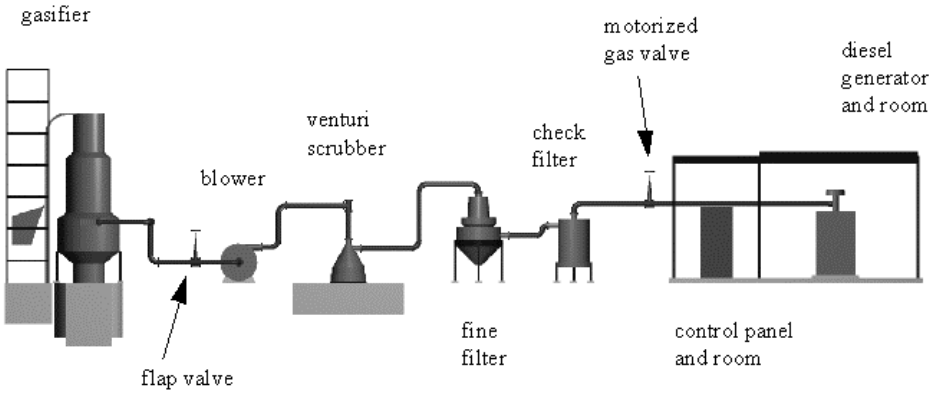

Figure 2 – Downdraft Gasification System

Table 5. Gasifier Contaminant Loadings

Gasifier Type	Tar Production	Relative Particulate Loading
Updraft	50,000–200,000 ppm	Intermediate
Downdraft	100–1000 ppm	Low
Fluidized Bed	1000–50,000 ppm	High

Analysis

Flex-Microturbine™

The Flex-Microturbine™ power system concept consists of the components shown in Figures 1 and 2. A small, simple downdraft gasification system is coupled to a microturbine that houses a small catalytic combustor (DeLaquil 1999). The catalytic combustor enables the microturbine to operate directly on low-Btu, low-pressure gas. An air–fuel mixture is induced through the compressor side of the turbine, then converted catalytically in the turbine and expanded through the power side of the turbine. This concept is currently being developed by Flex-Energy through DOE's small modular biomass program. Capital and operating costs are compared in Tables 6 and 7, respectively.

Battelle Indirect Gasifier PEM Fuel Cell

Briefly described, the Battelle system gasifies biomass by injecting steam and recycling hot sand from a char combustion unit. The initial gas contains about 20% hydrogen. This gas is then scrubbed, pressurized, steam-reformed, shift-reacted, cooled, and purified in a pressure swing absorption unit. The steam used for gasification is created from process waste heat. The reformed gas contains 62% hydrogen and is purified for use in a PEM fuel cell. A complete description of the Battelle indirectly heated gasifier for producing hydrogen can be found in Mann (1995). This report gives process flow information, capital, and operating costs. Three systems, 1000-, 300-, and 30-tpd, are described in the report. The 30-tpd system is equivalent to a 750-kW gasifier fuel cell power system. Component cost curves were generated on the basis of the given data and used to estimate system costs below 30 tpd. The results are shown in Tables 6 and 7. PEM fuel cell costs are estimated at $600/kW, which could be expected within the next 5 years.

Table 6. Capital Cost Comparison

Capital Cost Comparison	Battelle PEMFC System			Flex-Microturbine		MCFC	PAFC
Plant size biomass feed rate	30 tpd	8 tpd	0.5 tpd	5.4 tpd	0.7 tpd	2.8 tpd	3.6 tpd
Hydrogen production	31,773 scfh	8,473 scfh	530 scfh				
Power output	754 kW	201 kW	13 kW	210 kW	27 kW	200 kW	200 kW
Gasification System Installed	$ 655,964	$ 260,051	$ 37,340	$ 126,000	$ 16,200	$ 160,000	$ 200,000
Gas Preparation & misc.	$ 804,567	$ 296,977	$ 46,596			$ 75,000	$ 233,000
Catalyst Module				$ 21,000	$ 2,700		
PSA system Installed	$ 812,926	$ 216,784	$ 13,549				
PEMFC (projected $600/kW)	$ 452,400	$ 120,600	$ 7,800				
Microturbines @ $600/kW				$ 126,000	$ 16,200		
MCFC & PAFC fuel cell @ $2000/kW						$ 400,000	$ 400,000
total	$ 2,725,857	$ 894,412	$ 105,285	$ 273,000	$ 35,100	$ 635,000	$ 833,000
Power system $/kW Y2000	$ 3,615	$ 4,450	$ 8,099	$ 1,300	$ 1,300	$ 3,175	$ 4,165

Table 7. Operating Cost Comparison

Operating Cost Comparison	Battelle PEMFC System			Flex-Microturbine		MCFC	PAFC
Plant size biomass feed rate	30 tpd	8 tpd	0.5 tpd	5.4 tpd	0.7 tpd	2.8 tpd	3.6 tpd
PEM fuel cell output	754 kW	201 kW	13 kW	210 kW	27 kW	200 kW	200 kW
Capacity Factor	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Electricity @ $0.05/kWh	$ 165,279	$ 39,246	$ 2,471	$ 8,278	$ 1,064	$ 7,884	$ 7,884
Water	$ 3,250	$ 771	$ 49	$ 50	$ 10	$ 1,000	$ 2,000
Sand @ $7.00/ton	$ 5,878	$ 1,394	$ 88				
Catalyst				$ 1,000	$ 1,000	$ 2,000	$ 2,500
PSA operating cost	$ 5,284	$ 1,255	$ 298				
Labor, operators	$ 30,595	$ 30,595	$ 30,595	$ 30,595	$ 30,595	$ 30,595	$ 30,595
Total Annual Cost	$ 210,285	$ 73,261	$ 33,501	$ 39,923	$ 32,669	$ 41,479	$ 42,979

Downdraft Gasifier – Molten Carbonate Fuel Cell Process Options

The MCFC is technically well suited for use with gasfication technology. The MCFC can use both carbon monoxide and hydrogen as a fuel, which typically comprises 35% to 40% of a syngas stream. Sulfur in the gas is the major contaminant that presents difficulty in utilizing a MCFC. Several systems were considered for preparing syngas from a downdraft gasifier. Although wood fuel typically contains very low sulfur levels, each system included sulfur removal, tar removal/conversion, and particulate removal. The downdraft gasifier does not favor tar production, as product gases generally contain between 100 and 1000 ppm tars. However, all tars must be removed or converted so that blinding of catalyst and particulate collection surfaces

is avoided. Particulates are expected to be present in the product gas as ash and char, with a size distribution from 1 μm to greater than 100 μm.

Hot-gas cleanup, cold sulfur removal, and activated carbon systems for preparing syngas produced by a downdraft gasfier for use in a molten carbonate fuel cell were considered. Hot-gas cleanup appeared to be the most attractive option on the basis of cost and operating conditions. Hot product gases exit the gasifier at approximately 1400+EF and pass through a fluid-bed tar cracker (with steam injection) to convert both tars and unreacted char contaminants to H_2, CO, and light hydrocarbons. The refractory-lined fluid bed contains a zeolite catalyst that has been shown to provide excellent conversion of tars at high temperature as well as improved stability of the bed material relative to the degradation observed with dolomite catalysts (Milne et al. 1998, Timpe 1995). A cyclone is used to return catalyst material that is carried over with the gas stream. A portion of the CO stream will be converted in the tar cracker to H_2 and CO_2. Design and operation are consistent for conversion of tars at the 1000-ppm level, and it is expected to be marginally effective in converting CO. The hot gases then pass through a heat exchanger to control gas temperature to approximately 1000EF prior to entering the hot-gas filter. The lower temperature allows condensation of all vapor-phase alkalis such as potassium that may be present in the gas stream following the tar cracker. The filter vessel uses a metallic tube sheet to support ceramic candle filters for removal of particulates. Cleaning is achieved by backpulsing. The clean product gas then passes through a packed bed of zinc-based sorbent to remove sulfur species. The bed operates at a temperature of approximately 1000EF. Beds of ZnO doped with either iron, copper, or titanium have proven highly effective for removal of sulfur species (Pineda et al. 2000, Jothimurugesan et al. 1995). These beds can be regenerated by high-temperature oxidation for reuse upon sulfur breakthrough. However, the effectiveness decreases after three to five regeneration cycles and may be subject to replacement on a regular basis. Certainly, lower sulfur contents of the primary fuel will extend the life of the sorbent. After passing through the sorbent bed, the clean gas passes through the heat exchanger preceding the hot-gas filter to reheat the gases to 1200EF before entering the molten carbonate fuel cell stack.

Two potential cold-gas cleaning strategies were considered; however, costs were 12% higher than the hot-gas cleanup option. The systems considered included low-temperature sulfur removal and activated carbon cleanup. The low-temperature sulfur removal system was similar to the above process using a fluid-bed tar cracker followed by venturi scrubbing and hydrodesulfurization. The activated carbon process takes advantage of char produced by the gasifier to use in the removal of tars and sulfur compounds. A venturi scrubber would be followed by two packed beds containing active carbon.The clean product gas would be reheated to 1200EF for feed to the MCFC. Additional heating could be achieved by combustion of gasifier char and spent carbon sorbent.

Gasifier–Phosphoric Acid Fuel Cell

The PAFC can use only hydrogen as a fuel and can tolerate CO at levels approaching 5000 ppm. The PAFC operates at a temperature of about 400EF. Product gas from the down-draft gasifier must be cleaned to remove particulate, tars, and sulfur compounds and requires the conversion of CO to H_2 and CO_2 by steam shift reaction.

The gas preparation approach considered here is similar to the MCFC hot-gas cleanup system described above. Removal of tars, particulate, and sulfur are accomplished by high-temperature catalytic cracking of tars, hot-gas filtration of particulates, and high-temperature sulfur reduction by zinc oxide/zinc titanate sorbents. The clean product gas is then reheated to 1400EF by heat exchange with product gas supplemented with combustion of gasifier char and makeup natural gas. These hot gases are then moved through a nickel-based catalyst bed to convert any remaining CO. The product gases then pass through a heat recovery steam generator to produce steam for tar cracking and CO conversion, reducing the gas temperature to 400EF for use in the PAFC.

Conclusion

The results of this study are provided in Tables 6 and 7. The primary capital and operating costs for each small gasification power system are shown for various plant sizes. The size chosen for direct comparison between systems is 200 kW. In the case of the Battelle PEM fuel cell system, 754- and 13-kW systems are shown. The 754-kW system represents the actual data provided by Mann (1995) and is adjusted to year 2000 dollars. The 13-kW system was extrapolated from cost curves and shows the cost for a system designed to match the typical load of a 1000-acre dairy farm. The costs show that for any small system (approximately 13 kW), complete automation is a must to realize any return on investment. In the case of the Flex-Microturbine^{TM}, a 27-kW system is shown because that is the size of a Capstone microturbine unit. Flex-microturbine systems would be modular in construction, therefore costs scale linearly. Only the most cost-effective MCFC and PAFC options are presented in the tables.

The Flex-Microturbine^{TM} system appears to be the most cost-effective system when compared at 200 kW. This was the expected outcome of the study. However, the purpose for comparison is to show advanced small power system concepts for biomass gasification and to compare fuel cell systems in order to set cost goals and show where advances must be made in order for fuel cells to compete.

Comparing fuel cell systems overall, the MCFC system ($3200/kW) appears to be more cost-effective than the PAFC system ($4200/kW) or the Battelle PEM system ($4450/kW). However, only PAFC and PEM are commercially available at this time. It should be noted that costs for both the MCFC and the PAFC are shown at $2000/kW. MCFC cost targets are $1200/kW, and current costs are between $4000 and $8000/kW. The most significant cost barrier for MCFC systems is the cost of the fuel cell. If fuel cell manufacturers can hit cost targets, further reductions will need to occur in the gas preparation area. PAFC suffers the same constraint, with additional gas preparation requirements. PEM is discussed below. The higher efficiency of the MCFC system, which means lower gas volumes and lower fuel requirements, provides for a more competitive cost scenario. Operation of each system is expected to require a single person working an 8-hour shift each day. Labor is the primary operational cost for each system, at approximately $30,600 per year. Automation or applications in which operational costs are minimal are paramount for improving return on investment for small power systems.

Attempting to purify syngas for use in a PEM fuel cell is cost-prohibitive for this type of power system. Gasification system costs, gas preparation costs, and the pressure swing absorption

(PSA) system costs outweigh any gains in lowered fuel cell costs. However, for larger-scale power production (over 1 MW_e), the costs improve. High-volume sources of biomass may be well suited for the installation and operation of a Battelle PEM fuel cell power system.

The Flex-Microturbine™ system represents an advanced power generation concept for small biomass gasification. Costs are relatively competitive with gasifier internal combustion engine systems. The primary cost factor is the microturbine, which is expected to decrease in the future. The costs provided in these tables were intended for comparison purposes. Fuel cost was not included. A final report to DOE is due September 30, 2000, and will include all references to cost figures.

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