




Biogas and Fuel Cells Workshop Summary Report

Proceedings from the Biogas and Fuel Cells Workshop
Golden, Colorado
June 11–13, 2012

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Workshop Proceedings
NREL/BK-5600-56523
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NREL
NATIONAL RENEWABLE ENERGY LABORATORY

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Prepared under Task No. H279.1710

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Executive Summary

Introduction

The National Renewable Energy Laboratory (NREL), in association with the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE), held a Biogas and Fuel Cells Workshop on June 11–13, 2012, in Golden, Colorado, to discuss biogas and waste-to-energy technologies for fuel cell applications. The meeting was spearheaded by the Fuel Cell Technologies Program in coordination with the Biomass Program. The overall objective was to identify opportunities for coupling renewable biomethane with highly efficient fuel cells to produce electricity; heat; combined heat and power (CHP); or combined heat, hydrogen and power (referred to as CHHP or "trigeneration") for stationary or motive applications. The workshop focused on biogas sourced from wastewater treatment plants (WWTPs), landfills, and industrial facilities that generate or process large amounts of organic waste, including large biofuel production facilities (biorefineries).

Following were the specific objectives of the workshop:

1. To discuss current state-of-the-art for biogas and waste-to-energy technologies for fuel cell applications
2. To identify key challenges (technical and non-technical) preventing or delaying the near-term, widespread deployment of biogas fuel cells projects
3. To identify synergies and opportunities for biogas and fuel cell technologies
4. To develop strategies for accelerating the use of biogas for stationary fuel cell power and/or hydrogen fueling infrastructure for motive power fuel cells

Wastewater biogas cleanup system at the Joint Base Lewis McChord (JBLM), near Tacoma, WA. As part of a Defense Logistics Agency demonstration project at JBLM, the equipment was used for on-site hydrogen production from wastewater biogas for use in fuel cell-powered forklifts and fuel cell electric vehicles.

Photo from the Gas Technology Institute

The workshop was attended by 58 participants from industry; trade associations; national laboratories; universities; and federal, state, and local government agencies (see Workshop Participant List—Appendix A). The workshop featured a series of panel sessions, with presentations on biogas and fuel cell technology status, applications, legislative outlook, business perspectives, and success stories (see Agenda—Appendix B). The presentations are available online at the DOE's Fuel Cell Technologies Program website.[1] Feedback from participants was gathered in breakout discussion sessions that addressed three types of CHP or trigeneration fuel cell projects: (1) projects that use biogas from WWTP anaerobic digester gas (ADG), (2) projects that use landfill gas (LFG), or (3) projects in industrial facilities that generate or process large

[1] "Fuel Cell Technologies Program: Biogas and Fuel Cells Workshop," last modified June 27, 2012, http://www1.eere.energy.gov/hydrogenandfuelcells/wkshp_biogas_fuel_cells.html.

amounts of organic waste (e.g., food production). The results of these discussions, as described in this report, represent the output of the workshop participants rather than the views of the DOE or of specific individuals or industries.

Current Status

While both technical and non-technical challenges exist to the widespread use of biogas fueled fuel cells, as detailed below, commercial deployments of these technologies do exist and have been successful. Biogas from WWTPs, landfills, and commercial food processing has been utilized as well. Using fuel cells and other energy conversion devices, these renewable fuels have been employed to generate power and heat for onsite needs, power for export back to the grid, and hydrogen for fuel cell electric vehicles. Figure ES-1 provides details on some notable examples of operating projects.

Challenges to Widespread Biogas Fuel Cell Project Deployment

The examples provided in Figure ES-1 show that biogas fuel cell projects are being demonstrated in real world conditions and provide a foundation for growth. During the workshop, participants were asked to identify challenges and pathways for accelerating and expanding the commercialization of biogas and fuel cells in the United States. The challenges generally fell into six main categories: 1) cost and financing, 2) technology, 3) policy and regulations, 4) analysis, 5) education, and 6) utility issues.

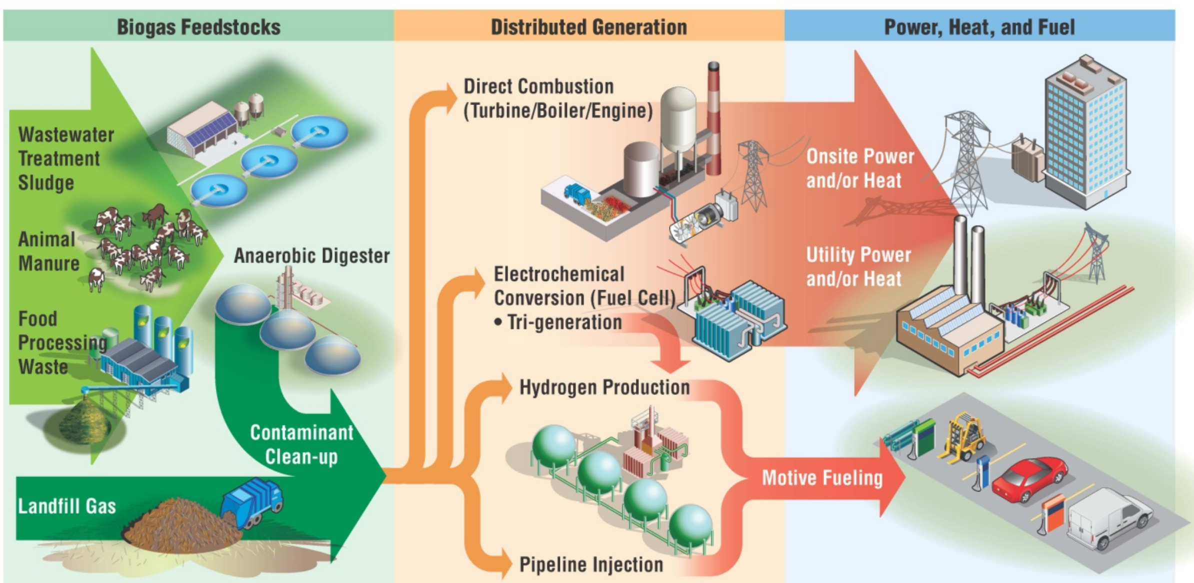

Figure ES-1. Biomass to electricity, heat, and hydrogen pathways

Strategies and Actions to Accelerate Biogas Fuel Cell Project Deployment

After discussing the challenges, participants identified possible strategies and actions that could overcome the challenges and help accelerate widespread deployment of biogas fuel cell projects. Following are the key strategies and actions suggested by workshop participants.

Reduce the cost of biogas cleanup systems

- Conduct research and development (R&D) projects on biogas cleanup
  - Lower cost cleanup equipment
  - Digester process modifications to minimize contaminants in biogas
  - Gas quality sensor and testing technology
- Develop a public database that includes biogas composition and maximum allowable concentrations of contaminants to fuel cells

Develop consistent, long-term national and state policies that are supportive of biogas fuel cell projects

- Evaluate successful state or international policies and potential impacts if implemented nationwide
- Create partnership of organizations representing biogas stakeholders to draft best practices and explain benefits to potential users
- Work with the U.S. Environmental Protection Agency (EPA) to modify Renewable Identification Number (RIN) and Renewable Fuel Standard (RFS) programs and consider regulatory changes for increasing capture and use of biogas

Develop and publish widely accepted value proposition for biogas versus alternatives

- Develop biogas fuel cell analysis tool
- Create detailed case studies of different types of successful projects to serve as reference plants
- Create a partnership of organizations representing all biogas stakeholders to communicate the value proposition to municipalities, private companies, and other stakeholders

Expand and identify key market opportunities

- Create an open-source database and multi-layer map that shows organic waste type/location, electricity and natural gas prices, large process energy and electricity users (especially those that require very high energy reliability), and potential hydrogen users.
- Conduct R&D to enhance production of biogas and co-products from anaerobic digesters

Increase access to utility grid (gas and electric)

- Develop a database of biomethane locations, quality and the impacts of gas and electric utility interconnection with biogas projects
- Develop targeted information products and conference presentations for regulators, utilities, and associations
- Work with regulators and utility associations to lower electric interconnection costs and make net metering favorable for biogas-to-electricity projects

Improve biogas fuel cell system integration and optimization

- Conduct collaborative R&D to develop biogas fuel cell systems that integrate and optimize the various process operations

- Develop an overall system model to predict system performance under different scenarios

Improve fuel cell systems for biogas applications

- Conduct fuel cell cost reduction R&D
- Conduct R&D to make fuel cells more robust to biomethane contaminants

Simplify project financing

- Convene select stakeholders to identify and price risks
- Develop case studies of project financing approaches, including innovative options for public/private risk sharing

Next Steps

The workshop participants suggested a wide range of possible next steps for government and industry organizations to pursue, as summarized in Section 5 of this document. Two main mechanisms to act upon these next steps should be enabled. First, a government/industry working group should be established to convene interested parties, determine and prioritize actions, and share information. Second, existing techno-economic and engineering analysis tools and global information system capabilities should be applied to produce publicly available, detailed evaluations of biogas resource location, quantity, availability, and distribution. These evaluations should also assess optimal integration schemes for fuel cells using biogas in CHP, trigeneration, biorefinery, and other applications that improve energy efficiency, reduce greenhouse gas (GHG) and criteria pollutant emissions, or increase deployment of hydrogen production technologies to assist in the development of a national hydrogen infrastructure.

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1 Introduction

The National Renewable Energy Laboratory (NREL), in association with the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE), held a Biogas and Fuel Cells Workshop on June 11–13, 2012, in Golden, Colorado, to discuss biogas and waste-to-energy technologies for fuel cell applications. The meeting was spearheaded by the Fuel Cell Technologies Program in coordination with the Biomass Program. The overall objective was to identify opportunities for coupling renewable biomethane with highly efficient fuel cells to produce electricity; heat; combined heat and power (CHP); or combined heat, hydrogen and power (referred to as CHHP or "trigeneration") for stationary or motive applications. The workshop focused on biogas sourced from wastewater treatment plants (WWTPs), landfills, and industrial facilities that generate or process large amounts of organic waste, including large biofuel production facilities (biorefineries).

Dale Gardner, NREL Associate Lab Director for Renewable Fuels and Vehicle Systems, welcomed the participants, who came from industry; trade associations; national laboratories; universities; and federal, state, and local government agencies, and provided an overview of his organization's capabilities (see Workshop Participant List – Appendix A). The workshop featured a series of panel sessions, with presentations on biogas and fuel cell technology status, applications, legislative outlook, business perspectives, and success stories (see Agenda – Appendix B). The presentations are available online at the DOE Office of Energy Efficiency and Renewable Energy, Fuel Cell Technologies Program website.[2] Feedback from participants was gathered in breakout discussion sessions that addressed three types of CHP or trigeneration fuel cell projects: (1) projects that use biogas from WWTP anaerobic digester gas (ADG), (2) projects that use landfill gas (LFG), or (3) projects in industrial facilities that generate or process large amounts of organic waste (e.g., food production).

2 Current Status

2.1 Biogas-Powered Fuel Cells – Considering the Opportunity

The U.S. consumed 98 quadrillion Btus (quads) of energy in 2011, with over 40 quads used to generate electric power. Of this, almost 27.5 quads (or 70%) came from fossil fuels.[3] Electricity generation at large centralized power plants and long-distance transmission of electricity are inefficient processes that waste more than two-thirds of the input energy as heat.[4] At the same time, heat for hot water and space heating of buildings is often supplied through combustion of additional fossil fuel. Generating electricity for commercial, industrial, and residential applications in CHP installations could greatly improve the overall efficiency of both electricity generation/delivery and heating by moving the electricity generation close enough to the point of use that waste heat can be used for space heating and hot water.

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[2] "Fuel Cell Technologies Program: Biogas and Fuel Cells Workshop," last modified June 27, 2012, http://www1.eere.energy.gov/hydrogenandfuelcells/wkshp_biogas_fuel_cells.html.

[3] U.S. Energy Information Administration, *Annual Energy Review* (Washington, D.C.: U.S. Energy Information Administration, October 2011). http://www.eia.gov/totalenergy/data/annual/index.cfm.

[4] Sunita Satyapal, "Expanding the Use of Biogas with Fuel Cell Technologies" (presentation, Biogas and Fuel Cells Workshop, Golden, CO, June 11–13, 2012). http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/june2012_biogas_workshop_satyapal.pdf.

Each year, biogas production in the United States generates methane emissions with about 0.74 quads of energy value – about 0.6 quads at landfills, 0.11 quads at manure management operations, and 0.03 quads at industrial and domestic wastewater treatment plants (WWTPs).[5] Of this amount, slightly over half of the biomethane produced is not captured, mostly at landfills. Furthermore, much of the gas that is captured at landfills is flared rather than used for power generation. Of the 0.34 quads of biomethane captured at landfills in 2010, more than half was flared.[6] As a whole, only 19 percent of the nation's WWTPs use biogas produced in their anaerobic digesters for power generation.[7]

Biogas is naturally produced from the anaerobic digestion of organic waste materials. Although its raw composition varies depending on the type of source material (Table 1), it is chiefly composed of methane and carbon dioxide (CO_2), with small amounts of oxygen, nitrogen, hydrogen sulfide, and other trace components not shown here. This mixture can be used as a fuel to produce energy, most commonly in an internal combustion engine to produce heat, electricity, or a combination of both (CHP).

Table 1. Biogas composition from various sources

Composition	Natural Gas	Biogases			
		Waste Water	Food Waste	Animal Waste	Landfill
Methane (Vol%)	80 – 100	~50 – 60	~50 – 70	45 – 60	40 – 55
Carbon Dioxide (Vol%)	<3	30 – 40	25 – 45	35 – 50	35 – 50
Nitrogen (Vol%)	<3	<4	<4	<4	<20
Oxygen (Vol%)	<0.2	<1	<1	<1	<2
H_2S, ppm	<0.1	<400	<10,000	<300	<200
Non-H_2S Sulfur, ppm	<10	<1	<1,000	<30	<30
Halogens, ppm	<0.1	<0.2	<0.2	<0.2	<100
Moisture, %	<0.02	~3	~3	~3	~3

Source: Frank Wolak, "Fuel Cell Power Plants: Biofuel Case Study – Tulare, CA," Biogas and Fuel Cells Workshop, Golden, CO, June 11–13, 2012, http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/june2012_biogas_workshop_wolak.pdf

The biogas can be used as-is, but is often cleaned up to the quality and heating value of natural gas (then termed "biomethane"). As with natural gas, biomethane can be compressed and stored in gaseous tanks or liquefied and stored in liquid tanks, and can be transported via truck or pipeline.

[5] U.S. Energy Information Administration, *Annual Energy Review* (Washington, D.C.: U.S. Energy Information Administration, October 2011). http://www.eia.gov/totalenergy/data/annual/index.cfm.
[6] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2010*, 430-R-12-001 (Washington, D.C.: U.S. Environmental Protection Agency, April 15, 2012). http://www.epa.gov/climatechange/ghgemissions/usinventoryreport.html.
[7] Shabbir Ahmed, "Biogas Impurities and Cleanup for Fuel Cells" (presentation, Biogas and Fuel Cells Workshop, Golden, CO, June 11–13, 2012). http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/june2012_biogas_workshop_ahmed.pdf.

Biomethane (with appropriate cleanup to remove trace contaminants) can also be used to power a fuel cell, a device that converts the chemical energy of a fuel directly into energy, without combustion. Like engine systems, fuel cell systems can be configured to produce heat as well as power. Certain types of fuel cell systems can also be configured to produce pure hydrogen, and the application of trigeneration is beginning to be explored. Figure 1 shows the major biogas energy pathways.

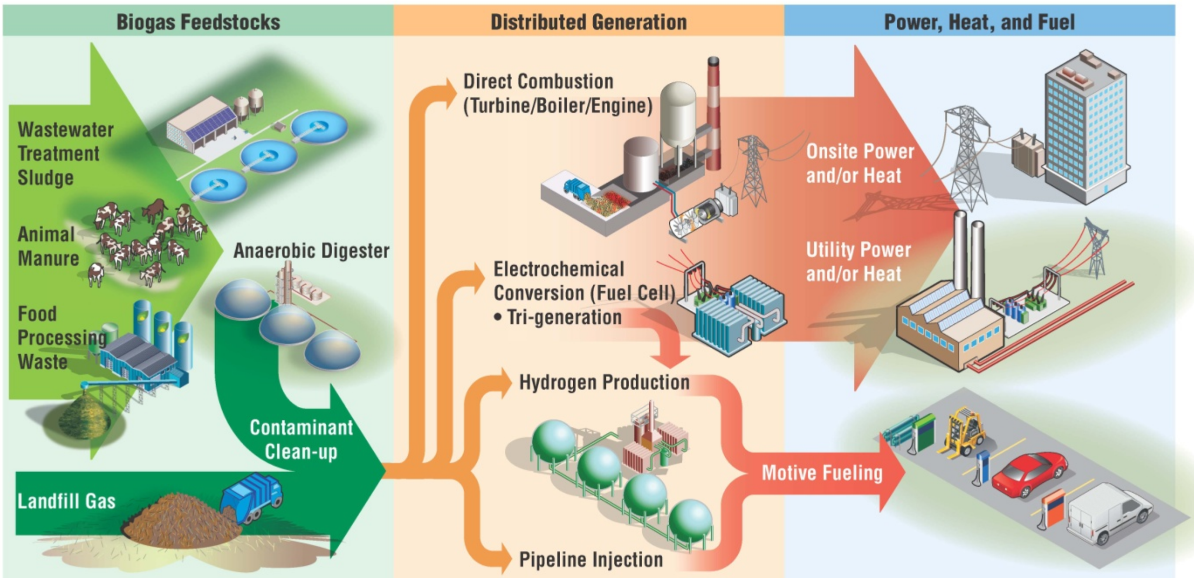

Figure 1. Biomass to electricity, heat, and hydrogen pathways

The use of biomethane in fuel cells has the potential to provide heat and power more efficiently than conventional combustion-based technologies (Figure 2). Fuel cells running on biomethane provide between 30 percent to 65 percent electrical efficiency in CHP applications versus approximately 15 percent to 40 percent in engine and turbine technologies.[8]

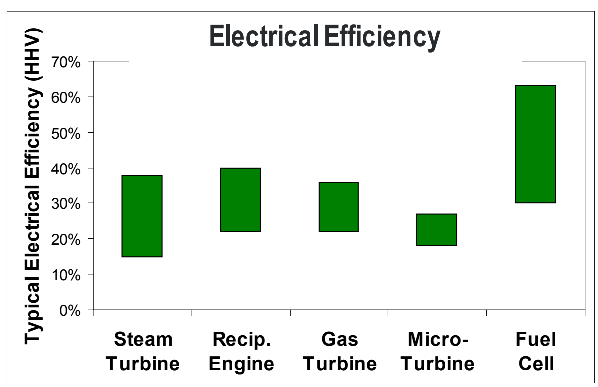

Figure 2. Comparison of electrical efficiency of power generation equipment

Source: EPA, Catalogue of CHP Technologies, Table III, December 2008

Fuel cells also generate much fewer criteria pollutants than conventional power generation technologies (Table 2). Capturing biogas for energy has other environmental benefits as well. Methane is a potent greenhouse gas (GHG), with twenty-one times the global warming potential of CO_2. Methane emissions from landfills and wastewater treatment plants account for about 30 percent of all methane emissions

[8] Sunita Satyapal, "Expanding the Use of Biogas with Fuel Cell Technologies" (presentation, Biogas and Fuel Cells Workshop, Golden, CO, June 11–13, 2012). http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/june2012_biogas_workshop_satyapal.pdf.

in the United States,[9] and about 10 percent of total national GHG emissions in CO_2 equivalents.[10] Generating power with biogas also displaces GHG emissions from conventional power generation. The benefit of displacing other sources of power generation depends both on the amount of biogas available in a particular region and on the fuel mix used in different locations. For example, California has a very "green" power generation fuel mix, so the benefit of displacing this electricity is lower. However, California has a large amount of biogas available in comparison to other states. The combination of these two factors makes California a good opportunity for GHG reduction using biogas.

Table 2. Comparison of criteria air pollutant emissions from power generation technologies

Technology	Air Pollutant (lb/M Wh)	
	NO_X	CO
Reciprocating Engine	1.51	2.52
Combustion Turbine	0.83	3.45
Microturbine	0.17	0.29
Fuel Cell	0.0001	0.0015

Source: Steve Hamilton, "Biogas from Municipal WWTPs: Fuel Cells Viewed as a Value Proposition," Biogas and Fuel Cells Workshop, Golden, CO, June 11–13, 2012, http://www1.eere.energy.gov /hydrogenandfuelcells/pdfs/june2012_biogas_workshop_hamilton.pdf

The economics of biogas fuel cell projects depends on a number of factors. Biogas competes with conventional sources of natural gas as a fuel for the fuel cell. High prices for the competing fuel (conventional natural gas) are favorable for biogas CHP/trigeneration. Likewise, power produced from biogas in a CHP application competes with grid electricity. High prices for grid electricity also are favorable for biogas CHP and trigeneration economics.

Anaerobic digestion with capture and use of biogas for the management of waste products like manure or food processing waste reduces odor, waste stream pathogens, and waste volume, which may have economic or public relations value. Waste heat from power generation can also be used to improve digester efficiency, especially in cold-winter climates.

In addition to traditional sources of biogas, the integration of fuel cells into the biomass, biogas, and bioproduct process streams of a new generation of biorefineries is seen as an opportunity with strong synergies. Electricity, heat, and, in some cases, hydrogen, are all needed during various steps of highly integrated biorefining processes. Fuel cells, powered by either biogas streams produced within the plant or externally sourced natural gas, offer the opportunity to provide these needs at high efficiency, reduce GHG and criteria pollutants compared to grid power, and create distributed generation sources.[11]

2.2 Available Biogas Resources

The major biogas resource segments for anaerobic digestion are landfills, WWTPs, farm operations, and business and industry sites that are involved in food and beverage production. Anaerobic digestion is a long-established and proven technology, with extensive markets in the

[9] Ibid.

[10] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2010*, 430-R-12-001 (Washington, D.C.: U.S. Environmental Protection Agency, April 15, 2012). http://www.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2012-Upfront.pdf.

[11] Brian Duff, "Biomass Program Perspectives on Anaerobic Digestion and Fuel Cell Integration at Biorefineries" (presentation, Biogas and Fuel Cells Workshop, Golden, CO, June 11–13, 2012). http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/june2012_biogas_workshop_duff.pdf.

Far East and Europe. Germany is considered the leading European country, with more than 7,000 facilities and 18 TWh of electricity generated from biogas.[12]

In the United States, there are more than 2,200 biogas-producing sites that are currently operational, including about 1,500 digesters at WWTPs, 186 digesters on farms, and 576 landfill-based energy projects.[13] Substantial opportunities exist to increase the number of biogas projects in all resource segments, with a large GHG reduction potential from the capture of biogas. The American Biogas Council estimates that there are over 120,000 sites available for development, not including private or industrial WWTPs and landfill sites. Table 3 summarizes current biogas production and potential production in the United States.

Table 3. Summary of current and potential biogas capture and use for farms, WWTPs, and landfills in the United States

	Number of Locations	Biogas Resource	Notes
Operational Digesters			
Wastewater Treatment	1,500		• Only 250 use the biogas they produce.
Landfills	576		
Potential Resources			
Farms	8,200	1,700 MW	• Only counting dairy and swine farms. • About 70-100 cubic feet per day of digester gas is produced per milking cow; a dairy farm of 500 cows can generate 100 kW of electricity.*
Wastewater Treatment	3,250	750 MW	• 2,000 WWTPs that process more than 1 million gallons per day (GPD) of wastewater do not have a digester. 1,250 WWTPs are producing but not using biogas. • A typical WWTP processes 100 GPD for every person served (1 cubic foot of digester gas can be produced per 100 gallons of wastewater). • 100 kW can be generated from 4.5 million GPD of wastewater.
Landfills	510		• Every 1 million tons of municipal solid waste equals 432,000 cubic feet per day of LFG for 20 years, or 1 MW of electricity.*

** assuming 30% conversion efficiency*
Sources: Patrick Serfass, "Biogas Markets and Federal Policy," Biogas and Fuel Cells Workshop, Golden, CO, June 11–13, 2012, http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/june2012_biogas_workshop_serfass.pdf, and Shabbir Ahmed, "Biogas Impurities and Cleanup for Fuel Cells," Biogas and Fuel Cells Workshop, Golden, CO, June 11–13, 2012, http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/june2012_biogas_workshop_ahmed.pdf

In 2012, total methane emissions from these facilities was 16.6 million metric tonnes (MMT), 13.3 MMT from landfills, 2.5 from manure management operations, and 0.8 from WWTPs.[14] If this methane was captured and used for fuel cell trigeneration, approximately 1.9 MMT of

[12] Ian Handley, "Biogas Technologies and Integration with Fuel Cells" (presentation, Biogas and Fuel Cells Workshop, Golden, CO, June 11–13, 2012). http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/june2012_biogas_workshop_handley.pdf.

[13] Patrick Serfass, "Biogas Markets and Federal Policy" (presentation, Biogas and Fuel Cells Workshop, Golden, CO, June 11–13, 2012). http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/june2012_biogas_workshop_serfass.pdf.

[14] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2010*, 430-R-12-001 (Washington, D.C.: U.S. Environmental Protection Agency, April 15, 2012). http://www.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2012-Upfront.pdf.

hydrogen and 81,000 GWh of electricity could be produced.[15] In addition, by generating power from the biogas, up to 300 MMT of CO_2 equivalent emissions would be avoided, equal to about 13% of national CO_2 equivalent emissions from electricity generation.[16]

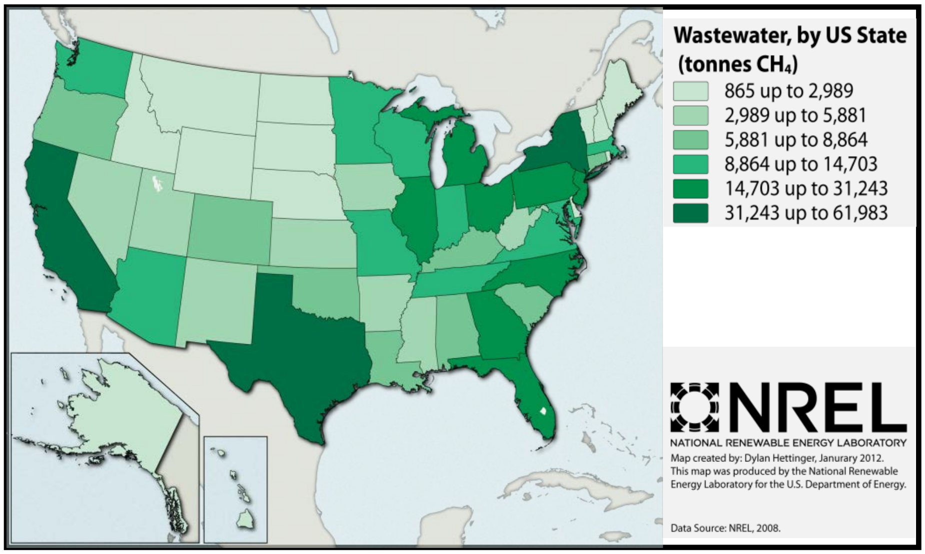

Figure 3. Biogas combined resources from landfill gas, WWTPs, and manure management

Biogas resources vary widely across the United States. California, New York, and Texas are examples of states with the richest resources for wastewater. California, Pennsylvania, and Texas have the richest resources for landfill gas. California and many states in the Midwest and Southeast have the richest biogas resources from agriculture. Figure 3 shows the combined biogas resources from WWTPs, landfills, and livestock operations in the United States.

As mentioned before, the cost of grid electricity can impact the value potential for a biogas-to-electricity project, and these costs vary a great deal across the country. California, a state with strong biogas resources and relatively high electricity prices, is an example of a state with a relatively attractive potential for biogas project opportunities. In terms of biogas production potential, Figure 4 shows that fats, greases, and food wastes from bakeries, restaurants, and groceries produce the largest amount of biogas per ton of waste digested. However, because collecting these types of wastes presents logistical difficulties, the net energy benefit may be significantly reduced.

[15] Darlene Steward, "Biomass Resources Overview and Perspectives on Best Fits for Fuel Cells" (presentation, Biogas and Fuel Cells Workshop, Golden, CO, June 11–13, 2012). http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/june2012_biogas_workshop_steward.pdf

[16] Darlene Steward, "Biomass Resources Overview and Perspectives on Best Fits for Fuel Cells."

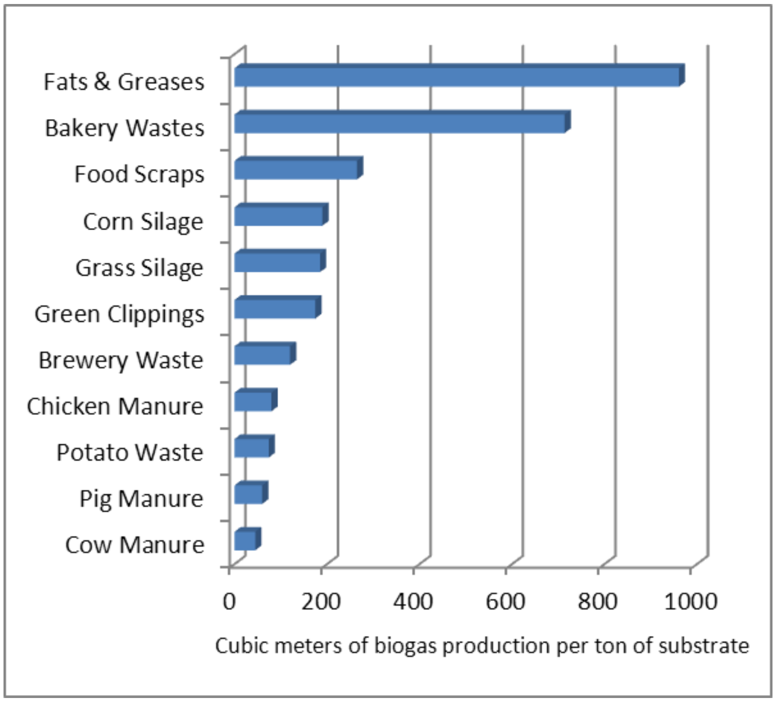

Figure 4. Cubic meters of biogas production per ton of substrate

Source: Patrick Serfass, "Biogas Markets and Federal Policy," Biogas and Fuel Cells Workshop, Golden, CO, June 11–13, 2012

2.3 Biogas and Fuel Cell Technologies – Current Status

A range of technologies is important for the effective use of biogas to power fuel cells, including creating the biogas from waste products, cleaning or upgrading the biogas to meet the fuel purity specifications required for fuel cells (or injection into pipelines), and the fuel cells themselves. In a biorefinery, integrating fuel cells into the biomass-to-biofuel production systems requires an understanding of the individual process technologies as well as the complex thermal and mass balances from process to process.

Anaerobic digestion (AD) is generally a mature technology for treatment of sewage, manure, some food wastes, and other low solids waste.[17] For WWTP, AD reduces the volume of solids and volatile content which lowers sludge disposal costs while creating biogas. Adding various food waste to wastewater sludge, or "co-digestion," can increase the output of biogas in some cases.[18] AD for higher solids waste streams is less well developed, especially in the United States, though research on the development of new processes is ongoing. R&D needs for AD include improving the understanding of the biological organisms used in different AD processes, improving reactor design and optimization, and understanding co-production and optimization of

[17] Ruihong Zhang, "Biogas Production Technologies" (presentation, Biogas and Fuel Cells Workshop, Golden, CO, June 11–13, 2012). http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/june2012_biogas_workshop_zhang.pdf.
[18] Steve Hamilton, "Biogas from Municipal WWTPs: Fuel Cells Viewed as a Value Proposition" (presentation, Biogas and Fuel Cells Workshop, Golden, CO, June 11–13, 2012). http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/june2012_biogas_workshop_hamilton.pdf.

useful by-product streams.[19] An issue with AD as a source of biogas for fuel cells is the stability in mass flow of the biogas stream, which can vary with temperature and with changes in the waste feed stream. Blending the upgraded biogas with natural gas is one method to overcome this challenge.

Biogas from landfills is essentially a special case of AD, where carbon-containing solid waste materials break down over time, and, in the generally anaerobic environment of the sealed landfill, generate methane. Other gaseous constituents are also generated, however, and given the variability of landfill waste, LFG often has more varied contaminants than methane from wastewater or industrial digestion. The typical, although not universal, components of biogas from various sources were shown in Figure 1 and include methane, CO_2, nitrogen, oxygen, water vapor, and trace amounts of hydrogen sulfide (H_2S), other sulfur species, and halogens. Siloxane species are also prevalent in both landfill and wastewater gases.

Landfills can be expected to produce LFG over lifespans of 20 years, with peak production rates between years 5 and 7.[20] In addition to use of LFG for power generation, liquefaction of methane from LFG has been demonstrated at industrial scales.[21]

Many cleanup or upgrading technologies have been used to meet the requirements of fuel cells and pipeline injection. Table 4 shows a variety of processes and their relative cost. Most of these technologies are well known. However, the variability of the types and concentrations of contaminants for each application and, indeed, each site, is high. Thus, while cleanup technologies may be well known, each installation generally requires a custom designed suite of cleanup equipment, which drives up cost. The complexity and cost of cleanup systems can also increase due to variability in the biogas production rate. Cleanup can be expected to add approximately 2 cents per kWh to electricity production costs.[22]

Table 4. Common cleanup processes and relative cost

Upgrade Method	Contaminant Removal	Cost to Upgrade ($/1000 cu ft)
Biological	H_2S	1.86
Iron Oxide (sulfa treat)	H_2S	0.79
Iron Oxide (Sulphur Rite)	H_2S	1.49
Membrane	CO_2, H_2O	2.13
Water Scrubber	H_2S, CO_2	0.38
PSA	CO_2	2.53
Activated Carbon	H_2S	0.45
Amine	H_2S, CO_2	4.58

Source: Ian Handley, "Biogas Technologies and Integration with Fuel Cells," Biogas and Fuel Cells Workshop, Golden, CO, June 11–13, 2012, http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/june2012_biogas_workshop_handley.pdf

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19 Brian Duff, "Biomass Program Perspectives on Anaerobic Digestion and Fuel Cell Integration at Biorefineries" (presentation, Biogas and Fuel Cells Workshop, Golden, CO, June 11–13, 2012). http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/june2012_biogas_workshop_duff.pdf.

20 Shabbir Ahmed, "Biogas Impurities and Cleanup for Fuel Cells" (presentation, Biogas and Fuel Cells Workshop, Golden, CO, June 11–13, 2012). http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/june2012_biogas_workshop_ahmed.pdf.

21 Mike McGowan, "Renewable LNG: Update on the World's Largest Landfill Gas to LNG Plant," (presentation, Biogas and Fuel Cells Workshop, Golden, CO, June 11-13, 2012); and Waste Management, Inc., "Case Study: Altamont Landfill and Resource Recovery Facility." www.wm.com/federal/case-studies/altamont.html.

Biorefineries using current food crops, such as corn and sugarcane, have been demonstrated at a commercial scale. For alternate biomass feedstocks, integrated biorefineries are being developed. These plants are designed to efficiently convert a broad range of biomass feedstocks into affordable biofuels, biopower, and other bioproducts.[23] In either case, opportunities exist to integrate fuel cells into the complex thermal and heat balances of the overall system. Biochemical and thermochemical processes for alternative feedstock biorefining are developed, but work is ongoing to improve and integrate these processes and validate their performance. System designs, to the unit process level, have been developed and modeling of performance and economics is ongoing.

Pilot, demonstration, and commercial scale integrated biorefineries, co-funded by the DOE and industry for data collection and technical and economic validation, have recently been constructed, or are under construction.[24]

Table 5. Fuel purity requirements for high temperature fuel cells (values in ppm)

Type of Fuel Cell	PAFC	MCFC	SOFC
H_2S	2.0	0.1 – 5.0	1.0
COS, CS_2, mercaptan		1.0	
Organic sulfur		6.0	
H_2S, COS, CS_2		0.5 – 10.0	
HCl, ppm		0.1	"few"
Halogens	4.0	0.1 – 1.0	1.0 – 5.0
Halogenated organics		0.1	
NH_3	1.0	10,000	5,000
Siloxanes		1.0	0.01
Tars		2,000	

Source: Shabbir Ahmed, "Biogas Impurities and Cleanup for Fuel Cells," Biogas and Fuel Cells Workshop, Golden, CO, June 11–13, 2012

High temperature fuel cell systems, including phosphoric acid, molten carbonate, and solid oxide fuel cells, would typically be considered for use with biomethane fuels because of the potential to generate large quantities of useful heat for CHP. These fuel cells are currently demonstrated and commercially available in modules from 100–400 kW in output. However, initial costs are high, and fuel purity requirements demand complex cleanup systems. Current costs for 100 kW – 3 MW stationary fuel cell systems capable of CHP are approximately $7,000/kW.[25] Fuel purity requirements for these high temperature fuel cells are given in Table 5. Fuel cell systems capable of trigeneration are currently in demonstration.

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[22] Shabbir Ahmed, "Biogas Impurities and Cleanup for Fuel Cells" (presentation, Biogas and Fuel Cells Workshop, Golden, CO, June 11–13, 2012). http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/june2012_biogas_workshop_ahmed.pdf.

[23] U.S. Department of Energy, Office of the Biomass Program, *Integrated Biorefineries: Biofuels, Biopower, and Bioproducts* (U.S. Department of Energy, Washington, D.C.: July 2012).

[24] U.S. Department of Energy, Office of the Biomass Program, *Biomass Multi-Year Program Plan* (U.S. Department of Energy, Washington, D.C.: April 2011).

[25] Sunita Satyapal, "Expanding the Use of Biogas with Fuel Cell Technologies" (presentation, Biogas and Fuel Cells Workshop, Golden, CO, June 11–13, 2012). http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/june2012_biogas_workshop_satyapal.pdf.

The majority of current biogas-to-energy projects are using the biogas in a conventional combustion-based system to produce heat and/or power for use on site or, in some cases, for sale back to the electric grid. However, as a result of generational improvements in commercial stationary fuel cell technologies, the costs of these technologies are declining, and their reliability and performance levels are improving in real-world environments. Accordingly, fuel cell technologies are becoming viable alternatives to the incumbent combustion-based technologies. The box on the next page shows a number of such installations.

2.4 Current Federal and State Incentives/Policies

Policies and energy incentives are widely regarded as major drivers to the extensive development of a biogas market in many European countries. Those policies considered to have the greatest impact in Europe include landfill bans, high tipping fees, source separation of waste, and feed-in tariffs.

Specific to the United States, projects to capture and use biogas resources can be eligible for government assistance at both the federal, state, and local levels. "DSIRE" (Database of State Incentives for Renewables and Efficiency) is a public database maintained by the DOE that provides a compendium of the available incentives and resources.[26] At the federal level, tax-related incentives include the investment tax credit (ITC) for fuel cells, the renewable energy production tax credit (PTC), and new market tax credits for projects located in low-income areas. The Energy Independence and Security Act of 2007 (EISA) has enabled biogas from wastewater or landfills that is used as transportation fuel to qualify for revenue from the sale of Renewable Identification Number (RIN) credits. The Rural Energy for America Program and other programs tied to the Farm Bill are also providing incentive opportunities for biogas projects.

At the state level, biogas projects can be eligible for incentives from a wide assortment of programs. From the DSIRE database, Renewable Portfolio Standard (RPS) programs exist in 29 states, Washington DC, and Puerto Rico. Interconnection policies are available in 43 states, Washington DC, and Puerto Rico. A total of 24 states offer renewable energy-related tax credits, and 38 states offer property tax incentives for sites that capture biogas resources.

[26] "DSIRE: Database of Energy Efficiency, Renewable Energy Solar Incentives, Rebates, Programs, Pol," North Carolina State University, under NREL Subcontract No. XEU-0-99515-01. www.dsireusa.org.

Biogas and fuel cell project success stories


Tulare, CA, Municipal Wastewater Treatment Plant with fuel cells and ancillary equipment in foreground
Photo from Frank Wolak, FuelCell Energy

- The Tulare WWTP processes 11.5 million gallons per day (GPD) of wastewater, producing 500,000 cubic feet of digester biogas/day, which was previously flared
- Four 300 kW fuel cells convert biogas to electricity (1.2 MW capacity) and heat is used for digester heating
- Supplies close to 50% of the WWTP's electricity demand, saves approximately $3,500/day in electricity cost (estimated 4.5 year payback period, with credits), and reduces CO_2 emissions by 6,200 tons/year
- Electric efficiency of 47% and CHP efficiency of 90%

Source: Fuel Cells 2000, "Fuel Cell System Turns Waste into Electricity at the Tulare Wastewater Treatment Plant," www.fuelcellsorg/info/TulareCaseStudy.pdf


Renewable liquefied natural gas (LNG) from landfill gas plant in Altamont, CA
Photo from Mike McGowan, Linde, North America

- Produces up to 13,300 GPD of LNG from landfill gas captured from the Altamont landfill, enough to fuel 300 refuse hauling trucks.
- The LNG liquefaction plant operates using renewable electricity generated on site
- Displaces 2.5 million gallons of diesel fuel/year and reduces approximately 30,000 tons CO_2, 200 tons of NO_x, and 4 tons of particulates/year
- $15.5 million total capital cost (approximately $2 million in public funding from multiple agencies)

Sources: Mike McGowan, "Renewable LNG: Update on the World's Largest Landfill Gas to LNG Plant" (presentation, Biogas and Fuel Cells Workshop, Golden, CO, June 11-13, 2012); and Waste Management, Inc., "Case Study: Altamont Landfill and Resource Recovery Facility," www.wm.com/federal/case-studies/altamont.html


World's first trigeneration plant at the Orange County Sanitation District's WWTP in Fountain Valley, CA
Photo from National Fuel Cell Research Center, UC-Irvine

- Produces CHHP (trigeneration) from anaerobic digester gas collected from the OCSD wastewater treatment plant
- Fuel cell plant has a capacity of 250 kW and excess hydrogen is refined to fuel up to 50 vehicles/day at a nearby hydrogen fueling station
- To date, the plant has produced more than 1.2 million kWh of electricity and close to 3,000 kg of hydrogen
- Total demonstrated efficiency of 54% (effective hydrogen production efficiency has reached 87% with electric efficiency up to 47%)

Source: Jack Brouwer, National Fuel Cell Research Center, University of California, Irvine, personal communication, September 17, 2012

Other successes:

- *BMW Manufacturing, Spartanburg, SC:* Uses delivered hydrogen to fuel 86 fuel cell-powered forklifts and LFG from a nearby landfill for CHP in a combustion engine, saving 1.8 million kWh and 1.2 million tons of CO_2 per year
- *Sierra Nevada Brewery, Chico, CA*: 1.2 MW fuel cell CHP using digester biogas and natural gas
- *Gills Onions, Oxnard, CA:* 600 kW fuel cell CHP using digester biogas produced from onion waste meets 95% of the food processing plant's electricity needs
- *East Bay Municipal Utility District (EBMUD), Oakland, CA*: Digesters at the municipal WWTP process post-consumer food waste, food processing waste, restaurant grease, and other waste streams and the biogas-fired CHP plant provides 90% of the WWTP's energy needs

3 Challenges to Widespread Deployment of Biogas Fuel Cell Projects

During the workshop, panel presenters and breakout group participants were asked to identify challenges to the near-term deployment of biogas fuel cell projects in the United States. Table 6 presents a summary of the key challenges identified. As shown in the table and described in more detail below, the challenges fell into six main categories: 1) cost and financing, 2) technology, 3) policy and regulations, 4) analysis, 5) education, and 6) utility issues.

3.1 Costs and Financing

Fuel cell cost was a key challenge identified by participants. As a base load power generation system, biogas fuel cell systems must be able to compete with natural gas-fired combined cycle or conventional combustion engines. Except in areas with very high electricity cost or very high natural gas costs, this can be difficult for today's biogas fuel cell systems. Fuel cells for biogas power applications currently have higher capital costs than combustion systems, and the gas cleanup system also has high capital and operating costs. Paybacks required by private investors are often too short term and policy incentives that are available often do not take into account the payback period for project capital, which can be over a longer (>4 year) timeframe. Also, because the value of RINs is volatile, payback through the sale of RINs over time is risky, even though the capital outlay is needed up front.

The cost of biogas cleanup systems was identified as another challenge area. Cleanup systems for biogas must be engineered for the worst case contaminant levels and fuel cell gas purity requirements are very stringent, both of which increase the cost and complexity of the biogas cleanup systems. More data are needed to better understand these issues.

Project financing is another challenging area, since it can be difficult to obtain private financing – problems in the bank market and the smaller appetite of tax equity buyers have led renewable energy developers to seek new sources of capital for project finance. Bonds are one often overlooked alternative – they can be the sole source of debt or a complement to bank and equity debt and offer structural advantages such as longer tenure, lower interest rates, and flexible amortization, which improve returns.

3.2 Technology

Technology challenges center around two key factors: 1) lack of energy production system standardization and 2) the cost and performance of biogas cleanup. Today's biogas fuel cell systems typically consist of separate technologies, e.g., biogas generation, cleanup, and fuel cell power, which were developed independent of each other. As such, these systems are custom-designed to meet the needs of a specific site. There is a need for an integrated systems approach that considers the design of a landfill/WWTP/farm/biorefinery as an energy/bioproduct producer, and integrates and optimizes the various process operations.

Table 6. Key challenges to biogas fuel cell project deployment

Cost & Financing	Technology	Policy & Regulations	Analysis	Education	Utility Issues
• High first cost of fuel cell systems vs. internal combustion engines • High capital and operating cost of gas cleanup systems • Uncertain or unknown value proposition for co-products or waste products of the biogas system	• Gas cleanup technology – systems are complex, not standardized, too costly, and not as reliable or efficient as they could be • Lack of integrated systems optimized for biogas fuel cell CHP or CHHP (and other by-product production, where possible) • Lack of component/ module standardization and variable quality and reliability of components • Lack of clarity and confidence in fuel cell feedstock quality specifications • Lack of low-cost, real-time in-line sensing for gas quality assurance • Inconsistent digester performance and biogas production (reliability) leads to risk when relying on biogas for operations and revenue • Inconsistent biogas output levels (quantity and quality) can hurt gas cleanup and fuel cell performance	• Incentives to offset project costs are only available in a few states • Lack of an economic value for carbon, watershed improvement, etc. • Limited- or short-term policies that are inconsistent with the tenure of financing packages • Policies that do not take into account the value of all by-products or “tangible externalities” • Risky value of RINs • Lack of organics diversion mandates • Variances between federal and state definitions of what qualifies for incentives and why, and what is considered acceptable means of biogas transportation • Every state and utility has their own standards for bio-methane pipeline injection • Federal agencies are not coordinated in providing information for policy and regulations (USDA, DOE, EPA)	• Do not now have data or tools to understand best use(s) of biogas and how to best structure a project • Lack of accounting for the avoided costs of making productive use of waste products • Lack of database of locations/sites where supply of biogas matches with demand for electricity	• Lack of information on and awareness of the value proposition and project benefits • Reference plants with credible data are needed • Lack of regulator and project stakeholder interaction • Lack of outreach and information sharing among the project stakeholder community of interested parties	• Limited access to the grid (i.e., natural gas pipelines and electricity transmission) – no incentives for the utilities to connect • High cost of grid interconnection or lack of support network • Lack of retail market access for electricity • Must sell power and gas at wholesale prices No or limited wheeling

In regard to biogas cleanup specifically, standardized, modular systems would help take advantage of the distributed, small-scale nature of many biogas resources. Fuel cell sensitivity to input gas contaminants and pressure drops can also be a challenge. In addition, the variability of biogas streams from different sources, in terms of both quantity and quality, makes standardization of the cleanup system difficult, and can also hurt fuel cell performance. The reliability and operation and maintenance needs of gas cleanup systems were also identified as technology-related challenges, with improvements needed in both areas. In this regard, there is a lack of sensor technology capable of providing real-time feedback on gas quality and system performance.

3.3 Policy and Regulations

Participants agreed that policies and incentives should enable loans to be structured to allow for payback of project capital over longer periods of time than conventional technologies. In addition, while qualification of biomethane under RPS is beneficial, more incentives that help to offset biogas fuel cell project costs are needed until full commercialization is realized. Few states offer specific incentives or requirements for source separation or collection of organic waste. State policies and incentives vary and often conflict, in terms of their definition of "renewable" (e.g., landfill gas is frequently excluded from RPS) and in terms of options for biomethane transport (i.e., what quality standards must be met in order for it to be injected into the natural gas pipeline). National standards are needed to help clarify these definitions. Policies for utility interconnection, net metering, and wheeling also vary from state to state, and can affect a project's viability.

Wastewater biogas cleanup system at Pt. Loma WWTP. This privately owned and operated project processes over 1 million cubic feet of digester gas per day (which was previously flared) to generate 4.5 MW of baseload renewable power. The biogas is cleaned, injected into the San Diego Gas & Electric natural gas pipeline, and wheeled to the University of California, San Diego and the City of San Diego South Bay WWTP, which operate two fuel cell power plants to produce 2.8 MW and 1.4 MW, respectively. A third fuel cell, a 300 kW system located on site at the Pt. Loma WTTP, also generates renewable power to upgrade the biogas to biomethane.

Source: Fuel Cells 2000 State Fuel Cell and Hydrogen Database. Photo from BioFuels Energy, LLC

In regard to policy opportunities at the federal level, there is an opportunity for hydrogen generated from biogas from WWTPs or landfills to qualify as a biomass-derived transportation fuel under EISA, which has established a Renewable Fuel Standard (RFS2) program that is administered by the U.S. Environmental Protection Agency (EPA). The RFS2 program mandates that fuel refiners obtain renewable fuel credits, designed as RINs, to meet a minimum percentage of renewable fuel production.

Under the present RFS2 program, the EPA has qualified biogas from WWTPs and landfills as an advanced biofuel, which enables producers to create and sell RINs when the biogas from wastewater or landfills is sold as a vehicle fuel. For hydrogen generated from biogas to qualify as a biomass-derived transportation fuel, the EISA requires the EPA to approve a pathway for this process.

3.4 Analysis and Education

Analysis-related challenges centered around three areas: 1) lack of data and tools for economic analysis and total cost accounting of biogas fuel cell projects, 2) lack of a clearly defined business case or value proposition for investors and project developers, and 3) lack of data on sites that could be considered rich opportunities for biogas. With respect to economic analysis, data and tools are needed to help a project owner/investor determine the best use for the biogas (e.g., inject to pipeline, provide power only, CHP, or trigeneration), assign a value to all of the revenue streams, and include the value of any "tangible externalities" (e.g., reductions of criteria pollutants). These data are needed to help create the business case or value proposition for biogas fuel cell projects. Many biogas producers do not understand the value of a biogas fuel cell project, and education of potential project developers is needed. Publicly accessible information on real-world examples or reference plants is needed to show the feasibility in operating environments. Another challenge is the lack of data on sites (especially in the food and beverage industries) that combine a large biogas resource supply with an internal (or nearby) demand for heat, hydrogen, and/or power.

3.5 Utility Issues

Several key barriers were identified that relate to electric and gas utilities. First is inconsistent, and sometimes costly, interconnection standards that regulate the process by which the distributed generation system is connected to the electrical grid, including fees and tariffs charged by the utility. The availability and pricing structure of net metering (where a utility credits a distributed generator for electricity sent to the grid) is also inconsistent from state to state. In many states that allow net metering, biogas projects receive less favorable treatment under the pricing rules than solar projects. For large biogas projects that produce more biomethane than can be economically used on site or electricity than can be sold to the electric grid, natural gas pipeline injection is needed to realize economies of scale and reduce distribution costs. However, many states prohibit the injection of biomethane derived from landfill gas into the pipeline, due to concerns about biomethane quality.

4 Next Steps

The workshop participants suggested a wide range of possible next steps to pursue, as summarized below. Two main mechanisms to act upon these next steps should be enabled. First, a government/industry working group should be established to convene interested parties, determine and prioritize actions, and share information. Second, existing techno-economic and engineering analysis tools and global information system (GIS) capabilities should be applied to produce publicly available, detailed evaluations of biogas resource quantity, availability, and distribution. These evaluations should assess optimal integration schemes for fuel cells using biomethane in CHP, trigeneration, biorefinery, and other applications that improve energy efficiency, reduce GHG and criteria pollutant emissions, or increase deployment of hydrogen production technologies to assist in the development of a national hydrogen infrastructure. Following are more specific actions suggested by workshop participants.

4.1 Information Sharing and Discussion Forums

- Jointly convene the Waste-to-Energy Working Group that has been formed by the DOD-DOE Memorandum of Understanding Executive Committee to assist in coordinating and collaborating on the deployment of biomethane fuel cell projects at targeted facilities.[27]

4.2 Analysis and Modeling

- Develop a biogas fuel cell analysis tool
    - Include heat balance (need energy analysis) and water balance
    - Include biorefinery integration: how much hydrogen is needed for different processes?
- Develop or evaluate existing biorefinery, LFG, and WWTP system and unit process models
    - Explore the following questions: Where do fuel cells optimally integrate, considering electricity, heat, and/or hydrogen generation? What are the most valuable uses of biogas?
- Quantify benefits and impacts of distributed generation using biogas compared with the grid
- Enhance and continue to develop the understanding of the biogas resource
    - Is the biogas resource large enough to support a requirement for biomethane content in natural gas?
    - How much food preparation waste is available? Businesses pay a lot of money to move waste off-site.
    - How many power co-ops (potential users) are out there and how much energy do they produce?
    - Produce multi-layer maps of biogas resources, key potential users, available infrastructure, synergistic sources, etc.

4.3 Regulatory

- Develop effective economic incentives for biogas use, including assessment of methods to monetize the actual environmental benefit of biogas use
- Address issues involving utility (gas and electric) interconnection
- Hold discussions with EPA about the potential for hydrogen that is generated from biogas to be considered a biomass-derived transportation fuel under EISA

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[27] DOD-DOE Workshop on Converting Waste to Energy Using Fuel Cells. http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/waste_to_energy_report.pdf.

4.4 Research, Development, and Demonstration

- Conduct R&D and systems integration/standardization to reduce cost and complexity of gas cleanup technology
  - Reduce part count and standardize components
  - Develop siloxane recovery methods
  - Develop gas cleanup for mixed-waste streams
- Improve fuel cell technology for use with biomethane
- Conduct collaborative (including public and private stakeholders) demonstration projects that will include integrated biogas and fuel cell energy systems

4.5 Data Collection and Sharing

- Share fuel cell contaminant tolerance specifications with biogas community
- Provide data on biomethane composition
  - Government or laboratory could complete industry-vetted database on biogas and biomethane composition – need to decide what additional data are necessary
- Develop open-source database on various biomass resources (needs government support)
  - Could partner with CHP Partnership for data collection

4.6 Information and Outreach Products

- Develop factsheets, case studies, and conference presentations
- Show value proposition for collecting and using biogas resources
- Understand how to assess and allocate risk from the financial industry point of view
  - Risk areas: feedstock, construction, and operation
  - Explore both private and public options for "bridge" funding for up-front capital equipment costs vs. longer-term variable costs (i.e., cost/revenue from biogas)

Appendices

Appendix A: List of Attendees

Name	Organization
Shabbir Ahmed	Argonne National Laboratory
Jim Alkire	U.S. Department of Energy (DOE), Golden Field Office
Gokhan Alptekin	TDA Research, Inc.
Charlie Anderson	Air Liquide
Mark Antkowiak	National Renewable Energy Laboratory
Richard Bain	National Renewable Energy Laboratory
Jack Brouwer	National Fuel Cell Research Center, UC Irvine
Bill Buttner	National Renewable Energy Laboratory
Steve Chalk	DOE, Office of Energy Efficiency and Renewable Energy
Kim Cierpik	CNJV
Jeff Coombe	Tetra Tech
James Dack	Stern Brothers
Peter Devlin	DOE, Fuel Cell Technologies Program
Brian Duff	DOE, Biomass Program
Sean Emerson	United Technologies Research Center
John Galloway	HDR
Dale Gardner	National Renewable Energy Laboratory
Jeff Glandt	Ballard
Steve Hamilton	SCS Energy
Ian Handley	RosRoca
Aaron Harris	Sandia National Laboratories
Michael Hicks	Fuel Cell and Hydrogen Energy Association
Jamie Holladay	Pacific Northwest National Laboratory
Jay Hooper	Land Fill Energy
Randy Hunsberger	National Renewable Energy Laboratory
Eric Jacobs	State of Colorado
Katie Jereza	Energetics Incorporated
Terry Johnson	Sandia National Laboratories
Nick Josefik	ERDC-CERL Army Corps
Greg Kleen	DOE, Golden Field Office
Jen Kurtz	National Renewable Energy Laboratory
Nick Lumpkin	Clean Energy
Brian Marchionini	Energetics Incorporated
Morry Markowitz	Fuel Cell and Hydrogen Energy Association
Joani Matranga	State of Colorado
Norma McDonald	Organic Waste Systems, Inc
Mike McGowan	Linde North America
Mac McGuire	Element Markets
Shawna McQueen	Energetics Incorporated

Name	Organization
Marc Melaina	National Renewable Energy Laboratory
Greg Moreland	SRA International
Frank Novachek	Xcel Energy
Shaun Onorato	DOE, Golden Field Office
Pinakin Patel	FuelCell Energy
Dave Peterson	DOE, Golden Field Office
Bryan Pivovar	National Renewable Energy Laboratory
Katie Randolph	DOE, Golden Field Office
Sunita Satyapal	DOE, Fuel Cell Technologies Program
Steven Sell	BioFerm Energy Systems
Patrick Serfass	American Biogas Council
Matthew Simon	Energetics Incorporated
Jonathan Sperry	UTC Power
Darlene Steward	National Renewable Energy Laboratory
Michael Ulsh	National Renewable Energy Laboratory
Brian Weeks	Gas Technology Institute
Keith Wipke	National Renewable Energy Laboratory
Frank Wolak	FuelCell Energy
Ruihong Zhang	University of California, Davis

Appendix B: Biogas and Fuel Cells Workshop Agenda

Workshop Objectives:

- Discuss current state-of-the art for biogas and waste-to-energy technologies for fuel cell applications.
- Identify key challenges (both technical and non-technical) preventing or delaying the widespread near term deployment of biogas fuel cells projects.
- Identify synergies and opportunities for biogas and fuel cell technologies.
- Identify and prioritize opportunities to address the challenges, and determine roles and opportunities for both government and industry stakeholders.
- Develop strategies for accelerating the use of biogas for stationary fuel cell power and/or hydrogen fueling infrastructure for motive power fuel cells.

Workshop POCs:

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Diane Littau
National Renewable Energy Lab (NREL)
303-815-6743

Monday, June 11, 2012

1:00 – 2:00 PM **Registration**

2:00 – 2:15 AM **Welcome**

- Dale Gardner, National Renewable Energy Laboratory

2:15 – 3:30 PM **DOE Perspective**

- Sunita Satyapal, Fuel Cell Technologies Program, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy
- Brian Duff, Biomass Program, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy

3:30 – 5:15 PM **Markets and Legislative Outlook**

- Michael Hicks, Fuel Cell and Hydrogen Energy Association
  - Fuel Cell and Biogas Industries Perspectives
- Norma McDonald, Organic Waste Systems
  - State Policy and Legislative Outlook
- Patrick Serfass, American Biogas Council
  - National Policy and Legislative Outlook

5:15 – 5:45 PM **General Discussion about Workshop**

- Pete Devlin, Fuel Cell Technologies Program
- Shawna McQueen, Energetics Incorporated
  - Overview of Topics of Workshop
  - Overview of Goals and Tasks

6:00 – 7:30 PM **Information Brainstorming Session**

- Dale Gardner, National Renewable Energy Laboratory

TUESDAY, JUNE 12

7:30 – 8:00 AM **Continental Breakfast**

8:00 – 8:30 AM **Biomass Resources Overview and Perspectives on Best Fits for Fuel Cells**

- Darlene Steward, National Renewable Energy Laboratory

8:30 – 9:30 AM **Success Stories**

- Frank Wolak, City of Tulare/ Fuel Cell Energy - wastewater treatment gas
- Jack Brouwer, UC Irvine - waste water treatment gas and hydrogen production/dispensing for fuel cell vehicles
- Mike McGowan, Linde North America – LNG from landfill gas

9:30 – 9:45 **Break**

9:45 – 11:15 AM **Biogas Technologies and Integration with Fuel Cells**

- Shabbir Ahmed, Argonne National Laboratory
- Charlie Anderson, Air Liquide
- Ruihong Zhang, UC Davis
- Ian Handley, RosRoca

11:15 – 12:00 PM **Putting Resources and Technology Together**

- Steve Hamilton, SCS Energy - value proposition for biogas from waste water treatment plant
- James Dack, Stern Brothers - financial options and opportunities

12:00 – 12:15 PM **Workshop Goals, Objectives, and Desired Outcomes**

- Steve Chalk, Office of Energy Efficiency and Renewable Energy, U. S. Department of Energy

12:15 – 1:00 PM **Working Lunch**

- Pete Devlin, Fuel Cell Technologies Program - participant pre-workshop input results

1:00 – 2:30 PM **Breakout Session #1** ***(3 parallel sessions – see Breakout Session Details)***

- Project Development Barriers and Challenges

2:30 – 2:45 PM **Break**

2:45 – 5:15 PM **Breakout Session #2** ***(3 parallel session – see Breakout Session Details)***

- Strategies and Actions for Success

5:15 – 6:00 PM **Reports from Breakout Group Discussions**

Wednesday, June 13, 2012

8:00 – 8:30 AM **Continental Breakfast**

8:30 – 9:30 AM **Critical Questions and Next Steps**

Sunita Satyapal and Pete Devlin, Fuel Cell Technologies Program, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy

- How can government actions catalyze private investment in deployments?
- What are the critical questions or topics for further analysis?

9:30 – 11:30 AM **NREL Tour**

- Walking tour of the Integrated Biorefinery Research Facility and the Thermochemical Users Facility

Appendix C: Raw Breakout Group Results

Group 1A. Barriers & Challenges – Wastewater Treatment Plant Anaerobic Digester Gas

Focus Question #1: What are the barriers and challenges to widespread deployment of combined heat and power (CHP) or combined heat, hydrogen, and power (CHHP or trigeneration) fuel cell projects using biogas from wastewater treatment plant (WWTP) anaerobic digester gas (ADG) today?

● Indicates top-priority vote; • Indicates vote for other priorities for action

Biogas and Fuel Cell Project Success Stories	Biogas and Fuel Cell Project Success Stories	Biogas and Fuel Cell Project Success Stories	Biogas and Fuel Cell Project Success Stories
• Need for better, more efficient, lower cost, and more robust hydrogen purification/separation systems for trigeneration ••	• Need lower cost fuel cell systems ••• • Combustion technologies are very good, becoming better, and can work with less purity in the feedstock •• • The cost of bio-fueled fuel cell systems does not compete well with natural gas (NG) fired combined cycle generation	• Opportunity cost for biogas – relative benefit to WWT should be well understood ••••• • Need a value assigned to carbon (GHG) reduction ●• • No accounting for life-cycle emissions and avoided costs •• • Need pricing that works for both suppliers and market	• There is limited access to the grid (i.e., NG pipelines and electric) – no incentives for the utilities to connect ●••• • There is a lack of awareness of the value proposition achieved by projects like Tulare and Orange County Sanitation District ●•• • Incentives to offset project costs are only available in a few states – CA and CT most noteworthy •• • Need good showcases of the technologies (cannot be a "science project")
Feedstock Impurities	**Systems Integration**	**Availability**	**Policy & Regulations**
• Need better ADG cleanup systems – more effective removal of complex mix of contaminants ●●••••• • Concern about fuel cell sensitivity to impurities in gas feedstocks •• • Need better, lower cost media for contaminant removal (operating and maintenance costs are too high) • • The feedstock fuel quality standard for fuel cells is too stringent • • Concern about increased cost due to overdesign for variable impurities in ADG cleanup	• Need better systems integration (e.g., heat, chemicals, etc.) – no standardization currently available ●••• • There is an increased cost of the fuel cell system to customize for low energy content / dilute gas feeds •	• Location – need to match the supply and demand ●•••• • Need a number of site locations with enough energy content to have many fuel cell power plant deployments ●•• • There are limited outlets/markets for hydrogen at small-scale facilities – no market on the demand side • • Need consistent availability of fuel gas to maintain operation of the fuel cell power plant, especially if pipeline NG is not co-fed	• There is a lack of policy certainty and variances exist between federal and state definitions of what qualifies and why, and what is considered acceptable means of transportation ••• • Industry is segmented – not taken seriously enough to affect policy ● • Commercial contracts take a long time to complete due to regulatory, legislative, and incentives (government, taxes, etc.), which are always changing

Group 1B. Strategies & Actions – Wastewater Treatment Plant Anaerobic Digester Gas

Focus Question #2: What are the specific strategies and actions to eliminate the top priority barriers and accelerate widespread deployment of CHP or trigeneration fuel cell projects using biogas from WWTP ADG in the U.S. today?

Top Priorities	Strategies	Actions
Wide spectrum of biogas contaminants to eliminate makes ADG cleanup too costly	• Develop more tolerant (not sensitive) fuel cells • Develop better, low-cost media/cleanup systems • Develop low-cost adjustments to the digester process to reduce digester contaminants (e.g., change inoculant or bacteria culture) • Optimize the WWT process with gas cleanup to reduce overall cost (e.g., iron treatment to remove sulfur)	• Conduct system study of digester, gas cleanup, and fuel cell system optimization • Survey fuel cell OEM providers for the contaminants (contaminant tolerance specs)
No widely accepted value proposition of biogas versus alternatives	• Develop Biogas Fuel Cell Analysis (BFCA) tool, modeled after H2A tool • Perform analysis study to determine values and scenarios for BFCA tool (e.g., GHG, various states' criteria pollutants). • Provide documented examples (large to small scale, CHHP vs. electricity vs. gas) to WWTP to use in making a commercial decision	• Demonstration of actual plant that addresses "value" gaps • Create factsheets on existing deployments • Develop the BFCA tool from non-partisan developer
Feedstock size and product alignment to expand market opportunities	• Enhance ADG production opportunities to increase gas supply (e.g., add vegetable oil to AD to increase kW) • Develop fuel cell products that are better matched to ADG sites • Identification/mapping of biogas feedstock locations and types • Develop economic modeling of cleaned biogas for hydrogen generation	• Industry and government need to work together to create a multi-layer map that shows organic waste type/location, electricity prices, NG grid, etc.
Inconsistent interconnection (gas and electric) standards and applications thereof	• Make data on actual biomethane quality available to gas utilities • Accompany data sharing with education & outreach	• Find out who allows net metering and if biogas-to-electricity qualifies
Better system integration & optimization	• Develop an overall system model to predict system performance under different scenarios. (Overall = fuel cell, AD, cleanup, etc.)	• Convene cross-cutting team (between Biomass and Fuel Cell Technologies Programs) to develop approach
Lower cost fuel cell systems	• Continue the Fuel Cell Technologies Program	

Group 2A. Barriers & Challenges – Landfill Gas

Focus Question #1: What are the barriers and challenges to widespread deployment of CHP or trigeneration fuel cell projects using landfill gas (LFG) today?

● Indicates top-priority vote; • Indicates vote for other priorities for action

Cost	Technology	Regulatory and Policy	Public Outreach and Education
• Lack of private funding sources ●••• • Do not know best markets/applications (e.g., fuel cell electricity only? CHP? pipeline gas? heat only?) •••• • Natural gas prices are expected to remain low for several years. The environmental benefits of LFG cannot always be quantified •••• • Individual LFG sites are too small to have a business case ••• • Stranded resource (usually not located near point of use) ••• • Mismatch between capital and variable costs (biogas has high capital but payback is variable)•• ○ Incentive/loan programs do not match project realities • Market for "Green Electricity" or "Green Fuel" is too small • North American energy market is unique and solutions in Europe/Asia not necessarily valid for U.S. • In head-to-head cost competition with natural gas biogas suffers • Fuel cell	• LFG needs a lot of cleanup before useful (siloxane, sulfur, nitrogen, etc.) ●●•• ○ Complex cleanup processes/ technologies • Pipelines will not accept LFG into the system (due to gas quality concerns) ●•• • Lack of real-time in-line sensing for quality assurance ••• • Low reliability of BOP/cleanup components •• • Variable quality of components • Variable output (both LFG gas quantity and quality) • We do not have clear guidelines for the actual fuel cell contaminant specifications for fuel cells (perception is that what exists is overly stringent)	• No strong economic driver for using LFG vs. flaring ●••••• ○ Cost of doing nothing is too low • Lack of emissions regulations ●•• • Pipeline injection is required to realize economies of scale and lower distribution costs ••• • Lack of regulator and stakeholder interaction •• • RINs are risky (value of payments is uncertain) ●• • LFG frequently excluded from RPS programs • • Lack of analysis of effective policies – what works and why? ● • Every state and utility has their own standards for bio-methane pipeline injection • Lack of effective supportive Federal policies • LNG/diesel disparity (diesel more favorable) ○ Fees and credits	• Partnerships needed for outreach and information sharing – landfill owners, fuel cell company, gas cleanup company, funding organization, government ●•• • Landfill owners may not know about the potential for fuel cells or what their incentive is to expand ●•• • Lack of public information ○ Need to promote technologies and benefits better •• • Lack of public domain information about fuel cell failures and contaminants

Group 2B. Strategies & Actions – Land Fill Gas

Focus Question #2: What are the specific strategies and actions to eliminate the top priority barriers and accelerate widespread deployment of CHP or trigeneration fuel cell projects using LFG in the U.S. today?

Top Priorities	Strategies	Actions
Identify best market applications (fuel cell [or other] electricity, fuel cell [or other] CHP, pipeline, heat)	• Where are energy security or power resilience needs very important? ○ What facilities are willing to pay for premium power?	• Target hospitals, areas with long-term outages, manufacturers who cannot afford to go down
Level the playing field for landfill air emissions regulations (more consistent enforcement)	• Institute tighter controls on methane from landfills	• Develop incentives for methane capture • Improve enforcement of regulations (this would require a lot of detailed support and guidance)! • Communicate benefits and impacts of methane collection
LFG cleanup is complex and costly	• Develop universal, standardized methods for gas testing and cleanup • R&D on modules that work together	• Joint solicitation between DOE-EERE, DOD, others • Focused R&D on cleanup technologies directed specifically at LFG • More R&D on fuel processing and hydrogen separation (also for power generation) • Segregate waste at source and at landfill → pull LFG for fuel off of the organics part of the landfill (this approach has been used in Europe)
No strong economic driver for use of LFG vs. flaring	• Assign a value to the LFG that is fungible • Front-load RINs → so that company can get the funding as a "loan" up front and pay it back over time from the value of the RINs	• Convene EPA and DOE to discuss possibilities for modifying RIN program • Develop differentiators for renewable natural gas versus conventional natural gas
	• Implement more effective incentives	• Study: why are current policies and RINs not enough? • Give credits for biogas use in the U.S. • Encourage culture of "stewardship" for municipal solid waste resource ○ "Transfer of custody" from waste producer to collector to landfill

Improve public outreach and education	• Develop communication forums for stakeholders (e.g., researchers, regulators technology developers, county and local government)
	  ○ Establish a goal for the group to address (targets for action)
		• Present case studies
		• Explain how private companies, municipalities can make money
		• Demonstrate technologies
		• Discuss regulations (e.g., standardization of landfill gas quality standards)
		• Inform cities that LFG can be a transit power fuel
		• Explore "co-op" or other ideas that could encourage private funding
		• Possible partner groups:
		  ○ Solid Waste Association of North America (SWANA)
		  ○ American Biogas Council (ABC)
		  ○ Clean Cities
		  ○ CalSTART
		  ○ EPA
		  ○ DOE
		  ○ ICLEI Local Governments for Sustainability USA
		  ○ NJ (E-Visions and Rutgers)

Group 3A. Barriers & Challenges – Biorefineries and Other Industrial Waste

Focus Question #1: What are the barriers and challenges to widespread deployment of CHP or trigeneration fuel cell projects at large biofuel production facilities or at industrial facilities that generate large amounts of organic waste (e.g., food processors) today?

● Indicates top-priority vote; • Indicates vote for other priorities for action

Technology Cost	Regulatory & Policy	Project Financing and Development

• Technology maturity and its impact on technology cost and project financing ●●••••
• Fuel cell value proposition vs. internal combustion engine not compelling (high first cost relative to incumbent technologies) ••••
  ○ Increased capital expenditure
  ○ Increased operating expenditure
  ○ Increased kWh
• Cost/complexity of upgrading product quality ●••
• IBRs using cellulosic feedstock in process of de-risking tech; decreasing dollars to reach competitive level
• High first cost of fuel cells (relative to incumbent technologies)
	• Lack of organics diversion mandates ●••••••
	• Lack of coordinated state/fed policies to support/incentivize these projects ●●••••
	• Lack of long-term consistent federal policies consistent with tenor of financing packages ••••
	• Carbon cost or GHG avoidance value not high enough ●●
	• Stakeholders not coordinated in providing information ••
	  ○ USDA
	  ○ DOE
	• Government policy keeps conventional fuel cost artificially low •
	• Government policies that do not take into account the value of by-products (e.g., only value electricity from the fuel cell, not heat or hydrogen) •
	• Uncertainty in environmental regulations (e.g., "Tailoring Rule" HAPS MACT)
	• High cost of grid interconnection or lack of support network
	• Fully capturing value of biogas electricity products relative to other renewables (i.e., baseload vs. as-available)
	• Not-in-my-back-yard opposition
	• Regulation hurdles: biomethane injection, permitting, incentives, state-by-state vs. federal policies and jurisdictional differences
		• Equipment providers & engineering, procurement and construction firms willing and able to guarantee performance for a reasonable period of time ●•
		• Maximizing revenues from effluent streams •
		• Lack of reference plants to address risk to financial community •
		• Bias toward big (central generation) •
		• Business partnership and development between customers and technology providers

Feedstock Quality/Availability	Operation & Maintenance	Market

• Competition for feedstocks •••
• Lack of established long-term feedstock agreements •
• Quality and quantity of feedstock supply (variability and seasonality)
• Scalability of the technology vs. the spread-out nature of the feedstock
• Lack of data on waste/ by-product streams for second generation biorefineries
	• Organic waste generators are hesitant to sign up:
	  ○ Scared to switch from sure thing (dump)
	  ○ Do not want to be responsible for operations •••
	• Variability of output stream in Btus and composition •••
	• High cost of O&M from complexity of equipment •
	• Inconsistent digester performance and biogas production (reliability) leads to risk when relying on biogas for operations and revenue
		• Low value proposition for co-products and uses of biomass waste ●•••••
		• Lack of retail market access; must sell power and gas at wholesale prices, no/limited wheeling ●•••
		• Buyers willing and able to contract for the high value products for a reasonable amount of time ●
		• Business case: complexity of issues we are exploring here are difficult to communicate to hosts/customers in terms of value proposition

Group 3B. Strategies & Actions – Biorefineries and Other Industrial Wastes

Focus Question #2: What are the specific strategies and actions to eliminate the top priority barriers and accelerate widespread deployment of CHP or trigeneration fuel cell projects at large biofuel production facilities or at industrial facilities that generate large amounts of organic waste in the U.S. today?

Top Priorities	Strategies	Actions
Technology maturity and its impact on technology cost and project financing	• Develop better understanding of integration opportunities with biorefineries to maximize efficiency • Invest in more federally-funded integrated demonstrations of combined unit operations – bench, pilot, and demo • Investigate ways to cost effectively extract H_2 from digestate or steam produced from waste heat utilization • Continue government R&D on pre-commercial projects • Invest in cost effective sorting and pre-processing; includes education of community • Support creation of an ADG/fuel cell database of projects and performance metrics • Provide financial assistance and support of 3rd party O&M/service providers to relieve host of operations responsibility • Develop cost effective retrofit packages backed by vendor O&M with performance guarantees • Fund development of on-line instrumentation and process control algorithms to maintain consistent/optimized biogas production and quality • Engage stakeholders (engineering, procurement and constructions firms) who can assess and price risk the best	• U.S. Department of Energy
	• Investigate cheaper ways to buy down risk instead of just government – warranty & efficiency risk sharing with feds, engineering, procurement and construction firms, insurers →contingent liability	• Public/private partnership – risk sharing arrangement
Lack of coordinated state/federal policies to support incentives for these projects	• Engage with industry associations to coordinate state/federal policies	• Industry associations draft model legislation
Lack of organics diversion mandates	• Identify economic case and replicate success in other specific regions/countries (bench marking those practices)	• Industry association look for successful projects and why they worked they worked overseas in U.S. • DOE fund analysis for benefits

Top Priorities	Strategies	Actions
Low value proposition for co-products uses of biomass waste	• Study integration opportunities – not aware of the most profitable ones • Recognize "green" value of co-products based on renewable generation method vs. conventional fuels/ways • Integrate biogas projects with aerobic composting to tap retail markets • Engage non-profit sector to monetize water quality benefit of AD, thermochemical process • Coordinate a focused session on operating systems and research design in conjunction with other conferences • Develop database for biogas quality from different types of digesters (feedstock)	• DOE
	• Invest in developing higher value added processes and products for effluent co-products and water	• Researchers/industry
Lack of retail market access must sell electric or gas at wholesale; no/limited wheeling	• Analyze impact of state and regions wheeling policies (not done at utility level) • Quantify tangible externalities of bio-projects – Example: analyze benefit of bio-distributed generation compared to central generation with grid losses	• DOE led analysis

Appendix D: List of Acronyms & Abbreviations

ABC	American Biogas Council
AD	anaerobic digestion
ADG	anaerobic digester gas
CHHP	combined heat, hydrogen and power
CHP	combined heat and power
CO_2	carbon dioxide
DOE	U.S. Department of Energy
EISA	Energy Independence and Security Act of 2007
EPA	U.S. Environmental Protection Agency
GHG	greenhouse gas
GPD	gallons per day
H_2S	hydrogen sulfide
LFG	landfill gas
LNG	liquefied natural gas
MMT	million metric tonnes
NREL	National Renewable Energy Laboratory
OEM	original equipment manufacturer
PTC	Production Tax Credit
R&D	research and development
RFP	Renewable Fuel Standard
RIN	Renewable Identification Number
RPS	Renewable Portfolio Standard
USDA	U.S. Department of Agriculture
WWTP	wastewater treatment plant

Appendix E: Survey Results

After the workshop, the participants were asked to provide feedback on the workshop process, content, and results via a short Internet questionnaire. The questions and the responses are given below.

1. What were the top three most valuable outcomes for you at the workshop?

- Biogas, natural gas, hydrogen, and fuel cells are clearly aligned and do not need to be competing platforms; eagerness by the government and industry organizations to engage the EPA on some possible opportunities to enhance the RIN program; and appreciation that low natural gas prices could impede utilization of our biogas resources.
- Collaboration with top level individuals from a variety of backgrounds; devoted attendees and highly focused tasks; and learning about the realm of possibility with integrating ADG and fuel cells.
- Networking with other stakeholders; opportunities to leverage resources between the biogas industry and DOE; and learning that the value proposition for biorefineries can be enhanced by hydrogen and fuel cells.

2. What were the top three items you would like to see addressed?

- Follow-up on renewable credits for hydrogen as a fuel and programs to encourage biogas-derived fuels in a market of low cost natural gas and Brazilian sugarcane ethanol.
- 1) Implementation of organics diversion mandates; 2) increased retrofitting of ADG or LFG systems that currently flare or waste biogas to make use of biogas for heat/electricity; and 3) assignment/establishment of RINs or carbon credits to drive system payback period.
- 1) A study on how different biorefinery technologies can benefit from integration with fuel cells and hydrogen; 2) case studies on the promise and economic challenges of biorefineries; and 3) a joint collaboration between the U.S. Department of Agriculture (USDA) and the DOE.

3. What follow-up actions or next steps would you suggest?

- Meet with EPA on shared program interests and get more directly involved with traditional natural gas producers to discuss shared interests.
- Promote technology that can be quickly installed on existing facilities to make use of biogas; government solicitation opportunities for ADG and stationary fuel cell power projects; and promote use of renewable energy over non-renewable energy (such as natural gas).
- Conduct another workshop to review specific study results and presentations by biorefinery project developers who have successfully met some of these challenges.

4. Other comments or suggestions?

- Great job pulling together two camps of interested parties who previously have not had much opportunity to work together. It was a great idea to quickly begin to explore how to align the biogas and hydrogen and fuel cell efforts.
- If a follow-on workshop is planned, choose a meeting venue at a biorefinery site if possible and make sure a USDA representative can participate to add value.
- Thanks to the DOE and NREL team for this very important workshop. Hopefully a follow-on workshop will lead to some joint projects or a joint funding opportunity between the DOE and USDA programs.

Ratings (% of respondents)

	Excellent	Good	Fair	Poor
Workshop Structure and Content	67	33	0	0
Plenary Presentations	67	0	33	0
Breakout Group Discussions	0	100	0	0
Meeting Arrangements	50	50	0	0