Toward a Renewable Power Supply: The Use of Bio-based Fuels in Stationary Fuel Cells

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Prepared for:

Northeast Regional Biomass Program
400 Capitol Street Northwest, Suite 382
Washington, DC 20001

Prepared by:

XENERGY
Three Burlington Woods
Burlington, MA 01803
Tel: (781) 273-5700
Web: www.xenergy.com
Contact: cclark@xenergy.com

Energetic Management Associates
Brunswick, ME 04011
Tel: (207) 729-9665

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This study was researched and written by XENERGY, Inc. and Energetic Management Associates.

The study represents the collaboration of the following individuals:

Jonathan Abe
Ryan Chaytors
Christopher Clark
Christine Marshall
Erika Morgan

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XENERGY is an energy services and consulting firm with a specialization in the development of distributed generation and renewable energy projects.

XENERGY
Three Burlington Woods
Burlington, MA 01803-4543
Tel: (781) 273-5700 ext. 314 Fax: (781) 229-4867
Web: http://www.xenergy.com
Email: cclark@xenergy.com

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Executive Summary

The states of the Northeast U.S. share significant natural resources in their forest and agricultural lands. Policymakers throughout the region have long been interested in finding ways to maximize the use of biomass resources to the benefit of their many public and private constituencies. Recent research indicates a significant, quantifiable opportunity to expand the biomass power industry through the use of advanced technologies. With upwards of 7000 megawatts (MW) of installed capacity nationwide, biomass power supports more than 66,000 jobs and is the second-most utilized renewable electricity resource in the U.S. The U.S. Department of Energy (DOE) predicts that advanced technologies currently under development will enable the biomass industry to install over 13,000 MW of additional biomass power by 2010 – enough to create an additional 100,000 jobs.

This project was undertaken to explore the possible intersection between two promising technologies: biomass energy conversion and fuel cells. On the one hand, the forest-wood products and agriculture industries have both interest in and increasing experience with the technologies of biomass conversion. These technologies convert biomass feedstocks to useable fuels and therefore into an array of useful energy forms: electricity, heat/ thermal energy, and liquid fuels. This report focuses on seven such conversion technologies and the bio-based fuels they produce: syngas from biomass gasification; landfill gas; digester gas; ethanol; pyrolysis oil; biodiesel; and MTHF from levulinic acid.

On the other hand, fuel cell technology also takes a variety of forms, has many possible applications, and holds great future promise for producing electricity in a clean, efficient manner. This report examines the four main types of fuel cells currently under development: molten carbonate (MCFC), phosphoric acid (PAFC), proton exchange membrane (PEMFC), and solid oxide (SOFC). More specifically, this report discusses the challenges and opportunities associated with the use of bio-based fuels in stationary fuel cells. The focus is on the key technical issues that have impacted and will continue to impact the potential use of bio-based fuels in fuel cells.

This study is intended to serve as a resource to help ensure that industry stakeholders, from manufacturers to researchers to project developers, are proactively involved in developing a stationary fuel cell industry within which biofuels play an important and prominent role. Our findings are summarized below.

General Findings: Applicability of Biomass Feedstocks to Fuel Cells

- **No insurmountable technical challenges:** While there are technical challenges associated with current fuel cell technology, these challenges are not insurmountable. They should not be considered as long-term barriers to the development of biomass-based fuel cell systems. Rather, these challenges serve to highlight potential public policy and research and development (R & D) investment priorities.

- **Economics constitute the primary hurdle:** To date, despite the promise of biomass conversion technologies, bio-based fuels have largely been and continue to be overlooked by fuel cell manufacturers, researchers, and project developers as an energy source for fuel cells. The primary reasons are economics and availability. High fuel cell system costs, coupled with the additional costs associated with the use of bio-based feedstocks, (e.g., for fuel reformers, gas collection units, and system modifications) constitute a significant barrier to the development of biomass fuel cell systems.

- **No single fuel cell stands out as the "best bet":** There is little consensus among members of the fuel cell community regarding which type of fuel cell, if any, is likely to have the greatest overall/ long-term impact on commercial markets in general. Different types of fuel cells will be more or less suitable for different applications. Cost will be the primary determinant of the ultimate market frontrunner.

- **Phosphoric acid fuel cells (PAFCs) are a reality today:** For most biomass-based applications, PAFCs, due to their commercial availability and general tolerance for contaminants, are likely to be most widely used in the short term.

- **Over time, high temperature fuel cells have considerable promise:** In the long term, high temperature molten carbonate fuel cells (MCFCs) and solid oxide fuel cells (SOFCs) seem to be most promising for biomass-based fuel cell applications. Their high operating temperatures translate into a greater tolerance for contaminants relative to other fuel cell technologies. In addition, these fuel cells demonstrate internal reforming technologies that are more compatible with bio-based fuels. Cost and availability, however, will hinder their short-term development.

- **Niche applications provide the best near-term opportunity for biomass-based fuel cell projects:** There are no immediately viable commercial opportunities for using bio-based fuels with fuel cells. However, certain niche opportunities may exist in the near term. The most promising near term opportunities include:

    - Those in which the biomass feedstock or bio-based fuel can be obtained at low or no cost; and/or

    - Those with favorable geography.

  Based on the above categories, plausible near-term scenarios in which biomass-based fuel cell systems might thrive can be identified. Examples include fuel cell applications on landfills, fuel cells used in conjunction with biogas produced on hog or poultry farms, and fuel cells powered by ethanol in remote rural or island locations. In addition to R & D funding for fuel cells and biomass energy technologies, policies that help lower feedstock costs, stimulate the growth of necessary infrastructure, and ensure parity pricing for distributed electricity will be essential to the development of projects in the near term.

- **The development of biomass-based fuel cell projects will result in the realization of significant external benefits**: Despite near term economic hurdles and marginal project economics in even the most desirable niche applications, biomass-based fuel cell projects warrant exploration due to their potential to stimulate a wide array of direct and indirect economic and environmental benefits in the near and long term.

  From an environmental standpoint, the regional development of biomass-based fuel cell systems will: utilize an abundant, renewable resource that is indigenous to the Northeast; generate renewable electricity with emissions that are nearly absent of regulated air pollutants; and offer significant reductions in carbon emissions relative to fossil fuel-based electricity generation.

  From an economic perspective, the use of biomass-based fuel cell systems promises a host of economic benefits, resulting both from the stimulation of jobs in the manufacturing industry, as well as direct and indirect jobs in the production of biomass.

  Finally, at a time when energy security is at the forefront of regional and national concerns, biomass-based fuel cell systems offer a long term electricity solution characterized by increased fuel flexibility and independence.

Specific Findings by Biomass Conversion Technology

To varying degrees, biomass conversion technologies have the potential to combine with fuel cells to provide efficient, low emission electricity generation. The diagram on the following page summarizes the relationships among raw biomass, biomass conversion technologies, bio-based fuels, and the four major types of fuel cells. The diagram suggests that each biomass conversion technology and its bio-based fuel product integrates differently with each type of fuel cell technology. A brief description of these biomass conversion technologies and the various considerations associated with their use in fuel cells is also provided on the following page.

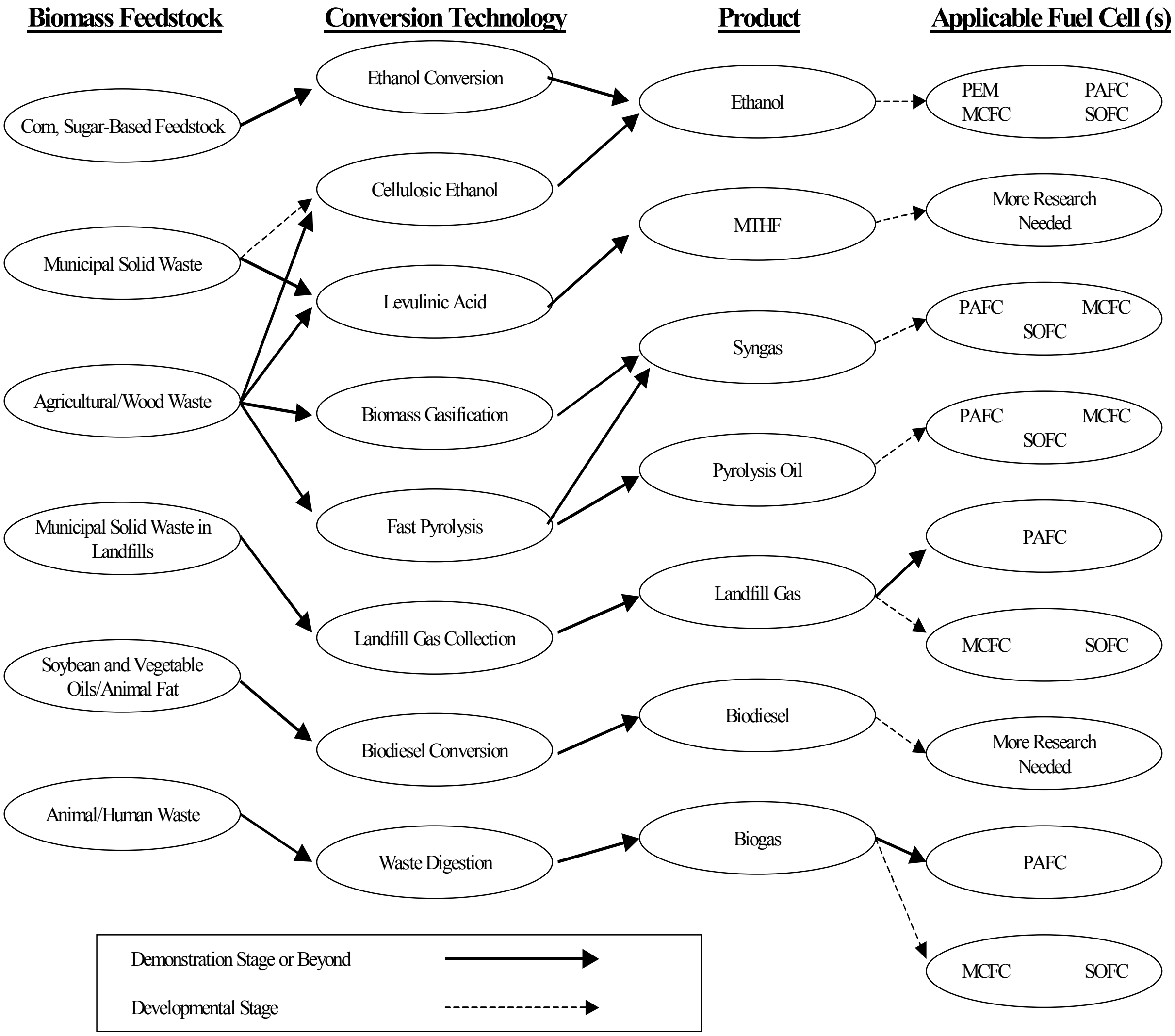

Figure 1. Linkages among biomass feedstocks, conversion technologies, end products, and fuel cells.

Biomass Gasification

The gasification of biomass to create combustible gas fuel is a reasonably well-established technology, although it has yet to move beyond the demonstration phase. Utilizing synthesis gas (syngas) from biomass gasification for electricity generation from fuel cells is a relatively new area of research. The current focus is on purifying the gas to meet the requirements of the fuel cell, which differ according to the particular gasification and fuel cell technology utilized. To varying degrees, all types of fuel cells can be utilized with biomass gasification systems. Due to their high operating temperatures and greater tolerance for contaminants, however, SOFCs and MCFCs are generally regarded as more compatible with biomass gasification over the long term. Commercial biomass gasification fuel cell applications are unlikely in the next five years.

Landfill Gas (LFG)

Landfill gas (LFG) has been successfully utilized with fuel cells in a handful of the 270 operating LFG recovery sites in the US. In order to use LFG in fuel cells, extensive clean-up is required to eliminate impurities and potential trace elements. Today, PAFCs are most commonly used with LFG. Over the long term, SOFCs and MCFCs have greater promise for use with LFG because they are more tolerant of impurities and integrate better with reforming technologies. Using a thermal host with the fuel cell improves project economics. Since LFG itself costs little, LFG applications will be relatively attractive for fuel cell developers in the near term.

Digester Gas

Like LFG, digester gas (biogas) requires extensive clean-up to scrub out impurities and contaminants. However, biogas typically contains fewer contaminants and has a higher Btu content than LFG. The composition of biogas also varies by site, feedstock characteristics, and season. PAFCs have been successfully demonstrated with biogas applications; a MCFC biogas system is now under development. SOFCs and MCFCs seem to hold more promise for use with biogas over the long term because the systems are more tolerant of impurities and integrate better with reforming technologies. The typically low cost of biogas relative to other bio-based fuels makes it a preferred option for near-term fuel cell demonstration projects.

Ethanol

By far, ethanol is the bio-based fuel with the most widespread commercial use. The most significant drawback with ethanol is its cost on a $ per Btu basis relative to other hydrocarbon alternatives, and relative to some other bio-based fuels. However, researchers note that ethanol has relatively abundant production capacity, is easy to transport, is relatively free of impurities, has low toxicity, and possesses a high power density. The internal reforming capabilities of MCFCs and SOFCs provide the temperature required (1112° F / 600° C) to efficiently reform ethanol. Identifying niche markets will be key to ethanol fuel cell project economics. One interviewee indicated that in the next few years ethanol-powered fuel cells will be an economically viable and environmentally preferable alternative to diesel generation on islands and in other remote locations.

Pyrolysis Oil, Biodiesel, and Levulinic Acid

Compared to research on the reformation of syngas, methane gas, and ethanol, work on the reformation of pyrolysis oil is limited, and research on the reformation of biodiesel and levulinic acid is scarce. Each of these biofuels is generally thought to be cheaper to produce than ethanol on a $ per Btu basis. However, due to their relatively complex chemical composition, converting any of them into hydrogen would require development of a reformer that operates at a higher temperature than the internal reformer in a SOFC (1800° F / 982° C).

- Pyrolysis Oil – Pyrolysis oil is typically created by a thermal process called fast pyrolysis. The resulting pyrolysis oil is a liquid mixture of oxygenated compounds containing various chemical functional groups such as carbonyl, carboxyl, and phenolic. Pyrolysis oil has not been tested in any fuel cell system.

- Biodiesel – Biodiesel is an oxygenated fuel made from soybean oil or other vegetable oils or animal fats. Like pyrolysis oil, biodiesel is a mixture of many chemical constituents and is therefore relatively difficult to reform. Researchers have recently successfully demonstrated the use of regular diesel fuel with a SOFC. They hypothesize that biodiesel would have similar characteristics, though sulfur removal would be necessary.

- Levulinic Acid – Biofine, Inc. has developed a high-temperature, dilute-acid hydrolysis process that converts biomass to levulinic acid and derivatives (MTHF). Little research has been conducted on the use of levulinic acid and its derivatives. However, based on its chemical make up, the reforming process for levulinic acid or its derivatives is anticipated to be easier than for pyrolysis oil and biodiesel, but more difficult than for ethanol. Levulinic acid has not been tested in fuel cells.

The following figure summarizes the compatibility of each type of fuel cell with the biomass conversion technologies covered in this study:

Fuel Source	**Type of Fuel Cell**			
	PEM	PAFC	MCFC	SOFC
Biomass Gasification	⭘	⊙	◎	◎
Methane from LFG	⭘	⊙	◎	◎
Methane from Digesters	⭘	⊙	◎	◎
Ethanol	⊙	⊙	◎	◎
Pyrolysis Oil	☐	☐	☐	☐
Biodiesel	☐	☐	☐	☐
Levulinic Acid	☐	☐	☐	☐

◎ -- Strong long-term potential
⊙ -- Somewhat compatible
⭘ -- Not very compatible
☐ -- More research necessary

Figure 2. Suitability of fuel cells for biomass fuel sources.

Barriers to the Development of Biomass Fuel Cell Systems

The widespread development of biomass-based fuel cell systems in the Northeast provides a strategy for sustainable electricity production that makes use of an indigenous, renewable fuel, does not foul the air, and provides a host of direct and indirect economic benefits. However, a variety of identifiable barriers stand in the way of their development. The consideration of these barriers is critical to the formation of policy solutions that will enable the development of biomass-based fuel cell systems, and a subsequent realization of the benefits they will provide.

Technology

- Researchers are generally confident that there are no insurmountable technical barriers to the more widespread development of fuel cell systems integrated with biomass fuels or conversion systems. Rather, cost is most often identified as the greatest obstacle. The most significant technical challenges are related to biomass fuel processing, clean-up, and reforming.

Economics

- Fuel cell system capital costs must decrease before fuel cells can become a viable power generation option. Fuel costs also impact project economics. Bio-based fuels will need to be cost-competitive with natural gas, a relatively clean and inexpensive fuel, in order to become a viable option for use in fuel cells. Therefore, inexpensive bio-based fuels in niche applications, such as landfill gas and biogas, have the greatest potential for use with fuel cells in the near term. Even in niche biomass applications, costs associated with fuel clean-up and conditioning are likely to be a barrier, especially when compared to natural gas. Combining heat recovery with fuel cell applications is one way to greatly improve project economics.

Infrastructure

- Infrastructure to deliver the bio-based fuels discussed in this report is largely nonexistent. Even for ethanol, which is widely available in the US relative to other bio-based fuels, infrastructure would have to be built or modified. Infrastructure is also necessary for storage and collection of raw biomass wastes that may be utilized with various conversion technologies. The added costs associated with developing this infrastructure are significant and create a formidable obstacle to the potential widespread development of biomass-based fuel cell systems.

Policy

- State and federal government must be supportive of fuel cells and bio-based fuels from both a financial and regulatory perspective. At the present time, biomass fuel cell systems are feasible only with the support of government subsidies and incentives. Current funding for R & D for fuel cells, biomass conversion technology, and systems that combine the two is inadequate.

Other

- A significant barrier to the development of biomass-based fuel cell systems is the lack of communication and collaboration among fuel cell researchers and biomass energy experts. A key short-term goal for parties involved in the research and development of biomass-based fuel cell systems should be to establish a trade or similar organization focused on providing a means to network and share research and ideas.

The figure below outlines the current status and important characteristics of each biomass conversion technology discussed above. For comparative purposes, natural gas, the likely market leader for stationary fuel cell applications, is also included.

Table 1. Important characteristics associated with the use of various bio-based fuels in fuel cells.

Fuel Cell Energy Source	Developmental Status	Technical Issues	Infrastructure Issues	Fuel Cost [1] ($ per mmBtu)
Syngas	R & D; no demonstrations w/ FC	Contaminant removal is difficult	No developed infrastructure for gathering biomass	Less than $9.00 to more than $50.00
Landfill Gas	Established demonstration projects w/ FCs	Btu content decreases over time	Must be located on site	$2.00 to 3.00
Digester Gas	Established demonstration projects w/ FCs	Wide variation in gas composition	Must be located on site	$1.50
Ethanol	Initial demonstration projects w/ FCs	Feasibility theorized but not demonstrated	In specific regions only (i.e., Midwest)	$12.50 (corn) $15.00 to 19.00 (cellulosic)
Pyrolysis Oil	Initial research w/ FCs	High reforming temperatures	No developed infrastructure	$2.00 to 6.00
Biodiesel	Little or no research w/ FCs	Not known	Utilize existing diesel infrastructure	$15.00 to 25.00
Levulinic Acid	Little or no research w/ FCs	Not known	No developed infrastructure	$9.00 to 51.00
Natural Gas	Some commercial projects	Minimal fuel pre-treatment necessary	Significant existing pipeline infrastructure	$3.00 to 4.00

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[1] Fuel cost is based on information gathered from relevant scientific literature and interviews with biomass experts. Cost ranges reflect differences associated with the type and price of the biomass feedstock utilized.

Policy Recommendations and Conclusions

Our research indicates quite clearly that biomass-based fuel cell systems, from a technical perspective, are capable of providing a source of clean, renewable electricity over the long-term. However, a number of economic and policy hurdles stand in the way of this opportunity. Without financial and policy support from the government, biomass-based fuel cell systems will be unable to compete with more traditional fuels and technologies in the short and long-term. These hurdles give rise to a number of policy recommendations regarding both macro-level electricity market issues, as well as considerations more specific to renewable energy and biomass-based fuel cell systems:

- In some states, through a variety of regulatory vehicles, incumbent utilities are able to make it difficult for small independent power producers to sell electricity. Independent power producers frequently observe a variety of barriers put in place by the incumbent utilities, including fees, undue technical concerns, and general resistance. Policies to overcome these macro-level barriers could have a positive and significant effect on the ultimate development of biomass-based fuel cell systems.

- Some states enable distributed generation facilities to sell power back to the grid at retail prices. If distributed generation facilities are able to receive retail prices for electricity sold, project economics will become more attractive to potential distributed generation developers.

- Current funding for R & D for fuel cells, biomass conversion technology, bio-based fuel reforming, and biomass infrastructure development is inadequate. Increased funding for research, demonstration projects, and feasibility studies in these areas is needed.

- Strong renewable energy policies that include biomass resources are necessary for the increased utilization of biomass feedstocks. Many states either limit or completely exclude biomass from renewable energy policies like renewable portfolio standards and system benefits charge funds.

Despite being in their relative infancy, stationary fuel cell technologies demonstrate great potential to provide clean, efficient, and economical electricity generation. Similarly, biomass fuel conversion technologies, which are either in their early stages of development or have captured minimal market share compared to fossil fuel alternatives, promise to provide significant benefits related to economic growth, environmental improvement, and long-term energy independence. While fuel cells and biomass conversion technologies are not entirely dependent on each other for commercial success, together they share unique synergies. The prospect of developing fuel cell and biomass technologies in tandem provides a prescription for electricity generation that is consistent with long term economic and environmental public policy goals. Greater collaboration among these industries, combined with public policies to support them, will be instrumental to overcoming the challenging, yet surmountable, economic, policy, and market barriers that stand in the way. A road map outlining this vision is provided on the following page.

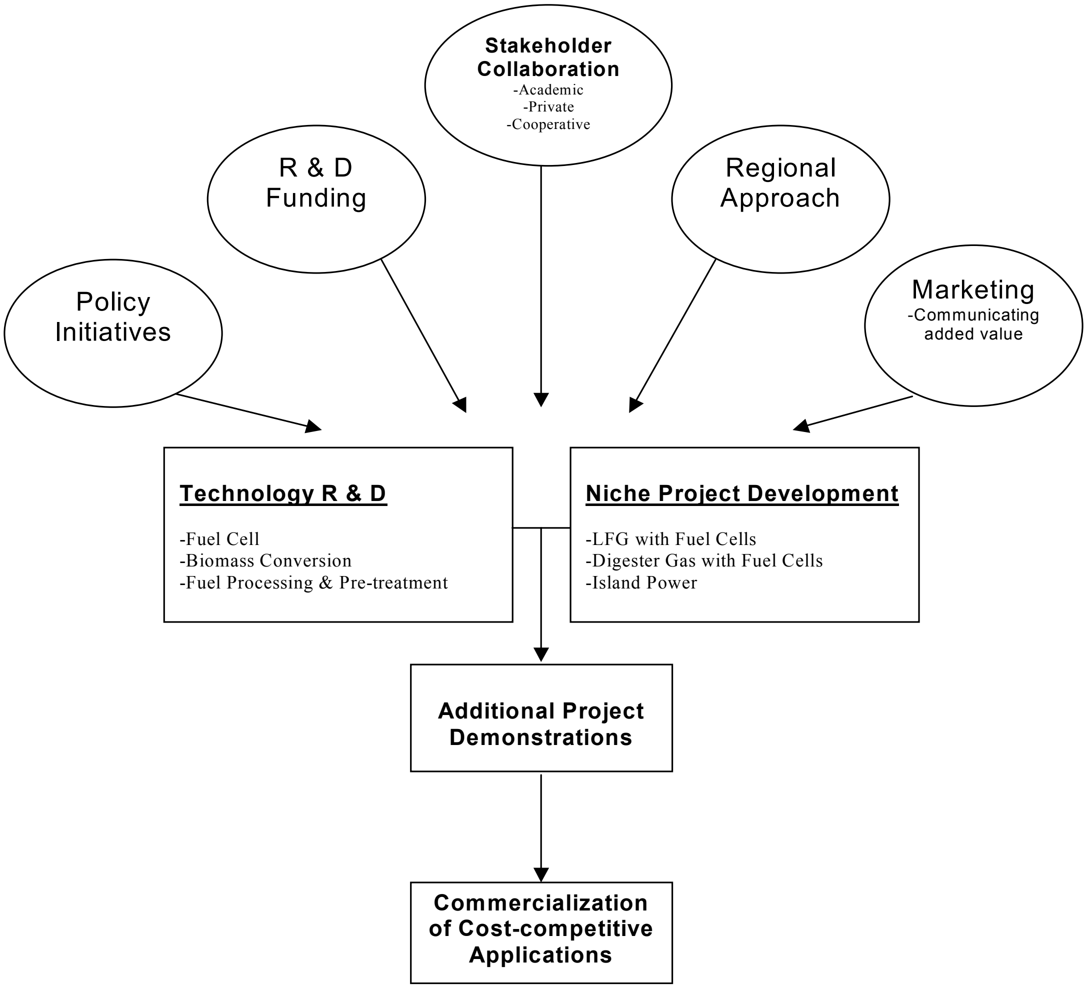

Figure 3. Road map for developing a cost-competitive biomass-based fuel cell industry.

1. Introduction

1.1. Background and Purpose

The past few years have seen a surge of interest in fuel cells as a clean source of energy on the part of policymakers, industry, and investors. As fuel cells approach commercialization, bio-based fuels, such as syngas from biomass gasification, ethanol, and landfill gas, offer considerable promise as energy sources for these emerging technologies. From a public policy standpoint, using biomass feedstocks to power fuel cells may address a variety of public issues, including solid waste management, air pollution and greenhouse gas emissions, rural economic development, and development of a renewable domestic energy source. However, despite these likely benefits, the fuel cell industry has been slow to adopt biomass feedstocks and fuels as a significant energy source.

At present there are nearly 50 megawatts (MW) of fuel cell demonstrations either planned or underway in the U.S., Japan, and Europe.[2] Looking to the future, a recent industry report forecasts that the current $10 million stationary fuel cell market will grow to more than $10 billion by 2010, while global stationary fuel cell electric generating capacity will increase to more than 15,000 MW by 2011.[3] Assuming that biomass-based feedstocks can be integrated with fuel cells, the development and commercialization of fuel cells would seem to provide a significant opportunity to expand the use of renewable biomass for electricity generation.

Recent biomass research by the U.S. government supports this conclusion. According to estimates by the National Renewable Energy Laboratory, biomass power presently is responsible for the generation of over 7,500 MW of electricity in the U.S. annually, and supports more than 66,000 jobs.[4] The U.S. Department of Energy (DOE) predicts that advanced technologies currently under development will enable the biomass industry to install over 13,000 MW of additional biomass power capacity by 2010 – enough to create an additional 100,000 jobs.

Concurrent with the emergence of fuel cells, advanced biomass conversion technologies continue to progress from a technological perspective. For our purposes, the term “advanced biomass conversion technologies” is used to refer to the bio-based fuels and processes detailed in this report: syngas from biomass gasification, landfill gas; biogas; ethanol; pyrolysis oil from pyrolysis; biodiesel; and levulinic acid. These technologies have shown promise in both demonstration and commercial applications.

Despite the promise of biomass conversion technologies, biomass-based feedstocks have been largely overlooked by fuel cell manufacturers, researchers, and project

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[2] Environmental & Energy Study Institute. “Fuel Cell Fact Sheet.” February 2000.
[3] Allied Business Intelligence. “The New Face of Stationary Fuel Cell Markets.” February 2001.
[4] “Biomass Power Research.” http://www.nrel.gov/research/industrial_tech/economic.html.

developers. At present, the predominant fuels used in fuel cell power systems are methanol, gasoline, and natural gas, with natural gas the most commonly used in stationary fuel cell applications. These fuels are typically perceived as less expensive and more readily available than bio-based fuels.

The purpose of this report is to present constructive information about the challenges and opportunities associated with the use of bio-based fuels in stationary fuel cells. This research focuses on key technical issues that have and will continue to impact the potential use of bio-based feedstocks in fuel cells. Also explored are some of the key market, policy, and economic issues that influence the development of bio-based fuel cell systems. Ultimately, this report is intended to serve as a resource for technology developers and policy makers to help ensure the development of a fuel cell industry within which biofuels play an important and visible role.

1.2. Approach

The research for this report began with a comprehensive literature review to assess the current and future applicability of biomass-based feedstocks to fuel cell systems. The literature review examined published reports and presentations from industry, trade groups, government research organizations, and academia.

To complement the literature review, 18 separate interviews were performed with fuel cell manufacturers, industry advocacy groups, trade organizations, and academic researchers. These interviews expanded upon the findings of the literature review, and ensured reporting of the most timely and accurate information possible.

Drawing from the interviews and literature review, this report is divided into the following sections:

- **Overview of Fuel Cell Technology and Types** --- This section discusses how a fuel cell works, how a fuel reformer works, the general benefits of using fuel cells, various fuel cell technologies, and introduces the potential for using bio-based fuels with fuel cells.

- **Biofuels – Background and Compatibility with Fuel Cells** --- This section considers the compatibility (opportunities and challenges) of four different fuel cell technologies and seven different bio-based fuels: syngas from biomass gasification; landfill gas; digester gas; ethanol; pyrolysis oil; biodiesel; and levulinic acid.

- **Barriers and Benefits** --- Interviewees from the fuel cell and biomass industries were asked to describe key barriers to the development of biomass-based fuel cell systems. Their comments are categorized under the following categories: Technology, Economics, Infrastructure, Policy, and Other.

- **Summary Findings and Recommendations** --- This section provides recommendations to industry stakeholders, project developers, and government officials interested in promoting the use of bio-based fuels in fuel cell systems.

- **Case Studies** --- This section reviews several recent projects that utilize bio-based fuels in fuel cells.

1.3. Experts Interviewed

We would like to thank the following biomass and fuel cell industry experts who agreed to be interviewed for this report:

- John Appleby, Director, Center for Applied Electrochemistry, Texas A&M University
- Tony Bridgewater, Director, BioEnergy Research Group, Aston University, UK
- Gregory Bush, Manager of Technology Assessment and Resource Recovery, King County Department of Natural Resources
- Pat Davis, Fuel Cell Manager, DOE, EERE
- John Fitzgerald, Technology Developer, Energy Transition Technology, Inc.
- Raymond Gorte, Professor and Chairman, Department of Chemical Engineering, University of Pennsylvania
- Mark Holtzapple, Professor of Chemical Engineering, Texas A&M University
- Kevin Kendall, Professor, School of Chemical Engineering, University of Birmingham, UK
- Michael Kimble, Vice President & Chief Technology Officer, Electrochem
- Charles Kinoshita, Professor and Chair, Biosystems Engineering Department, University of Hawaii at Manoa
- Michael Krumpelt, Manager Fuel Cell Program, Argonne National Laboratory
- Robert Lifton, Chairman & CEO, Medis Technologies
- Scott Samuelson, Director, National Fuel Cell Research Center
- Duane Sanger, City of Portland Environmental Services
- Darren Schmidt, Research Manager, Energy and Environmental Research Center, University of ND

- Norman Scott, Professor, Department of Biological and Environmental Engineering, Cornell University

- Ronald Spiegel, National Risk Management Research Lab, US EPA

- Xenophon Verykios, Professor, Department of Chemical Engineering, University of Patras, Greece

- Mark Williams, Fuel Cell Manager, National Energy Technology Laboratory, US DOE

To encourage participation by experts who might otherwise have preferred not to have their company or organization aligned with certain views or perspectives and to allow experts to discuss their true opinions, the comments of interviewees have been identified in the final report by industry sector only.

1.4. Review Process

An expert panel of five reviewers was assembled following completion of a draft of this study. The review panel included: Tony Bridgewater, Director, BioEnergy Research Group, Aston University, UK; Steve Morgan, President, EUA Citizens Conservation Services; Xenophon Verykios, Professor, Department of Chemical Engineering, University of Patras, Greece; Norman Scott, Professor, Department of Biological and Environmental Engineering, Cornell University; and Ronald Spiegel, National Risk Management Research Lab, US EPA.

Comments from members of this review team are reflected throughout this final version of the report. It is also worthwhile to note that the reviewers made several suggestions that were beyond the scope of this study. These comments are listed below in the hope that future research endeavors might include them:

- One reviewer suggested that we provide a better cost break down of the component parts and processes of a biomass-based fuel cell system. For example, the entire fuel cell system includes: a biomass conversion technology, a fuel cell stack, fuel processing equipment, electrical conditioning equipment, and site installation. By breaking out costs for each, one could emphasize that fuel cell operating systems are made up of a variety of components, each with their own separate costs and issues.

- One reviewer commented that we should further emphasize the specific bottlenecks (technical and/ or economic) that may occur in each key stage of the utilization of bio-based fuels in fuel cells: biomass growth/ collection, biomass conversion, fuel reforming, and fuel cell development. The reviewer went on to suggest that if such bottlenecks could be identified, a forecast of likely developments toward alleviating them could be made, as well as a time-frame of likely technical and economic progress. We agreed with this assessment, although we also felt that we had insufficient information and resources to complete that level of analysis at this stage.

- One reviewer suggested that we provide more technical information about fuel reforming and clean-up processes. We would like to note that greater detail about fuel reforming and clean-up of bio-based fuels for use in fuel cells can be found in a recently completed study by the National Renewable Energy Laboratory:

  Dayton, D.C. *Fuel Cell Integration – A Study of the Impacts of Gas Quality Impurities."* June 2001. For the Chemistry of BioEnergy Systems Division of the National BioEnergy Center. NREL/MP-510-30298.

2. Overview of Fuel Cell Technology and Types

2.1 How a Fuel Cell Works

Fuel cells convert chemical energy directly into electrical energy through the chemical reaction of hydrogen and oxygen. In general, a fuel cell operates like a battery, but it requires refueling instead of recharging. When hydrogen is supplied to a fuel cell, it reacts with oxygen from the air to create electricity and heat. If pure hydrogen is used as the fuel source, the sole by-product of the reaction is water. However, challenges associated with both producing and storing pure hydrogen necessitate the use of other fuels as hydrogen sources. A fuel reformer attached to the fuel cell can create hydrogen from most any hydrocarbon fuel, including gasoline, methanol, ethanol, and other bio-based fuels, through an electrochemical process.

An individual fuel cell is made up of two thin carbon electrodes, separated by a permeable material that contains the electrolyte. A fuel cell power plant would be comprised of stacks of cells, along with inverters that would convert DC output to AC power.

A fuel cell produces electricity through the following steps. First, pure hydrogen gas -- usually hydrogen extracted from a fuel like natural gas -- is fed to the anode, one of two electrodes in each cell. The process strips the hydrogen atoms off their electrons, turning them into positively-charged hydrogen ions. Next, the positively charged ions pass through an electrolyte (which varies by fuel cell type) to a second electrode, known as the cathode. Meanwhile, the negatively charged electrons, which are unable to travel through the electrolyte, move to the cathode via an external circuit. This movement produces electric current, the intensity of which is related to the size of the electrodes. At the cathode, the electrons are brought back together with their ions and combined with oxygen from the air to produce water. The other byproduct is waste heat, which in some applications is captured and reused.

The following figure illustrates the electricity production process in a basic hydrogen fuel cell:[5]

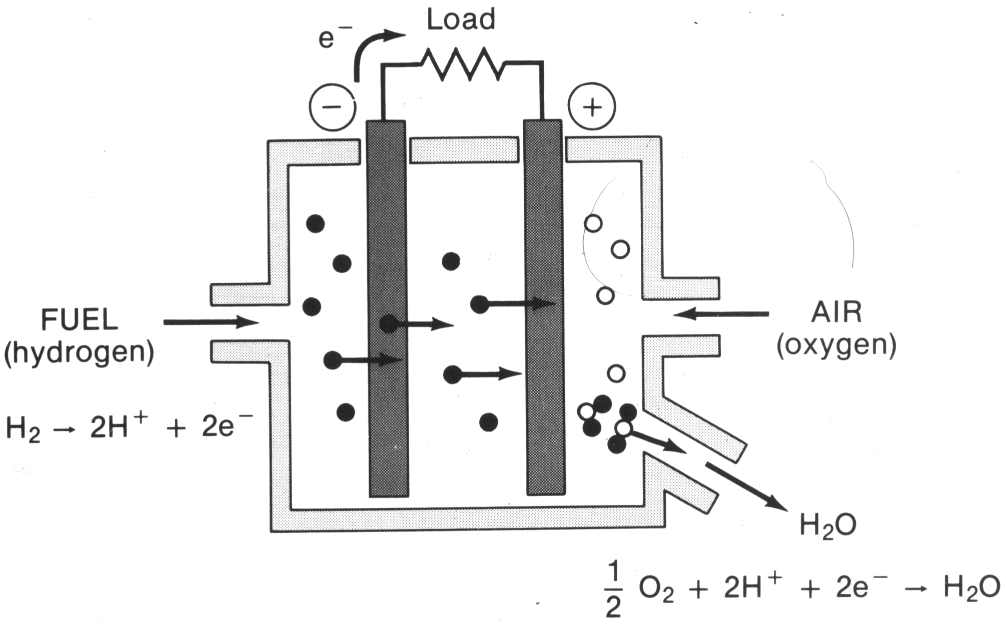

Figure 4. A typical hydrogen fuel cell.

In most cases, the fuel cell is coupled with a reformer.

Certain fuel cell technologies, known as “direct” fuel cells, do not include the reformer. Such direct fuel cells utilize a catalytic process that separates the hydrogen from the hydrocarbon fuel without a reformer, usually at high temperature.

2.2 How a Fuel Cell Reformer Works

The fuel cell reformer is a critical component of any fuel cell system. The function of the fuel cell reformer is to convert fuel into relatively pure hydrogen for use in the fuel cells. Fuel processors must be able to carry out their function efficiently and with minimal pollution.

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[5] Picture taken from Hinrichs, Roger. *Energy*. Saunders College Publishing, 1992.

The exact nature of a fuel cell reforming system can vary significantly depending on the type of fuel being used and the type of fuel cell technology being applied. In general terms, a fuel cell reformer works by breaking apart the chemical bonds of the fuel feedstock to create hydrogen and oxygen separately. The process typically takes place at a high temperature – 1300 to 1750° F (700 to 950° C). Water vapor is injected into the feedstock in the presence of a catalyst to break down the fuel into carbon monoxide (CO) and hydrogen (H_2). The water vapor also breaks down into hydrogen and oxygen. The oxygen from this reaction combines with the carbon monoxide to create carbon dioxide.

As noted above, different fuels and fuel cell systems require different types of reformers. Depending on the feedstock utilized, various other control devices may be needed to eradicate other pollutants that may be present in the exhaust stream. Likewise, the operational temperature of the fuel cell itself has important ramifications on the temperature and composition of the fuel stream. Both of these topics will be further discussed in subsequent sections of this report.

2.3 General Benefits of Fuel Cells

With the potential to provide a wide array of benefits in both mobile and stationary applications, fuel cell technology has been researched by government and industry for more than four decades. The most commonly cited benefits of fuel cells include: 1) efficiency; 2) size flexibility; 3) high reliability/ low maintenance; 4) low emissions; 5) ease of siting/permitting; and 6) fuel flexibility. In addition, fuel cells are also generally associated with additional benefits related to economic growth and distributed generation applications.

- **Efficiency** --- Capable of converting fuel directly into electricity through an electrochemical reaction, fuel cells are able to extract more power out of a given quantity of fuel than traditional combustion technologies. This results in greater overall fuel efficiencies, depending on the type of fuel cell system and whether or not the surplus heat is utilized. In contrast, combustion-based energy generation first converts fuel into heat, and then into mechanical energy, which provides motion or drives a turbine to produce energy. The additional steps associated with using combustion result in energy losses for heat, friction, and conversion, leading to lower overall efficiencies. The following figure depicts fuel efficiency ranges for common electricity generation technologies.[6]

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[6] Picture taken from Kordesch, K. and Simander, G. *Fuel Cells and Their Applications*. VCH Publishers, 1996.

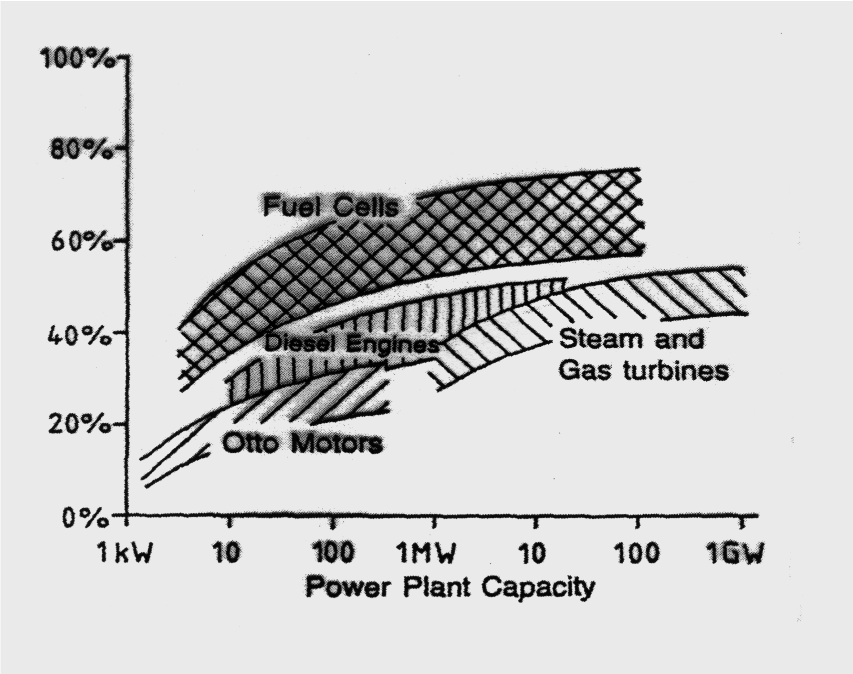

Figure 5. Fuel cell efficiency relative to conventional electricity generation options.

Present fuel cell power plants achieve fuel to electricity conversion efficiencies in the range of 35 to 55%, depending on the heating value of the fuel. If the thermal energy also produced by the fuel cell can be used as well, overall efficiencies of up to 75% can be achieved. In contrast, according to the U.S. Department of Energy, the most advanced combined-cycle natural gas power plants can reach efficiencies of 50 to 60%.

- **Size Flexibility** --- An individual fuel cell typically provides less than one volt of electrical potential. To produce larger voltages, individual cells are stacked and connected in series. Thus, cells can be stacked to provide the appropriate voltage for an infinite number of applications. For example, a few cells (< 1 kW) can be combined for applications such as fire detectors, or several hundred fuel cells (1 MW +) can be combined for power plants.

Manufacturers are presently able to develop commercial-ready stationary fuel cells in sizes up to 200 kW, with prototypes up to 2 MW. United Technologies Corporation manufactures a 200 kW phosphoric acid fuel cell; Fuel Cell Energy (FCE) is developing a 2 MW stationary molten carbonate fuel cell. FCE is also developing modular prototypes for 10 to 50 MW applications. For perspective, FCE's 2 MW fuel cell would occupy a space 54' x 83' (approximately 4500 square feet).

Similar to size, fuel cell modularity is another benefit. Because fuel cells are modular, the power-generating capability of a given system can typically be increased or decreased as needed by adding more fuel cell modules.

- **High Reliability/ Low Maintenance** --- Fuel cells systems have no moving parts. Thus, even the first generation of commercial fuel cells is proving highly reliable and requires little maintenance, and fuel cell power plants are shut down less often then conventional power plants. With high electric reliability in increasing demand by today's businesses, especially those with manufacturing operations or advanced computer applications, fuel cells are emerging as a likely technology for meeting high reliability needs. Fuel cells do require downtime for maintenance, but their requirements are less than for conventional gas turbines.
- **Low Emissions** --- Since water is the only by-product of the reaction between hydrogen and oxygen in a fuel cell, no pollutants are produced if pure hydrogen is used to power fuel cells. Even when non-pure hydrogen sources are used as fuels, most of the contaminants are removed prior to use of the fuel in the fuel cell. This fact, combined with the fact that fuel cells do not rely on combustion, means that regulated air pollutants, such as sulfur and nitrogen oxides, carbon monoxide, and unburned hydrocarbons, are nearly absent from fuel cell emissions. Fuel cells are therefore able to meet even the strictest of air pollution standards.

The following figure compares emissions from a common type of fuel cell unit to an average U.S. fossil fuel powered plant:[7]

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[7] "About Fuel Cells." http://www.internationalfuelcells.com/fuelcell/benefits_fl.shtml.

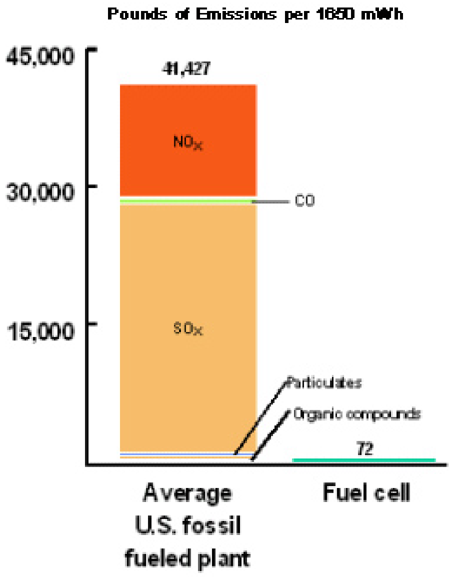

Figure 6. Fuel cell air emissions from one year of operation for a common fuel cell.

- **“Good Neighbor” Power Plants/ Ease of Siting** --- Since fuel cells have no moving parts, noise and vibrations from their operation are minimal. This obviates the need for soundproofing or hearing protection, which is often a prerequisite for combustion systems, and makes the siting and permitting process more friendly for fuel cell project developers. Because fuel cells are so quiet, they are well-suited for applications in buildings like hospitals, hotels, offices, or schools. Thermal emissions from fuel cells can also be used in cogeneration applications.

- **Fuel Flexibility** --- Fuel cells produce electricity directly from the reaction between hydrogen and oxygen. In almost all cases, the hydrogen for the reaction comes from a fuel source other than pure hydrogen. A fuel reformer attached to a fuel cell creates hydrogen from hydrocarbon fuels through an electrochemical process. A fuel cell system can therefore be adapted to utilize diverse fuels, such as methanol, ethanol, landfill gas, natural gas, or gasoline.

In addition to the direct benefits of fuel cells cited above, the commercialization of fuel cells is widely expected to open up a considerable array of additional applications and associated economic benefits:

- **Economic Growth** --- The growth of fuel cells has the potential to create new markets for steel, electronics, electrical equipment, vehicle design, etc. and to create thousands of skilled jobs. Consultants at Arthur D. Little estimate that each 100 MW of fuel cell production capacity will create 5,000 jobs.[8] The development of biomass-based fuel cell systems also promises to create jobs in rural communities by promoting biofuel production.

- **Distributed Generation Applications** --- Distributed generation using fuel cell technology can help electricity customers mitigate uncertainty associated with reliance on grid electricity by providing additional energy capacity, combined heat and power, peak load shaving, back-up power, and reliability. The installation of fuel cell modules where load is required can also help to avoid large capital expenditures for remote power plants and upgrades of transmission and distribution systems.

2.4 Fuel Cell Technology Overview

Fuel cells are named according to the electrolyte that defines their key properties. At present, four primary fuel cell types are in varying stages of development. Each type operates at a different temperature and is best suited for particular applications. The four major fuel cell types are described below:

2.4.1 Molten Carbonate Fuel Cell (MCFC)

In a MCFC, carbonate salts act as the electrolyte. When heated to approximately 1,200° F (650° C), the salts melt and conduct carbonate ions (CO_3) from the cathode to the anode, where hydrogen reacts with the ions to produce water, carbon dioxide, and electrons. The electrons travel through an external circuit, providing electricity along the way, and then return to the cathode. At that point, oxygen from the air and carbon dioxide recycled from the anode react with the electrons to form carbonate ions that replenish the electrolyte and transfer current through the fuel cell. Notably, MCFCs can utilize nickel catalysts, which are less expensive than the platinum catalysts used in other fuel cells.

MCFCs produce high quality waste heat that can be used for fuel processing and cogeneration. The heat is of sufficient temperature to produce high-pressure steam for industrial processes. As a result, these fuel cells are best suited for onsite or utility-scale generation applications. MCFCs have operated on natural gas and synthetic coal gas; it is anticipated that they will be able to operate on other fuels as well. They are expected to reach electrical conversion efficiencies of 50 to 60%. The major drawback to MCFCs is their potentially short lifetime due to corrosion resulting from their high operating temperature.[9] In addition, carbonate ions from the electrolyte are used up, making it necessary to inject carbon dioxide to compensate. It should be noted that

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[8] Arthur D. Little, Inc. "The Role of Fuel Cell Technology in the International Power Equipment Market." Cambridge, MA, September 1993.

[9] For first generation systems, Fuel Cell Energy anticipates that stacks will need replacement approximately every five years.

many bio-based fuels contain up to 50% carbon dioxide, so injection of CO_2 does not necessarily pose a substantial difficulty. A basic MCFC is depicted below.[10]

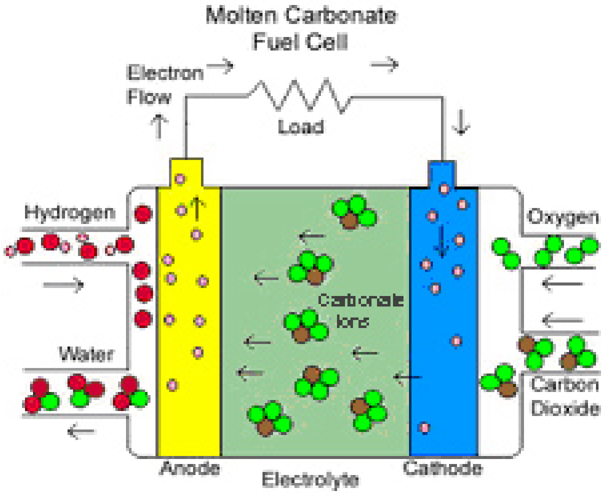

Figure 7. A molten carbonate fuel cell.

2.4.2 Phosphoric Acid Fuel Cell (PAFC)

In a PAFC, phosphoric acid serves as the electrolyte. Positively charged hydrogen ions migrate through the phosphoric acid electrolyte from the anode to the cathode. The electrons generated at the anode travel through an external circuit. When electrons return to the cathode, they combine with hydrogen ions and oxygen to form water, which is expelled from the cell. A platinum catalyst at the electrodes speeds the reactions.

PAFCs are the only commercially available fuel cells today. PAFCs have been used to generate electricity in hospitals, nursing homes, hotels, office buildings, schools, and utility power plants. United Technologies Corporation's PC25 units have also operated on natural gas, propane, landfill gas, and digester biogas. PAFCs can operate at elevated pressures (up to 8 atm), at ambient temperatures of –57.6 °F to 120.2 °F (-49.7° C to 49.0° C), and have demonstrated lifetimes of 40,000 hours. PAFCs have a standard operating temperature of about 375 °F to 400° F (190° C to 204° C). Electrical conversion efficiencies fall between 37 and 42%, and are considered relatively low. However, the use of thermal output for co-generation applications can significantly improve efficiency. Additionally, PAFCs are somewhat tolerant of fuel contaminants.

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[10] Picture taken from "Fuel Cells: Collecting History on the World Wide Web," Smithsonian Institute. http://americanhistory.si.edu/csr/fuelcells/basics.htm.

2.4.3 Proton Exchange Membrane Fuel Cell (PEMFC)

The PEMFC uses a polymer electrolyte in the form of a thin, permeable sheet. This small, light membrane works at low temperatures (about 80 °C, or 175 °F) in combination with a platinum catalyst that is used on both sides of the membrane. During operation, hydrogen atoms are stripped of their electrons at the anode, and positively charged protons diffuse through one side of the porous membrane and migrate toward the cathode. The electrons pass from the anode to the cathode through an exterior circuit and provide electric power along the way. At the cathode, the electrons, hydrogen protons, and oxygen from the air combine to form water. For this fuel cell to function, the proton exchange membrane electrolyte must allow hydrogen protons to pass through the membrane, while prohibiting the passage of electrons and heavier gases.

Due to their rapid start-up capability, light weight, high power density, low operating temperature (80-85°C or 176-185 °F), and low cost relative to other types, PEMFCs are good candidates for light-duty (50 to 100 kW) and medium-duty vehicles (200 kW), for small residential (2 to 10 kW) and commercial (200 to 500 kW) power generation, and eventually for small/portable applications, such as cell phones and video cameras. PEMFCs can operate at elevated air pressures (up to 8 atm) and have an electrical efficiency of nearly 50%. However, because the temperature of waste heat is too low to be used in the fuel reforming process, overall system efficiencies are only about 42%, the lowest of all the fuel cells. Because carbon monoxide levels of over 50 ppm can poison the catalyst, all carbon fuels used in PEMFCs require additional processing. Other contaminants are also preferentially absorbed by the membrane and catalyst (electrodes) and therefore can contaminate and significantly impede the performance of the cell.

PAFCs and PEMFCs, similar in operation, are depicted in the diagram on the following page:[11]

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[11] Picture taken from “Fuel Cells: Collecting History on the World Wide Web,” Smithsonian Institute. http://americanhistory.si.edu/csr/fuelcells/basics.htm.

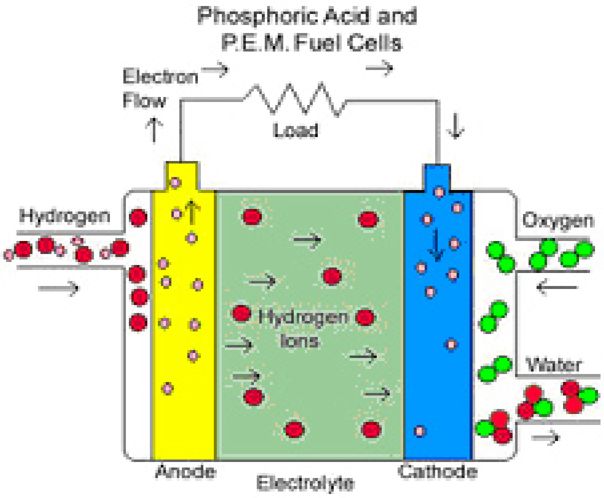

Figure 8. A standard phosphoric acid / proton exchange membrane fuel cell.

2.4.4 Solid Oxide Fuel Cells (SOFC)

SOFCs utilize a hard ceramic electrolyte and operate at temperatures up to about 1,800° F (980° C). A mixture of zirconium oxide and calcium oxide form a crystal lattice electrolyte structure, which is coated on both sides with specialized porous electrode materials.

During fuel cell operation, oxygen ions migrate through the crystal lattice. When a fuel gas containing hydrogen is passed over the anode, oxygen ions flow across the electrolyte to oxidize the fuel. The oxygen is supplied, usually from air, at the cathode. Electrons generated at the anode travel externally to the cathode, completing the circuit and supplying electricity along the way.

SOFCs are likely to be used initially in small portable generators and remote or premium power applications. Electrical efficiencies are around 45%. However, if waste heat is effectively utilized, SOFCs have the potential to obtain overall system efficiencies of 70 to 75%, significantly higher than other fuel cell technologies, because of the usable temperatures of the waste heat generated by their operation. In addition, SOFCs have lifetimes of 10 to 20 years, two to four times the lifetime of other fuel cells. These high temperature fuel cells are also more easily integrated with reforming technologies, and in some cases, an external reformer may not be required at all. Disadvantages include their high costs, difficult manufacturing techniques and stringent materials requirements. Operation of a standard SOFC is depicted in the figure below:[12]

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[12] Picture taken from "Fuel Cells: Collecting History on the World Wide Web," Smithsonian Institute. http://americanhistory.si.edu/csr/fuelcells/basics.htm.

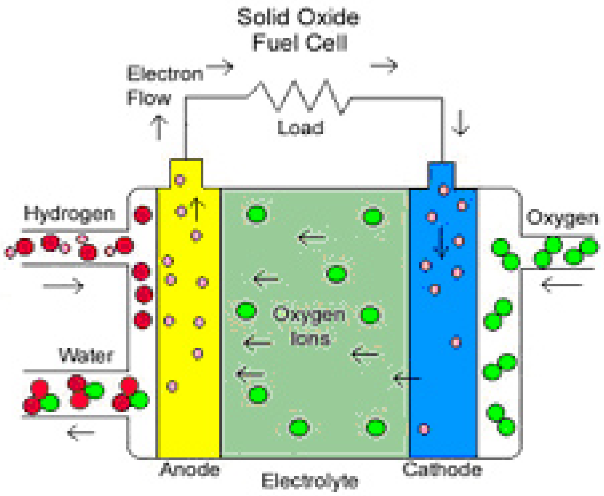

Figure 9. Diagram of a solid oxide fuel cell.

The following table summarizes the major characteristics of the above fuel cell technologies[13]:

Table 2. Operating characteristics of primary fuel cell technologies.

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

2.5 Fuel Cell Costs

Despite the various benefits of fuel cells, the ultimate ability of fuel cells to achieve widespread commercial status hinges first and foremost on the capital costs of the fuel cell system. To become a viable option, fuel cells need to be cost-competitive both with

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[13] Schmidt, D. and Gunderson, J. "Opportunities for Hydrogen: An Analysis of the Application of Biomass Gasification to Farming Operations Using Microturbines and Fuel Cells." Proceedings of the 2000 Hydrogen Program Review, NREL/CP-570-28890.

conventional electricity generation options, such as gas turbines, as well as with evolving distributed generation technologies, such as wind turbines, photovoltaic solar cells, and microturbines.

The table below shows the capital costs of fuel cells relative to other electricity generation technologies:

Table 3. Capital costs of electricity generation technologies.

Generation Technology	Typical Installed Capital Cost ($ per kilowatt)
Gas Turbine	700 to 900
Microturbine	700 to 1300
Steam Turbine	800 to 1000
Wind Turbine	800 to 1250
Natural Gas Engine	800 to 1500
Fuel Cell	> 2800
Solar PV	> 5000

As indicated by the table above, with the exception of solar PV, fuel cell capital costs at present are significantly higher than other renewable and non-renewable electricity generation technologies, though this higher capital cost may be offset slightly by higher efficiency. Given the high cost of fuel cells, fuel choice is another important factor. The following section provides an introduction to the prospect of utilizing bio-based fuels with fuel cells.

2.6 Integrating Fuel Cells with Bio-based Fuels

At present, methanol, gasoline, and natural gas are the fuels most commonly used to provide a hydrogen source for fuel cell power generation systems. Natural gas is the fuel most commonly used in stationary fuel cell applications. Fossil fuel-based fuel cell systems are typically perceived as less expensive than those that use biofuels, and in general, have been more rigorously researched. ***High costs associated with both the bio-based fuels themselves and the prerequisite biomass conversion technologies (e.g., fuel reformers, gas collection units, and system modifications) are a deterrent to fuel cell developers.*** In contrast, natural gas and gasoline are attractive because they are inexpensive, a widespread infrastructure for their production and distribution already exists, and the public is familiar and comfortable with them. Methanol is somewhat attractive because it is relatively easy to convert to hydrogen from a chemical standpoint.

Hydrogen typically makes up about 6% by weight of dry biomass.[14] In order to obtain hydrogen from biomass for use in fuel cells, one of several conversion methodologies must be utilized. Biomass gasification and pyrolysis technologies are both capable of converting dry biomass into a gas containing up to 20% hydrogen by volume. Hydrogen for fuel cells can also be obtained from the methane produced by landfill gas and in waste digesters. Hydrogen for fuel cells can also be converted from bio-based fuels like ethanol, biodiesel, and levulinic acid.

To varying degrees, each of the above-mentioned biomass energy sources can be further steam-reformed to yield high-purity hydrogen streams for use in the various types of fuel cells. However, there is often considerable variance in the chemical composition of the fuel produced by each conversion technology. For instance, in addition to hydrogen, bio-based fuel streams, whether from digester gas, landfill gas, or pyrolysis oil, contain varying amounts of carbon monoxide (CO), methane (CH_4), carbon dioxide (CO_2), and sulfur (S). This variability creates a challenge for fuel cells, which differ in their electrochemical reactions, tolerance to contaminants, and ability to utilize the various components of the biomass derived fuel.

Major operating characteristics distinguish the four major fuel cell types, and several are relevant to biomass conversion. These characteristics are outlined below and summarized in the tables at the end of the chapter.

2.6.1 Molten Carbonate Fuel Cells

MCFCs are both tolerant of carbon dioxide and capable of using hydrogen and carbon monoxide as fuel to produce electricity. The MCFC's high operating temperature yields waste heat at recoverable temperatures capable of providing high grade steam in addition to low temperature waste heat for water.[15]

Despite its developmental immaturity relative to PAFCs, the high temperature MCFC is considered by many experts to offer significant long-term potential. It is well-suited for large, stationary applications, and is relatively tolerant of contaminants. Additionally, its ability to utilize multiple fuel gas constituents makes the MCFC more suitable for power generation with low energy hydrogen feedstocks, like many bio-based fuels. The high operating temperatures of the MCFC also provide opportunity to improve fuel cell economics through heat recovery.

In the long run, the MCFC is generally expected to be more reliable and less costly than the PAFC. A few interviewees noted the high corrosivity of its electrolyte and subsequent shorter system life as technical concerns that need to be resolved during the development of the MCFC.

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[14] "Biopower Technologies – Gasification." http://www.eren.doe.gov/biopower/projects/ia_tech_gas.htm.

[15] McIlveen-Wright, D., Williams, B., and McMullan, J. "Wood gasification integrated with fuel cells." *Renewable Energy* 19 (2000) 223-228.

2.6.2 *Phosphoric Acid Fuel Cells*

PAFCs are insensitive to carbon dioxide and other acid components and are able to tolerate 1 to 2% carbon monoxide at an operating temperature of 390° F (200° C). The PAFC is capable of efficiently using waste heat for steam reforming and for providing space heating or hot water.[16]

Of the four major types of fuel cells, PAFCs are widely considered to be the farthest along in terms of commercialization (systems have been field tested up to 11 MWe (MW of electricity)). The PAFC can be adapted to biomass, but in most studies its efficiency is relatively low. The PAFC was described by one academic researcher as “a fuel cell that’s here until something better comes along. In the long run it won’t be the choice for many applications.” Another researcher noted its high cost, and speculated that “it’s not coming down anytime soon.”

2.6.3 *Proton Exchange Membrane Fuel Cells*

PEMFCs require a high level of gas purity; carbon monoxide levels of more than 10 to 50 parts per million (ppm) poison the catalyst, causing severe degradation in cell performance. All carbon containing fuels require additional fuel processing, contributing to reduced efficiency.[17,18]

In general, the PEMFC is generally regarded as optimal for small-scale applications, such as residential or transportation. Its potential for use with bio-based fuels is limited by its low temperature and subsequent inability to integrate efficiently with high temperature processes typical of biomass conversion and fuel reforming. PEMFCs also require clean, cold hydrogen gas for optimum performance, making them somewhat incompatible with most contaminant-ridden bio-based fuel streams. A number of interviewees suggest, however, that PEMs are a relatively mature fuel cell technology, and are likely to become cost-competitive in small-scale applications.

2.6.4 *Solid Oxide Fuel Cells*

SOFCs are relatively tolerant of fuel impurities and are capable of using hydrogen and carbon monoxide fuel directly at the anode; they do not require costly external reformers or catalysts to produce hydrogen. The relative insensitivity of SOFCs to gas contaminants otherwise considered poisonous to lower temperature fuel cells makes SOFCs attractive for bio-based fuels.[19]

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[16] McIlveen-Wright, D., *et al.*, 2000.

[17] Schmidt, D. and Gunderson, J. 2000.

[18] “Fuel Cells for Distributed Generation: A Technology and Marketing Summary.” Energy Center of Wisconsin. March 2000.

[19] “Fuel Cells for Distributed Generation: A Technology and Marketing Summary.” Energy Center of Wisconsin. March 2000.

Although it is the least well-developed of all the fuel cell technologies, the SOFC may have the greatest long-term potential of all the fuel cells, at least for stationary applications. The SOFC solves the corrosivity problem of the MCFC by utilizing a non-corrosive solid-state zirconium oxide ceramic material as its electrolyte. It also has the greatest tolerance for sulfur, carbon monoxide, and other contaminants. Its ability to reform methane internally also has important implications for its potential use with bio-based fuels.

The ability of the SOFC to utilize numerous fuel gas constituents (carbon monoxide and methane, in addition to hydrogen) is expected to make it highly suitable for power generation with low energy hydrogen feedstocks, like many bio-based fuels. Like the MCFC, the high operating temperature of the SOFC offers important opportunities to improve fuel cell economics through heat recovery.

The table below summarizes common integration issues with respect to the four different fuel cell types. The table on the next page details the impacts of common gas species on each of the four major types of fuel cells[20,21]:

Table 4: Fuel cell integration issues by fuel cell type.

Issues	PEMFC	PAFC	MCFC	SOFC
Tolerance for Contaminants	Intolerant	Moderately tolerant	Tolerant	Most tolerant
Waste Heat	Not usable	Usable	Usable	Usable
System Efficiency	Lowest	Moderate	Moderate	Highest
Other Concerns	Low temperature	Efficiency issues	Corrosivity; short life span	High cost

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[20] Hirschenhofer, J., Stauffer, D., Engleman, R., and Klett, M. 1998. "Fuel Cell Handbook, 4th Ed.," DOE/FETC-99/1076 for Contract No. DE-AC21-94MC31166. Reading, PA: Parson Corporation.

[21] Dayton, D. "Fuel Cell Integration – A Study of the Impacts of Gas Quality and Impurities." For the Chemistry of BioEnergy Systems Division of the National BioEnergy Center. June 2001, NREL/MP-510-30298.

Table 5: Impacts of common gas species on four common types of fuel cells.

Gas Species	PEMFC	PAFC	MCFC	SOFC
Hydrogen	Fuel	Fuel	Fuel	Fuel
Carbon Monoxide	Poison (10 ppmv)	Poison (10 ppmv)	Fuel	Fuel
Methane	Inert, fuel w/ reformer	Inert, fuel w/ reformer	Fuel reformed internally or externally	Fuel reformed internally or externally
Carbon Dioxide and Water	Diluent	Diluent	Re-circulated	Diluent
Sulfur (as Hydrogen Sulfide and Carbonyl Sulfide)	No studies to date	Poison <20 ppm H_2S <50 ppm H_2S + COS	Poison <10 ppm H_2S in fuel <1 ppm SO_2 in oxidant <0.1-0.5 ppm H_2S	Poison <1 ppm H_2S
Halogens (HCl)	No studies to date	Poison 4 ppm	Poison $<0.1 – 1.0$ ppm	Poison <1 ppm

It should be noted that insofar as the fuel cell systems described in the table above utilize steam reforming with nickel catalysts, a process which requires removal of sulfur from the gas stream below 1 ppm, they will be equally impacted relative to sulfur.

3. Biomass Conversion Technologies – Background and Fuel Cell Compatibility

Before it can be utilized in fuel cells, raw biomass must first be processed and converted into a usable energy form. This section considers the compatibility of fuel cells and seven different biomass conversion technologies and their product biofuels: syngas from biomass gasification; landfill gas; digester gas; ethanol; pyrolysis oil; biodiesel; and levulinic acid.

3.1. Biomass Gasification

3.1.1. Background

The gasification of biomass to create a combustible gas fuel is a reasonably well-established technology, although it has yet to move beyond the demonstration phase. Through thermochemical gasification, hydrogen can be produced from many biomass feedstocks. These include municipal solid waste, agricultural waste, manures, forest waste, and wood chips from short rotation forestry plantations.

Gasification is typically a two-step, endothermic (heat absorbing) process during which a solid fuel, such as biomass or coal, is converted into a low- or medium-Btu gas. In the first step, pyrolysis, components of the fuel are volatilized or heated to a gaseous state. Pyrolysis is completed as those volatile components are vaporized at temperatures below 1100° F (600° C) through a series of complex reactions. The resulting vapor contains hydrocarbon gases, hydrogen, carbon monoxide, carbon dioxide, tar, and water vapor. Char (fixed carbon) and ash are the non-vaporized by-products. In the second step of gasification, char is gasified through reactions with oxygen, steam, and hydrogen. The end product of gasification is called synthesis gas, or syngas. Additionally, some of the unburned char is combusted to release heat that is needed for the endothermic gasification reactions.

The following figure depicts a basic biomass gasification process.[22]

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[22] Energy Efficiency and Renewable Energy Network web site. http://www.eren.doe.gov/biopower/projects/ia_tech_gas1.htm.

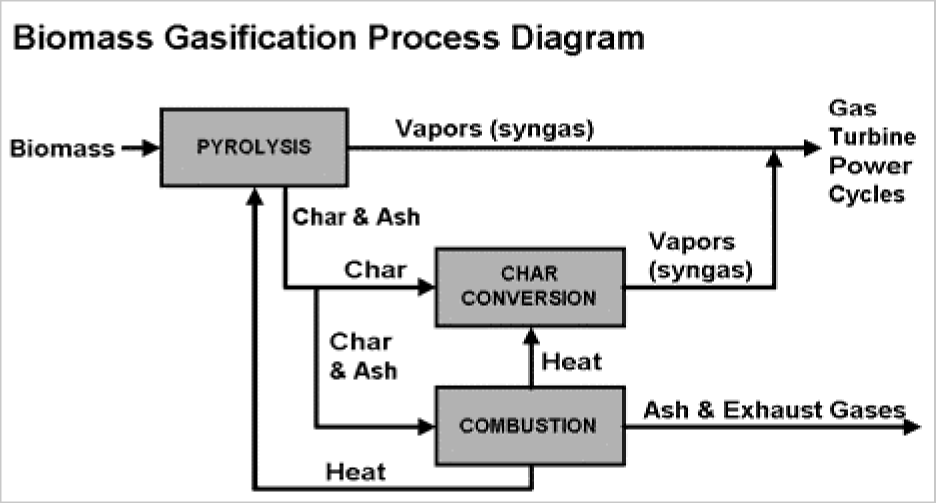

Figure 10. Biomass gasification process.

Combined heat and power (CHP) gasification systems utilizing conventional gas-fired engines and turbines have proven capable of achieving overall efficiencies in the range of 22 to 37%.[23] If the resulting syngas is used in fuel cells, an even higher overall efficiency in the range of 25 to 50% can be achieved. This holds true even in small scale biomass gasification plants and/or under partial load operation.[24]

The exact composition of the syngas product is affected by the different materials that are used as feedstock, as well as by certain key process variables. The gas composition is generally as follows: hydrogen 30 to 40%; carbon monoxide 20 to 30%; methane 10 to 15%; water 6%; nitrogen 1%; ethylene 1%. The syngas produced via gasification contains an array of contaminants that challenge its usefulness, and treating syngas for use in fuel cells is a relatively new area of research. Central to this developmental work is the need to purify the gas to meet the specifications of the fuel cell. As noted by several interviewees, the requirements of the purification process will vary according to the particular gasification and fuel cell technology utilized.[25]

3.1.2. Fuel Pre-Treatment and Other Fuel Cell Integration Issues

Prior to its use in a fuel cell (or turbine), syngas must be pre-treated to remove both diluents and contaminants (such as tar, particulates, sulfur and alkali metals).

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[23] The coupling of conventional biomass combustion technologies with steam generation and steam turbines commonly achieves 15 to 18 percent efficiencies.

[24] Office of Technology Assessment at the German Parliament (TAB). Summary of TAB working report No. 49 “Gasification and pyrolysis from Biomass.” April 1997. http://www.tab.fzk.de/en/projekt/zusammenfassung/AB49.

[25] A variety of different biomass gasification technologies are either in use or under development. For a detailed description of these technologies, visit the U.S. Department of Energy’s Energy Efficiency and Renewable Energy Network web site at http://www.eren.doe.gov/biopower/projects/ia_tech_gas2.htm.

Depending on the type of fuel cell to be utilized, these gases and contaminants will have to be treated or removed to varying degrees. As is the case with other bio-based fuels, pre-treatment requires two primary steps:

- Reforming – Steam is added at high temperature to the syngas. This converts the methane to carbon monoxide and hydrogen. Also during the reforming step but at a lower temperature, the steam will react with the carbon monoxide to form hydrogen and carbon dioxide; and

- Clean-up – The process by which contaminants are removed or cracked. The level or nature of clean-up will depend on both the type of contaminant present and type of fuel cell used.

Various methodologies for the reforming and clean-up steps above have been developed or are presently under development.

Our research finds that there is general agreement both among interviewees and in the literature that these pre-treatment processes are technically feasible, given present technology. With regard to the reforming step, McIlveen-Wright notes that the equipment required for converting syngas to hydrogen utilizes well-established commercial technologies in the chemical process industries.[26]

To achieve the purified syngas there are at least four different procedures that can be utilized: leaching, activated carbon clean-up, cold sulfur removal, and hot-gas clean-up. A brief description of each is provided in the table below:

Table 6. Description of syngas purification processes.

Pre-Treatment	Post-Treatments	Description
Leaching		Removes soluble organics and alkali compounds by “washing” biomass at the front end.
	Activated Carbon	Cleans gas by adsorbing contaminants on a bed of activated carbon.
	Cold Sulfur Removal	Use a fluid-bed tar cracker followed by scrubbing and hydro-desulfurization.
	Hot Gas Clean-up	Utilizes a cracking process to convert tars and unreacted char to H_2, CO, and light hydrocarbons.

According to one report, the hot-gas method is preferable from both an operational and a cost perspective. However, depending on the type of fuel cell to be used, and

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[26] McIlveen-Wright, D., *et al.*, 2000.

therefore the nature of the clean-up required, one approach may be preferable to another.[27]

One academic researcher called gas clean-up the greatest hurdle preventing the widespread integration of gasification with fuel cell technology. Noting the presence of alkaline metals in the syngas, he discussed technical problems associated with both pre- and post-gasification conditioning. Front-end leaching has proven capable of removing up to 75% of alkali compounds. Post-gasification clean-up has reduced the presence of alkali compounds by up to 90%. The researcher suggested that commercialization of these processes is about five years away. Another researcher echoed this sentiment, noting that the process of cleaning syngas, although technically feasible, is not ready for commercialization.

Although there is general consensus among interviewees and in the literature that the integration of gasification with fuel cells shows promise, the idea is not without its skeptics. One government researcher noted the low Btu content of the syngas as a reason for its likely economic failure. A number of interviewees also pointed out that the costs associated with syngas reforming and clean-up, even when technical feasibility is demonstrated, are likely to be a potential barrier.

One interesting finding is reported in a recent study by Lobachyov and Richter.[28] The authors report:

> Feeding the gasification product gas (syngas) into a MCFC instead of a gas turbine allows one to lower the restrictions on the contaminants level – the challenge faced by developers of the biomass fueled power generation plants.

The authors' analyses predict that a fuel cell system into which biomass gasification has been integrated will be more efficient and will have better economic performance than a syngas turbine system. This is deemed particularly likely when the Battelle Columbus gasification process is used.[29] The study concludes with the following statement:

> The authors strongly recommend that researchers and practitioners give a close consideration to this concept from both design and implementation perspectives.

In a countering view, one interviewee did not agree with the findings in the Lobachyov and Richter study, on the grounds that a good hot gas filtering system has yet to be developed. In this view, the integration of fuel cells with biomass gasification is considered impractical under present conditions. Instead, the interview suggested that microturbines, which better tolerate contaminants like tars, show considerably more immediate promise.

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[27] For more information about clean-up techniques and types of gasifiers, see Schmidt and Gunderson.

[28] Lobachyov, K. and Richter, H. "An advanced integrated biomass gasification and molten fuel cell power system." *Energy Convers. Mgmt.* Vol. 39, No 16-18, pp. 1931-1943, 1998.

[29] The Battelle gasifier is a two reactor, indirectly heated gasifier developed by Battelle Columbus Laboratory. For more information, visit www.eren.doe.gov/power/success_stories/pdfs/biomass.pdf.

A final issue worth mentioning concerns the cost of syngas produced from biomass gasification. Based on published research on the cost of electricity produced from a biomass gasification combined cycle system, syngas is calculated to cost less than $9 per mmBtu (million Btu).[30] According to an academic researcher, if dedicated biomass crops are used as a primary feedstock, the cost of syngas is calculated to cost up to $68 per mmBtu. For perspective, the current cost of natural gas, the likely market leader for stationary fuel cell applications, is approximately $3 to $4 per mmBtu.

3.1.3. Biomass Gasification and Issues of Fuel Cell Compatibility

When considering the integration of fuel cells and biomass gasification, the nature of the resulting syngas influences the choice of fuel cell. This section discusses the issues of matching and compatibility.

Our research indicates that from a technical perspective, all types of fuel cells can, to varying degrees, be utilized with biomass gasification systems. However, due to their inherent operating characteristics, SOFCs and MCFCs are generally regarded as more compatible with biomass gasification.

Almost half of all interviewees suggested that SOFCs and MCFCs are ideal for biomass gasification. One interviewee, a senior researcher from a government laboratory, described this compatibility by saying, “MCFCs and SOFCs are similar – both are high temperature fuel cells, so thermal integration with gasification processes is not a problem. Also, at these temperatures carbon monoxide is a fuel and not a contaminant. The result is a very efficient system.”

The research literature also supports the contention that SOFCs and MCFCs are a good match for biomass gasification systems. Research by Schmidt and Gunderson points out that high temperature SOFCs are capable of converting all the combustible components of wood gas, after the removal of dust and tar, to electricity. They also find that the MCFC is quite “robust,” and “is technically well-suited for use with gasification technology.”

This relative compatibility stems from several factors. The MCFC is capable of using both carbon monoxide and hydrogen as fuel, which typically comprise 35 to 40% of a syngas stream. Sulfur in the gas is the major contaminant impeding use of a MCFC. All tars must also be removed. Unlike SOFCs, however, MCFCs require the use of an additional catalyst in order to make use of the diluent methane.[31] Other research points out that high temperature MCFCs and SOFCs are more attractive in the long term

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[30] “Renewable Energy Technology Characterizations,” Prepared for EPRI and the U.S. Department of Energy by Office of Utility Technologies, Energy Efficiency and Renewable Energy, U.S. Department of Energy and EPRI. EPRI-TR-109496, December 1997.

[31] Schmidt, D. and Gunderson, J. “Opportunities for Hydrogen: An Analysis of the Application of Biomass Gasification to Farming Operations Using Microturbines and Fuel Cells.” Proceedings of the 2000 Hydrogen Program Review, NREL/CP-570-28890.

because their overall system efficiency (i.e., electrical conversion and thermal use) is likely to be higher than that of the medium temperature PAFC. Finally, the integration of MCFCs and SOFCs with biomass gasification has two other advantages: First, no separate unit is needed for a carbon monoxide-shift reaction prior to gas injection into the fuel cell. Second MCFC and SOFC fuel cells provide high temperature process heat in addition to electricity.[32]

PEMFCs and PAFCs have also been considered for applications with biomass gasification. While our research shows a variety of opinions exist, the general sentiment is that these two fuel cell types do not integrate well with biomass gasification as their high temperature counterparts. Interviewees noted the lower relative operating temperatures of these types of fuel cells, and their subsequent lower tolerance to contaminants in the gas stream. Interviewees also mentioned the inherent difficulty of integrating the high temperature gasification process with the lower relative operating temperatures of PEMFCs and PAFCs.

The scientific literature broadly supports these findings. In their techno-economic assessments of systems that integrate biomass gasification with fuel cells, McIlveen-Wright *et al.* chose MCFCs over PAFCs. They found that PAFCs linked with wood gasification were “unlikely to be considered for further development as an electricity generation system.” Conversely, they deemed MCFC technology promising for further development, assuming the lifetime and capital costs could be improved.[33] Schmidt and Gunderson found that attempting to purify syngas for use in a PEMFC is cost-prohibitive.[34]

Despite the greater relative compatibility of high temperature fuel cells with gasification processes, it is difficult to say with certainty which fuel cell type, if any, will ultimately be linked to biomass gasification. As a senior government fuel cell researcher pointed out, all the fuel cells can be made to work from a technical and chemical perspective. The one that costs the least will ultimately win out.

3.1.4. Demonstration Projects

At present time, there have been no major experimental biomass gasification – fuel cell projects. The work that has been completed to date on this topic has occurred on paper or in the laboratory. With regard to biomass gasification itself, there are numerous examples of projects currently in the demonstration phase. However, the only units that are commercially deployed are circulating fluidized bed atmospheric pressure, air-blown units in biomass-based industries that provide fuel gas for lime kilns, boilers, and other applications.

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[32] Summary of TAB working report No. 49. “Gasification and pyrolysis from Biomass.” April 1997.
[33] McIlveen-Wright, D., *et al.*, 2000.
[34] Schmidt, D. and Gunderson, J. 2000.

There are several examples of integrated biomass gasification combined cycle (IGCC) turbine demonstration projects in various stages of development in Europe and the US [35,36]:

- The first full-scale demonstration IGCC biomass power plant began operation in Varnamo, Sweden in 1999. The plant produces 6 MWe (electrical output) and 9 MWth (thermal output) that is used for district heating.
- Project ARBRE in the Yorkshire Region of the UK is an 8 MWe coppice (brushwood) fueled gasification plant.
- The Thermie Energy Farm Project in Tuscany, Italy will produce 14 MWe from short rotation forestry biomass when it begins operating in 2002.
- The Hawaii Biomass Gasifier project, sponsored by the U.S. Department of Energy (DOE), provided a successful demonstration of a 6 MW biomass gasifier.
- The Future Energy Resources Company (FERCO) unit at the McNeil 50 MWe power station in Vermont will integrate the Battelle gasification process with a gas turbine.

3.2. Methane from Landfill Gas

3.2.1. Background

Methane, the main component of natural gas, is generated in landfills by the natural degradation of municipal solid waste (MSW) by anaerobic micro-organisms. Once the gas is produced, it can be collected with a relatively simple collection system and converted to electricity or heat. Recovering landfill gas (LFG) prevents it from escaping into the atmosphere. Recovery also helps to control odor, develops an indigenous energy resource, supplants fossil fuel production, and reduces greenhouse gas emissions. Methane is 20 times more potent than carbon dioxide from a greenhouse gas potency perspective.[37]

LFG is actually made up of multiple gases. The typical dry composition of LFG is around 57% methane; 42% carbon dioxide; .5% nitrogen; .2% hydrogen; and .2% oxygen. In addition, a significant number of other compounds are found in trace quantities, including alkanes, aromatics, chlorocarbons, oxygenated compounds, other hydrocarbons, and sulfur compounds. For comparison, natural gas is itself approximately 80 to 99% methane, with the remainder composed mostly of

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[35] Overend, R. "Biomass Gasification: the enabling technology." *Renewable Energy World*. Sept–Oct 2000.

[36] Lobachyov, K. and Richter, H. 1998.

[37] "Landfill methane outreach program." US EPA 430-F-96-051. September 1996.

hydrocarbons (ethane, propane, butane, etc.), in addition to some nitrogen, oxygen, water, carbon dioxide, sulfur, and other contaminants.

In 1996, the EPA promulgated MSW landfill emission rules under the Clean Air Act. Minor changes were made in 1998, 1999, and 2000. All MSW landfills that were active on or after November 8, 1987 are potentially affected by the rule. Affected municipal solid waste landfills must collect and burn, or use, their landfill gas. There are two compliance options: installation of a landfill gas collection system and flare, or installation of a landfill gas collection system and an energy recovery system. The regulations require the control of emissions of methane and non-methane organic compounds (NMOCs), effectively requiring the implementation of LFG collection. As of May 2001, more than 330 LFG utilization projects are in operation, up from just 162 in 1996.[38] The EPA estimates that there are hundreds of untapped landfills that could install economically viable LFG recovery systems.[39] Recovered LFG can be used in boilers for manufacturing processes, as well as for electricity generation via reciprocating engine and gas turbine technologies. Approximately 50% of the landfill gas utilization projects in the U.S. utilize reciprocating engines; approximately 10% use gas turbines.[40] With adequate processing, LFG can also be utilized in fuel cell applications. Demonstration fuel cell plants have already proven capable of cleanly and efficiently converting LFG to electricity.

3.2.2. Fuel Pre-treatment and Other Fuel Cell Integration Issues

Like syngas from biomass gasification, LFG must undergo pretreatment prior to its use in a fuel cell. Because LFG is actually a mixture of multiple gases, there are four or five separate steps required to process it for fuel cell use. Prior to entering the cell, pretreatment must remove the contaminants, primarily the sulfur and halogen compounds. The design of the LFG pretreatment unit and cleaning process is impacted by three factors: 1) the final gas purity requirements of the fuel cell; 2) the composition of the incoming LFG; and 3) a requirement that the gas cleanup process be capable of handling periods of substandard gas quality, which occurs as a result of periodic variations in the composition of the incoming gas.[41] The gas that reaches the fuel cell must be essentially free of all sulfur and halogen contaminants. It must consist primarily of a mixture of methane, nitrogen, oxygen, and carbon dioxide (depending on the type of fuel cell to be utilized).

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[38] "Landfill Gas Utilization: The Future's So Bright." MSW Management web site: http://www.forester.net/mw_0107_gas.html.

[39] "Consumer Energy Information: EREC Reference Briefs." US Department of Energy, Energy Efficiency and Renewable Energy Network web site: http://www.eren.doe.gov/consumerinfo/refbriefs/vg7.html.

[40] Thorneloe, S., Roquetta, A., Pacey, J. and Bottero, C. "Database of Landfill Gas to Energy Projects in the United States." Published by MSW Management. http://www.forester.net/msw_0003_database.html#6.

[41] Spiegel, R., Trocciola, J., and Preston, L. "Test Results for Fuel Cell Operation on Landfill Gas." *Energy*. Vol. 22, No. 8, pp. 777-786. 1997.

So far, the gas pretreatment process proven most successful on LFG - fuel cell projects consists of ambient temperature hydrogen sulfide removal, followed by cooling, condensation, drying, additional cooling, hydrocarbon removal, and filtration. The treatment process removes sulfur contamination and water early in the process, and is designed so the process is relatively insensitive to changes in incoming gas composition over time.[42] One case reported in the literature found that untreated LFG used to generate electricity using a SOFC led to “a relatively rapid falling off in power due to hydrogen sulfide poisoning.” However, adding a “simple de-sulfurization system” solved the problem.[43]

Following pretreatment, LFG is converted to hydrogen and carbon dioxide through a reforming step prior to its introduction into the fuel cell stack. The conversion process also includes a low temperature step whereby exhaust from the reformer is further processed to provide additional hydrogen and carbon dioxide.[44]
Among interviewees, there was general consensus regarding the feasibility of utilizing LFG for fuel cells. All interviewees noted the need to remove sulfur and halides from LFG prior to its use in a fuel cell. However, almost all agreed that pretreatment was technically feasible and was not a significant barrier to the use of LFG in fuel cells.
In addition to problems associated with contamination and gas pretreatment, one interviewee suggested that LFG had a relatively low Btu value, and that its Btu value diminishes over time. This results in a gradual reduction of the power plant’s thermal efficiency and power output over time. The extent to which this occurs will vary by landfill site. In cases where it may be desirable to mitigate this effect, R.J. Spiegel *et al.* 1999 suggest that natural gas blending may be considered as a way to maintain a desirable gas heating value.[45]

With regard to cost, LFG is available at a price that is competitive with natural gas. According to the US EPA, LFG is presently available at a price of $2.00 to 3.00 per mmBtu.

3.2.3. Landfill Gas and Issues of Fuel Cell Compatibility

The scientific literature on fuel cells provides information on several LFG demonstration projects that have taken place in the past few years. Most of these projects have utilized phosphoric acid fuel cells, which were described as commercially demonstrated on LFG as early as 1993.[46] However, as is the case with syngas and other bio-based

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[42] For a more complete description of this process see Spiegel *et al*. 1997.

[43] Staniforth, J. and Kendall, K. “Cannock Landfill Gas Powering a Small Tubular Solid Oxide Fuel Cell – A Case Study.” *Journal of Power Sources*. Vol. 86 (2000) 401-403.

[44] Spiegel, R., Preston, J., and Trocciola, J. “Fuel Cell Operation on Landfill Gas at Penrose Power Station.” *Energy*. Vol. 24, pp.723-742, 1999.

[45] Spiegel, R. *et al*., 1999.

[46] Arthur D. Little, Inc., 1993. “The role of fuel cell technology in the International Power Equipment Market – Policy/Strategy Issues.” Prepared for the World Fuel Cell Council, Frankfurt, Germany, Ref. 44335, 1993.

fuels, it is reasonable to conclude that other fuel cell technologies are suitable for LFG applications as well, though pretreatment and reforming processes will vary depending on the fuel cell technology utilized. Based on our research, we conclude that PAFCs, which have been utilized to date largely because they are more fully developed than other fuel cell types, will continue to be the fuel cell of choice for LFG applications in the short term. Over the long term, high temperature MCFC and SOFC fuel cells will become preferable.

These findings are substantiated by interview results. According to one academic researcher, all of the steps required to process LFG for fuel cells have been demonstrated with PAFCs. However, because MCFCs and SOFCs are tolerant of carbon dioxide, they may utilize LFG with fewer pretreatment steps. Another interviewee suggested that LFG is most compatible with high temperature fuel cell technologies, given the nature of the methane reforming process. A third interviewee noted that PAFCs, MCFCs, and SOFCs are all applicable to LFG applications. In contrast, PEMFC technology is not a good fit because heat is needed to reform the methane, and any such heat would have to be removed prior to using the resulting gas in the fuel cell.

3.2.4. Demonstration Projects

At present time, there have been a handful of demonstration projects involving LFG and fuel cells. Several examples are provided below. For a detailed Case Study of the Penrose Station fuel cell demonstration project, see Section 6.0.

- A demonstration at Cannock landfill in Great Britain validated the feasibility of utilizing a SOFC with landfill gas. The fuel cell ran at 18.5% efficiency for a five hour period.[47]
- A 200 kW PAFC from ONSI operated by EPA at Penrose Station in Sun Valley, California from 1994-1996. In 1996 the fuel cell was relocated to a different landfill situated at Groton, Connecticut. The fuel cell was operated by the EPA at that location until 1998, when it was turned over to Northeast Utilities of Hartford, Connecticut.
- In December 1994, the Electric Power Research Institute, National Energy Technology Laboratory, U.S. Department of Energy, and Energy Efficiency and Renewable Energy entered into a joint effort to evaluate contaminant removal processes in conjunction with a MCFC. The pilot plant cleaned approximately 970,000 standard cubic feet of natural gas over 1,000 hours of operation.[48]

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[47] Staniforth, J. and Kendall, K. 2000.

[48] Steifeld, G. and Sanderson, R. “Landfill Gas Clean-up for Carbonate Fuel Cell Power Generation.” Prepared for U.S. DOE, Contract No. DE-FC21-95MC31184. February 1998.

3.3. Methane from Digesters

3.3.1. Background

Methane can also be produced from the anaerobic digestion of biomass wastes. Anaerobic digesters are used by agricultural facilities and waste water treatment plants as a waste treatment methodology that promotes nutrient recycling and odor control.[49] The digesters utilize bacteria to stimulate a biological reaction that converts approximately 40% of the solid input into methane-rich gas.[50]

The biomass waste available for conversion into digester gas is an abundant resource. In the U.S., estimates suggest that a half pound of wastewater sludge is generated per person each day.[51] In addition, dairy and poultry farmers are increasingly looking to anaerobic digesters as a way to comply with federal and state regulations concerning the handling and treatment of agricultural wastes.[52]

Digester gas (biogas) typically contains 57 to 66% methane, 33 to 39% carbon dioxide, 1 to 10% nitrogen, a small amount of oxygen, and other trace fuel cell contaminants including sulfur compounds like hydrogen sulfide, halogen compounds, and non-methane organic compounds.[53] The composition of digester gas varies with feedstock material and the type of digester process used.

There are two basic types of digesters used in wastewater sludge and agricultural waste treatment, distinguished by the input of biomass into the digester:

- **Batch-type Digesters** – Batch-type digesters break down one "batch" of waste material at a time. They are typically loaded with biomass waste and then capped. The digester produces heat as a result of the waste decomposition, but can also be heated manually to facilitate increased anaerobic activity.[54] The covered lagoon and complete mix digesters are common batch-type systems. In a covered lagoon digester, a storage pit is covered with an impermeable material that traps the digester gas as the solid waste decomposes. Covered lagoon digesters are used for large volume wastes that are primarily liquid, and can be used with agricultural waste or sewage sludge. Complete mix digesters consist of large heated tanks located above or below ground. Waste that is between 2 to 10% solid waste is

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[49] "Consumer Energy Information: EREC Reference Briefs." US Department of Energy, Energy Efficiency and Renewable Energy Network web site: http://www.eren.doe.gov/consumerinfo/refbriefs/ab5.html.

[50] Spiegel, R.J. and Preston, J.L. "Test results for fuel cell operation on anaerobic digester gas." *Journal of Power Sources*. Vol. 86, pp. 283-288. 2000.

[51] Brown, Robert C. "The Potential for Biomass Production and Conversion in Iowa: Final Report to the Iowa Energy Center." August 31, 1994.

[52] "Anaerobic Digester Technology." Oregon Office of Energy web site: http://www.energy.state.or.us/biomass/digester/digestech.htm.

[53] Spiegel, R.J. and Preston, J.L. 2000.

[54] "Consumer Energy Information: EREC Reference Briefs." US Department of Energy, Energy Efficiency and Renewable Energy Network web site: http://www.eren.doe.gov/consumerinfo/refbriefs/ab5.html.

continuously mixed to keep the solids in suspension. Although very effective, mix digesters are more expensive than other types.

- **Continuous Digesters** – Continuous digesters utilize biomass waste that is fed either constantly or at regular intervals into the digester. Wastes move through the digester, continuously producing biogas.[55] Continuous agricultural digesters are also called plug-flow digesters. These digesters process biomass wastes consisting of 11 to 13% solids. The manure is inputted at one end of a rectangular tank and is digested as it moves through the tank.[56]

The rate of biomass waste digestion, and, thus, biogas production, for each of the digester types is dependent upon numerous factors, including pH, the water/solids ratio, the carbon/nitrogen ratio, the mixing rate of digested material, the particle size of the biomass waste, and the retention time. These characteristics, in turn, vary significantly by the source of the biomass feeding the digester. Municipal facilities with large residential loads will show different compositions of metals, pH, etc., than either farm-based systems or municipal systems with large components of commercial or industrial use.

The most significant characteristic influencing biogas production is temperature. Although anaerobic bacteria can withstand a wide range of temperatures, they are most productive in the mesophilic (98° F/36° C) and the thermophilic (130° F/54° C) ranges. In addition, digestion occurs much more rapidly in the thermophilic range as compared to the mesophilic range. However, the thermophilic process is much more sensitive to system changes like input variances and temperature changes. Bacterial activity drops significantly from 125° F to 103° F (51° C to 39° C) and slows more gradually from 95° F to 32° F (95° C to 0° C).[57]

At present, most of the biogas currently produced by anaerobic digesters is either released into the air or flared at the digester facility. However, several facilities are looking into different opportunities for using the potential resource. Some have processed the biogas to remove the carbon dioxide and other compounds and yield natural gas for resale. Others burn the gas on site to produce heat that can be recovered for use with various digester systems. In general, a cubic foot of biogas, when combusted, produces about 10 Btus of heat energy for each percentage of methane content.

Biogas can also fuel internal combustion engines to produce electricity. However, noise and air quality issues impede the siting of these facilities. Researchers are therefore looking to fuel cells as a source of economically efficient and environmentally sound

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[55] US Department of Energy, Energy Efficiency and Renewable Energy Network web site: http://www.eren.doe.gov/consumerinfo/refbriefs/ab5.html.

[56] "Anaerobic Digester Technology." Oregon Office of Energy web site: http://www.energy.state.or.us/biomass/digester/digestech.htm.

[57] "Consumer Energy Information: EREC Reference Briefs." US Department of Energy, Energy Efficiency and Renewable Energy Network web site: http://www.eren.doe.gov/consumerinfo/refbriefs/ab5.html.

energy production from digester gas.[58] A professional in the wastewater treatment industry estimated that there are at least 400 wastewater treatment plants in the US that are capable of supporting a 1 MW fuel cell facility.

A senior government researcher stated that biogas was the biomass application that he supported the most. This was due to its high methane content, low contaminant composition, and consistent supply over time.

3.3.2. Fuel Pre-treatment and Other Fuel Cell Integration Issues

Like other bio-based fuels that have been discussed, biogas must undergo a pretreatment and reforming process prior to its use in a fuel cell. As mentioned above, biogas typically contains several fuel cell contaminants, including the sulfur and halogen compounds. Other common contaminants include solids, liquid water, condensate, and bacteria.

As in the case of LFG, the biogas should be pretreated to remove contaminants. The design of the pretreatment process is impacted by the final gas purity requirements of the fuel cell and the composition of the digester gas, which may fluctuate somewhat depending on inputs into the digester. The gas that reaches the fuel cell must be essentially free of all sulfur and halogen contaminants and consist primarily of a mixture of methane, nitrogen, oxygen, and carbon dioxide (depending on the type of fuel cell to be utilized).

Spiegel and Preston have successfully demonstrated a pretreatment process for use with a PAFC at a wastewater treatment facility.[59] In designing the pretreatment process, they first examined the specific contaminants in the digester gas stream. This step revealed that halide levels in that specific gas stream were sufficiently low to be handled by a halogen guard bed in the fuel cell processor itself. In addition, filters installed before the pretreatment facilities would be able to prevent the solids, liquids, and bacteria from entering the fuel cell. The pretreatment facility for this demonstration project was used primarily for hydrogen sulfide removal, which was present in relatively high amounts in the gas stream.

A non-regenerable desulfurizer bed in conjunction with a carbon bed was used to remove the hydrogen sulfide from the gas stream prior to its entrance into the fuel processor. Spiegel and Preston found that this treatment system removed sulfur and halides with efficiencies greater than 98%. With this clean-up efficiency, the plant's fuel reformer was expected to operate for the life of the catalyst, or 5 years. The researchers noted that the applicability of this pretreatment process would be site specific. Interviews confirmed the need to adapt pretreatment systems to the contaminants specific to a particular digester gas system. However, interviews also

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[58] Spiegel, R.J. and Preston, J.L. 2000.
[59] Spiegel, R.J. and Preston, J.L. 2000.

suggested that no significant technical barriers stood in the way of greater development of biogas fuel cell systems.

As with LFG, once the biogas is purified through pretreatment, it requires reforming to create the hydrogen necessary for fuel cell operation. In the reformer, biogas is mixed with hot steam. At approximately 1650° F (900° C), a nickel catalyst triggers a reaction forming hydrogen and carbon monoxide. The carbon monoxide and steam is processed again with a copper catalyst to form hydrogen and carbon dioxide.[60]

Because current fuel cells are manufactured primarily to operate on natural gas, some modifications to the fuel cell are needed to accommodate biogas. Hydrogen produced by reforming biogas is significantly diluted by carbon dioxide. Specifically, Spiegel and Preston found that digester gas contains up to 35 to 43% diluents (carbon dioxide) by volume[61]. Thus, the fuel cell plant had to be modified to accept higher mass and volume flow rates and/or a reduced heating value for the fuel. These modifications included resizing fuel inlet valves and plumbing in order to increase fuel flow capacity and pressure. The researchers also found that while the plant did show decreases in efficiency compared to a natural gas fuel cell facility, the low cost of fuel for the digester gas fuel cell plant could balance the ultimate economic impact.

Due to the variable consistency of biogas, a fuel cell power plant must be operated at a lower capacity than a continuous feed natural gas system. For instance, researchers have found that methane content from a single digester can vary by +/- 10%. In contrast, natural gas fuel cells have been designed to accommodate only a +/-3% variance. As a result, the fuel cell is typically operated at less than full output in order to avoid shut-downs associated with decreases in methane content. [62]

Several interviewees commented on the treatment process necessary for biogas and in particular, the wide variation of contaminants potentially found. A senior government researcher also noted that biogas tends to be seasonal in composition, which means that biogas fuel cell systems need to accommodate seasonal fluctuations in Btu content and gas composition. A fuel cell developer reiterated the need for biogas treatment systems to accommodate the wide variation in digester gases. The developer also suggested that agricultural digester facilities have some control over the input of biomass waste into the digester, and thus, are more capable of preventing significant variations in the resulting biogas. An academic researcher concurred with this evaluation, stating that current experimentation is on "bioreactor" columns -- digesters filled with different agricultural wastes that would pre-clean the H_2S from the biogas.

With regard to cost, biogas is available at a price that is very competitive with natural gas. According to academic researchers, biogas is presently available at a price of approximately $1.50 per mmBtu.

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[60] "Fuel cell using digester gas." GEW Köln AG web site: http://www.brennstoffzelle-koeln.de/Pages/StartE.htm.

[61] Spiegel, R.J. and Preston, J.L. 2000.

[62] Spiegel, R.J. and Preston, J.L. 2000.

3.3.3. Digester Gas and Issues of Fuel Cell Compatibility

Based on our research and interviews with stakeholders in the industry, it is apparent that PAFCs, MCFCs, and SOFCs are all compatible with biogas. Several demonstration projects have already used PAFCs with biogas, and a demonstration project is currently underway that will use an MCFC. As with syngas and LFG, PEMFCs are not likely to be as suitable, given the heat associated with the gas reforming process. In order to be used in conjunction with a PEMFC, significant heat would have to be removed from the gas stream prior to its use in the fuel cell.

3.3.4. Demonstration Projects

There have been several demonstration projects using biogas as a fuel source for fuel cell power plants:

- A wastewater treatment plant in the town of Rodenkirchen, a suburb of Cologne, Germany, has installed a 200 kW PAFC from ONSI Corporation (now United Technologies Corporation). The fuel cell facility is the first plant in Europe to utilize biogas for electricity generation.

- The first installation of a fuel cell power plant fueled by biogas is located in Yonkers, NY at a wastewater treatment facility. The 200 kW PAFC was purchased from ONSI Corporation with funding from the US Environmental Protection Agency. The demonstration project found that, depending on the energy content of the biogas, the fuel cell facility could produce electrical outputs close to full power. In addition, air emissions are similar to fuel cell facilities run on natural gas. All of the electricity produced by the fuel cell is used on site.

- The Department of Natural Resources in King County, Washington recently entered into a demonstration project with Fuel Cell Energy. In the project, a MCFC from Fuel Cell Energy, Inc. will be located at the King County wastewater treatment plant and will be fueled by biogas from the facility. The project will be under construction as of February of 2002 and should be operational by the third quarter of 2002.

- A 200 kW PAFC fuel cell from ONSI is currently operational at the Columbia Boulevard Wastewater Treatment Plant in Portland, Oregon. A detailed case study of this project is provided in Section 6.0.

3.4. Ethanol

3.4.1. Background

The U.S. ethanol fuel industry supports more than two billion gallons of annual production capacity (the equivalent of more than 1% of U.S. annual gasoline consumption). According to the Renewable Fuels Association, ethanol fuel is available in all 50 states at the terminal level.[63] This makes ethanol the bio-based fuel with the most widespread commercial use in the U.S. However, ethanol is primarily used as a gasoline additive/ transportation fuel, and little to no ethanol fuel is directly used for the production of electricity.

Ethanol production technology can generally be divided into two main categories: 1) technologies that convert starch or sugar-based feedstock into ethanol; and 2) technologies that convert cellulosic biomass into ethanol. For cellulosic ethanol, sugars must be formed from the cellulosic material as a first step. Once formed, these sugars can be fermented and distilled into ethanol. The following figure illustrates the process for converting starch or sugar and cellulosic biomass to ethanol.[64]

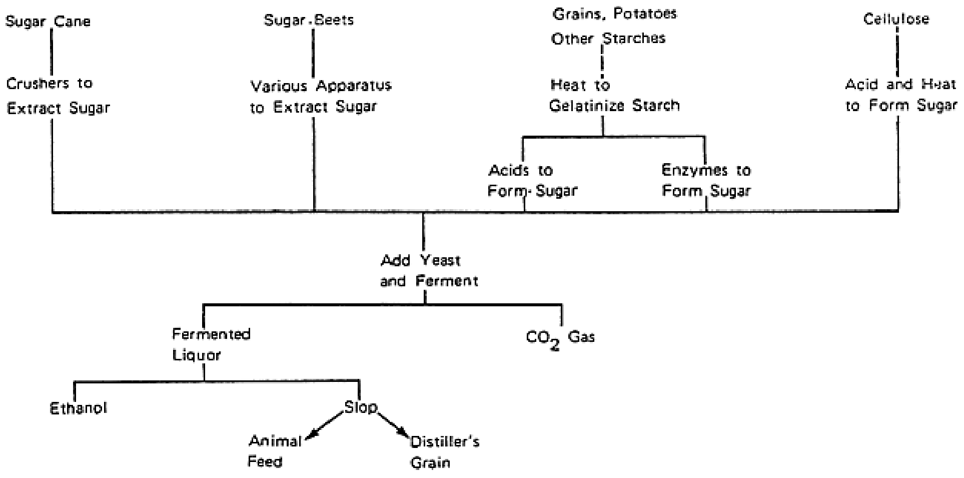

Figure 11. The ethanol production process.

3.4.2. Fuel Pre-treatment and Other Fuel Cell Integration Issues

Like other bio-based fuels, ethanol needs to undergo a reforming process to produce hydrogen. However, no other pretreatment is required, and relative to other bio-based fuels there are very few clean-up issues associated with ethanol because it is commercially available in very pure forms. According to relevant literature and feedback from interviewees, the reforming of ethanol is technically feasible. Two types of reforming processes are used to convert ethanol to hydrogen: steam reforming and partial oxidation, both of which most efficiently convert ethanol to hydrogen at temperatures above 1100° F (593° C).

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[63] Renewable Fuels Association. "Ethanol as a Renewable Fuel Source for Fuel Cells". http://www.ethanolrfa.org/leg_position_fcell.html.

[64] "Energy Efficiency and Environmental News: Alcohol Production from Biomass." http://edis.ifas.ufl.edu/EH341.

The following schematic illustrates the two reforming processes.[65]

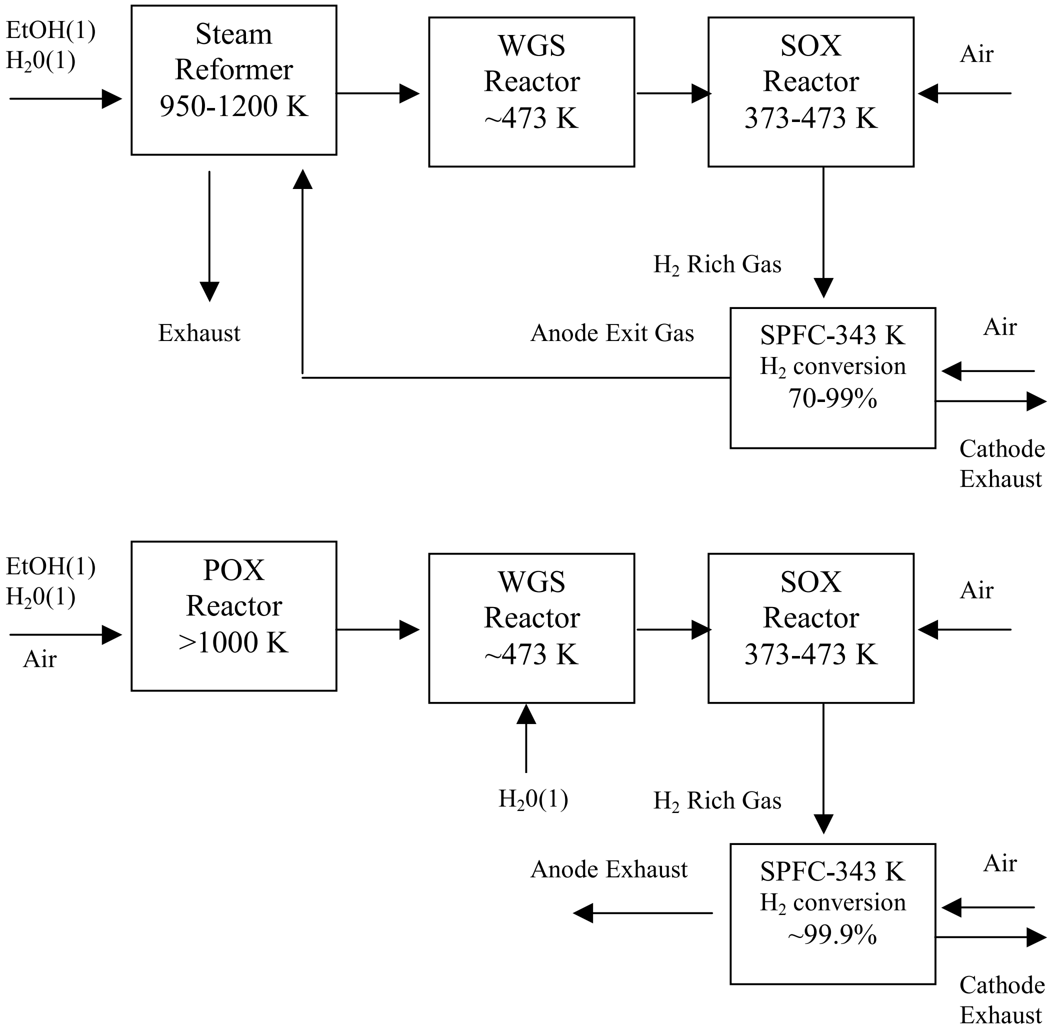

Figure 12. Schematic diagram of SPFC system with (A) SR-processor and (B) POX-processor.

A recent study by Ioannides finds that, for stationary applications, steam reforming of ethanol is preferable for dilute ethanol water mixtures (about 55% ethanol and 45% water by volume, e.g. partially distilled ethanol) while partial oxidation is preferable for more pure ethanol fuel mixtures (e.g., 95% ethanol by volume).

It has yet to be determined which reforming process is better suited for the use of ethanol in stationary fuel cell applications. One academic interviewee noted that, while there is very little difference between the two reforming processes, partial oxidation may

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[65] Ioannides, Theophilos and Stylianos Neophytide. “Efficiency of a Solid Polymer Fuel Cell Operating on Ethanol.” *Journal of Power Sources.* February 2000.

be preferable because it requires a smaller energy input. Another academic noted that while steam reformation requires additional heat integration technology, steam reformation is favored because it uses dilute ethanol and produces a fuel stream with a greater concentration of hydrogen.

The use of dilute ethanol could be economical in certain stationary applications, especially where the fuel cell plant is located near the ethanol production facility and distillation costs can be reduced.[66] Both the Ioannides study and a study by Maggio highlight the importance of additional research on the economics of using dilute ethanol.

There is little information that compares the efficiency or performance of the ethanol reforming process with that of natural gas, the likely market leader for stationary fuel cell applications. The Magglio study notes that, compared to the use of methane and methanol in indirect internal reforming MCFCs, ethanol is superior "in terms of energy density, cell voltages, and electrical power density." The energy density (MW per cm^2) of ethanol can be almost twice that of methane or methanol.[67]

Ethanol fuel is expensive on a $ per Btu basis compared to hydrocarbon alternatives and some of the other bio-based fuels discussed in this study. Our interviews with government researchers indicate that conventional grain or sugar-based ethanol costs $12.50 per mmBtu; cellulosic ethanol costs $15-19.00 per mmBtu.

3.4.3. Ethanol and Issues of Fuel Cell Compatibility

High temperature MCFCs and SOFCs are capable of reforming ethanol using a direct internal reformer. These higher temperature fuel cells can also use carbon monoxide as a fuel. In lower temperature fuel cells, however, the same carbon monoxide poisons the internal reformers.[68] An external reformer that operates at high enough temperatures to convert ethanol can be integrated with lower temperature fuel cell technologies, making ethanol a technically viable fuel for the full range of fuel cell technologies. Nuvera Fuel Cells has developed a multi-fuel reformer capable of reforming ethanol that is compatible with several fuel cell technologies.[69]

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[66] Ioannides, Theophilios. "Thermodynamic Analysis of Ethanol Processors For Fuel Cell Applications." *Journal of Power Sources.* April 2000.

[67] Maggio, G., Freni, S., and Cavallaro, S. "Light Alcohols/ Methane Fueled Molten Carbonate Fuel Cells: A Comparative Study." *Journal of Power Sources.* December 1997.

[68] Maggio, G., *et al*., 1997.

[69] The use of ethanol in fuel cell vehicles that would operate on PEM technology presents a significant market for biofuels that is worth noting, but outside the scope of this study.

The literature on the topic also stresses the potential environmental benefits of ethanol, its handling advantages, and overall availability. A study by Fatsikostas, *et al*. finds:

> In contrast to the fossil-fuel based systems, the bioethanol-to-hydrogen system has the significant advantage of being nearly CO_2 neutral…..In addition, the use of ethanol offers important storage and handling safety advantages.[70]

The Ioannides and Neophytides study adds:

> Among the candidate liquid fuels, ethanol is a particular case, because it can be readily produced from renewable sources (biomass) available throughout the world.[71]

Most of the interviewees support the technical feasibility of utilizing ethanol with fuel cells. Nonetheless, several add that cost is the most significant barrier facing the widespread use of ethanol in fuel cells. The U.S. ethanol transportation fuel market is supported by a $.57 per gallon government subsidy, and little to no ethanol has been used directly for the generation of electricity due to the cost of ethanol. It is worth pointing out that over the long-term, the National Renewable Energy Laboratory (NREL) projects cost reductions for cellulosic ethanol of about 50 cents per gallon by 2005, and about 60 cents per gallon by 2010. If these predictions hold true, ethanol would become cost competitive with other bio-based fuels and hydrocarbon alternatives on a $ per Btu basis, especially if a subsidy were to remain in place.[72]

While some interviewees write off ethanol as “too expensive,” others are more optimistic. One interviewee says “ethanol is the most straightforward [biofuel for fuel cell use].” Another notes that his research and planning indicate that in five years, ethanol powered fuel cells will be an economically viable and environmentally preferable alternative to diesel generation for island communities. Identifying another niche market, a Fuel Cell Energy research project finds that an ethanol powered fuel cell can generate electricity for as low as $.04 per kWh when co-located with an ethanol production plant.[73] In addition to ongoing technical research and development efforts, the literature and interview findings support further research into: 1) dilute ethanol; 2) comparisons of ethanol with various fuels; and 3) niche markets for ethanol powered fuel cells.

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[70] Fatsikostas, A., Kondarides, D., and Verykios, X. “Steam Reforming of Biomass-Derived Ethanol for the Production of Hydrogen for Fuel Cell Applications.” *ChemComm Communication.* April 2001.

[71] Ioannides, T. and Neophytide, S. 2000.

[72] National Renewable Energy Laboratory. "Bioethanol Multi-Year Technical Plan, FY 2000 and Beyond."

[73] Fuel Cell Energy. “Direct Fuel Cells in a Rural Situation.” 1996.

3.4.4. Demonstration projects

Recognizing the cost issues that need to be addressed, there are very few ethanol powered stationary fuel cell demonstration projects:

- In Summer 2001, Caterpillar Inc., Williams Bio-Energy, and Nuvera started a $2.5 million ethanol powered stationary fuel cell project in Illinois. The 13 kW PEM stationary ethanol powered fuel cell system will power the Williams Visitor Center in Pekin, Illinois. This will be the first commercial demonstration of an ethanol powered stationary fuel cell in the U.S. Nuvera Fuel Cells has developed a multi-fuel processor that is cable of converting both ethanol and hydrocarbon fuels into hydrogen. Tests indicate that ethanol provides higher efficiencies, fewer emissions, and better performance than gasoline.[74]

- Recently, the University of Patras teamed with Commercial Capital (a venture capital firm) to develop an ethanol fueled 15 kW fuel cell demonstration project in Greece. The project is expected to be up and running by mid-2002. The project will most likely use PEMFC technology, although a manufacturer has not yet been selected.

3.5. Pyrolysis Oil

Compared to research on the reformation of syngas, methane gas, or ethanol, work on the use of pyrolysis oil, or bio oil, as a hydrogen source for fuel cells is limited but exists in both academia and the business world.

3.5.1. Background

Pyrolysis oil is typically created by a thermal process called fast pyrolysis. During fast pyrolysis, biomass materials including forest waste (sawdust, bark) and agricultural by-products (sugar cane waste bagasse, wheat straw, etc.) are rapidly heated to moderate temperatures of typically around 950° F (500° C) in the absence of oxygen and then vaporized and condensed to a liquid oil. The feedstock is converted into vapors, non-condensable inert gases, and solid char (char makes up about 15%).[75] The gaseous products from the reactor pass through a cyclone where the char is removed and then to a quench chamber where the gases are quickly quenched to prevent cracking of the newly produced pyrolysis oil. Pyrolysis oil vapors are condensed into a liquid and are collected in a product tank. The non-condensable gases are re-circulated in the process and used as fluidizing gases in the reactor.[76]

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[74] "Ethanol as a Renewable Fuel Source for Fuel Cells." http://www.ethanolrfa.org/leg_position_fcell.html.

[75] Studies have shown that the char byproduct can be converted in high concentration hydrogen and carbon monoxide synthesis gas via steam gasification. This is one example of the potential for integrating various biofuel processes to cost effectively produce hydrogen and other useful chemicals (For more information on biomass gasification see Section 3.1.)

[76] DynaMotive Technologies Corporation. http://www.dynamotive.com.

According to one interviewee, pyrolysis oil has been successfully used as a clean fuel for power generation in gas turbines, diesel engines, and boilers. The commercial production of pyrolysis oil is still in its infancy. However, it is worth pointing out that bio-oil has a significant advantage over some other bio-based fuels in that it can be easily stored and/ or transported. Hence, good economies of scale can be utilized in the conversion of bio-oil to hydrogen by transporting the liquid to a central processing plant.

One pyrolysis oil manufacturer, Dynamotive, recently completed construction of a pilot plant that produces 10 tons per day of pyrolysis oil for use in power generation. Dynamotive plans to increase capacity to 100 to 400 tons per day at commercial plants within the next three years.

3.5.2. Fuel Pre-treatment and Other Fuel Cell Integration Issues

Most of the interviewees were not familiar with work on the reformation of bio oil, and noted that reformation would be difficult because bio oil is a complex mixture of different compounds. Research and development, though, indicate that it is technically feasible to reform bio oil and that there is some interest in commercializing this process.

A 1997 study by D. Wang, *et al* finds that while, "bio oil is a complex aqueous mixture" of various chemicals, the steam reforming of bio oil is chemically and thermodynamically feasible at up to 1382° F (780° C). The study also projects that hydrogen could be produced for $7.30 per mmBtu from pyrolysis oil assuming that an added value phenolic substitute for resin formation is a saleable co-product.[77] Our interview research suggests that pyrolysis oil itself can be produced for as little as $2.00 to 6.00 per mmBtu, depending on the cost of the raw feedstocks.

One of the interviewees is currently studying the reformation of pyrolysis oil. He finds that it is technically feasible to reform pyrolysis oil into hydrogen and other gases, but notes that it might not be cheap to reform pyrolysis oil on a commercial level due in part to the high temperatures required. He adds that reformation technology for other bio-based fuels is closer to commercialization, and potentially more cost-effective. Another interviewee noted that another challenge is the "coking deposits" that the reformation of bio oil would leave on catalysts.

At least one pyrolysis oil producer is more optimistic about the market potential for pyrolysis oil as fuel source in fuel cells. This company is researching a catalytic reforming process that would convert pyrolysis oil into gases, mostly hydrogen and carbon monoxide (at a 2 to1 ratio), some methane (2 to 4%), and carbon dioxide (15%), that could be easily used by fuel cells. The company expects to have a commercial reformer in five years.

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[77] Wang, D., Czernik, S., Mantane, D., Mann, M., and Chornet, E.. "Biomass to Hydrogen via Fast Pyrolysis and Catalytic Steam Reforming of the Pyrolysis Oil or its Fractions." National Renewable Energy Laboratory. Industrial Engineering Chemical Research. American Chemical Society. 1997.

3.5.3. Pyrolysis Oil and Issues of Fuel cell Compatibility

Many interviewees note that pyrolysis oil is generally thought to be cheaper to produce than ethanol on a $ per Btu basis. However, due to its complex nature, the conversion of pyrolysis oil into hydrogen would require development of reformers that operate at a higher temperature than the internal reformers in any fuel cell technology.

One interviewee noted that the higher temperature fuel cells would be more compatible with the gases created by the reformation of bio oil because they could process the carbon monoxide. Other interviewees stated that the key issue surrounding the feasibility of pyrolysis oil as a feedstock for fuel cells is the cost of related reforming technology and fuel clean-up issues.

3.5.4. Demonstration Projects

While there are no ongoing demonstration projects that utilize pyrolysis oil in fuel cells, pyrolysis oil is being tested as a fuel for generating power and heat from small stationary diesel engines, gas turbines, and boilers. DynaMotive and Orenda Aerospace Corporation teamed up to demonstrate and test the use of pyrolysis oil in a 2.5 MW gas turbine. Over 2000 hours of testing have shown that this application is technically and potentially economically feasible. Estimates suggest that if the cost of biomass feedstock is assumed to be zero, the electricity can be generated for between $.04 and $.06 per kWh (cogeneration applications are more cost effective). Second generation work is ongoing. Furthermore, a study by Morris *et al.* shows that relative to diesel, the use of bio oil would be carbon neutral, have no SO_x emissions, and would produce more than 50% fewer NO_x emissions than diesel.[78]

3.6. Biodiesel and Levulinic Acid

Research on the use of biodiesel or levulinic acid in fuel cells is scarce. The market for biodiesel as a transportation fuel is rapidly growing. Biodiesel is also used in niche applications as fuel for stationary electricity generation and boilers. Levulinic acid production is in the nascent stages of commercialization.

3.6.1. Background

The following section provides background on the conversion process and commercial status of biodiesel and levulinic acid.

- **Biodiesel** --- Biodiesel is the name of a clean burning mono-alkyl ester-based oxygenated fuel made from soybean oil or other vegetable oils or animal fats. A

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[78] Morris, K., Johnson, W., and Thamburaj, R. “Gas Pyrolysis of Biomass for Green Power Generation”. DynaMotive Technologies Corporation and Orenda Aerospace Corporation. 2000.

renewable fuel domestically produced from agricultural resources, biodiesel is biodegradable, nontoxic, and essentially free of sulfur and aromatic compounds. Most biodiesel is produced through a process of base catalyzed transesterification. The reaction is low temperature (150°F), low pressure (20 psi), and has a high conversion factor (98%) with minimal side reactions and reaction time. During the manufacturing process, a fat or oil is reacted with an alcohol (like methanol) in the presence of a catalyst to produce glycerine and methyl esters or biodiesel. The methanol is charged in excess to assist in quick conversion and recovered for reuse. The catalyst is usually sodium potassium hydroxide that has already been mixed with methanol.[79]

The use of biodiesel in vehicle fleets appears to be on the rise. In early 1999, very few vehicle fleets purchased biodiesel, but as recently as September 2001, there were well over 100 major fleets that had implemented biodiesel programs across the US, including federal fleets such as the US Postal Service, the US Air Force, and the US Army, and major public utility fleets such as Commonwealth Edison, Florida Power and Light, Duke Energy, and Georgia Power. Current dedicated production capacity is estimated to be between 60 and 80 million gallons per year.

- **Levulinic Acid** --- Biofine, Inc. has patented a high-temperature, dilute-acid hydrolysis process that converts cellulosic biomass to levulinic acid and derivatives. During this process, cellulose is initially converted to soluble sugars, which are then transformed to levulinic acid. By-products of the process include furfural, formic acid, and condensed tar, all of which have commercial value as commodities or fuel. Feedstocks used in the process include paper mill sludge, municipal solid waste, unrecyclable waste paper, waste wood, and agricultural residues. Levulinic acid serves as a building block in the synthesis of useful chemical products. Markets already exist for tetrahydrofuran, succinic acid, and diphenolic acid, all of which are levulinic acid derivatives. There are other derivatives with potential commercial value including methyltetrahydrofuran (MTHF), a fuel additive.[80]

3.6.2. Fuel Pre-treatment and Other Fuel Cell Integration Issues

The interviews and literature review revealed little about the conversion of biodiesel or levulinic acid for use in fuel cells. While interviewees generally did not comment on these two bio-based fuels, one interviewee hypothesized that since biodiesel is a mixture of several complex and simple compounds, it would be relatively complex to reform, though perhaps not as difficult as pyrolysis oil. In contrast, an academic researcher noted that biodiesel should be similar to traditional diesel, except for its elevated sulfur composition. Therefore, biodiesel could be utilized in SOFC technologies currently demonstrating diesel use (see below) if a de-sulfurization pre-treatment technology were also employed.

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[79] The National Biodiesel Board. http://www.biodiesel.org.
[80] The U.S. Department of Energy. http://www.oit.doe.gov/factsheets/chemicals/pdfs/levulinic.pdf.

Only one interviewee commented on levulinic acid. This interviewee suggested that the reformation of levulinic acid or its derivatives might be simpler than biodiesel but more difficult than ethanol. No further details were provided.

Based on our interview research, the costs of biodiesel and levulinic acid are high. Biodiesel presently costs as much as $15.00 to $25.00 per mmBtu; levulinic acid and its derivatives currently cost between $9.00 to $50.00 per mmBtu. Neither biodiesel nor levulinic acid appear to be cost competitive with natural gas in the short term.

3.6.3. Biodiesel and Issues of Fuel Cell Compatibility

Several interviewees noted that biodiesel and levulinic acid have several desirable characteristics for use in fuel cells, such as their ease of transport, relatively low cost per Btu, and positive impact on net energy balance. Some interviewees also speculated that it should be technically feasible to use these bio-based fuels in fuel cells. However, additional research is needed to determine the actual technical and economic compatibility of biodiesel or levulinic acid with stationary fuel cells.

Notably, chemical engineers at the University of Pennsylvania have developed a prototype fuel cell that will run on ordinary diesel fuel. The prototype is a SOFC with direct fuel technology, which does not require an external fuel reformer. Given the assumption that biodiesel performs in a similar manner to traditional diesel, a University of Pennsylvania researcher speculated that the fuel could be used in the prototype diesel fuel cell if the elevated sulfur levels were reduced through pre-treatment technologies.

3.6.4. Demonstration Projects

There are no known demonstration projects involving the use of biodiesel or levulinic acid in fuel cells. There is no information on the use of levulinic acid or its derivatives for the use of electricity generation. Although biodiesel is used mostly as a transportation fuel, it can be used in boilers and generators as well. For example, in Summer 2001, the University of California at Riverside demonstrated three 2 MW back-up internal combustion generators that ran exclusively on biodiesel.[81]

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[81] Southern States Power Company. http://www.sspowerco.com.

4. Barriers to and Benefits of Developing Biofuel-based Fuel Cell Systems

Interviewees from the fuel cell and biomass industries were asked to comment on what they saw as key barriers to the development of biomass-based fuel cell systems. This section describes their comments, categorized under Technology, Economics, Infrastructure, and Policy. The section concludes with a discussion of notable benefits associated with the development of biomass-based fuel cell systems.

4.1. Technology

The parties interviewed for this report were largely optimistic about the future of fuel cell technology. Many interviewees commented that while minor problems certainly exist with current fuel cell technology, all of these problems are solvable from a technical perspective. None should be classified as a major barrier to the overall development of biomass-based fuel cell systems.

The following technical issues were most frequently identified by interviewees:

- Current fuel cell production is accomplished primarily by hand, and fuel cell systems are all designed on an individual basis. As a result, until fuel cell manufacturing is more automated, costs will continue to be high.

- The high operating temperatures of SOFCs and MCFCs mean that these fuel cells require a thermal host in order to make project economics more viable.

- Most interviewees felt that the immature stage of reforming and gas-cleaning technologies was an issue, but did not constitute a major technical barrier. Rather, this was an area for potential cost and efficiency improvements. Only one interviewee described these barriers as “significant.”

While most interviewees considered fuel cell technologies to be approaching commercialization, there was a higher degree of uncertainty about the prospects of utilizing fuel cells with bio-based feedstocks. The following key issues were most often mentioned by interviewees:

- Biomass conversion technologies are still in their early stages of development. These technologies need to become more standardized, efficient, and economical before they can be integrated with fuel cells on a commercial scale.

- Fuel processing systems need to be further developed to increase efficiencies. Reforming technologies have largely been proven from a technical standpoint, but are not yet economical.

- Fuel clean-up systems also need to be further developed. In most cases, clean-up systems have been able to significantly reduce the amount of contaminants reaching the fuel cell, but costs associated with fuel clean-up are still high. Fuel clean-up systems for fuel cells also need to have greater flexibility, because many bio-based fuels vary in composition over time.

4.2. Economics

Almost all interviewees noted that the potential application of fuel cells with biomass conversion technologies will depend more on economics than any other single factor. The following economic issues were consistently raised by interviewees:

- Although no significant technical barriers stand in the way of the greater use of fuel cells, there was consensus among interviewees that both fuel cells and fuel cell system costs must decrease significantly before fuel cells can become a viable power generation option. Currently, fuel cells cannot compete economically with other distributed generation options like microturbines.

- The combination of high fuel cell system costs, high costs for bio-based fuels, and high costs associated with reforming and de-contaminating bio-based fuels for use in fuel cells, presently creates a formidable barrier to the increased development of biomass-based fuel cell systems. Combining heat recovery with fuel cell applications is one way to greatly improve project economics. Credits for NO_x and SO_x emissions offsets, as well as for CO_2 in some countries and potentially the U.S., have the potential to improve the project economics of biomass-based fuel cell systems.

- Raw feedstock cost is another critical factor that impacts potential project viability. The use of biomass waste streams that would otherwise require disposal, i.e., have zero or negative costs, can have a positive impact on project economics. It is worth noting that in coming years, progress that has been achieved in the area of genetic engineering will likely be applied toward improving the characteristics of dedicated biomass energy crops. This is a future development that may positively influence feedstock economics.

- The physical properties of the bio-based fuel have important implications on the economics of the process. When the bio-based fuel takes the form of a gaseous product only, as is the case with gasification, LFG, and biogas, electricity production via fuel cells is generally limited to the site where it is produced. However, when the bio-based fuel can take the form of a liquid, as in the case of pyrolysis oil and ethanol, electricity can be produced virtually anywhere. This issue has important bearing on the flexibility, infrastructure requirements, and subsequent economics of each process.

- Another barrier has to do with the sale of electricity produced by the system. In some cases, electricity generated by fuel cells is wholly used by a host on-site.

However, in other cases and in many potential applications, the fuel cell generates surplus electricity that is sold to a local utility or distribution company. In most states, utilities are required to pay only the avoided costs for the power purchased from the fuel cell. According to participants in demonstration projects, fuel cell facilities must be able to sell their power at parity prices in the retail market in order to approach economic viability.

4.3. Infrastructure

Most interviewees highlighted a variety of infrastructure barriers to the greater use of biomass feedstocks and bio-based fuels in fuel cells. Infrastructure-related hurdles to development include the following:

- Any biomass energy conversion facility must be located near the source of the feedstock, otherwise costs associated with feedstock transport will likely be prohibitive. For example, a biomass gasification fuel cell facility would have to be located close to the source of its feedstock.

- There is currently no transportation or distribution infrastructure in place to deliver non-petroleum liquid fuels in the U.S. For instance, while ethanol supplies are readily available, the fuel delivery structure in the US would have to be modified to accommodate ethanol transportation and delivery to end users.

- In most areas, there is little infrastructure to support the collection, transportation, and delivery of raw biomass feedstocks for biomass energy conversion. Any raw biomass to be utilized in conjunction with biomass conversion technologies would have to be collected and transported to a conversion facility. While a handful of dedicated biomass facilities might have such infrastructure in place, most biomass resources, such as forest thinnings and wood wastes, are not currently used or collected, so a collection and transportation infrastructure would have to be developed. Landfill gas and digester gas at municipal solid waste facilities are exceptions, since the waste/ feedstock is already aggregated on site.

Some interviewees also noted potential benefits associated with facility location. Biomass-based fuel cell electricity generation is capable of providing electricity generation resources where they are most needed and where biomass resources are readily available, for example, in rural communities. Development of stationary fuel cells in rural areas could translate into greater system reliability and reduced electricity system costs, achieved by eliminating the need for some distribution and transmission lines.

4.4. Policy

Our research indicates quite clearly that biomass-based fuel cell systems, from a technical perspective, are capable of providing a source of clean, renewable electricity over the long-term. However, a number of economic and policy hurdles stand in the way of this opportunity. Without financial and policy support from the government, biomass-based fuel cell systems will be unable to compete with more traditional fuels and technologies in the short and long-term. These hurdles give rise to a number of policy recommendations regarding both macro-level electricity market issues, as well as considerations more specific to renewable energy and biomass-based fuel cell systems:

- In some states, through a variety of regulatory vehicles, incumbent utilities are able to make it difficult for small independent power producers to sell the electricity they produce. Independent power producers frequently observe a variety of barriers put in place by the incumbent utilities, including fees, undue technical concerns, and general resistance. Policies to overcome these macro-level barriers could have a positive and significant effect on the ultimate development of biomass-based fuel cell systems.

- Some states enable distributed generation facilities to sell power back to the grid at retail prices. If distributed generation facilities are able to receive retail prices for electricity sold, project economics will become more attractive to potential distributed generation developers.

- Current funding for R & D for fuel cells, biomass conversion technology, bio-based fuel reforming, and biomass infrastructure development is inadequate. Increased funding for research, demonstration projects, and feasibility studies in these areas is needed.

- Strong renewable energy policies that include biomass resources are necessary for the increased utilization of biomass feedstocks. Many states either limit or completely exclude biomass from renewable energy policies like renewable portfolio standards and system benefits charge funds.

4.5. Potential Benefits

When asked to comment upon any other barriers or benefits that may affect the potential for increased development of bio-based fuel cell systems, an array of benefits were frequently mentioned by interviewees. The positive environmental aspects of these systems were most frequently highlighted.

- A majority of interviewees noted benefits associated with the displacement of fossil fuels, and the subsequent reduction in greenhouse gas emissions that would be attributable to bio-based fuel cell systems. Several interviewees emphasized the potential for increase biomass-based electricity production to achieve drastic reductions of carbon emissions, especially when compared to coal and oil-based electricity production.

- Many interviewees noted the economic and environmental benefits associated with the reuse of significant waste streams.

- Many interviewees noted the ability of biomass-based fuel cell systems to avoid or significantly reduce SO_x and NO_x emissions, both of which are currently regulated under the Clean Air Act. Other emissions would be reduced as well.

- Other interviewees stressed the positive impacts that the greater use of biomass fuels would have on the U.S. net energy balance by offsetting fossil fuel imports.

- Interviewees also noted the dual economic development impacts of having the fuel cell and biomass fuel industries each help to support the other's continued growth.

- One interviewee noted the synergy between fuel cells and bio-based fuels. He felt that pursuing this synergy was in the interests of both the fuel cell developers and the agriculture industry, as it both opens new niche applications to fuel cells and offers significant new opportunities for agricultural communities and rural economic development.

- It is worth noting the importance of incorporating net energy analysis and life cycle accounting into the evaluation of the benefits of bio-based fuel cell projects. For example, the net energy and life cycle characteristics of biodiesel from soybeans and ethanol from corn may not be as desirable as the characteristics of a closed cycle biomass system. This is an area that warrants further research.

Policies that create incentives for technologies that provide these various environmental benefits could be instrumental in stimulating increased development of bio-based fuel cell systems.

5. Recommendations

This section outlines our recommendations to industry stakeholders, project developers, and government officials that have an interest in promoting the development of fuel cell technology using biomass.

5.1. Funding and Policy

- Cost remains the single most important concern for developers of fuel cell projects involving bio-based energy. Policies are required that enact incentives or tax credits to buy down the risk for companies seeking to enter the business of biomass-based fuel cell power generation.

- Current funding for R & D is inadequate for both biomass conversion technologies in general and biomass-based fuel cell applications in specific. R & D funding is needed to continue development of biomass processing, reforming, and clean-up processes, as well as for biomass-based fuel cell systems. R & D funding for demonstration projects needs to last for the life of the project, not for one to two years as is often the case.

- Strong renewable energy policies that incorporate biomass resources are necessary for the increased utilization of biomass feedstocks. Numerous states have regulatory incentives for renewable energy, like renewable portfolio standards (RPS) and systems benefits charges (SBC), that do not include biomass resources. Making biomass-based fuel cells eligible under state SBCs will provide much-needed funding for project research and development. Including biomass-based fuel cells within state RPS mechanisms creates a regulatory value for biomass electricity above and beyond the market price of electricity.

- State-level policies that redefine net metering to allow distributed power generators to sell excess kWh on grid at “parity” prices will improve project economics.

- State and regional groups should seek to establish independent advisory boards to evaluate and support potential bio-based fuel cell projects. Utilization of an independent authority for these purposes would have numerous advantages, including an ability to provide careful screening, stakeholder involvement, public education, and other forms of market development and support. In states where similar organizations already exist, e.g. for distribution of funds associated with systems benefits charges, it may make sense to structure efforts within the confines of those groups.

- To the extent practicable, policy efforts should be coordinated on both a state a regional basis. For instance, policies that designate what type of technologies qualify under a RPS are currently defined on a state by state basis. Stakeholders in the Northeast could benefit from the certainty associated with having a region-wide standard for these policies, rather than one that is fragmented by state lines.

5.2. Models, Experience and Information

- **Demonstrations --** Good demonstration projects are needed. Potential developers need to be able to see successful demonstrations firsthand. Initial projects should focus on easily replicable applications using proven technology. LFG and biogas applications are good candidates.

- **Feasibility Studies --** Fuel cell manufacturers, developers, and end-users need to be able to perform financial and technical feasibility studies to explore bio-based fuels, fuel cells, and applications involving a combination of the two. Even if feasibility studies do not ultimately result in completed projects, they provide clear information and signals about technical and cost-related barriers, and the steps that should be taken to overcome them.

- **Biomass Waste Inventories --** State energy offices can assist potential project developers by conducting statewide surveys to identify and inventory biomass waste streams as well as identify potential thermal hosts for fuel cell projects. Linking waste streams and thermal hosts is a prerequisite step for developing stationary fuel cell projects with favorable economics. Early efforts should focus on LFG and biogas, both of which involve proven technologies and have relatively promising economics.

- **Funding Intelligence --** Information about grants, subsidies, and other incentives is currently difficult to find. Developers need to stay on top of potential funding opportunities. An up-to-date web site with links to funding opportunities could help achieve this purpose.

- **Professional Linkages --** A key short-term goal for parties involved in research and development of biomass-based fuel cell systems should be to establish a trade organization focused on providing a means to network and share research and ideas. A number of interviewees confessed to knowing little about the similar work of others on the integration of bio-based fuels and fuel cells. Conspicuously absent is the presence of a trade or other professional association specializing in this area.

- **Market Support --** Make sure the right people are being informed about the potential for bio-based fuels and fuel cells and ensure that they are kept abreast of progress, demonstration projects, and other important issues. Make sure that potential developers of bio-based fuel cell projects have access to helpful information, such as potential funding opportunities and niche market opportunities.

- **Realistic Pragmatism --** Developers, state officials, and other individuals or groups interested in the development of bio-based fuel cell applications need to be realistic, move slowly, and think small. Demonstration plants are a realistic goal; commercial pilot plants are not. The economics are simply not there yet. It will take a long time to prove performance and show a positive return on investment (ROI).

- **Caution --** Potential project developers should carefully screen manufacturers. Projects that fail because a manufacturer goes out of business or otherwise fails to fulfill project obligations are not infrequent and are detrimental to the long term goal.

5.3. Vision

Using bio-based fuels in fuel cells provides a promising long-term strategy for producing electricity from a domestic, environmentally friendly energy source. To date, however, there have been few projects linking bio-based fuels with fuel cells. Champions of this technology need a realistic and unified vision moving forward.

Our research has identified many of the barriers to increased development of fuel cell projects using bio-based fuels. At a macro level, obstacles that impede the development of distributed generation in general will ultimately impact the development of technologies discussed in this report. Similarly, competition between fuel cells and potential fuel cell alternatives, like microturbines, solar, and wind, will necessarily affect the potential for using bio-based fuels with fuel cells. Likewise, competition between bio-based fuels and low cost fossil fuels is another concern. Understanding these larger issues is key to developing an appropriate roadmap for the short and long-term.

At present, our research indicates that although certain niche opportunities may exist in the near term, there are no immediately viable commercial opportunities for using fuel cells with bio-based fuels. There are, however, possible opportunities on the horizon. The most promising near term opportunities include:

- Those in which the biomass feedstock or bio-based fuel can be obtained at low or no cost; and/or

- Those with favorable geography.

Based on the above categories, plausible near-term scenarios in which biomass-based fuel cell systems might thrive can be identified. Examples include fuel cell applications on landfills, fuel cells used in conjunction with biogas produced on hog or poultry farms, and fuel cells powered by ethanol in remote rural or island locations. In addition to R & D funding for fuel cells and biomass energy technologies, policies that help lower feedstock costs, stimulate the growth of necessary infrastructure, and ensure parity pricing for distributed electricity will be essential to the development of projects in the near term.

Coincident with the establishment of project demonstrations, industry stakeholders should be prepared to focus their efforts in a number of key arenas:

- **Policy --** Develop, implement, and communicate policies that will remove barriers and enhance the growth climate for fuel cells, biomass conversion technology, and related infrastructure.

- **Funding --** Obtain allocations for funding R & D and feasibility studies for fuel cells, biomass conversion, and related technologies.

- **Institutional Links --** Academics, private organizations, and other researchers should endeavor to find ways to collaborate and share ideas and findings.

- **Market Education and Development --** Stakeholders should seek out ways to educate, inform, and market to the public regarding the opportunities of biomass and fuel cells. And, stakeholders should work with local and state governments, but as well, they should seek to realize the economies of scale associated with tackling policy and related challenges at a regional, if not a national level.

Despite being in their relative infancy, stationary fuel cell technologies demonstrate great potential to provide clean, efficient, and economical electricity generation. Similarly, biomass fuel conversion technologies, which are either in their early stages of development or have captured minimal market share compared to fossil fuel alternatives, promise to provide significant benefits related to economic growth, environmental improvement, and long-term energy independence. While fuel cells and biomass conversion technologies are not entirely dependent on each other for commercial success, together they share unique synergies. The prospect of developing fuel cell and biomass technologies in tandem provides a prescription for electricity generation that is consistent with long term economic and environmental public policy goals. Greater collaboration among these industries, combined with public policies to support them, will be instrumental to overcoming the challenging, yet surmountable, economic, policy, and market barriers that stand in the way. A road map outlining this vision is provided on the following page.

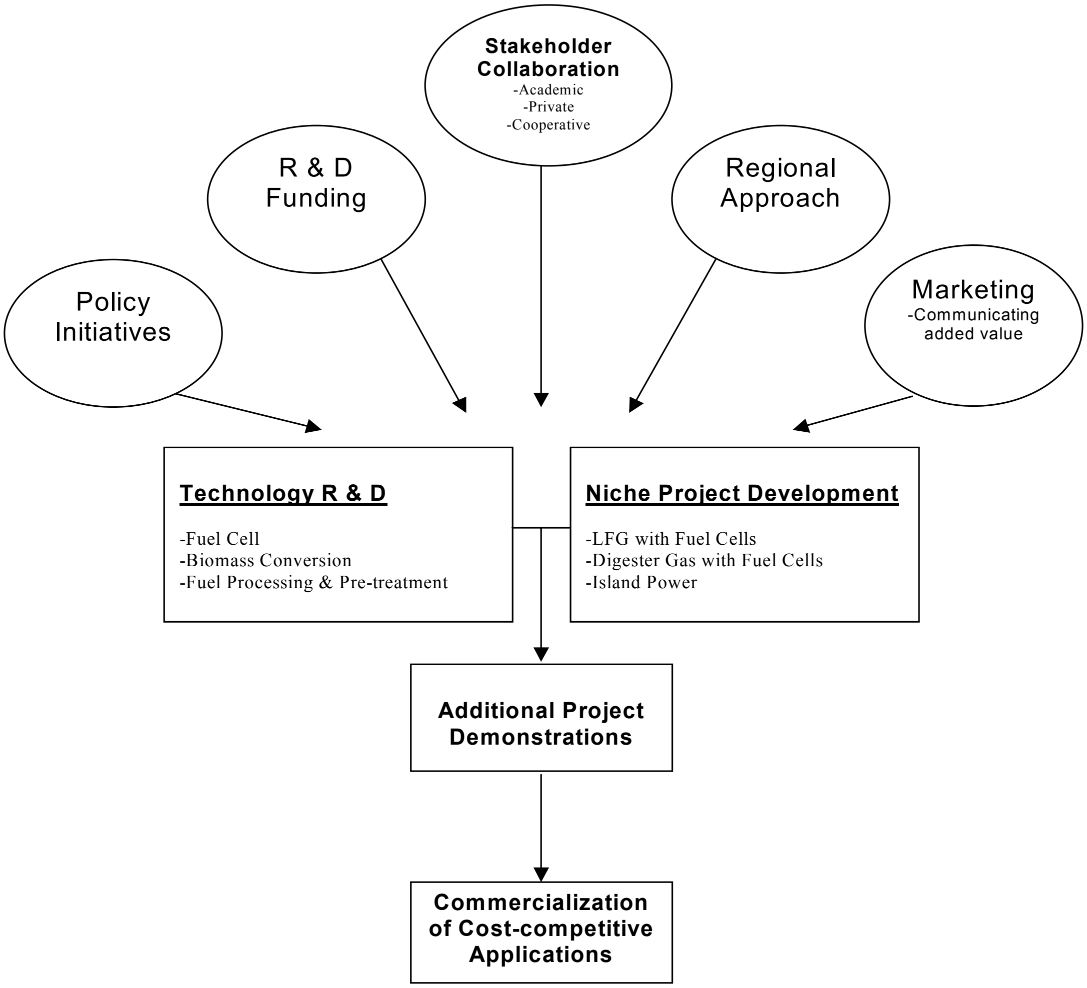

Figure 13. Road map for developing a cost-competitive biomass-based fuel cell industry.

6. Case Studies

6.1. Columbia Boulevard Fuel Cell[82]

The Columbia Boulevard Wastewater Treatment Plant (CBWTP) is publicly owned by the City of Portland, Oregon, and managed by the Bureau of Environmental Services Wastewater Group. The facility was built in 1952 for the primary treatment of wastewater in Portland, and was expanded in 1974 to provide secondary treatment. CBWTP is the largest wastewater treatment facility in Oregon, and has the capacity to treat 100 million gallons of water a day. CBTWP uses several anaerobic digesters to decompose the sludge produced from the treatment process in a more energy efficient and less chemically-intensive process than other decomposing methods. CBWTP is one of the largest treatment plants in the United States to employ anaerobic digesters. These digesters produce approximately 1 million cubic feet of biogas each day.

In 1998, a fuel cell was installed at the plant that utilizes the digester gas to produce electricity. Currently about half of the digester gas produced at the facility is diverted to the fuel cell.

6.1.1. Impetus for the Project

There were three motivating factors behind the installation of the fuel cell at the CBWTP. First, the City of Portland Office of Sustainable Development Energy Division saw a fuel cell as a source of energy that would not negatively impact air quality in the region. Second, staff at the CBWTP wanted to find another use for the methane produced as a part of the digester gas. About 16% of the methane was sold to a nearby manufacturing plant. Another portion was burned, or flared, providing heat to boilers used in the sewage treatment process. The fuel cell facility enabled the plant to utilize the methane gas that previously did not have a specific function. Finally, a fuel cell would provide a source of energy at the CBWTP, thus reducing the energy needs of the plant.

6.1.2. Type of Technology Utilized

The fuel cell at the CBWTP is a PAFC manufactured by International Fuel Cell, Inc. (formerly ONSI Corporation, now United Technologies Corporation). The project

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[82] Case Study information obtained from:
Interview with Duane Sanger, City of Portland Environmental Services Wastewater Division.
Oregon Office of Energy, "Columbia Boulevard Fuel Cell." www.energy.state.or.us/biomass/FuelCell.htm
Back, Brian J. "Portland wants to make energy gold from waste," *The Business Journal of Portland*. 27 July 2001.
"Portland Wins EPA Clean Air Excellence Award," Municipal Waste Management Association, October 2000.

development team at the CBWTP chose this type of fuel cell and the ONSI Corporation because, at the time of installation, it was the only fuel cell that was commercially available.

6.1.3. Use of Electricity Generated

The electricity generated by the fuel cell is used to reduce the overall energy needs of the plant. Specifically, the electricity is used to power the communications center.

6.1.4. Major Obstacles Encountered

There were two obstacles in the development of the fuel cell project. The first and most significant obstacle was facility cost. The total cost of the PAFC system was approximately $1.3 million. As a result of this high cost, the City of Portland had to seek financial support from many different entities. These included the Oregon Office of Energy, Portland General Electric, and the Fuel Cell Climate Change Program. Assistance from the Office of Energy included support through the Business Energy Tax Credit Program and several grants.

The second obstacle in the development process related to the use of digester gas to power a fuel cell that was primarily intended for natural gas consumption. Modifications in the size of the pipe for inputting lower-Btu digester gas into the fuel cell were necessary. As a result, the fuel cell system was no longer a listed, standardized product. The CBWTP had to arrange for an independent group to evaluate the fuel cell system in order for it to maintain UL approval

6.1.5. Project Performance and Outlook

The fuel cell system has proven to be reliable and operationally sound for the CBWTP. The system has a capacity of approximately 170 kW and generates approximately 1.4 million kWh annually. As a result, CBWTP saves approximately $60,000 annually in energy costs.

The costs of the fuel cell project, however have not gone unnoticed. Approximately half of the methane gas produced by the digesters is still flared. While the City of Portland would like to utilize this gas, the expense of the fuel cell system has prompted the city to look to other biomass conversion technologies. In July 2001, the Office of Sustainable Development issued an RFP to study the feasibility of a large biogas turbine generator at the CBWTP. Currently it is estimated that the CBWTP could support a generator ranging from 1.5 to 9 MW. A 2 MW plant has the potential to provide the city with 10% of its total energy consumption, or a savings of $1 million annually.

6.2. Penrose Station Fuel Cell Demonstration Project[83]

In 1994, a fuel cell demonstration project began at the Penrose Station, a generation facility operated by Pacific Energy in Sun Valley, CA. Penrose Station began in 1990 as LFG-to-energy system utilizing a reciprocating engine. The 8.9 MW engine was supplied with LFG from four landfills. The site was chosen for the third phase of an EPA-sponsored program evaluating the technical and non-technical feasibility of applying fuel cell technologies to LFG utilization. The EPA provided funding for International Fuel Cell, Inc. (IFC) to perform the research and demonstration project.

In the first phase, which commenced in January 1991, a study was developed to analyze the conceptual design, cost, and overall feasibility of using LFG as a feedstock for fuel cell technologies. The second phase began in September 1991 and ended in the beginning of 1994. In Phase II, the LFG pretreatment unit to be used in the demonstration program was constructed and tested. Phase III, which commenced in October 1994, utilized the LFG already collected at the site to produce electricity from the installed fuel cell system. Phase III field tests were conducted in December 1994.

6.2.1. Impetus for the Project

Fuel cell demonstration projects were of particular interest to the EPA because of the specific characteristics of the technology. The EPA recognized the high efficiency and low air emissions associated with fuel cell electricity production. In addition, because fuel cell systems are modular, they can be applied to a variety of different landfill sizes. The EPA granted funding to IFC for the Penrose Station Demonstration Project in order to further evaluate the potential for using fuel cell technologies with LFG.

6.2.2. Type of Technology Utilized

The fuel cell system employed at Penrose Station included a LFG collection system, the LFG pretreatment unit, a phosphoric acid fuel cell, and a fuel cell energy conversion system. At the time of the demonstration project, the PAFC was more advanced in its development stage than other fuel cell technologies and had been demonstrated commercially. It was expected that the other fuel cell technologies, including SOFC and MCFC, would not be commercially available for another 10 to 20 years. The PAFC utilized in the demonstration project was manufactured by IFC originally for use with natural gas, and had a capacity of 200 kW. The LFG pretreatment unit developed for the project had the capacity to process approximately 18,000 cubic feet of LFG per hour.

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[83] Case Study Information obtained from:
"Emerging Technologies for the Management and Utilization of Landfill Gas," Prepared for the US Environmental Protection Agency by E.H. Pechan & Associates, Inc. EPA-600/R-98-021, February 1998.
Interview with Dr. R. Spiegel, US EPA.

6.2.3. Use of Electricity Generated

The electricity generated during the Penrose Station field tests was sold onto the electric utility grid of Southern California Edison.

6.2.4. Major Obstacles Encountered

Many modifications had to be made to the PAFC in order to accommodate the LFG. These included a larger fuel control valve, a new process fuel recycling orifice, a new cathode exit orifice, a new start fuel shut-off valve, and changes to the control software.

In addition, at Penrose Station there were a total of eight shut-downs throughout the six-week test program. The causes of the shut-downs included power loss, interrupted LFG flow to the fuel cell, pretreatment system failures, and failure of the PAFC cooling system.

Another obstacle was related to system costs. At the time, IFC guaranteed the capital costs of the fuel cell system to be $3,000 per kW in 1995. In addition, the company estimated that the pretreatment of LFG would cost an additional $250 per kW. The engine already operating at the Penrose site ranged in costs from only $950 to $1,250 per kW. As a result, without EPA funding, the project would have not been economically viable.

6.2.5. Project Performance and Outlook

At Penrose Station, the fuel cell system operated for 2,297 hours, of which only 709 hours were powered by LFG. Although the fuel cell had an original capacity of 200 kW as a natural gas system, during the Penrose Station field tests, the system had a peak power production of 137 kW. The endurance operating capacity was 120 kW. The PAFC efficiency was calculated to be between 36% and 37%.

The LFG pretreatment unit ran for approximately 2000 hours during the field tests at Penrose Station. The pretreatment system was more than 99% efficient at removing sulfur and halide compounds. The PAFC system specified a maximum level of 3 ppmv for sulfur and halide compounds contained in the LFG; the pretreatment unit achieved a level significantly below this.

After December 1994, the fuel cell system used at Penrose Station was moved to a landfill site in Groton, CT. The fuel cell system operated at the Groton site from July 1996 to May 1997. It operated at 130 kW capacity. Use of the fuel cell at the Groton site was discontinued in 1997. Both the Penrose Station and the Groton site have not installed fuel cells since the completion of the demonstration project.

APPENDIX – INTERVIEW QUESTIONS

Project Background and Purpose

EFI is working with the Northeast Regional Biomass Program to write a white paper on the “Applicability of Biomass Feedstocks to Stationary Fuel Cell Technologies.” We are interviewing stakeholders in the fuel cell industry, including manufacturers, project developers, and academics, to learn more about the present and future potential of integrating biomass feedstocks with fuel cell technology. Your answers will not be quoted directly. Rather, we will attribute specific responses to industry sector only. Do you have any questions?

Current Status

(Questions for All Interviewees)

1. What is the technical feasibility of producing electricity from bio-based fuels (ethanol, methane, etc.) for each of the following fuel cell technologies?

    a. Proton Exchange Membrane (PEM)
    b. Phosphoric Acid Fuel Cell (PAFC)
    c. Molten Carbonate Fuel Cell (MCFC)
    d. Solid Oxide Fuel Cell (SOFC)

2. Which technology is best suited and why?

3. Can you expand upon the technical feasibility of using each of the following bio-based fuels in conjunction with fuel cell technologies?

    a. Biomass Gasification
    b. Methane from landfill gas
    c. Methane from digester gas
    d. Ethanol
    e. Pyrolysis oil, biodiesel, levulinic acid

4. What sort of pre-treatment or modification of biomass feedstock processing is necessary to accommodate fuel cell technology from each of the following bio-based fuels

    a. Biomass Gasification
    b. Methane from landfill gas
    c. Methane from digester gas
    d. Ethanol
    e. Pyrolysis oil, biodiesel, levulinic acid

(if expert on one topic area, ask about interviewee’s area of expertise only)

5. Are there any demonstration or research and development projects that involve the use of bio-based fuels and fuel cells? What insights are these projects providing? What other scenarios could you envision involving bio-based fuels and fuel cells?

Barriers and Benefits
(All Interviewees)

6. What do you see as the barriers of using bio-based fuels in stationary fuel cells in each category?
   a. Technology
   b. Market
   c. Economic
   d. Infrastructure
   e. Policy
   f. Other

7. What do you see as the benefits of using bio-based fuels in stationary fuel cells?
   a. Technology
   b. Market
   c. Economic
   d. Infrastructure
   e. Policy
   f. Other

Recommendations
(All Interviewees)

8. What measures (if any) would you recommend to help increase the use of bio-based fuels in fuel cells?

9. Do you have any specific message(s) you would want to convey to policy makers regarding the integration of bio-based fuels and fuel cell technology?

10. What advice would you have for potential project developers evaluating the feasibility of developing bio-based fuel cell systems?

Outlook
(All Interviewees)

11. In your opinion what is the greatest challenge for the widespread use of bio-based fuels in fuel cells?

12. Which bio-based fuel cell technology do you envision will have the greatest future impact?

13. How do you expect bio-based fuel cell technologies to compete with other fuel cell energy sources in the future?

14. What sort of timeline would you place on the commercialization of fuel cell systems using bio-based feedstocks?

Company and Product Specific
(Manufacturers Only)

15. What type of fuel cell technology does your company utilize?

16. What are the product specifications for your largest-scale stationary fuel cell?
    - Size
    - System efficiency
    - System output
    - Operating time per year
    - Installed system price and operating cost

17. What are the applications for your large-scale stationary fuel cell?
    - Customer Sited Cogeneration
    - Grid Sited
    - Other

18. Where along the commercialization pathway would you classify your product?
    - Research and Development
    - Demonstration – Initial System Prototypes
    - Demonstration – Refined Prototypes
    - Demonstration – Commercial Prototypes
    - Market Entry
    - Market Penetration

19. What fuels work with your fuel processor? Specifically, are bio-based fuels from biogasification, resource recovery, or ethanol compatible with your technology? (Mention specific fuels – biogas from gasification; methane from landfill gas and digesters; ethanol; pyrolysis oil, biodiesel, levulinic acid).

20. (If applicable) Where along the commercialization pathway would you classify your products integration with bio-based fuels?
    - Research and Development
    - Demonstration – Initial System Prototypes
    - Demonstration – Refined Prototypes
    - Demonstration – Commercial Prototypes
    - Market Entry
    - Market Penetration

21. What level of prioritization does your company place on continued research and development to integrate the use of bio-based fuels into your fuel cell technology?
    - None
    - Minimal
    - Moderate
    - High

Case Study
(Case Study Interviewees Only)

22. What was the impetus of the project?

23. What type of fuel cell technology and manufacturer does your company utilize? How did you decide on this?

24. For what do you use electricity generated at your site?

25. What were the major obstacles (expected and unexpected) you encountered during development of the project?

26. How is the project performing? Plans for expansion?