

# **Technology Characterization: Fuel Cells**

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# Technology Characterization – Fuel Cell Systems

## Introduction and Summary

Fuel cell systems employ an entirely different approach to the production of electricity than traditional prime mover technologies. Fuel cells are similar to batteries in that both produce a direct current (DC) through an electrochemical process without direct combustion of a fuel source. However, whereas a battery delivers power from a finite amount of stored energy, fuel cells can operate indefinitely provided the availability of a continuous fuel source. Two electrodes (a cathode and anode) pass charged ions in an electrolyte to generate electricity and heat. A catalyst enhances the process.

Fuel cells offer the potential for clean, quiet, and efficient power generation. Because the fuel is not combusted, but instead reacts electrochemically, there is virtually no air pollution associated with its use. Fuel cells have been under development for over 35 years as the power source of the future. There are now systems that are commercially available. However, fuel cells as a class of technologies face a number of formidable market entry issues resulting from expensive materials, system complexities, low power densities and unproven product durability and reliability. These factors translate into high capital cost, lack of support infrastructure, and technical risk for early adopters. Based on their environmental benefits, high efficiency and virtually no emissions of criteria pollutants, fuel cells are supported by a number of State and Federal incentive programs that help to offset the current cost levels. There is a belief that these incentives will help to promote further development and cost reduction.

The inventor of fuel cell technology is Sir William Grove, who demonstrated a hydrogen fuel cell in London in the 1830s. Grove's technology remained without a practical application for 100 years. Fuel cells returned to the laboratory in the 1950s when the United States space program required the development of new power systems. Today, the topic of fuel cells encompasses a broad range of different technologies, technical issues, and market dynamics that make for a complex but potentially promising outlook. Significant amounts of public and private investment are being applied to the development of fuel cell products for both stationary and transportation applications.

There are five types of fuel cells. These are: 1) phosphoric acid (PAFC), 2) proton exchange membrane (PEMFC), 3) molten carbonate (MCFC), 4) solid oxide (SOFC), and 5) alkaline (AFC). The electrolyte and operating temperatures distinguish each type. Operating temperatures range from near ambient to 1,800°F, and electrical generating efficiencies range from 30 to over 50 percent HHV.<sup>1</sup> As a result, they can have different performance characteristics, advantages and limitations, and therefore will be suited to distributed generation applications in a variety of approaches.

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<sup>1</sup> Most of the efficiencies quoted in this report are based on higher heating value (HHV), which includes the heat of condensation of the water vapor in the products. In engineering and scientific literature the lower heating value (LHV – which does not include the heat of condensation of the water vapor in the products) is often used. The HHV is greater than the LHV by approximately 10% with natural gas as the fuel (i.e., 50% LHV versus 45% HHV).

The different fuel cell types share certain important characteristics. First, fuel cells are not Carnot cycle (thermal energy based) engines. Instead, they use an electrochemical or battery-like process to convert the chemical energy of hydrogen into water and electricity and can achieve high electrical efficiencies. The second shared feature is that they use hydrogen as their fuel, which is typically derived from a hydrocarbon fuel such as natural gas. Most, but not all, fuel cell systems are composed of three primary subsystems: 1) the fuel cell stack that generates direct current electricity; 2) the fuel processor that converts the natural gas into a hydrogen-rich feed stream; and 3) the power conditioner that processes the electric energy into alternating current or regulated direct current. There are a small number of special application fuel cell systems that are designed to operate on stored hydrogen fuel, and fuel cells that are configured to utilize the DC power output directly.

As previously mentioned, all types of fuel cells have low emissions profiles. This is because the only combustion processes are the reforming of natural gas or other fuels to produce hydrogen and the burning of a low energy hydrogen exhaust stream that is used to provide heat to the fuel processor.

In 2007, there are two main fuel cell types that are commercially available for commercial and industrial combined heat and power generation. The 200 kW PAFC unit<sup>2</sup> has been sold commercially (installations in 19 countries) for over 10 years with over 75 MW installed and over 8 million operating hours. More recently, 300 and 1,200 kW MCFC fuel cells have been offered commercially and have been installed in a number of CHP applications.<sup>3</sup> A number of other systems are in development and demonstration phases including 0.5 to 10 kW residential/small commercial PEMFC units, larger commercial and industrial PEMFC units, and SOFC units.<sup>4</sup>

## Applications

Fuel cells are either available or being developed for a number of stationary and vehicle applications. The power applications include commercial and industrial CHP (200-1200 kW), residential and commercial systems for CHP (3-10 kW), back-up and portable power systems (0.5-5 kW). In DG markets, the primary characteristic driving early market acceptance is the ability of fuel cell systems to provide reliable premium power. The primary interest drivers have been their ability to achieve high efficiencies over a broad load profile and low emission signatures without additional controls. **Figure 1** illustrates two actual sites with fuel cell systems functioning in DG applications.

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<sup>2</sup> Sold and fully warranted by UTC Fuel Cells as the PC25.

<sup>3</sup> Fuel Cell Energy, Inc in Danvers, CT offers the 300 kW DFC300MA and the 1,200 kW DFC1500MA with full product support and service.

<sup>4</sup> *Fuel Cells for Power Generation*, U.S. Fuel Cell Council, Washington DC. (provides a list and brief description of companies and products with commercial and developmental systems for the stationary power generation market.

**Figure 1. Commercial Fuel Cells in Distributed Generation Applications**



Source: [www.utcfuelcells.com](http://www.utcfuelcells.com).

### Combined Heat and Power

Due to the high installed cost of fuel cell systems, the most prevalent DG application envisioned by product development leaders is CHP. CHP applications are on-site power generation in combination with the recovery and use of by-product heat. Continuous baseload operation and the effective use of the thermal energy contained in the exhaust gas and cooling subsystems enhance the economics of on-site generation applications.

Heat is generally recovered in the form of hot water or low-pressure steam (<30 psig), but the quality of heat is dependent on the type of fuel cell and its operating temperature. The one exception to this is the PEM fuel cell, which operates at temperatures below 200°F, and therefore has only low quality heat. Generally, the heat recovered from fuel cell CHP systems is appropriate for low temperature process needs, space heating, and potable water heating. In the case of SOFC and MCFC technologies, medium pressure steam (up to about 150 psig) can be generated from the fuel cell's high temperature exhaust gas, but the primary use of this hot exhaust gas is in recuperative heat exchange with the inlet process gases.

The simplest thermal load to supply is hot water. Primary applications for CHP in the commercial/institutional sectors are those building types with relatively high and coincident electric and hot water/space heating demand such as colleges and universities, hospitals and nursing homes, and lodging. Technology developments in heat activated cooling/refrigeration and thermally regenerated desiccants will enhance fuel cell CHP applications by increasing the thermal energy loads in certain building types. Use of these advanced technologies in applications such as restaurants, supermarkets, and refrigerated warehouses provides a base-thermal load that opens these applications to CHP.

### Premium Power

Consumers who require higher levels of reliability or power quality, and are willing to pay for it, often find some form of DG to be advantageous. These consumers are typically less concerned about the initial prices of power generating equipment than other types of consumers. Premium power systems generally supply base load demand. As a result, and in contrast to back-up generators, emissions and efficiency become more significant decision criteria.

Fuel cell systems offer a number of intrinsic features that make them suitable for the premium power market. These market-driving features include low emissions/vibration/noise, high availability, good power quality, and compatibility with zoning restrictions. As emissions become more relevant to a business's bottom line in the form of zoning issues and emissions credits, the fuel cell becomes a more appealing type of DG.

Some types of fuel cell systems have already demonstrated high availability and reliability. As fuel cells further mature in the market, they are expected to achieve the high reliability associated with fewer moving parts.

While the fuel cell requires significant power conditioning equipment in the form of direct current to alternating current conversion, power from fuel cell systems is clean, exhibiting none of the signal disturbances observed from grid sources.

Finally, zoning issues for fuel cell systems are quite possibly the least problematic of all DG systems. Fuel cell systems can be designed for both indoor and outdoor installation, and in close proximity to sensitive environments, people, or animals.

#### Remote Power

In locations where power from the local grid is unavailable or extremely expensive to install, DG is a competitive option. As with premium power, remote power applications are generally base load operations. Consequently, emissions and efficiency become more significant criteria in much of the remote power DG market. Coupled with their other potential advantages, fuel cell systems can provide competitive energy into certain segments of the remote power DG market. Where fuel delivery is problematic, the high efficiency of fuel cell systems can also be a significant advantage.

#### Grid Support

One of the first applications that drew the attention of electric utilities to fuel cell technologies was grid support. Numerous examples of utility-owned and operated distributed generating systems exist in the U.S. and abroad. The primary application in the U.S. has been the use of relatively large diesel or natural gas engines for peaking or intermediate load service at municipal utilities and electric cooperatives. These units provide incremental peaking capacity and grid support for utilities at substations. Such installations can defer the need for T&D system expansion, can provide temporary peaking capacity within constrained areas, or be used for system power factor correction and voltage support, thereby reducing costs for both customers and the utility system. The unique feature of fuel cell systems is the use of power conditioning inverters to transform direct current electricity into alternating current. These power conditioners can be operated almost independent of the fuel cell to correct power factors and harmonic characteristics in support of the grid.

#### Standby Power

Fire and safety codes require standby power systems for hospitals, elevator loads, and water pumping. Standby is an economic choice for customers with high outage costs such as those in

the telecommunications, retail, gaming, banking, and certain process industries. The standby engine-driven generator set is typically the simplest distributed generation system, providing power only when the primary source is out of service or falters in its voltage or frequency. This application requires low capital cost, minimal installation costs, rapid black start capability, onsite fuel storage, and grid-isolated operation. In standby power applications, efficiency, emissions, and variable maintenance costs are usually not major factors in technology selection. Based on this definition of standby power, fuel cells do not appear to have much application. Fuel cell systems are characteristically high in capital cost and do not have rapid black start capability.

### Peak Shaving

In certain areas of the country, customers and utilities are using on-site power generation to reduce the need for costly peak-load power. Peak shaving is also applicable to customers with poor load factor and/or high demand charges. Typically, peak shaving does not involve heat recovery, but heat recovery may be warranted where the peak period is more than 2,000 hours/year. Since low equipment cost and high reliability are the primary requirements, equipment such as reciprocating engines are ideal for many peak-shaving applications. Emissions may be an issue if operating hours are high. Combining peak shaving and another function, such as standby power, enhances the economics. High capital cost and relatively long start-up times (particularly for MCFC and SOFC) will most likely prevent the widespread use of fuel cells in peak shaving applications.

## Technology Description

Fuel cells produce direct current electricity through an electrochemical process, much like a standard battery. Unlike a standard battery, a fuel supply continuously replenishes the fuel cell. The reactants, most typically hydrogen and oxygen gas, are fed into the fuel cell reactor, and power is generated as long as these reactants are supplied. The hydrogen (H<sub>2</sub>) is typically generated from a hydrocarbon fuel such as natural gas or LPG, and the oxygen (O<sub>2</sub>) is from ambient air.

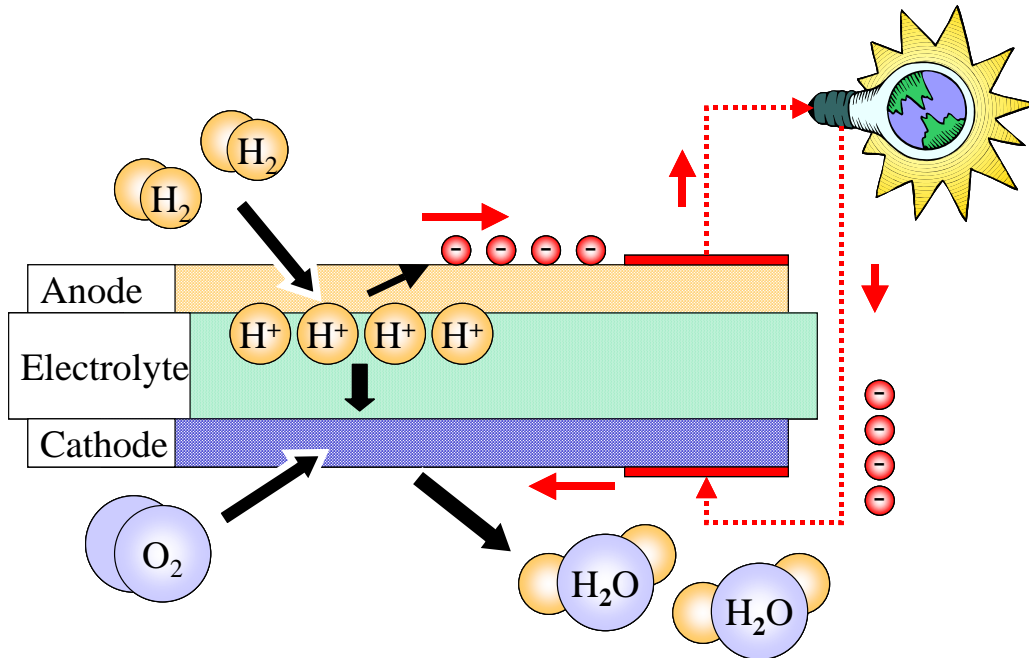
### Basic Processes and Components

Fuel cell systems designed for DG applications are primarily natural gas or LPG fueled systems. Each fuel cell system consists of three primary subsystems: 1) the fuel cell stack that generates direct current electricity; 2) the fuel processor that converts the natural gas into a hydrogen rich feed stream; and 3) the power conditioner that processes the electric energy into alternating current or regulated direct current.

**Figure 2** illustrates the electrochemical process in a typical single cell, acid-type fuel cell. A fuel cell consists of a cathode (positively charged electrode), an anode (negatively charged electrode), an electrolyte and an external load. The anode provides an interface between the fuel and the electrolyte, catalyzes the fuel reaction, and provides a path through which free electrons conduct to the load via the external circuit. The cathode provides an interface between

the oxygen and the electrolyte, catalyzes the oxygen reaction, and provides a path through which free electrons conduct from the load to the oxygen electrode via the external circuit. The electrolyte, an ionic conductive (non-electrically conductive) medium, acts as the separator between hydrogen and oxygen to prevent mixing and the resultant direct combustion. It completes the electrical circuit of transporting ions between the electrodes.

**Figure 2. Fuel Cell Electrochemical Process**



Source: Energy Nexus Group.

The hydrogen and oxygen are fed to the anode and cathode, respectively. The hydrogen and oxygen gases do not directly mix and combustion does not occur. Instead, the hydrogen oxidizes one molecule at a time, in the presence of a catalyst. Because the reaction is controlled at the molecular level, there is no opportunity for the formation of NO<sub>x</sub> and other pollutants.

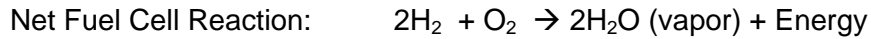
At the anode the hydrogen gas is electrochemically disassociated (in the presence of a catalyst) into hydrogen ions (H<sup>+</sup>) and free electrons (e<sup>-</sup>).



The electrons flow out of the anode through an external electrical circuit. The hydrogen ions flow into the electrolyte layer and eventually to the cathode, driven by both concentration and potential forces. At the cathode the oxygen gas is electrochemically combined (in the presence of a catalyst) with the hydrogen ions and free electrons to generate water.



The overall reaction in a fuel cell is as follows:



The amount of energy released is equal to the difference between the Gibbs free energy of the product and the Gibbs free energy of the reactants.

When generating power, electrons flow through the external circuit, ions flow through the electrolyte layer and chemicals flow into and out of the electrodes. Each process has natural resistances, and overcoming these reduces the operational cell voltage below the theoretical potential. There are also irreversibilities<sup>5</sup> that impact actual open circuit potentials. Therefore, some of the chemical potential energy converts into heat. The electrical power generated by the fuel cell is the product of the current measured in amps and the operational voltage. Based on the application and economics, a typical operating fuel cell will have an operating voltage of between 0.55 volts and 0.80 volts. The ratio of the operating voltage and the theoretical maximum of 1.48 volts represents a simplified estimate of the stack electrical efficiency on a higher heating value (HHV<sup>6</sup>) basis.

As explained, resistance heat is also generated along with the power. Since the electric power is the product of the operating voltage and the current, the quantity of heat that must be removed from the fuel cell is the product of the current and the difference between the theoretical potential and the operating voltage. In most cases, the water produced by the fuel cell reactions exits the fuel cell as vapor, and therefore, the 1.23-volt LHV theoretical potential is used to estimate sensible heat generated by the fuel cell electrochemical process.

The overall electrical efficiency of the cell is the ratio of the power generated and the heating value of the hydrogen consumed. The maximum thermodynamic efficiency of a hydrogen fuel cell is the ratio of the Gibbs free energy and the heating value of the hydrogen. The Gibbs free energy decreases with increasing temperatures, because the product water produced at the elevated temperature of the fuel cell includes the sensible heat of that temperature, and this energy cannot be converted into electricity without the addition of a thermal energy conversion cycle (such as a steam turbine). Therefore, the maximum efficiency of a pure fuel cell system decreases with increasing temperature. **Figure 3** illustrates this characteristic in comparison to the Carnot cycle efficiency limits through a condenser at 50 and 100°C<sup>7</sup>. This characteristic has led system developers to investigate hybrid fuel cell-turbine combined cycle systems to achieve system electrical efficiencies in excess of 70 percent HHV.

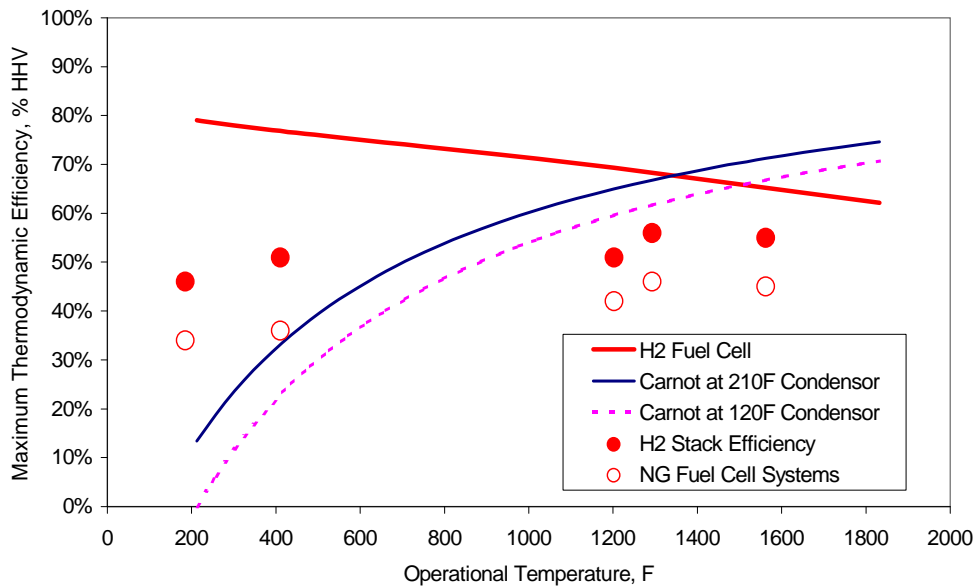
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<sup>5</sup> Irreversibilities are changes in the potential energy of the chemical that are not reversible through the electrochemical process. Typically, some of the potential energy is converted into heat even at open circuit conditions when current is not flowing. A simple example is the resistance to ionic flow through the electrolyte while the fuel cell is operating. This potential energy “loss” is really a conversion to heat energy, which cannot be reconverted into chemical energy directly within the fuel cell.

<sup>6</sup> Most of the efficiencies quoted in this report are based on higher heating value (HHV), which includes the heat of condensation of the water vapor in the products.

<sup>7</sup> Larminie, James and Andrew Dicks, Fuel Cell Systems Explained. John Wiley & Sons, Ltd., West Sussex, England, 2000.

**Figure 3. Effect of Operating Temperature on Fuel Cell Efficiency**



Source: Siemens/Westinghouse Electric Corp.

### Fuel Cell Stacks

Practical fuel cell systems require voltages higher than 0.55 to 0.80. Combining several cells in electrical series into a fuel cell stack achieves this. Typically, there are several hundred cells in a single cell stack. Increasing the active area of individual cells manages current flow. Typically, cell area can range from 100 cm<sup>2</sup> to over 1 m<sup>2</sup> depending on the type of fuel cell and application power requirements.

### Fuel Processors

In distributed generation applications, the most viable fuel cell technologies use natural gas as the system's fuel source. To operate on natural gas or other fuels, fuel cells require a fuel processor or reformer, a device that converts the fuel into the hydrogen-rich gas stream. While adding fuel flexibility to the system, the reformer also adds significant cost and complexity. There are three primary types of reformers: steam reformers, autothermal reformers, and partial oxidation reformers. The fundamental differences are the source of oxygen used to combine with the carbon within the fuel to release the hydrogen gases and the thermal balance of the chemical process. Steam reformers use steam, while partial oxidation units use oxygen gas, and autothermal reformers use both steam and oxygen.

Steam reforming is extremely endothermic and requires a substantial amount of heat input. Autothermal reformers typically operate at or near the thermal neutral point, and therefore, do not generate or consume thermal energy. Partial oxidation units combust a portion of the fuel (i.e. partially oxidize it), releasing heat in the process. When integrated into a fuel cell system that allows the use of anode-off gas, a typical natural gas reformer can achieve conversion efficiencies in the 75 to 90 percent LHV range, with 83 to 85 percent being an expected level of performance. These efficiencies are defined as the LHV of hydrogen generated divided by the LHV of the natural gas consumed by the reformer.

Some fuel cells can function as *internally steam reforming* fuel cells. Since the reformer is an endothermic catalytic converter and the fuel cell is an exothermic catalytic oxidizer, the two combine into one with mutual thermal benefits. More complex than a pure hydrogen fuel cell, these types of fuel cells are more difficult to design and operate. While combining two catalytic processes is difficult to arrange and control, these internally reforming fuel cells are expected to account for a significant market share as fuel cell based DG becomes more common.

### *Power Conditioning Subsystem*

The fuel cell generates direct current electricity, which requires conditioning before serving a DG application. Depending on the cell area and number of cells, this direct current electricity is approximately 200 to 400 volts per stack. If the system is large enough, stacks can operate in series to double or triple individual stack voltages. Since the voltage of each individual cell decreases with increasing load or power, the output is considered an unregulated voltage source. The power conditioning subsystem boosts the output voltage to provide a regulated higher voltage input source to an electronic inverter. The inverter then uses a pulse width modulation technique at high frequencies to generate simulated alternating current output. The inverter controls the frequency of the output, which can be adjusted to enhance power factor characteristics. Because the inverter generates alternating current within itself, the output power is generally clean and reliable. This characteristic is important to sensitive electronic equipment in premium power applications. The efficiency of the power conditioning process is typically 92 to 96 percent, and is dependent on system capacity and input voltage-current characteristic.

### *Types of Fuel Cells*

There are five basic types of fuel cell under consideration for DG applications. The fuel cell's electrolyte or ion conduction material defines the basic type. Two of these fuel cell types, polymer electrolyte membrane (PEM) and phosphoric acid fuel cell (PAFC), have acidic electrolytes and rely on the transport of  $H^+$  ions. Two others, alkaline fuel cell (AFC) and carbonate fuel cell (MCFC), have basic electrolytes that rely on the transport of  $OH^-$  and  $CO_3^{2-}$  ions, respectively. The fifth type, solid oxide fuel cell (SOFC), is based on a solid-state ceramic electrolyte in which oxygen ions ( $O^{2-}$ ) are the conductive transport ion.

Each fuel cell type operates at optimum temperature, which is a balance between the ionic conductivity and component stability. These temperatures differ significantly among the five basic types, ranging from near ambient to as high as 1800°F. The proton conducting fuel cell type generates water at the cathode and the anion conducting fuel cell type generates water at the anode.

**Table 1** below presents fundamental characteristics for each fuel cell type.

**Table 1. Characteristics of Major Fuel Cell Types**

	<b>PEMFC</b>	<b>AFC</b>	<b>PAFC</b>	<b>MCFC</b>	<b>SOFC</b>
<b>Type of Electrolyte</b>	H <sup>+</sup> ions (with anions bound in polymer membrane)	OH <sup>-</sup> ions (typically aqueous KOH solution)	H <sup>+</sup> ions (H <sub>3</sub> PO <sub>4</sub> solutions)	CO <sub>3</sub> <sup>=</sup> ions (typically, molten LiKaCO <sub>3</sub> eutectics)	O <sup>=</sup> ions (Stabilized ceramic matrix with free oxide ions)
<b>Typical construction</b>	Plastic, metal or carbon	Plastic, metal	Carbon, porous ceramics	High temp metals, porous ceramic	Ceramic, high temp metals
<b>Internal reforming</b>	No	No	No	Yes, Good Temp Match	Yes, Good Temp Match
<b>Oxidant</b>	Air to O <sub>2</sub>	Purified Air to O <sub>2</sub>	Air to Enriched Air	Air	Air
<b>Operational Temperature</b>	150- 180°F (65-85°C)	190-500°F (90-260°C)	370-410°F (190-210°C)	1200-1300°F (650-700°C)	1350-1850°F (750-1000°C)
<b>DG System Level Efficiency, percent HHV</b>	25 to 35%	32 to 40%	35 to 45%	40 to 50%	45 to 55%
<b>Primary Contaminate Sensitivities</b>	CO, Sulfur, and NH <sub>3</sub>	CO, CO <sub>2</sub> , and Sulfur	CO < 1%, Sulfur	Sulfur	Sulfur

Source: Energy Nexus Group

*PEMFC (Proton Exchange Membrane Fuel Cell or Polymer Electrolyte Membrane)*

NASA developed this type of fuel cell in the 1960s for the first manned spacecraft. The PEMFC uses a solid polymer electrolyte and operates at low temperatures (about 200°F). Over the past ten years, the PEMFC has received significant media coverage due to the large auto industry investment in the technology. Due to their modularity and potential for simple manufacturing, reformer/PEMFC systems for residential DG applications have attracted considerable development capital. PEMFC's have high power density and can vary their output quickly to meet demand. This type of fuel cell is highly sensitive to CO poisoning.

*AFC (Alkaline Fuel Cell)*

F.T. Bacon in Cambridge, England first demonstrated AFC as a viable power unit during the 1940s and 1950s. NASA later developed and used this fuel cell on the Apollo spacecraft and on the space shuttles. AFC technology uses alkaline potassium hydroxide as the electrolyte. The primary advantages of AFC technology are improved performance (electrical efficiencies above 60 percent HHV), use of non-precious metal electrodes, and the fact that no unusual materials are needed. The primary disadvantage is the tendency to absorb carbon dioxide, converting the alkaline electrolyte to an aqueous carbonate electrolyte that is less conductive. The attractiveness of AFC has declined substantially with the interest and improvements in PEMFC technology.

*PAFC (Phosphoric Acid Fuel Cell)*

PAFC uses phosphoric acid as the electrolyte and is generally considered the most established

fuel cell technology. The first PAFC DG system was designed and demonstrated in the early 1970s. PAFCs are capable of fuel-to-electricity efficiencies of 36 percent HHV or greater. A 200 kW PAFC has been commercially available since the early 1990s. About 370 of these commercial units were manufactured, delivered, and are operating in the U.S., Europe, and Japan. The current 200 kW product has a stack lifetime of over 40,000 hours and commercially based reliabilities in the 90 to 95 percent range. The major market barrier has been the high initial cost.

#### *MCFC (Molten Carbonate Fuel Cell)*

The MCFC uses an alkali metal carbonate (Li, Na, K) as the electrolyte and has a developmental history that dates back to the early part of the twentieth century. Due to its operating temperature range of 1,100 to 1,400°F, the MCFC holds promise in both CHP and DG applications. This type of fuel cell can be internally reformed, can operate at high efficiencies (50 percent HHV), and is relatively tolerant of fuel impurities. Government/industry R&D programs during the 1980s and 1990s resulted in several individual pre-prototype system demonstrations. As previously indicated, one manufacturer sells and supports commercial systems in 300 kW and 1200 kW sizes.

#### *SOFC (Solid Oxide Fuel Cell)*

The SOFC uses solid, nonporous metals oxide electrolytes and is generally considered less mature in its development than the MCFC and PAFC technologies. Several SOFC units up to 100 kW in size and based on a concentric tubular design have been built and tested.<sup>8</sup> In addition, there are many companies developing planar SOFC designs, which offer higher power densities and lower costs than the tubular design, but these have yet to achieve the reliability of the tubular design. Despite relative immaturity, the SOFC has several advantages (high efficiency, stability and reliability, and high internal temperatures) that have attracted development support. The SOFC has projected service electric efficiencies of 45 to 60 percent and higher, for larger hybrid, combined cycle plants. Efficiencies for smaller SOFC DG units are expected to be in the 50 percent range.

Stability and reliability of the SOFC are due to an all-solid-state ceramic construction. Test units have operated in excess of 10 years with acceptable performance. The high internal temperatures of the SOFC are both an asset and a liability. As an asset, high temperatures make internal reforming possible. As a liability, these high temperatures add to materials and mechanical design difficulties, which reduces stack life and increases cost. While SOFC research has been ongoing for 30 years, costs of these stacks are still comparatively high.

One manufacturer is preparing to enter the market with a 125 kW CHP system.<sup>9</sup>

#### Design Characteristics

The features that have the potential to make fuel cell systems a leading prime mover for CHP and other distributed generation applications include:

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<sup>8</sup> By Siemens/Westinghouse Electric Corp.

<sup>9</sup> The SFC-200 fuel cell producing 125 KW of electricity and 100 kW of thermal energy is listed by Siemens Westinghouse as a *pre-commercial* product.

Size Range:	Fuel cell systems are constructed from individual cells that generate 100 W to 2 kW per cell. This allows systems to have extreme flexibility in capacity. Systems under development for DG application range in sizes from 5 kW to 2 MW. Multiple systems can operate in parallel at a single site to provide incremental capacity.
Thermal output:	Fuel cells can achieve overall efficiencies in the 65 to 85 percent range. Waste heat can be used primarily for domestic hot water applications and space heating.
Availability:	The commercially available 200 kW PC25 system fleet (370 plus units) has demonstrated greater than 90 percent availability during over eight million operating hours.
Part-load operation:	Fuel cell stack efficiency improves at lower loads, which results in a system electric efficiency that is relatively steady down to one-third to one-quarter of rated capacity. This provides systems with excellent load following characteristics.
Cycling:	While part-load efficiencies of fuel cells are generally high, MCFC and SOFC fuel cells require long heat-up and cool-down periods, restricting their ability to operate in many cyclic applications.
High quality power:	Electrical output is computer grade power, meeting critical power requirements without interruption. This minimizes lost productivity, lost revenues, product loss, or opportunity cost.
Reliability and life:	While the systems have few moving parts, stack assemblies are complex and have had problems with seals and electrical shorting. Recommended stack rebuilds required every 5-7 years are expensive.
Emissions:	The only combustion within a fuel cell system is the low energy content hydrogen stream exhausted from the stack. This stream is combusted within the reformer and can achieve emissions signatures of < 2 ppmv CO, <1 ppmv NOx and negligible SOx (on 15 percent O <sub>2</sub> , dry basis).
Efficiency:	Different types of fuel cells have varied efficiencies. Depending on the type and design of fuel cells, electric efficiency ranges from 30 percent to close to 50 percent HHV.
Quiet Operation:	Conversational level (60dBA @ 30 ft.), acceptable for indoor installation.
Siting and Size:	Indoor or outdoor installation with enclosure.

Fuel Use: The primary fuel source for the fuel cell is hydrogen, which can be obtained from natural gas, coal gas, methanol, and other fuels containing hydrocarbons.

## Performance Characteristics

Fuel cell performance is a function of the type of fuel cell and its capacity. Since the fuel cell system is a series of chemical, electrochemical, and electronic subsystems, the optimization of electric efficiency and performance characteristics can be a challenging engineering task. The electric efficiency calculation example provided in the next section illustrates this.

**Table 2** summarizes performance characteristics for representative commercially available and developmental natural gas fuel cell CHP systems over the 10 kW to 2 MW size range. This size range covers the majority of the market applications currently envisioned for fuel cell CHP and represents the most likely units to be commercially introduced within the next five years. Of the systems included in **Table 2**, only the PAFC and MCFC products are commercially available as of 2007. The other systems are in various phases of prototype or pre-commercial demonstration. Estimated performance is shown for developing systems, but costs not included.

**Table 2. Fuel Cell CHP - Typical Performance Parameters**

Cost and Performance Characteristics <sup>10</sup>	System 1	System 2	System 3	System 4	System 5	System 6
Fuel Cell Type	PAFC	PEM	PEM	MCFC	MCFC	SOFC
Nominal Electricity Capacity (kW)	200	10	200	300	1200	125
Commercial Status 2007 <sup>11</sup>	Com'l	Demo	Demo	Com'l	Com'l	Demo
Operating Temperature (° F)	400	150	150	1200	1200	1750
Package Cost (2007 \$/kW) <sup>12</sup>	4,500	8,000	n.a.	4,000	3,870	n.a.
Total Installed Cost (2007 \$/kW) <sup>13</sup>	6,310	9,100	n.a.	5,580	5,250	n.a.
O&M Costs (2007 \$/kW) <sup>14</sup>	0.038	n.a.	n.a.	0.035	0.032	n.a.
Electric Heat Rate (Btu/kWh) <sup>15</sup>	9,480	11,370	9,750	8,022	8,022	8,024
Electrical Efficiency (percent HHV) <sup>16</sup>	33%	30%	35%	43%	43%	43%
Fuel Input (MMBtu/hr)	1.9	0.1	2	2.4	9.6	1.00
<b>CHP Characteristics</b>						
Heat Avail. >160° F ( MMBtu/hr)	0.375	0	0	n.a.	n.a.	n.a.
Heat Avail. <160° F (MMBtu/hr)	0.475	0.04	0.72	0.48	1.9	0.34
Heat Output (MMBtu/hr)	0.850	0.04	0.72	0.48	1.90	0.34
Heat Output (kW equivalent)	249.0	11.7	211.0	140.6	556.7	100.0
Total CHP Efficiency (percent), HHV <sup>17</sup>	81%	65%	72%	62%	62%	77%
Power/Heat Ratio <sup>18</sup>	0.80	0.85	0.95	2.13	2.16	1.25
Net Heat Rate (Btu/kWh) <sup>19</sup>	4,168	6,370	5,250	6,022	6,043	4,611
Effective Electrical Eff (percent), HHV	81.90%	53.58%	65.01%	56.67%	56.48%	74.02%

Source: EEA/ICF

<sup>10</sup> Data are representative typical values for developmental systems based on available information from fuel cell system developers. PAFC estimate based on UTC *PC25*, MCFC systems based on Fuel Cell Energy *DFC300MA* and *DFC1500MA*, the small and large PEMFC estimates represent a fusion of a variety of developmental projects, the SOFC system is based on the Siemens Westinghouse pre-commercial *SFC-200*.

<sup>11</sup> Com'l = Commercially Available; Demo = Multiple non-commercial demonstrations completed or underway in field sites with potential customers; Lab = Characteristics observed in laboratory validation testing of complete systems; Exp = Only experimental prototypes have been tested.

<sup>12</sup> Packaged Cost includes estimates of typical costs for a CHP compatible system with grid interconnection functionality built into power conditioning subsystem.

<sup>13</sup> Total Installed Cost include estimates for packaged cost plus electrical isolation equipment, hot water CHP interconnections, site labor and preparation, construction management, engineering, contingency, and interest during construction. See Table 3.

<sup>14</sup> O&M costs are estimated based on service contract nominal rate, consumables, fixed costs, and sinking fund for stack replacement at end of life. See Table 4.

<sup>15</sup> All equipment manufacturers quote heat rates in terms of the lower heating value (LHV) of the fuel. On the other hand, the usable energy content of fuels is typically measured on a higher heating value (HHV) basis. In addition, electric utilities measure power plant heat rates in terms of HHV. For natural gas, the average heat content of natural gas is 1,030 Btu/scf on an HHV basis and 930 Btu/scf on an LHV basis – or about a 10% difference.

<sup>16</sup> Electrical efficiencies are net of parasitic and conversion losses.

<sup>17</sup> Total Efficiency = (net electric generated + net heat produced for thermal needs)/total system fuel input

<sup>18</sup> Power/Heat Ratio = CHP electrical power output (Btu)/ useful heat output (Btu)

<sup>19</sup> Effective Electrical Efficiency = (CHP electric power output)/(Total fuel into CHP system – total heat recovered/0.8). Equivalent to 3,412 Btu/kWh/Net Heat Rate and Net Heat Rate = 3412/Effective Elec Eff.

Heat rates and efficiencies shown were taken from manufacturers' specifications and industry publications or are based on the best available data for developing technologies. Available thermal energy was calculated from estimated overall efficiency for these systems. CHP thermal recovery estimates are based on producing low quality heat for domestic hot water process or space heating needs. This feature is generally acceptable for commercial/institutional applications where it is more common to have hot water thermal loads.

The data in the table show that electrical efficiency increases as the operating temperature of the fuel cell increases. Also illustrated is an increase as system size becomes larger. As electrical efficiency increases, the absolute quantity of thermal energy available to produce useful thermal energy decreases per unit of power output, and the ratio of power to heat for the CHP system generally increases. A changing ratio of power to heat impacts project economics and may affect the decisions that customers make in terms of CHP acceptance, sizing, and the desirability of selling power.

### Electrical Efficiency

As with all generation technologies, the electrical efficiency is the ratio of the power generated and the heating value of the fuel consumed. Because the fuel cell system has several subsystems in series, the electrical efficiency of the DG unit is the multiple of the efficiencies of the individual section. The concept of stack electric efficiency was introduced earlier. The electric efficiency of a fuel cell system is calculated as follows:

$$\text{ElecEff} = (\text{FPS Eff} * \text{H2 Utilization} * \text{Stack Eff} * \text{PC Eff}) * (\text{HHV/LHV ratio of the fuel})$$

Where:

FPS Eff	= Fuel Processing Subsystem Efficiency, LLV = (LHV of H2 Generated/LHV of Fuel Consumed)
H2 Utilization	= percent of H2 actually consumed in the stack
Stack Eff	= (Operating Voltage/Energy Potential ~1.23 volts)
PC Eff	= AC power delivered/(dc power generated) (auxiliary loads are assumed dc loads here)

For example: PAFC = (84 percent FPS)\*(83 percent util)\*(0.75V/1.25V)\*(95 percent PC)\*(0.9HHV/LHV) = 36 percent electric efficiency HHV

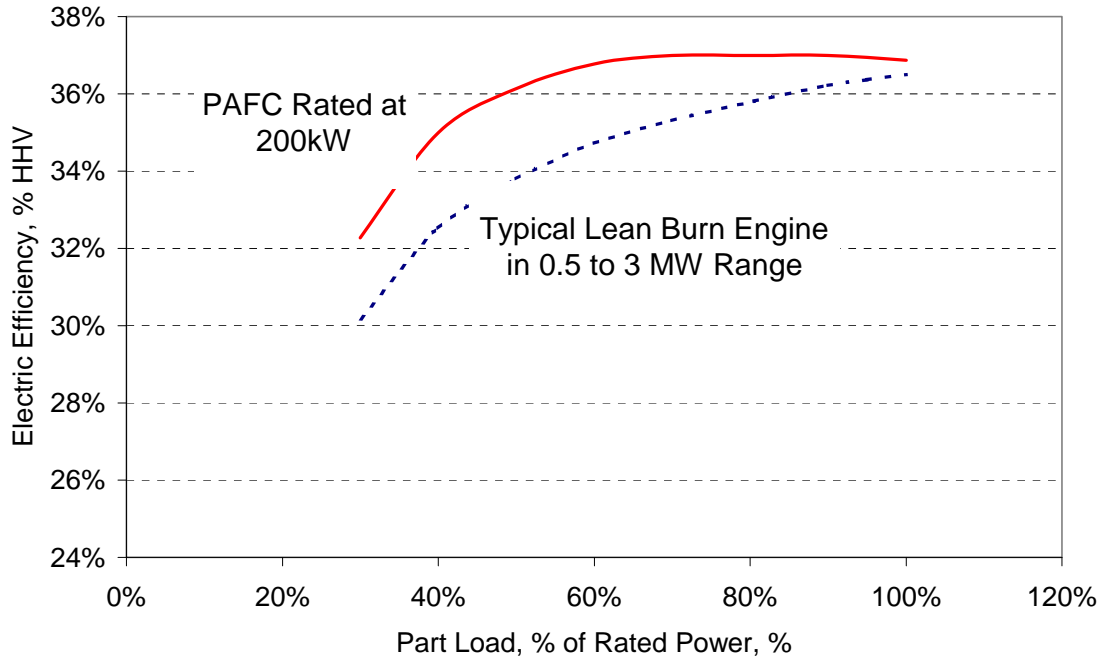
As the operating temperature range of the fuel cell system increases, the electric efficiency of the systems tends to increase. Although the maximum thermodynamic efficiency decreases as shown in **Figure 3**, improvements in reformer subsystem integration and increases in reactant activity balance out to provide the system level increase. Advanced high temperature MCFC and SOFC systems are projected to achieve simple cycle efficiencies in the range of 50 to 55 percent HHV, while hybrid combined fuel cell-heat engine systems are calculated to achieve efficiencies above 60 percent in DG applications.

### Part Load Performance

In power generation and CHP applications, fuel cell systems are expected to follow either the electric or thermal load of the applications to maximize DG energy economics. **Figure 4** shows the part load efficiency curve for a market entry PAFC fuel cell in comparison to a typical lean burn natural gas engine. The efficiency at 50 percent load is within 2 percent of its full load efficiency characteristic. As the load decreases further, the curve becomes somewhat steeper,

as inefficiencies in air blowers and the fuel processor begin to override the stack efficiency improvement.

**Figure 4. Comparison of Part Load Efficiency Derate**



Source: Gas Research Institute, Caterpillar, and Energy Nexus Group.

#### Effects of Ambient Conditions on Performance

Fuel cells are generally rated at ISO conditions of 77° F and 0.987 atmospheres (1 bar) pressure. Fuel cell system performance – both output and efficiency – can degrade as ambient temperature or site elevation increases. This degradation in performance is related to ancillary equipment performance, primarily the air handling blowers or compressors. Performance degradations will be greater for pressurized systems operating with turbo-chargers or small air compressors as their primary air supply components.

#### Heat Recovery

The economics of fuel cells in on-site power generation applications depend less on effective use of the thermal energy recovered than is the case with lower efficiency prime movers, but thermal load displacements can improve operating economics as in any CHP application. Generally, 25 percent of the inlet fuel energy is recoverable from higher quality heat from the stack and reformer subsystems, and another 25 percent is contained in the exhaust gases that include the latent heat of the product water generated in the fuel cell. The most common use of this heat is to generate hot water or low-pressure steam for process use or for space heating, process needs, or domestic hot water.

Heat can generally be recovered in the form of hot water or low-pressure steam (< 30 psig), but the quality of heat is very dependent on the type of fuel cell and its operating temperature. The one exception to this is the PEM fuel cell, which operates at temperatures below 100° C, and therefore has only low quality heat.

As an example, there are four primary potential sources of usable waste heat from a fuel cell system: exhaust gas including water condensation, stack cooling, anode-off gas combustion, and reformer heat. The PAFC system achieves 36 percent electric efficiency and 72 percent overall CHP efficiency, which means that it has a 36 percent thermal efficiency or power to heat ratio of one. Of the available heat, 25 to 45 percent is recovered from the stack-cooling loop that operates at approximately 400° F and can deliver low- to medium-pressure steam. The balance of heat is derived from the exhaust gas-cooling loop that serves two functions. The first is condensation of product water, thus rendering the system water self-sufficient, and the second is the recovery of by-product heat. Since its primary function is water recovery, the balance of the heat available from the PAFC fuel cell is recoverable with 120° F return and 300° F supply temperatures. This tends to limit the application of this heat to domestic hot water applications. The other aspect to note is that all of the available anode-off gas heat and internal reformer heat is used internally to maximize system efficiency.

In the case of SOFC and MCFC fuel cells, medium-pressure steam (up to about 150 psig) can be generated from the fuel cell's high temperature exhaust gas, but the primary use of these hot exhaust gas is in recuperative heat exchange with the inlet process gases. Like engine and turbine systems, the fuel cell exhaust gas can be used directly for process drying.

#### Performance and Efficiency Enhancements

Air is fed to the cathode side of the fuel cell stack to provide the oxygen needed for the power generation process. Typically, 50 to 100 percent more air is passed through the cathode than is required for the fuel cell reactions. The fuel cell can be operated at near-ambient pressure, or at elevated pressures to enhance stack performance. Increasing the pressure, and therefore the partial pressure of the reactants, increases stack performance by reducing the electrode over potentials associated with moving the reactants into the electrodes where the catalytic reaction occurs. It also improves the performance of the catalyst. These improvements appear to optimize at approximately three atmospheres pressure if optimistic compressor characteristics are assumed.<sup>20</sup> More realistic assumptions often result in optimizations at ambient pressure where the least energy is expended on air movement. Because of these characteristics, developers appear to be focused on both pressurized and ambient pressure systems.

#### Capital Cost

This section provides estimates for the installed cost of fuel cell systems designed for CHP applications. Capital costs (equipment and installation) are estimated in **Table 3** for four of the six typical fuel cell systems presented in **Table 1**. Estimates are “typical” budgetary price levels. Installed costs can vary significantly depending on the scope of the plant equipment, geographical area, competitive market conditions, special site requirements, prevailing labor rates, and whether the system is a new or retrofit application.

Costs for the three commercial systems are based on developer estimates and project filings under the California Self Generation Incentive Program. The cost estimate for the small PEMFC system is based on a published assessment of available systems.<sup>21</sup>

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<sup>20</sup> Ibid., p. 90.

<sup>21</sup> “Status of Fuel Cell Technology for Distributed and Portable Power Generation,” Breakthrough Technologies, Inc., [www.fuelcells.org](http://www.fuelcells.org).

**Table 3. Estimated Capital Cost for Typical Fuel Cell Systems in Grid Interconnected CHP Applications (2007 \$/kW)\***

<b>Installed Cost Components</b>	<b>System 1</b>	<b>System 2</b>	<b>System 4</b>	<b>System 5</b>
Fuel Cell Type	PAFC	PEM	MCFC	MCFC
Nominal Capacity (kW)	200	10	300	1200
Equipment				
Fuel Cell Package	\$4,500	\$8,000	\$4,000	\$3,870
Heat Recovery and other equipment	\$80	\$0	\$60	\$30
Interconnect/Electrical	\$150	\$500	\$120	\$40
Total Equipment	\$4,730	\$8,500	\$4,180	\$3,930
	\$0	\$0	\$0	\$0
Labor/Materials	\$330	\$600	\$290	\$280
Total Process Capital	\$5,060	\$9,100	\$4,470	\$4,210
Project and Construction Management	\$710		\$630	\$590
Engineering and Fees	\$240		\$210	\$200
Project Contingency	\$240		\$210	\$200
Project Financing (interest during construction)	\$70		\$60	\$60
Total Plant Cost \$/kW	\$6,310	\$9,100	\$5,580	\$5,250

\* Estimated capital costs for current technology fuel cell systems in the 2007 timeframe.

Source: EEA/ICF

### Maintenance

Maintenance costs for fuel cell systems will vary with type of fuel cell, size and maturity of the equipment. Some of the typical costs that need to be included are:

- Maintenance labor
- Ancillary replacement parts and material such as air and fuel filters, reformer igniter or spark plug, water treatment beds, flange gaskets, valves, electronic components, etc., and consumables such as sulfur adsorbent bed catalysts and nitrogen for shutdown purging.
- Major overhauls include shift catalyst replacement (3 to 5 years), reformer catalyst replacement (5 years), and stack replacement (4 to 8 years).

Maintenance can either be performed by in-house personnel or contracted out to manufacturers, distributors or dealers under service contracts. Details of full maintenance contracts (covering all recommended service) and costing are not generally available, but are estimated at 0.7 to 2.0 cents/kWh excluding the stack replacement cost sinking fund. Maintenance for initial commercial fuel cells has included remote monitoring of system performance and conditions and an allowance for predictive maintenance. Recommended service is comprised of routine short interval inspections/adjustments and periodic replacement of filters (projected at intervals of 2,000 to 4,000 hours).

Maintenance costs are estimated in **Table 4** for the three commercial systems.

**Table 4. Estimated Operating and Maintenance Costs Of Typical CHP Fuel Cell Systems\***

O&M Cost Analysis <sup>22</sup>	System 1	System 4	System 5
Nominal Capacity (kW)	200	300	1200
Fuel Cell Type	PAFC	MCFC	MCFC
Net O&M cost (2007 \$/kWh)	0.038	0.035	0.032

\* Estimated costs for current technology fuel cell systems in the 2003/04 timeframe

Source: EEA/ICF

## Fuels

Since the primary fuel source for the fuel cell is hydrogen produced from hydrocarbon fuels, fuel cell systems can be designed to operate on a variety of alternative gaseous fuels including:

- Liquefied petroleum gas (LPG) – propane and butane mixtures
- Sour gas - unprocessed natural gas as it comes directly from the gas well
- Biogas – any of the combustible gases produced from biological degradation of organic wastes, such as landfill gas, sewage digester gas, and animal waste digester gas
- Industrial waste gases – flare gases and process off-gases from refineries, chemical plants and steel mill
- Manufactured gases – typically low- and medium-Btu gas produced as products of gasification or pyrolysis processes.

Factors that impact the operation of a fuel cell system with alternative gaseous fuels include:

- Volumetric heating value – Since fuel is initially reformed by the fuel cell's fuel processing subsystem, the lower energy content fuels will simply result in a less concentrated hydrogen-rich gas stream feeding the anode. This will cause some loss in stack performance, which can affect the stack efficiency, stack capacity or both. Increased pressure drops through various flow passages can also decrease the fine balance developed in fully integrated systems.
- Contaminants are the major concern when operating on alternative gaseous fuels. If any additional sulfur and other components (e.g., chlorides) can be removed prior to entering the fuel processing catalyst, there should be no performance or life impact. If not, the

<sup>22</sup> Maintenance costs presented in **Table 4** are based on 8,000 operating hours expressed in terms of annual electricity generation. Fixed costs are based on an interpolation of engine manufacturers' estimates and applied to fuel cell system. The variable component of the O&M cost represents the inspections and minor procedures that are normally conducted by the original equipment manufacturer through a service agreement, and have been estimated based on 60% of reciprocating engine service contracts. Major overhaul procedures primarily representing stack replacements have been handled as a separate item.

compounds can cause decreased fuel processor catalyst life and potentially impact stack life.

### Availability

Although fuel cell systems are generally perceived as low maintenance devices, their technical immaturity and market entry status cause concern in DG applications. Close attention has been given to the availability of the initial fleet of over 200 commercial PAFC fuel cell units. In a recent 12-month period, the fleet of units in North America has been recorded as achieving 89 percent availability, with 94 percent during the last 30 days of the time period. In premium power applications, 100 percent customer power availability, and 96.3 percent fleet availability has been reported during the same time period.<sup>23</sup> This performance is a preliminary indicator that fuel cells can provide high levels of availability, even in high load factor applications.

The use of multiple units at a site can further increase the availability of the overall facility. Analysis conducted during the fuel cell field demonstration programs of the 1980s indicated that three to five units sized to 120 percent of application load, operating in parallel, could provide 99.99 percent -plus availabilities under typical commercial building load profile characteristics.

## Emissions

As the primary power generation process in fuel cell systems does not involve combustion, very few emissions are generated. In fact, the fuel processing subsystem is the only source of emissions. The anode-off gas that typically consists of 8 to 15 percent hydrogen is combusted in a catalytic or surface burner element to provide heat to the reforming process. The temperature of this very lean combustion can be maintained at less than 1,800° F, which also prevents the formation of oxides of nitrogen (NO<sub>x</sub>) but is sufficiently high to ensure oxidation of carbon monoxide (CO) and volatile organic compounds (VOCs – unburned, non-methane hydrocarbons). Other pollutants such as oxides of sulfur (SO<sub>x</sub>) are eliminated because they are typically removed in an absorbed bed before the fuel is processed.

### Nitrogen Oxides (NO<sub>x</sub>)

NO<sub>x</sub> is formed by three mechanisms: thermal NO<sub>x</sub>, prompt NO<sub>x</sub>, and fuel-bound NO<sub>x</sub>. Thermal NO<sub>x</sub> is the fixation of atmospheric oxygen and nitrogen, which occurs at high combustion temperatures. Flame temperature and residence time are the primary variables that affect thermal NO<sub>x</sub> levels. The rate of thermal NO<sub>x</sub> formation increases rapidly with flame temperature. Prompt NO<sub>x</sub> is formed from early reactions of nitrogen molecules in the combustion air and hydrocarbon radicals from the fuel. It forms within the flame and typically is on the order of 1 ppm at 15 percent O<sub>2</sub>, and is usually much smaller than the thermal NO<sub>x</sub> formation. Fuel-bound NO<sub>x</sub> forms when the fuel contains nitrogen as part of the hydrocarbon structure. Natural gas has negligible chemically bound fuel nitrogen. Fuel-bound NO<sub>x</sub> can be at significant levels with liquid fuels.

### Carbon Monoxide (CO)

CO and VOCs both result from incomplete combustion. CO emissions result when there is inadequate oxygen or insufficient residence time at high temperature. Cooling at the combustion

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<sup>23</sup> According to manufacturer United Technology Corporation ([www.UTCFuelCells.com](http://www.UTCFuelCells.com), 3/28/02).

chamber walls and reaction quenching in the exhaust process also contribute to incomplete combustion and increased CO emissions. Excessively lean conditions can lead to incomplete and unstable combustion and high CO levels.

#### Unburned Hydrocarbons

Volatile hydrocarbons, also called volatile organic compounds (VOCs), can encompass a wide range of compounds, some of which are hazardous air pollutants. These compounds are discharged into the atmosphere when some portion of the fuel remains unburned or just partially burned. Some organics are carried over as unreacted trace constituents of the fuel, while others may be pyrolysis products of the heavier hydrocarbons in the gas. Volatile hydrocarbon emissions from reciprocating engines are normally reported as non-methane hydrocarbons (NMHCs). Methane is not a significant precursor to ozone creation and smog formation and is not currently regulated. Methane is a green house gas and may come under future regulations.

#### Carbon Dioxide (CO<sub>2</sub>)

While not considered a pollutant in the ordinary sense of directly affecting health, emissions of carbon dioxide (CO<sub>2</sub>) are of concern due to its contribution to global warming. Atmospheric warming occurs since solar radiation readily penetrates to the surface of the planet but infrared (thermal) radiation from the surface is absorbed by the CO<sub>2</sub> (and other polyatomic gases such as methane, unburned hydrocarbons, refrigerants and volatile chemicals) in the atmosphere, with resultant increase in temperature of the atmosphere. The amount of CO<sub>2</sub> emitted is a function of both fuel carbon content and system efficiency. The fuel carbon content of natural gas is 34 lbs carbon/MMBtu; oil is 48 lbs carbon/MMBtu; and (ash-free) coal is 66 lbs carbon/MMBtu.

#### Fuel Cell Emissions Characteristics

**Table 5** illustrates the emission characteristics of fuel cell system. Fuel cell systems do not require any emissions control devices to meet current and projected regulations.

**Table 5. Estimated Fuel Cell Emission Characteristics without Additional Controls\***

<b>Emissions Analysis<sup>24</sup></b>	<b>System 1</b>	<b>System 2</b>	<b>System 3</b>	<b>System 4</b>	<b>System 5</b>	<b>System 6</b>
Electricity Capacity (kW)	200	10	200	300	1200	100
Electrical Efficiency (HHV)	33%	30%	35%	43%	43%	43%
Fuel Cell Type	PAFC	PEM	PEM	MCFC	MCFC	SOFC
<b>Emissions</b>						
NOx, (lb/MWh)	0.035	0.06	0.06	0.02	0.02	0.05
CO, (lb/MWh)	0.042	0.07	0.07	0.10	0.10	0.04
VOC, (lb/MWh)	0.012	0.01	0.01	0.01	0.01	0.01
CO2, (lb/MWh)	0.035	0.06	0.06	0.02	0.02	0.05

\* *Electric only, for typical systems available or under development in 2007. Estimates are based on fuel cell system developers' goals and prototype characteristics. All estimates are for emissions without after-treatment and are adjusted to 15 percent O<sub>2</sub>.*

Source: Energy Nexus Group

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<sup>24</sup> Emissions estimates are based on best available data from manufacturers and customer data. Emission expressed in lb/MWh are for electric only performance and do not credit emissions for CHP operations. Typically CHP emissions are calculated by Emissions = (lb emissions/(MWh of Elec generated + (MWh of Heat Recovered/80% Boiler eff)\*(ratio of Boiler Regulations/Electric Regulations both in lb/MWh equivalent))) and then compared to the Electric Only Regulations.