Catalog of CHP Technologies

Section 6. Technology Characterization – Fuel Cells

**U.S. Environmental Protection Agency
Combined Heat and Power Partnership**

March 2015

Disclaimer

The information contained in this document is for information purposes only and is gathered from published industry sources. Information about costs, maintenance, operations, or any other performance criteria is by no means representative of EPA, ORNL, or ICF policies, definitions, or determinations for regulatory or compliance purposes.

The September 2017 revision incorporated a new section on packaged CHP systems (Section 7).

Section 6.   Technology Characterization – Fuel Cells

6.1   Introduction

Fuel cell systems employ an entirely different approach to the production of electricity than traditional combustion based prime mover technologies. Fuel cells are similar to batteries in that they 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 minimal air pollution associated with its use. Fuel cells have been under development for over 40 years as an emerging power source however, fuels cells of many different sizes are commercially available now. 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 tax incentive programs that help to offset the overall system costs. These incentives have been designed to promote continued fuel cell development, cost reductions, and overall market deployment.

The inventor of fuel cell technology was Sir William Grove, who demonstrated a hydrogen fuel cell in London in the 1830s. Grove's technology remained without a practical application for over 100 years. Fuel cells returned to the laboratory in the 1950s when the United States space program required the development of new power systems with low to no air emissions. Today, the topic of fuel cells encompasses a broad range of different technologies, technical issues, and market dynamics that make for a complex but promising outlook. Significant public and private investment are being applied to the development of fuel cell products for both stationary and transportation applications.

There are four primary types of fuel cells that are used for stationary combined heat and power (CHP) applications. These include: 1) phosphoric acid (PAFC), 2) molten carbonate (MCFC), 3) solid oxide (SOFC), and 4) proton exchange membrane (PEMFC). Two additional primary fuel cell types - direct methanol (DMFC) and alkaline (AFC) - are used primarily in transportation and non-stationary fuel cell applications, in addition to PEMFC.

The electrolyte and operating temperatures vary for each of the fuel cell types. Operating temperatures range from near-ambient to 1,800°F, and electrical generating efficiencies range from 30 percent to over 50 percent on a Higher Heating Value (HHV) basis. As a result, fuel cells can have different performance characteristics, advantages, and limitations, which can be suited to distributed generation applications in a variety of approaches. **Table 6-1** provides a summary of the primary advantages and disadvantages of the various types of fuel cells.

Table 6-1. Comparison of Fuel Cell Applications, Advantages, and Disadvantages

	Applications	Advantages	Disadvantages
Alkaline (AFC)	• Military • Space	• Cathode reaction faster in alkaline electrolyte, leads to high performance • Low cost components	• Sensitive to CO_2 in fuel and air • Electrolyte management
Direct Methanol (DMFC)	• Backup power • Portable power • Military	• No need for reformer (catalyst separates H2 from liquid methanol) • Low temperature	• Expensive catalysts • Low temperature waste heat
Phosphoric Acid (PAFC)	• Auxiliary power • Electric utility • Distributed generation	• Higher temperature enables CHP • Increased tolerance to fuel impurities	• Platinum catalyst • Startup time • Low current and power
Proton Exchange Membrane (PEMFC)	• Backup power • Portable power • Distributed generation • Transportation • Specialty vehicles	• Solid electrolyte reduces corrosion & electrolyte management problems • Low temperature • Quick startup	• Expensive catalysts • Sensitive to fuel impurities • Low temperature waste heat
Molten Carbonate (MCFC)	• Auxiliary power • Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Suitable for CHP	• High temperature corrosion and breakdown • Long startup time • Low power density
Solid Oxide (SOFC)	• Auxiliary power • Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Solid electrolyte • Suitable for CHP & Combined heat, hydrogen, and powerHybrid/GT cycle	• High temperature corrosion and breakdown of cell components • High temperature operation requires long startup time and limits

While there are many different types of fuel cells, there are a few important shared characteristics. Instead of operating as Carnot cycle engines, or thermal energy-based engines, fuel cells use an electrochemical or battery-like process to convert the chemical energy of hydrogen into water and electricity and through this process achieve high electrical efficiencies. Second, fuel cells use hydrogen as the input fuel, which is typically derived from a hydrocarbon fuel such as natural gas or biogas. Third, 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 fuel (i.e. 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 those fuel cells are configured to utilize the DC power output directly.

As previously mentioned, all types of fuel cells also 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 to provide heat to the fuel processor.

Current CHP fuel cell installations total about 83.6 MW domestically.[89] California leads the nation in fuel cell installations, with just under 45 MW, roughly split half natural gas and half biogas. Connecticut and New York follow as the second and third-ranked states with current fuel cell installations at 25 MW and 10 MW, respectively. Those three states comprise 95 percent of the current domestic fuel cell market.

There is a significant amount of biogas fuel cells in California (representing almost a quarter of all fuel cell installations domestically by MW). Many of these systems were developed recently (i.e. 2010) as a result of additional incentives stemming from the California Self-Generation Incentive Program (SGIP).[90] Specifically, "directed biogas" projects (i.e. projects that consume biogas fuel produced at a different location) are eligible for higher incentives under the SGIP. Both CHP and electric-only fuel cells qualify for the SGIP incentive.

6.2   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 (200-2800 kW), pure electrical generation[91] (105-210 kW), residential and commercial systems for CHP (3-10 kW), back-up and portable power systems (0.25-5 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 6-1** illustrates an actual site with a fuel cell system functioning in CHP configuration.

---

[88] *http://energy.gov/eere/fuelcells/comparison-fuel-cell-technologies*

[89] CHP Installation Database. Maintained by ICF International for Oak Ridge National Laboratory. 2014. *http://www.eea-inc.com/chpdata/index.html*

[90] "2012 SGIP Impact Evaluation and Program Outlook" Itron. February 2014

[91] Based on Bloom Energy models ES-5700, ES-5400, and UPM-570

Figure 6-1. Commercial Fuel Cell for CHP Application

Source: FuelCell Energy

6.2.1   Combined Heat and Power

Due to the high installed cost of fuel cell systems, the most prevalent and economical DG application 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. PEMFC and DMFC operate at temperatures below 200°F, and therefore have 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, 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.

6.2.2   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, fuel cells become 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 fuel cells require 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 for fuel cell systems is easier than other types of DG systems. Fuel cell systems can be designed for both indoor and outdoor installation, and in close proximity to sensitive environments, people, or animals.

6.2.3 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.

6.2.4 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 if there is enough capacity.

6.2.5 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.

6.2.6   Resiliency

Fuel cells can be configured to operate independently of the grid, and can therefore provide emergency power during outages. This was evident particularly during recent hurricane events, where significant power outages occurred. For instance, during Hurricanes Irene and Superstorm Sandy, fuel cells helped keep communication lines open for different communications service providers.[92] Fuel cells are also generally resilient based on the undergrounded natural gas supply.

6.3   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_2) is typically generated from a hydrocarbon fuel such as natural gas or LPG, and the oxygen (O2) is from ambient air.

6.3.1   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 6-2 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.

---

[92] *The Business Case for Fuel Cells, Reliability, Resiliency & Savings (2013)*. See www.fuelcells.org.

## Figure 6-2. Fuel Cell Electrochemical Process
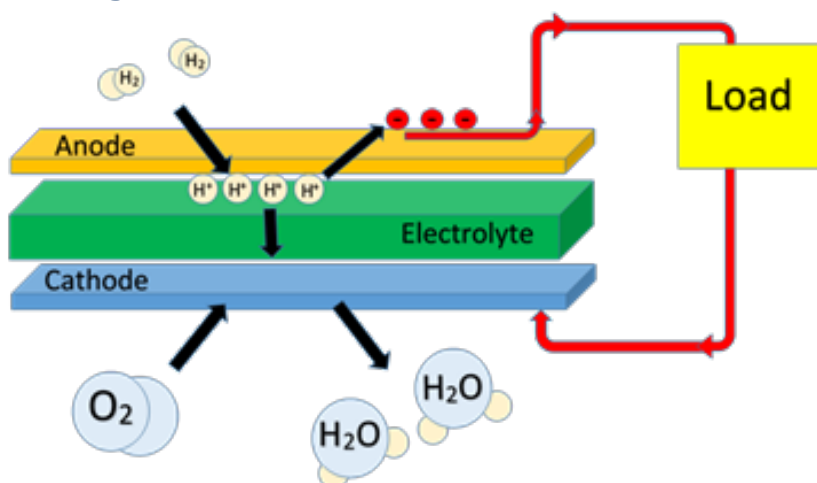
Source: ICF

The hydrogen and oxygen are fed to the anode and cathode, respectively. However, they do not directly mix, and result in combustion. 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_x and other pollutants.
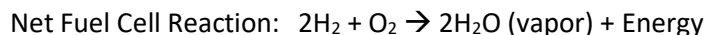
At the anode the hydrogen gas is electrochemically dissociated (in the presence of a catalyst) into hydrogen ions (H_+) and free electrons (e_-).

$$\text{Anode Reaction:} \qquad 2H_2 \rightarrow 4H^+ + 4e^-$$

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.

$$\text{Cathode Reaction:} \qquad O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$$
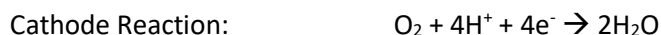
The overall reaction in a fuel cell is as follows:

$$\text{Net Fuel Cell Reaction:} \quad 2H_2 + O_2 \rightarrow 2H_2O \text{ (vapor)} + \text{Energy}$$

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 irreversible processes[93] that affect 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

---

[93] An irreversible process is a change in the potential energy of the chemical that is not recovered 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.

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 HHV[94] basis.

As described above, 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 6-3** illustrates this characteristic in comparison to the Carnot cycle efficiency limits through a condenser at 50 and 100°C[95]. 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.

---

[94] 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.

[95] Larminie, James and Andrew Dicks, Fuel Cell Systems Explained. John Wiley & Sons, Ltd., West Sussex, England, 2000.

Figure 6-3. Effect of Operating Temperature on Fuel Cell Efficiency
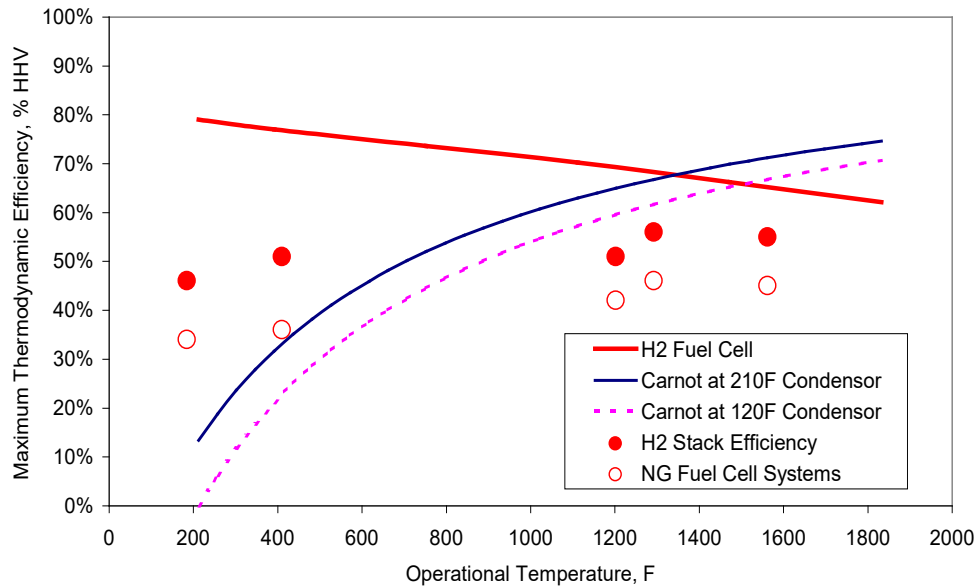
6.3.1.1 Fuel Cell Stacks

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^2 to over 1 m^2 depending on the type of fuel cell and application power requirements.

6.3.1.2 Fuel Processors

In distributed generation applications, the most viable fuel cell technologies use natural gas (CH_4) 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 natural gas fuel into a 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.

It is also during this process, depending on the efficiency of the fuel cell, that CO_2 is emitted as part of the reforming of the natural gas into usable hydrogen. CO_2 emissions range between 700 to 900 lb/MWh depending on the fuel cell technology used.

6.3.1.3 Power Conditioning Subsystem

Fuel cells generate direct current electricity, which requires conditioning before serving a load. 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 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.

6.3.1.4 Types of Fuel Cells

There are four basic types of fuel cells most suitable for stationary CHP applications. The fuel cell's electrolyte or ion conduction material defines the basic type. Two of these fuel cell types, polymer electrolyte membrane (PEMFC) and phosphoric acid fuel cell (PAFC), have acidic electrolytes and rely on the transport of H_+ ions. Carbonate fuel cell (MCFC) has basic electrolytes that rely on the transport of $CO3^2$ions. The fourth 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 an optimum temperature, which is a balance between the ionic conductivity and component stability. These temperatures differ significantly among the four 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 6-2 presents fundamental characteristics for the primary fuel cell types most suitable for stationary CHP.

Table 6-2. Characteristics of Major Fuel Cell Types

	PEMFC	PAFC	MCFC	SOFC
Type of Electrolyte	H^+ ions (with anions bound in polymer membrane)	H^+ ions (H_3PO_4 solutions)	$CO_3^=$ ions (typically, molten $LiKaCO_3$ eutectics)	$O^=$ ions (Stabilized ceramic matrix with free oxide ions)
Common Electrolyte	Solid polymer membrane	Liquid phosphoric acid in a lithium aluminum oxide matrix	Solution of lithium, sodium, and/or potassium carbonates soaked in a ceramic matrix	Solid ceramic, Yttria stabilized zirconia (YSZ)
Typical construction	Plastic, metal or carbon	Carbon, porous ceramics	High temp metals, porous ceramic	Ceramic, high temp metals
Internal reforming	No	No	Yes, good temp match	Yes, good temp match
Oxidant	Air to O_2	Air to Enriched Air	Air	Air
Operational Temperature	150- 180°F (65-85°C)	302-392°F (150-200°C)	1112-1292°F (600-700°C)	1202-1832°F (700-1000°C)
DG System Level Efficiency (% HHV)	25 to 35%	35 to 45%	40 to 50%	45 to 55%
Primary Contaminate Sensitivities	CO, Sulfur, and NH3	CO < 1%, Sulfur	Sulfur	Sulfur

Source: DOE Fuel Cells Technology Program[96]

6.3.1.5   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 (less than 200°F). Due to their modularity and simple manufacturing, reformer/PEMFC systems for residential DG applications (i.e. micro CHP) have enjoyed considerable market success, particularly in Asia. 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. PEMFCs have historically been the market leader in terms of number of fuel cell units shipped. There is a wide range of PEMFC manufacturers.

6.3.1.6   PAFC (Phosphoric Acid Fuel Cell)

PAFC uses phosphoric acid as the electrolyte and is one of the most established fuel cell technologies. 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. The current 400 kW product has a stack lifetime of over 40,000 hours and commercially based reliabilities in the 90 to 95 percent range. ClearEdge

---

Power is a primary US manufacturer of PAFC systems after buying the PAFC assets from United Technologies. Recently however ClearEdge has encountered financial problems.[97]

6.3.1.7   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 CHP 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. Fuel Cell Energy is one of the primary manufacturers of commercially available MCFCs, ranging from 300 kW to 2800 kW.

6.3.1.8   SOFC (Solid Oxide Fuel Cell)

SOFC uses solid, nonporous metal oxide electrolytes and is generally considered less mature in its development than the MCFC and PAFC technologies. 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 units are typically 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 reduce stack life and increase cost. While SOFC research has been ongoing for 30 years, costs of these stacks are still comparatively high. Currently, two of the primary SOFC manufacturers include Bloom Energy, which is a pure electric fuel cell (i.e. no waste heat is captured) and Ceramic Fuel Cells.

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:

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. 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 95% range. Waste heat can be used primarily for domestic hot water applications and space heating.
Availability	Commercially available systems have demonstrated greater than 90% availability.
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.

---

[97] ClearEdge Power filed for Chapter 11 bankruptcy in May of 2014.
http://www.oregonlive.com/business/index.ssf/2014/05/clearedge_power_files_for_bankruptcy_as_financial_woes_mount.html

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 5-10 years are expensive.
Emissions	The only combustion within a fuel cell system is the low energy content hydrogen stream exhausted from the stack when using pure hydrogen as a fuel source. This stream is combusted within the reformer and can achieve emissions
	Signatures of < 2 ppmv CO, <1 ppmv NO_x and negligible SO_x (on 15% O2, dry basis). However most fuel cells need to convert natural gas (CH_4) to hydrogen (H_2). During this process CO_2 is emitted at varying levels based on the efficiency of the fuel cell.
Efficiency	Different types of fuel cells have varied efficiencies. Depending on the type and design, electric efficiency ranges from 30% to close to 50% 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 fuel cells is hydrogen, which can be obtained from natural gas, coal gas, methanol, and other fuels containing hydrocarbons.

6.4   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 6-3 summarizes performance characteristics for representative commercially available and developmental natural gas fuel cell CHP systems over the 0.7 kW to 1,400 kW size range. This size range covers the majority of the market applications. All systems included in **Table 6-3** are commercially available as of 2014.

Table 6-3. Fuel Cell CHP - Typical Performance Parameters

Performance Characteristics	System 1	System 2	System 3	System 4	System 5
Fuel Cell Type	PEMFC	SOFC	MCFC	PAFC	MCFC
Nominal Electricity Capacity (kW)	0.7	1.5	300	400	1,400
Net Electrical Efficiency (%), HHV	35.3%	54.4%	47%	34.3%	42.5%
Fuel Input (MMBtu/hr), HHV	0.0068	0.0094	2.2	4.0	11.2
Total CHP Efficiency (%), HHV	86%	74%	82%	81%	82%
Power to Heat Ratio	0.70	2.78	1.34	0.73	1.08
Net Heat Rate (Btu/kWh), HHV	9,666	6,272	7,260	9,948	8,028
Exhaust Temperature (°F)	NA	NA	700	NA	700
Available Heat (MMBtu/hr)	NA	NA	0.78 (to 120°F)	0.88 (to 140°F)	3.73 (to 120°F)
Sound (dBA)	NA	47 (at 3 feet)	72 (at 10 feet)	65 (at 33 feet)	72 (at 10 feet)

NA = not available or not applicable
Source: ICF, specific product specification sheets

Heat rates and efficiencies shown were taken from manufacturers' specifications and industry publications or are based on the best available data for developing technologies. 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.

Generally, electrical efficiency increases as the operating temperature of the fuel cell increases. SOFC fuel cells have the highest operating temperatures (which can be advantageous as well as disadvantageous) and they also have the highest electric efficiencies. In addition, 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.

6.4.1 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 fuel cells have several subsystems in series, the electrical efficiency of the unit is the multiple of the efficiencies of each individual section. The electric efficiency of a fuel cell system is calculated as follows:

$$Eff_{Elec} = (Eff_{FPS} * H_2 \text{ Utilization} * Eff_{Stack} * Eff_{PC})*(HHV/LHV \text{ ratio of the fuel})$$

Where:

Eff_{FPS}	=	Fuel Processing Subsystem Efficiency, LLV (LHV of H2 Generated/LHV of Fuel Consumed)
H_2 Utilization	=	% of H_2 actually consumed in the stack
Eff_{Stack}	=	(Operating Voltage/Energy Potential ~1.23 volts)
Eff_{PC}	=	AC power delivered/(dc power generated) (auxiliary loads are assumed dc loads here)

For example, the electrical efficiency of a PAFC can be calculated as follows:

$$Eff_{Elec} = (84\%FPS)*(83\% \text{ util})*(0.75V/1.25V)*(95\%PC)*(0.9HHV/LHV)$$
$$= 36\% \text{ electric efficiency HHV}$$

As the operating temperature range of the fuel cell system increases, the electric efficiency of the system tends to increase. Although the maximum thermodynamic efficiency decreases as shown in **Figure 6-3**, 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 can achieve simple cycle efficiencies in the range of 50 to 60 percent HHV, while hybrid combined fuel cell-heat engine systems are calculated to achieve efficiencies above 60 percent in DG applications.

6.4.2 Part Load Performance

In CHP applications, fuel cell systems are expected to follow the thermal load of the host site to maximize CHP energy economics. **Figure 6-4** shows the part load efficiency curve for a PAFC fuel cell in the 100 kW to 400 kW size range in comparison to a typical lean burn natural gas engine. It shows that

fuel cells maintain efficient performance at partial loads better than reciprocating engines. The fuel cell 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 6-4. Comparison of Part Load Efficiency Derate
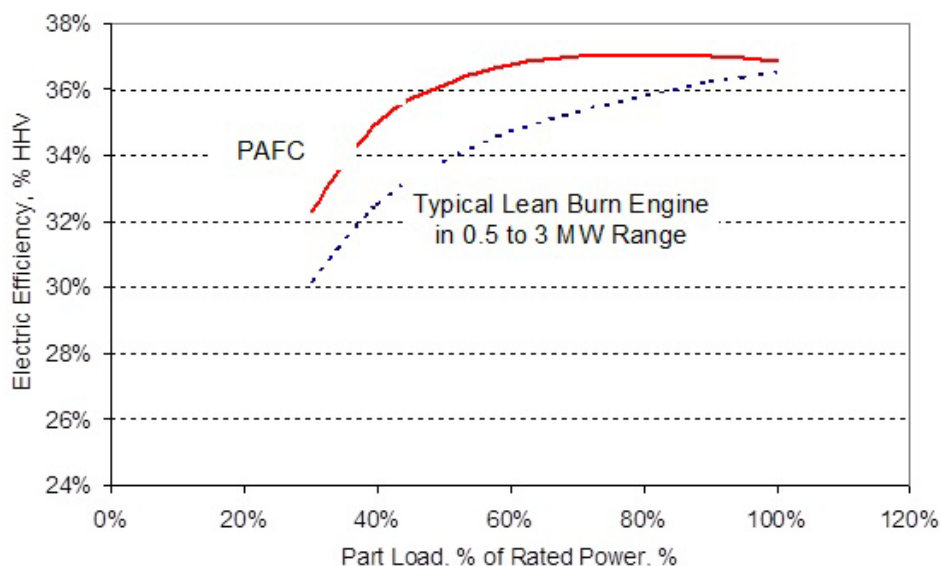
Source: Gas Technology Institute, Caterpillar, Energy Nexus Group.

6.4.3   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.

6.4.4   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.

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 that some manufactures of SOFC do not recover the heat for use in other

---

applications but use the heat to boost the internal process and to improve electrical generation efficiencies.

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. A sample 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 gases is in recuperative heat exchange with the inlet process gases. Like engine and turbine systems, fuel cell exhaust gas can be used directly for process drying.

6.4.5 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.[98] 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.

6.4.6 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 6-4** for five representative CHP fuel cell systems**.** 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.

---

[98] Larminie, James and Andrew Dicks, <u>Fuel Cell Systems Explained</u>. John Wiley & Sons, Ltd., West Sussex, England, 2000. , p. 90.

Table 6-4. Estimated Capital and O&M Costs for Typical Fuel Cell Systems in Grid Interconnected CHP Applications (2014 $/kW)

Installed Cost Components	System 1 Residential	System 2 Residential	System 3 C&I	System 4 C&I	System 5 C&I
Fuel Cell Type	PEMFC	SOFC	MCFC	PAFC	MCFC
Nominal Electricity Capacity (kW)	0.7	1.5	300	400	1400
Total Package Cost (2014 $/kW)[99]	$ 22,000	$ 23,000[100]	$10,000	$ 7,000	$ 4,600
O&M Costs (2014 $/MWh)	$ 60	$ 55	$45	$ 36	$ 40

Source: ICF Manufacturer Data Collection

6.4.7 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 (5 to 10 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).

6.4.8 Fuels

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

- **Natural Gas** – methane from the pipeline.
- **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.

---

[99] Total package cost includes all equipment (including heat recovery) as well as estimated labor and installation costs.
[100] Total package costs for larger (i.e. 200 kW) SOFC systems are significantly less expensive than $23,000, however those data were not made available to us for estimation.

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

6.4.9 System Availability

Fuel cell systems are generally perceived as low maintenance devices. Fuel cells in North America have been recorded achieving more than 90 percent availability. In premium power applications, 100 percent customer power availability, and 95 percent+ fleet availability has been reported during the same time period. Fuel cells can provide high levels of availability, especially in high load factor (i.e. baseload) applications.

6.5 Emissions and Emissions Control Options

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_x) 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_x) are eliminated because they are typically removed in an absorbed bed before the fuel is processed.

6.5.1 Primary Emissions Species

6.5.1.1 Nitrogen Oxides (NO_x)

NO_x is formed by three mechanisms: thermal NO_x, prompt NO_x, and fuel-bound NO_x. Thermal NO_x 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_x levels. The rate of thermal NO_x formation increases rapidly with flame temperature. Prompt NO_x is formed from early reactions of nitrogen modules 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_2, and is usually much smaller than the thermal NO_x formation. Fuel-bound NO_x forms when the fuel contains nitrogen as part of the hydrocarbon structure. Natural gas has negligible chemically bound fuel nitrogen. Fuel-bound NO_x can be at significant levels with liquid fuels.

6.5.1.2   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 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.

6.5.1.3   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 greenhouse gas and may come under future regulations.

6.5.1.4   Carbon Dioxide (CO_2)

Carbon dioxide (CO_2) emissions 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_2 (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_2 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.

6.5.2   Fuel Cell Emission Characteristics

Table 6-5 illustrates the emission characteristics of fuel cell systems. Fuel cell systems do not require any emissions control devices to meet current and projected regulations. As previously noted, fuel cells generally have very low emissions.

Table 6-5. Estimated Fuel Cell Emission Characteristics without Additional Controls

| Emissions Characteristics	System 1	System 2	System 3	System 4	System 5
Fuel Cell Type	PEMFC	SOFC	MCFC	PAFC	MCFC
Nominal Electricity Capacity (kW)	0.7	1.5	300	400	1,400
NO_x (lb/MWh)	Negligible	Negligible	0.01	0.01	0.01
SO_x (lb/MWh)	Negligible	Negligible	0.0001	Negligible	0.0001
CO (lb/MWh)	Negligible	Negligible	Negligible	0.02	Negligible
VOC (lb/MWh)	Negligible	Negligible	Negligible	0.02	Negligible
CO_2 (lb/MWh)	1,131	734	980	1,049	980
CO_2 with heat recovery (lb/MWh)	415	555	520-680	495	520

Source: ICF Manufacturer Data Collection

6.6 Future Developments

Over the past years fuel cell capital costs have decreased and their use in multiple applications have increased. In 2007, SOFC were not even commercially shipping and now there are many of them being shipped in multiple sizes globally. In the US multiple factors point towards continued levels of fuel cell market penetration. These factors include: relatively low domestic natural gas prices, continued fuel cell technological advancements reducing capital costs and new business models such as leasing, favorable incentives and policies, continued desire for low emissions profiles, and general resiliency and reliability advantages of distributed energy.

Globally, MCFC shipments by MW have been on par with that of vehicle PEMFC, as shown in **Figure 6-5**. As the only commercial developer of MCFCs in the United States, Fuel Cell Energy is uniquely positioned to continue its successes, both domestically and internationally.

Figure 6-5. Recent Worldwide Fuel Cell Installations by Fuel Cell Type, in Megawatts
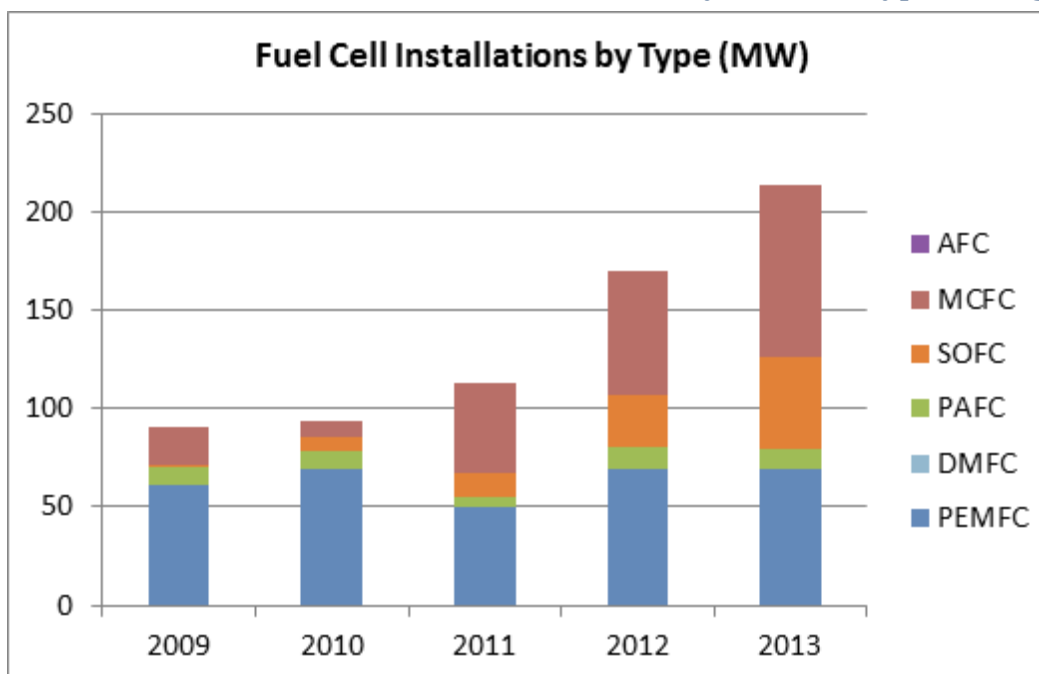
Source: Fuel Cell Today[101]

Large-scale stationary fuel cells for CHP have also been successfully deployed in Asia (specifically Korea and Japan). Europe could also be a growth opportunity as FuelCell Energy has formed joint ventures in the European continent.[102] It is likely through these international joint ventures that US-based fuel cell manufacturers can leverage local market experience and technological expertise in international markets. These sales opportunities will also increase demand leading to potentially more reductions in costs as we have seen in solar photovoltaic panels and now batteries.

---

[101] "The Fuel Cell Industry Review 2013", Fuel Cell Today. *http://www.fuelcelltoday.com/media/1889744/fct_review_2013.pdf*
[102] "FuelCell Energy Announces Completion of Asset Acquisition and German Joint Venture with Fraunhofer IKTS", June 26, 2012. *http://fcel.client.shareholder.com/releasedetail.cfm?releaseid=686425*

What may be the next significant growth engine for fuel cells is the development of micro-CHP fuel cells. According to a 2013 report from Fuel Cell Today, residential micro-CHP fuel cells outsold conventional micro-CHP boilers for the first time in 2012 in Japan. The report elaborates that this micro-CHP application is migrating to Europe and it may become a trend in the US with both PEMFC and SOFC technologies.