Fuel Cells

Fuel cells use an electrochemical process to convert the chemical energy in a fuel to electricity. In contrast to reciprocating engines and gas turbines, fuel cells generate electricity without combusting the fuel. The first practical application for fuel cells emerged in the 1950s when fuel cells were used to provide onboard power for spacecraft. Fuel cells continue to be used in space exploration, but over the past few decades the technology has migrated to other applications, including vehicle transportation and stationary power generation. For stationary power, fuel cells are used for distributed generation (electricity only) and are also configured for combined heat and power (CHP). **Table 1** provides an overview of fuel cell operation in CHP applications.

CHP fuel cell installation at Verizon data center.[1]
Photo courtesy of Verizon Communications.

Applications

Based on data from the CHP Installation Database,[2] there are 126 fuel cells installations in the United States that are configured for CHP operation. These fuel cell CHP installations have an average capacity of 532 kW and a combined capacity of 67 MW. The majority of these fuel cells are used in commercial and institutional buildings where there is a relatively high coincident demand for electricity and thermal energy. Thermal energy recovered from fuel cells is most often used to satisfy hot water or space heating demands, although in some cases fuel cells have been integrated with absorption chillers to provide space cooling. In distributed generation markets, the primary characteristic driving early market acceptance is the ability of fuel cell systems to provide reliable premium power. A major driver has been the ability of fuel cells to achieve high efficiencies over a broad load profile and low emission signatures without additional controls. Sites where fuel cell CHP systems have been used include universities, hospitals, nursing homes, hotels, and office buildings.

Table 1. Fuel Cell Attributes for CHP Applications

Size range	Fuel cells for CHP are available with capacities from 5 to 2,800 kW
Thermal output	Heat from fuel cells configured for CHP can be recovered to produce hot water, low pressure (<30 psig) steam, and chilled water (with an absorption chiller)
Part-load operation	Fuel cells have good part-load performance. At 50% of full load, the efficiency of a fuel cell will typically decline less than 2% compared to the full load value
Fuel	Most fuel cells for CHP applications use natural gas or biogas. The gas is reformed into hydrogen, and the hydrogen is then reacted to generate electricity
Reliability	Fuel cells use an electrochemical process with few moving parts and offer high reliability. While mechanical wear is not an issue, fuel cells do require periodic replacement or refurbishment of catalysts and fuel cell stacks
Other	Fuel cells are quiet, have low emissions, and produce high quality power

1 U.S. Department of Energy, Case Study: Fuel Cells Provide Combined Heat and Power at Verizon's Garden City Central Office, 2010.

2 U.S. *DOE Combined Heat and Power Installation Database*, data compiled through December 31, 2015.

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. **Figure 1** illustrates a single fuel cell element that consists of a cathode (positively charged electrode), an anode (negatively charged electrode), and an electrolyte. Hydrogen and oxygen are fed to the anode and cathode, respectively, and chemical reactions occur in the presence of catalysts at the anode and cathode. The chemical reactions generate ions and electrons that produce direct current (DC) electricity and water. The voltage generated from a single fuel cell element is low (< 1 volt DC). For practical applications, over a hundred cells are typically combined ("stacked") in series to generate voltages in the range of 200 to 400 volts DC.

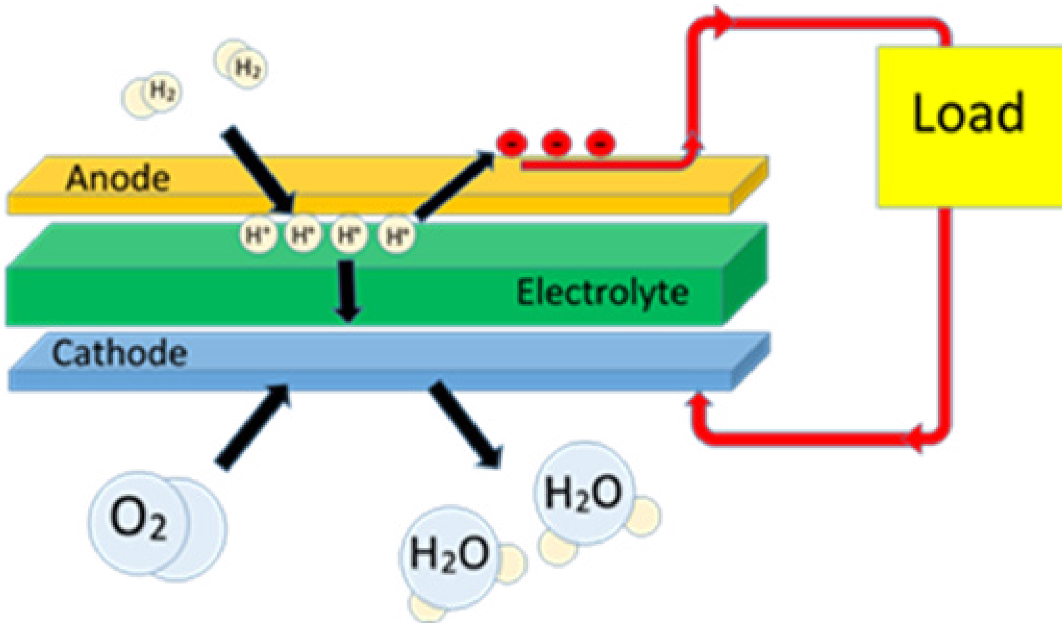

Figure 1. Fuel cell electrochemical process.
Photo credit ICF International.

Several electrolytes have been successfully developed, and fuel cells are often categorized by the type of electrolyte, or in some cases, the type of fuel. Six leading fuel cell technologies are alkaline (AFC), direct methanol (DMFC), phosphoric acid (PAFC), proton exchange membrane (PEMFC), molten carbonate (MCFC), and solid oxide (SOFC). Four of these technologies – PAFC, PEMFC, MCFC, and SOFC – have been used for CHP.

In addition to the fuel cell stack, commercially available fuel cells are typically packaged with two other integrated subsystems: a fuel processor and a power conditioner. The fuel processor, or reformer, converts the fuel (e.g., natural gas or biogas) into a hydrogen rich feed stream for the fuel cell stack. The power conditioner regulates the DC electricity generated from the stack and converts this DC power to alternating current (AC).

Table 2. Fuel Cell Performance Characteristics

Description	System		
	1	2	3
Net Electric Power (kW)	300	400	1,400
Fuel Cell Type	MCFC	PAFC	MCFC
Fuel	Natural Gas	Natural Gas	Natural Gas
Fuel Input (MMBtu/hr, HHV)[3]	2.41	3.59	11.24
Useful Thermal (MMBtu/hr)[4]	0.79	0.88	3.63
Power to Heat Ratio[5]	1.30	1.55	1.31
Electric Efficiency (%, HHV)	42.5%	38.0%	42.5%
Thermal Efficiency (%, HHV)	32.7%	24.5%	32.3%
Overall Efficiency (%, HHV)	75.2%	62.5%	74.8%

Note: *Performance characteristics are average values and are not intended to represent a specific product.*

3 Manufacturers often express fuel input and efficiency values based on the lower heating value (LHV) of the fuel. All quantities in this fact sheet are based on the higher heating value (HHV) unless noted otherwise. For natural gas, the ratio of LHV to HHV is approximately 0.9.

4 Useful thermal energy is based on producing hot water at a temperature of 140 °F.

5 Power to heat ratio is the electric power output divided by the useful thermal output. The quantities are expressed in equivalent units, and the ratio is unit-less.

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. However, successful PEMFC and SOFC systems have been developed for microCHP (< 10 kW) applications that are suitable for residential and small commercial buildings, with most microCHP installations in Europe and Asia. In the United States, nearly all CHP fuel cell systems utilize MCFC and PAFC technologies and are designed to meet loads that are typical for large commercial and institutional buildings.

Table 2 summarizes performance characteristics for three representative fuel cell CHP systems available in the United States, ranging in size from 300 kW to 1,400 kW. As indicated, all three systems operate at overall efficiencies above 60% (MCFC above 70%), with power to heat ratios between 1.3 and 1.6. The thermal energy for all three fuel cells is based on producing 140 °F water. Fuel cells maintain efficient performance at partial loads better than some other CHP technologies. Fuel cell efficiency at 50 percent load is within 2 percent of its full load efficiency characteristic.

While PAFC and MCFC technologies are both used for CHP, the technologies do have significantly different thermal characteristics. PAFC systems operate with temperatures in the range of 150 – 200 °C (302 – 392 °F) compared to MCFC systems that operate at higher temperatures in the range of 600 – 700 °C (1,112 – 1,292 °F). For PAFC systems, thermal energy is typically used to generate hot water or low pressure (<30 psig) steam. With MCFC systems, low or medium pressure (<150 psig) steam can be generated along with hot water.

Compared to prime movers with lower efficiency, the economics of fuel cells in on-site power generation are less dependent on effective use of recovered thermal energy. However, as in any CHP application, thermal load displacement can improve operating economies of a fuel cell system. 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 lowpressure steam (<30 psig), but the quality of heat is very dependent on the type of fuel cell and its operating temperature.

Capital and O&M Costs

Installed costs for fuel cell CHP systems are shown in **Table 3**. For the three representative systems, installed costs range from $4,600 to $10,000 per kW. Similar to other CHP technologies, installed costs for fuel cell CHP systems decline on a per-kW basis as capacity increases. As is the case with most CHP systems, installed costs can vary significantly depending on the scope of the plant equipment, geographic location, and other site-specific conditions.

Several factors influence fuel cell operation and maintenance (O&M) costs, including the type of fuel cell, capacity, and maturity of the equipment. For commercially available fuel cells, maintenance can either be performed by in-house personnel or contracted to a service provider. For contracted maintenance, costs are estimated at 0.7 to 2.0 cents/kWh excluding replacement and/or refurbishment of the fuel cell stack. With stack replacement/refurbishment included, maintenance costs range from 3.6 to 4.5 cents/kWh for the three representative fuel cell systems shown in **Table 3**. 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, and consumables such as sulfur adsorbent bed catalysts and nitrogen for shutdown purging
- Major overhauls, including shift catalyst replacement (3 to 5 years), reformer catalyst replacement (5 years), and stack replacement (5 to 10 years).

Table 3. Fuel Cell Capital and O&M Costs

Description	System		
	1	2	3
Net Electric Power (kW)	300	400	1,400
Fuel Cell Type	MCFC	PAFC	MCFC
Installed Cost ($/kW)	$10,000	$7,000	$4,600
O&M Cost, excluding fuel (¢/kWh)	4.5	3.6	4.0

Note: *Costs are average values and are not intended to represent a specific product.*

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).

Table 4. Fuel Cell Emission Characteristics

Description	System		
	1	2	3
Net Electric Power (kW)	300	400	1,400
Fuel Cell Type	MCFC	PAFC	MCFC
Emissions (lbs/MWh, based on electric power only)[6]			
NOx	0.01	0.01	0.01
CO	0.02	0.02	0.02
VOCs	0.02	0.02	0.02
CO_2 Emissions (lbs/MWh)			
Electric Power Only	939	1,050	939
CHP with thermal credit[7]	555	729	559

Note: *Emissions are average values and are not intended to represent a specific product.*

Emissions

A fuel cell stack uses an electrochemical process to convert fuel to electricity, and this process does not produce carbon monoxide (CO), nitrogen oxides (NOx), or volatile organic compounds (VOCs). Fuel cell reformers do rely on combustion, but reformer emissions are low. Anode off-gas, which is generated in the fuel cell stack, typically consists of 8% to 15% hydrogen. This hydrogen is combusted in the reformer with a catalytic or surface burner that operates at temperatures below 1,800° F, which minimizes NOx formation, but is sufficiently high to oxidize CO and VOC emissions.

Fuel cells, like other CHP technologies that use natural gas, produce carbon dioxide emissions. **Table 4** shows CO_2 emissions based on electric power output and overall CHP performance. For CHP performance, CO_2 emissions are calculated with a thermal credit for natural gas fuel that would otherwise be used by an on-site boiler. With this thermal credit, CO_2 emissions for the three representative CHP fuel cell systems range from 555 to 729 lbs/MWh. For comparison, a typical natural gas combined cycle power plant will have emissions of 800-900 lbs/MWh, and a coal plant will have CO_2 emissions near 2,000 lbs/MWh. 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.

Future Developments

Over the past years, fuel cell capital costs have decreased, and fuel cell use in multiple applications have increased. In the United States, multiple factors point toward continued levels of fuel cell market penetration. These factors include: continued fuel cell technological advancements reducing capital costs, 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. ■

6 CO and VOC values were not available for the 300 and 1,400 kW systems. Values shown are estimated.

7 The CHP CO_2 emissions include a thermal credit for avoided fuel that would otherwise be used by an on-site boiler. The boiler is assumed to operate on natural gas with an efficiency of 80%.

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