PG&E GAS R&D AND INNOVATION

Fuel Cells Technical Analysis

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What is Fuel Cell

A fuel cell is a device that converts chemical potential energy from a fuel into electrical energy through an electrochemical reaction of hydrogen with oxygen or another oxidizing agent. The inputs are hydrogen and oxygen, and the outputs are electricity, water, and heat. There is a wide range of applications and is scalable to either power to systems as large as a utility power station or as small as a laptop.

Like batteries, they do not run down or need recharging. They produce electricity and heat as long as fuel is supplied. Due to the lack of moving parts, maintenance for fuel cells is relatively simple. Fuel cells operate at higher efficiencies (60%) and with lower emissions compared to combustion engines. If the fuel cell is fed with hydrogen produced through electrolysis of water driven by renewable energy, then the fuel cell system eliminates greenhouse gases over the whole cycle.

How Does a Fuel Cell Work

A fuel, in this case hydrogen, is fed through the anode, where a catalyst will separate the hydrogen molecules into positively charged protons and negatively charged electrons. The protons travel toward the cathode through the electrolyte, while the electrons travel through an external circuit. The electrons moving through the electrical circuit is what creates the flow of direct current electricity. The protons and electrons reunite at the cathode and react with oxygen to produce water. The outputs are electrical current and water.

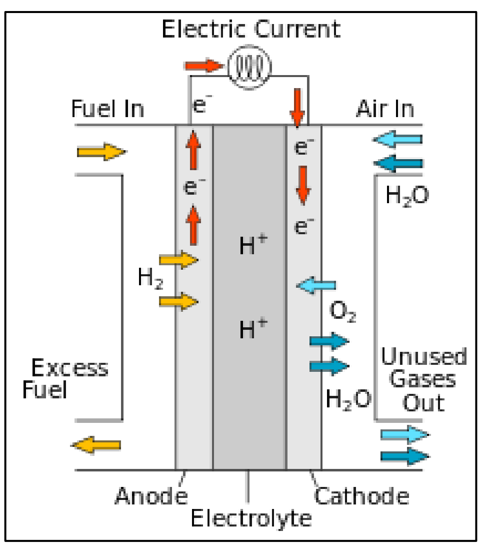

Figure 1 How a fuel cell works (Barone, 2018)

Different Types of Fuel Cells

The type of electrolyte used is what differentiates most types of fuel cells.

Hydrogen Fuel Cells

PROTON EXCHANGE MEMBRANE FUEL CELLS (PEM FUEL CELLS OR PEMFC)

PEMFC are used for vehicle applications, such as cars and buses, and some stationary applications. They deliver high power density and are usually low weight and volume compared with other fuel cells. They employ a solid polymer as an electrolyte and porous carbon electrodes containing platinum catalyst. The inputs are hydrogen, oxygen from air, and water.

They operate in relatively low temperatures (176 degrees F), which allows them to start up quickly with minimal warm-up time. Durability is increased due to minimal wear on system components. (Energy Efficiency & Renewable Energy, 2018)

There are some key components that can increase the cost. A noble-metal catalyst is needed to separate the hydrogen's electrons and electrons, which is costly. Also, the system is very sensitive to carbon monoxide, so a reactor is needed to reduce the amount of carbon monoxide, especially if the fuel gas is from a hydrocarbon fuel.

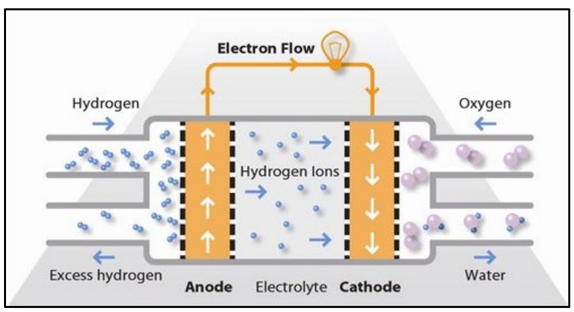

Figure 2 How PEMFC works

DIRECT METHANOL FUEL CELLS (DMFC)

DMFCs are used to provide power to portable fuel cell applications such as cell phones or laptop computers.

Unlike most fuel cells, which are powered by hydrogen, DMFCs are powered by pure methanol, which is usually mixed with water and fed directly to the fuel cell anode. Since methanol has a very high energy density, fuel storage is not an issue. Methanol is also a liquid, so it is easy to transport using existing infrastructure.

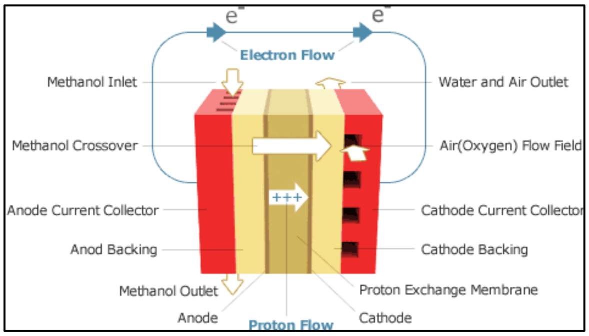

Figure 3 How DMFC works

ALKALINE FUEL CELLS (AFCS)

One of the first types of fuel cells to be developed, and the first widely used in the U.S. space program to produce electricity and water on the spacecraft.

What is unique about AFCs is that they use a potassium hydroxide solution with water as the electrolyte. At the anode and cathode, a variety of non-precious metals can be used as the catalyst. The highly-rated performance is due to the rate at which the electro-chemical reactions take place in the cell. An alkaline membrane is used instead of an acid membrane. Up to 60% efficiency in space applications. (Energy Efficiency & Renewable Energy, 2018)

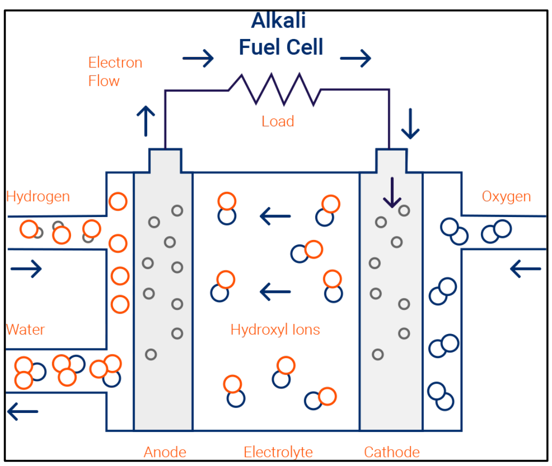

Figure 4 How Alkali Fuel Cells work

PHOSPHORIC ACID FUEL CELLS (PAFC)

PAFCs are commonly used for stationary power generation, but some PAFCs have been used to power large vehicles such as city buses. They are usually large and heavy compared to other fuel cells.

In PAFCs, phosphoric acid is used as an electrolyte, which is contained in a Teflon-bonded silicon carbine matrix. Porous carbon electrodes containing platinum are used for the catalysts. This system is very sensitive to impurities from fossil fuels that might have made their way into the hydrogen. This can have an impact on efficiency, however these systems have been proven to be 85% efficient when used with co-generation of electricity and heat. With that said, they are only about 37-42% efficient when used to generate electricity alone, which is only slightly higher than combustion-based power plants (33% efficient). (Office of Energy Efficiency and Renewable Energy, 2018)

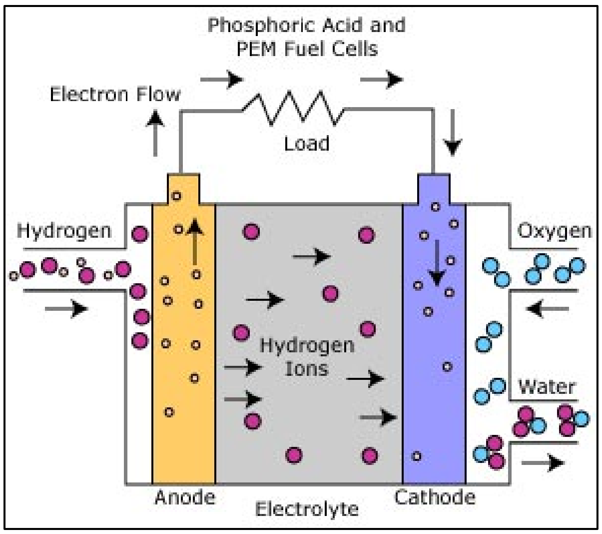

Figure 5 How PAFC work

Natural Gas Fuel Cells

MOLTEN CARBONATE FUEL CELLS (MCFC)

MCFCs are being developed for natural gas and coal-based power plants for electrical utility, industrial, and military applications. Current lifespan is about 5 years (40,000 hours). (EERE Fuel Cell Comparison, 2018)

They operate with a high temperature (1200 degrees F) and use an electrolyte composed of molten carbonate salt suspended in a porous, chemically inert ceramic lithium aluminum oxide matrix. Due to the high temperatures, non-precious metals are used for the anode and cathode. When coupled with a turbine, MCFCs can reach efficiencies around 65%. However, when waste heat is captured and used, the fuel efficiencies of 85% can be achieved.

Another advantage of the high operating temperature is that no reformer is needed to purify the hydrogen from natural gas or biogas. Methane and other light hydrocarbons in these fuels are converted to hydrogen within the fuel cell through a process called internal reforming.

One drawback of using a MCFC is the durability. High temperatures and a corrosive electrolyte can lead to component breakdown and corrosion.

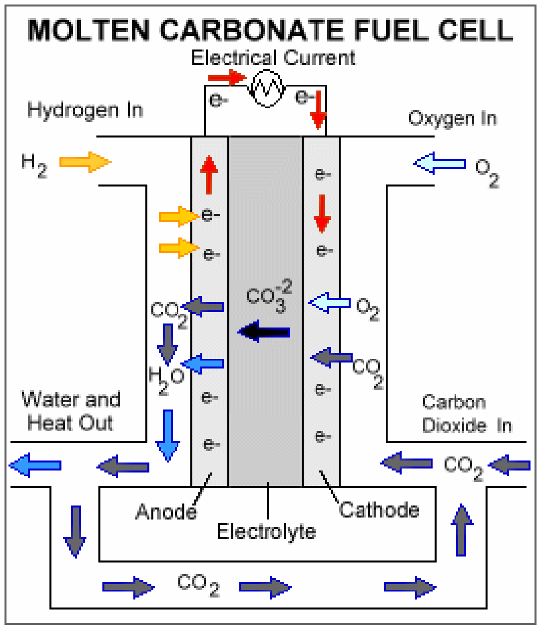

Figure 6 How a Molten Carbonate Fuel Cell works

SOLID OXIDE FUEL CELLS (SOFC)

SOFCs are commonly used in utility applications, especially when natural gas is the fuel source. Hydrogen is the ideal fuel source for powering fuel cells. The main advantage of using natural gas (methane) as a fuel source is the possibility of extracting hydrogen in an abundant way. However, there are complications that come with separating out the hydrogen and the CO_2 byproduct.

Similar to MCFCs, SOFCs operate at very high temperatures (1,830 degrees F) which reduces the need for non-precious materials for the anode and cathode. Also, internal reforming occurs which eliminates the need for a reformer. However, durability can be an issue with the high temperatures.

An advantage of SOFCs is that they are highly resistant to sulfur and are not poisonous to carbon monoxide. For this reason, the use of natural gas, biogas, and gases made from coal can be used. They are usually 60% efficient at converting fuel to electricity, however when the systems are designed to capture and use heat through co-generation, the fuel efficiency can be as high as 85%. Due to the slow startup time and thermal shielding required, SOFCs are better utilized for utility applications, and not vehicles. (Barone, 2018)

Natural gas combines with a steam creating four H^+ molecules and one CO molecule, as shown by the equation below. The H_2 molecules move through the fuel cell as if the system was fed with pure hydrogen from the start, generating H_2O in the form of steam, and pure CO_2. Hydrogen is the ideal fuel to power a fuel cell. The main issue is the CO_2 that is produced which will have to be contained and disposed of.

A high temperature is required to create reaction efficiency that will shift towards the desired products. However, as the temperature approaches 750 degrees C, the process is wasting energy since your energy input would negate the energy produced.

$$CH_4 + 2H_2O \leftrightarrow CO + 4H_2$$

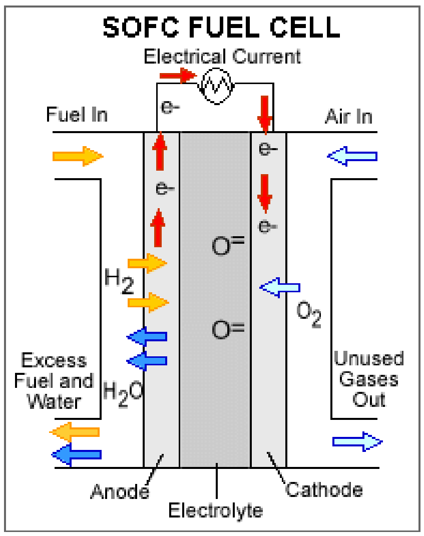

Figure 7 How a SOFC works

Table 1 Comparison of different types of fuel cells

Fuel Cell Type	Common Electrolyte	Operating Temperature	Typical Stack Size	Efficiency	Applications	Advantages	Disadvantages
Polymer Electrolyte Membrane (PEM)	Perfluoro sulfonic acid	50-100°C 122-212° typically 80°C	< 1kW–100kW	60% transportation 35% stationary	• Backup power • Portable power • Distributed generation • Transporation • Specialty vehicles	• Solid electrolyte reduces corrosion & electrolyte management problems • Low temperature • Quick start-up	• Expensive catalysts • Sensitive to fuel impurities • Low temperature waste heat
Alkaline (AFC)	Aqueous solution of potassium hydroxide soaked in a matrix	90-100°C 194-212°F	10–100 kW	60%	• 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
Phosphoric Acid (PAFC)	Phosphoric acid soaked in a matrix	150-200°C 302-392°F	400 kW 100 kW module	40%	• Distributed generation	• Higher temperature enables CHP • Increased tolerance to fuel impurities	• Pt catalyst • Long start up time • Low current and power
Molten Carbonate (MCFC)	Solution of lithium, sodium, and/ or potassium carbonates, soaked in a matrix	600-700°C 1112-1292°F	300 kW-3 MW 300 kW module	45-50%	• Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Suitable for CHP	• High temperature corrosion and breakdown of cell components • Long start up time • Low power density
Solid Oxide (SOFC)	Yttria stabilized zirconia	700-1000°C 1202-1832°F	1 kW–2 MW	60%	• Auxiliary power • Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Solid electrolyte • Suitable for CHP & CHHP • Hybrid/GT cycle	• High temperature corrosion and breakdown of cell components • High temperature operation requires long start up time and limits

https://upload.wikimedia.org/wikipedia/commons/3/36/EERE_Fuel_Cell_Comparison_Chart.pdf

(EERE Fuel Cell Comparison, 2018)

BLOOM BOX BY BLOOM ENERGY

Refrigerator sized units that contain solid oxide fuel cells and are designed for modularity, similar to a building block, to form solutions from hundreds of kilowatts to many tens of megawatts. They use oxygen and fuel to create electricity without any emissions. The fuel cells are stacked into brick-sized towers sandwiched with metal alloy plates.

Fuel sources that can be used include traditional fuel, natural gas, biomass gas, landfill gas, and ethanol. It is estimated that 64 stacks of fuel cells would be able to power a Starbucks franchise. The cost of a Bloom Box is between $700,00 and $800,000. The energy conversion rate is around 50%-55%. CO_2 is produced as a byproduct. The amount of CO_2 emissions when running on natural gas is 0.8 lbs/kWh, which is still favorable to the 2 lbs/kWh when electricity is produced from coal-fired plants, or 1.3 lbs/kWh from natural gas-powered plants. If the box is run on landfill gas or biogas, it produces net zero carbon emissions. (Barnard, 2015)

Many have questioned the comparisons that Bloom Energy has provided. The Bloom Box peaks at a capacity of 100KW, which is 30 times less than utility-scale onshore wind (3MW). 100 KW would be useful for local buildings for electricity generation in a dense urban setting where solar might not be an option. The amount of CO_2 that is produced, 884 lbs of CO_2/MWH, is still significant. In California, where the grid electricity has an average of 469 lbs/MWH of CO_2, the carbon emissions of the Bloom Box are greater than the grid. (Haq, 2010)

Table 2 Bloom Box data (Bloom Energy, 2018)

Parameter Name	Value	Unit / description
Fuel (natural gas) flow rate for 200 kW Bloom Energy Server	1.32	MMBtu/hr
Fuel energy in rate in kW (1 MMBTU/hr CH_4 = 293 kW)	386.76	kW
Fuel cost	$3.96	per hour
Electric output rate	200	kW
System efficiency natural gas -> electricity	52%	percent conversion of natural gas energy to electrical energy
Electricity cost	$0.10	per kWh
Electricity produced revenue	$20.00	per hour
CO_2 produced	773	lb/MWh
Run cost savings per bloom box (electricity revenue less fuel cost)	$16.04	per hour
Cost savings per year assuming 24X7 full load operation	$140,510.40	per year
Capital cost (estimated minimum cost after projected reductions)	$800,000.00	for each 200 kW unit
Annual maintenance / operation cost	6%	as a fraction of capital cost, per year
Cost savings after maintenance costs	$92,510.40	per year
Break even period	8.6	years

Other key players: Siemens, GE Power, United Technologies, Toshiba, Sprint, Altergy, Ceramic Fuel Cells

NATURAL GAS (METHANE FUEL) CELLS LIMITATIONS

The abundant amount of readily-available natural gas makes fuel cells a desirable generation method. Some manufacturers are looking for alternative fuels to hydrogen because of the lack of large-scale hydrogen production. The difficulty is converting hydrocarbons into hydrogen within the fuel cell.

Issues:

(Union of Concerned Scientists, 2017) (Haq, 2010)

- Build-up of carbon-rich solids (coke) on the anodes
- Fuel cells will need to break methane's strong carbon-hydrogen bonds which requires high operating pressures, usually between 650-1,100 degrees C. This high required temperature adds significantly to the operating costs
- Carbon dioxide is produced as a byproduct which will need to be contained and disposed of
- The sulfur in the mercaptans can degrade the metallic catalyst, so they must be removed prior to being fed into the fuel cell. H2S can also be poisonous to the fuel cell stack.

- The long-term performance and reliability of certain fuel cell systems has not been significantly demonstrated to the market.

Where R&D Efforts should be focused:

- Improve and optimize the structure and composition of the anodes to be compatible with natural gas
- Investigate the effects of sulfur-containing compounds and whether it is necessary to include a sulfur-removal step. Would also require a disposal system.
- Endurance and longevity
- Widespread utilization for distributed power generation

USES FOR TRANSPORTATION

Much like all-electric vehicles, fuel cell electric vehicles (FCEV) are propelled using electricity to power the electric motor. The main difference is that hydrogen is fed into a fuel cell to create the electricity, whereas an all-electric EV is fed electricity from a battery. The other byproduct of fuel cells, water, is emitted as water vapor and warm air. Similar to conventional internal combustion engine vehicles, FCEVs can be fueled in under five minutes and have a driving range over 300 miles. Since fuel cells can be stacked very easily, fuel cell technology can be scaled up for different vehicle types. (Union of Concerned Scientists, 2017)

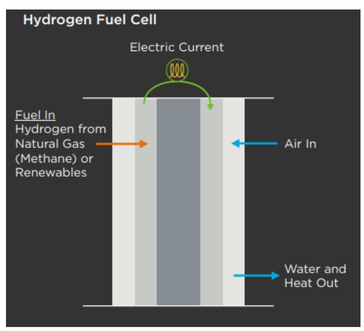

Figure 8 How a hydrogen fuel cell works

Unique Components of a FCEV

Hydrogen Fuel Tank:

Where the hydrogen is stored until it is needed by the fuel cell.

Fuel Cell Stack:

An assembly of individual membrane electrodes that use hydrogen and oxygen to produce electricity.

Electric Traction Motor:

This drives the vehicles wheels by using the power from the fuel cell and the traction battery pack.

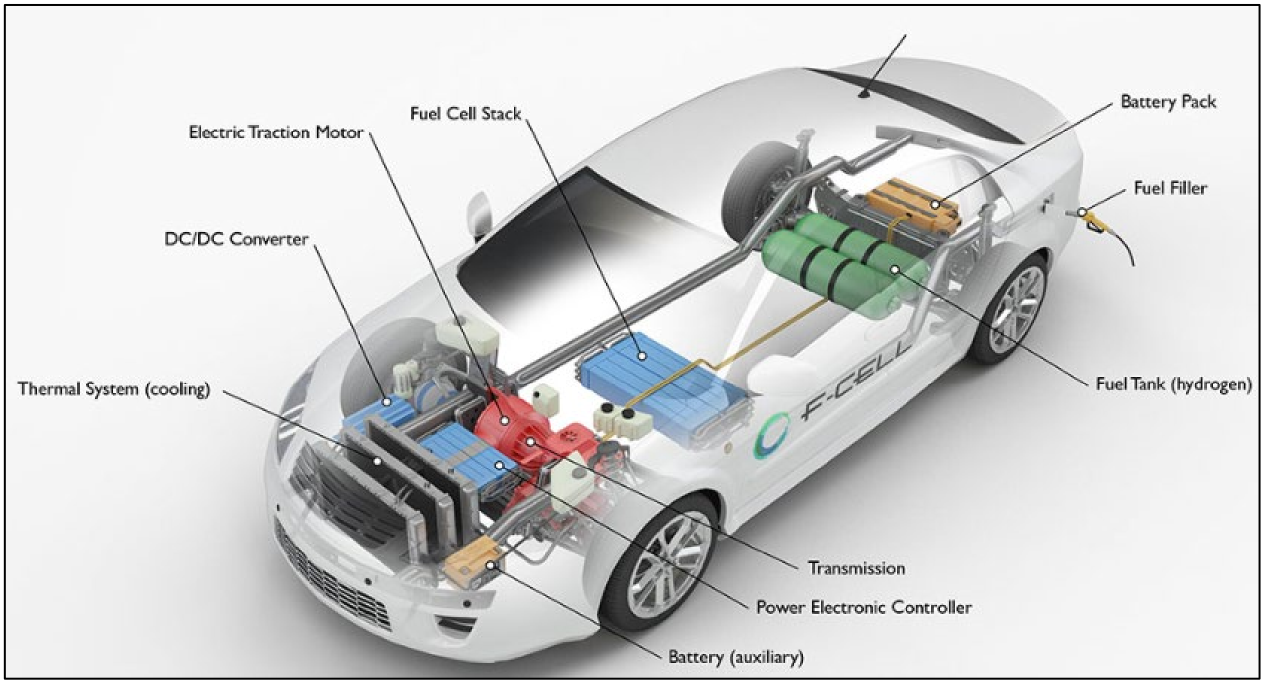

Figure 9 Illustration of a fuel cell vehicle (Energy Efficiency & Renewable Energy, 2018)

Biomethane used to power a battery and FCEV result in lower emissions of smog-forming nitrogen oxides (NO_x) compared to biomethane used in compressed natural gas (CNG) vehicles. Hydrogen is considered an alternative fuel under the Energy Policy Act of 1992 and qualifies for alternative fuel vehicle tax credits. It is commonly to find FCEVs with other advanced technologies to improve efficiency such as regenerative braking.

One of the downsides of FCEVs is the lack of hydrogen infrastructure for fueling.

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