Fuel Cells

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MSRE Program

CONVERTING NATURAL GAS AND RENEWABLE FUELS INTO HEAT AND ELECTRICITY
History

- **19th Century** - First fuel cell concept demonstrated by Humphry Davy.
- **1839** - William Grove invents gas voltaic battery that produces an electrochemical reaction between hydrogen and oxygen.
- **1950s-1960s** - NASA collaboration with the industrial creates fuel cell generators for manned space missions.
- **1980s** - Increase in R&D for fuel cell technology for transportation applications.
- **1990s** - CA Air Resource Board introduces **Zero Emission Vehicle Mandate**. Drives development and improvement in alternative powertrains (not improving internal combustion engine).
- **2000s** - Increased concern over energy security, efficiency and CO2 emissions drives investment into fuel cells as potential alternative energy source.
- **2007** - Fuel cells are commercialized and sold to end-users.
How do they work?

- Produces electricity electrochemically without combusting fuel
  - Gas enters fuel cell stack, reacts with oxygen and an electrolyte membrane to produce electricity, heat, H₂O and CO₂
  - Thermal energy and water by-products can be recycled and reused in the fuel processor
  - Harnessed thermal energy can be supplied to the customer for heating, cooling and making steam = Cogeneration (CHP)

**Fuel Processor:**
- Filters contaminants to purify methane and separates hydrogen from carbon in a process called reforming.

**Fuel Cell Power Section:**
- Hydrogen is then combined with oxygen to create an electric current (e-), water, heat and CO₂.

**Power Conditioner:**
- Converts DC power to usable AC "grid" power electric current

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### Fuel Cell Types

- Fuel cells are classified according to the nature of their electrolyte.
- Each type requires particular materials and fuel.
- Each fuel cell type also has its own operational characteristics, offering advantages to particular applications.
- This makes fuel cells a very versatile technology.

<table>
<thead>
<tr>
<th>Technology</th>
<th>MW Class</th>
<th>Sub-MW Class</th>
<th>Micro CHP</th>
<th>Mobile</th>
</tr>
</thead>
<tbody>
<tr>
<td>System size</td>
<td>Carbonate (MCFC)</td>
<td>Phosphoric Acid (PAFC)</td>
<td>Solid Oxide (SOFC)</td>
<td>PEM / SOFC</td>
</tr>
<tr>
<td>range</td>
<td>300kW – 2.8MW</td>
<td>400kW</td>
<td>up to 200 kW</td>
<td>&lt; 10 kW</td>
</tr>
<tr>
<td>Typical</td>
<td>Utilities, large</td>
<td>Commercial buildings – baseload</td>
<td>Commercial buildings – baseload</td>
<td>Residential and small commercial</td>
</tr>
<tr>
<td>Application</td>
<td>universities,</td>
<td></td>
<td></td>
<td>up to 100 kW</td>
</tr>
<tr>
<td></td>
<td>industrial – baseload</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel</td>
<td>Natural gas, Biogas, others</td>
<td>Natural gas</td>
<td>Natural gas</td>
<td>Natural gas</td>
</tr>
<tr>
<td>Advantages</td>
<td>High efficiency, scalable, fuel flexible &amp; CHP</td>
<td>Cogeneration-Combined Heat &amp; Power (CHP)</td>
<td>High efficiency</td>
<td>Load following &amp; CHP</td>
</tr>
<tr>
<td>Electrical</td>
<td>43%-47% (higher w/ turbine or organic rankine cycle)</td>
<td>40% – 42%</td>
<td>50% – 60%</td>
<td>25% – 35%</td>
</tr>
<tr>
<td>efficiency</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combined Heat &amp;</td>
<td>Steam, hot water, chilling &amp; bottoming cycles</td>
<td>Hot water, chilling</td>
<td>Depends on technology used</td>
<td>Suitable for facility heating</td>
</tr>
<tr>
<td>Power (CHP)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Benefits**

- **Absence of pollutants**
  - Ultra clean energy virtually absent of common emissions such as Nitrogen Oxide, Sulfur Oxide and particulate matter (PM).
  - Fuel cells release significantly less CO₂ compared to standard internal combustion-based power generators.

- **Greater electrical efficiency compared to average internal combustion generators**
  - Generates more power from a given unit of fuel compared to similar sized internal combustion-based power generator

### Fuel Source Emissions (Lbs./MWh)

<table>
<thead>
<tr>
<th>Fuel Source Emissions</th>
<th>NOX</th>
<th>SO2</th>
<th>PM10</th>
<th>CO2</th>
<th>CO2 with CHP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average U.S. Fossil Fuel Plant</td>
<td>5.06</td>
<td>11.6</td>
<td>0.27</td>
<td>2,031</td>
<td>NA</td>
</tr>
<tr>
<td>Direct Fuel Cell® Power Plant</td>
<td>0.01</td>
<td>0.0001</td>
<td>0.0002</td>
<td>940</td>
<td>520 – 680</td>
</tr>
<tr>
<td>Microturbine (60 kW)</td>
<td>0.44</td>
<td>0.008</td>
<td>0.09</td>
<td>1,596</td>
<td>520 – 680</td>
</tr>
<tr>
<td>Small Gas Turbine</td>
<td>1.15</td>
<td>0.008</td>
<td>0.08</td>
<td>1,494</td>
<td>520 – 680</td>
</tr>
</tbody>
</table>

*FuelCellEnergy.com, 2014*
**Benefits**

- **On-site distribution of energy**
  - Less dependent on energy from the “grid”.
  - Reduced risk of power outage due to natural disasters, brown-outs and black-outs
  - Avoids line power losses: 8-10% loss of line power when electricity is distributed over long distances

- **Reliable base load power**
  - Continuous operation as long as fuel is supplied

- **Fuel flexible**
  - Able to generate electricity from clean natural gas, renewable biogas or directed biogas, bio-diesel, propane, gasoline, coal-derived fuel and military logistics fuel.

- **Cogeneration = Combined Heat and Power (CHP)**
  - Produces electricity and heat from a single fuel source; up to 90% energy efficient.
  - Heat is typically generated by combustion-based boilers. Reducing the use of boilers reduces emissions of pollutants and CO₂ and decreases energy costs
Challenges

- **High Material Cost**
  - Precious metals → high cost for fabrication
  - Research & Development: redesign processes and formulations to reduce manufacturing costs

- **Location and Variability of Gas**
  - Gas varies from state to state and season to season
  - Highly specialized contaminant removal equipment needed to filter out specific contaminants
  - Anaerobic Digester, Land Fill Gas, Wastewater Treatment Facilities
    - Hydrogen sulfide, nitrogen, ammonia, oxygen, halogenated hydrocarbons, and organic silicon compounds.
    - Carbon dioxide content may range as high as 40% of the recovered gas
    - Sulfur contaminants may be as high as several percent.”¹

- **Contaminant removal cost**
  - Pipeline-quality natural gas = $400/kW
  - Renewable biogas (wastewater treatment facilities) = up to $3,000/kW

- **Other contaminants of concern**
  - Odorants added to natural gas for detection of gas leaks; adsorption & hydrodesulphurization (HDS) process can be costly
  - Cost for additional fuel processing equipment can amount to several thousands of dollars per kilowatt in first costs and operating costs.
    - First cost: the cost to manufacture, install and condition the fuel cell power plant
    - Operating cost: the cost to run and maintain the fuel cell power plant for the duration of its cell stack life

Bloom Energy: (1)Google, Apple, Wal-Mart, eBay, FedEx, Coca-Cola, Bank of America, La Jolla Commons II

- High tech: data centers and computer system rooms
- Hospitals: labs, biomedical facilities
- Supermarkets
- Hospitality: large hotels and medium-sized hotels, convention centers
- Big and small commercial business
- Large manufacturing complexes, utility/grid support, wastewater treatment facilities
- Used in both new properties and retrofit properties
- Airports

A willingness to pay much higher prices for the guarantee of high quality, uninterrupted power to protect very valuable IT equipment or life-supporting equipment
Cost & Maintenance
Molten Carbonate Fuel Cells (MCFC)

Cost breakdown for Fuel Cell Energy’s DFC-1500 power plant ~($4,200/kW):

- $5.9MM - $6.3MM
  - **Materials - ~$2,400/kW (57%)**
    - Increase power density by 30% = $330/kW cost reduction
  - **Overhead - ~$840/kW (20%)**
    - Conditioning, Installation & Commissioning - $700/kW
    - Economies of Scale: reduce costs by $200/kW
    - Manufacturing →30MW/year to 70MW/year = 20% cost reduction
  - **Balance of Plant - ~$1,100/kW (26%)**
    - Gas clean-up system, pre-reformer, process control system, heat exchangers, H2O management systems and power conditioning system

**Operations and Maintenance**

- DFC-1500 = **$445,000/year for 5 year stack life**
- Double stack life to 10 years will reduce costs by 40% = $267,000/year

Average cost of DFC 1500 at wastewater treatment plant or landfill = **$7,200/kW**

DFC-1500 mated to an anaerobic digester at a wastewater treatment plant requires custom-designed fuel clean up system = up to **$3,000/kW** to upgrade and clean fuel.

Competitive price for electricity = **$1,500/kW (installation cost)**
Cost & Maintenance
Solid oxide fuel cell (SOFC) - Bloom Energy
Federally subsidized

• Bloom Energy 400kW Fuel Cell facility cost is an estimated $4,000,000
  =$10,000 per kilowatt (installation cost)
• 400kW system = ~$425,000/year warranty/maintenance costs*

Competitive price for electricity = $1,500/kW (installation cost)

### Data source: GreenAppealed.com

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Bloom ES-5700 (235)</th>
<th>Advanced Combined Cycle Gas Turbine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>equal</td>
<td>equal</td>
</tr>
<tr>
<td>Efficiency</td>
<td>45.20%</td>
<td>61%</td>
</tr>
<tr>
<td>CO2 emissions (lbs/MWhr)</td>
<td>884</td>
<td>730</td>
</tr>
<tr>
<td>*Volatile Organic Compounds (lbs./day)</td>
<td>22.56</td>
<td>0.249</td>
</tr>
<tr>
<td>Cost of Electricity ($/MWh)</td>
<td>200</td>
<td>65.50</td>
</tr>
<tr>
<td>Capacity (MW)</td>
<td>47</td>
<td>350</td>
</tr>
</tbody>
</table>

*For the same amount of power generated Bloom vs. Advanced Combined Cycle Gas Generator*

### Site CO2 Emissions Comparison Summary

http://www.instituteforenergyresearch.org/2013/06/18/the-bloom-is-off-bloom-energy/

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Bloom System</th>
<th>Natural Gas Cogeneration Facility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical Output, kW</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Thermal Output, therms.hr.</td>
<td>0.0</td>
<td>7.0</td>
</tr>
<tr>
<td>Fuel Input, therms/hr.</td>
<td>6.61</td>
<td>12.8</td>
</tr>
<tr>
<td>Fuel Credit for Using Waste Heat to Reduce Site Boiler Natural Gas Usage, therms/hr.</td>
<td>0</td>
<td>-9.33</td>
</tr>
<tr>
<td>Net Site Fuel Use, Therms/Hr.</td>
<td>6.61</td>
<td>3.47</td>
</tr>
<tr>
<td>Operating Hours per year</td>
<td>7884</td>
<td>7884</td>
</tr>
<tr>
<td>Net Change in CO2 Site Emissions (Tons per Year)</td>
<td>98.2</td>
<td>(-22.8)</td>
</tr>
<tr>
<td>100 kw System Cost</td>
<td>$ 800,000</td>
<td>$ 300,000</td>
</tr>
</tbody>
</table>
Subsidies

► Self Generation Incentive Program (SGIP)-California (2001)
  ► Gives tax credits for using renewable energy technology
  ► Enacted to lower carbon emissions by promoting wind and solar
  ► Now includes fuel cells
  ► SGIP funds $3,450 per kW = 35% installation cost for renewable technology

► Federal Government = 30% tax credit for green technology
► We the People of California pay for 65% of the cost of fuel cells
Review - The future for fuel cells

- Find low-cost material alternatives
- Decrease dependency on non-renewable methane sources
- Continue R&D of contaminant removal technologies from renewable energy sources
- Increase power density, reduce complexity of integrated system, minimize temperature constraints
- Increased use as a technology (first costs and operating costs) improves efficiency, cell stack life and reduced GHGs.
- Economies of scale, streamline manufacturing process

Short Life Cycle
- Increase cell stack life from 5 years to 10 years
- Degradation: increase durability of existing component materials and/or create new materials with same essential properties, greater durability and performance

Efficiency of Technology
- Decrease cost per kW of existing technology → Increase power density by 20%
Questions?
Thank you
References


FuelCellEnergy.com

www.fuelcelltoday.com/about-fuel-cells/technologies/sofc

BloomEnergy.com

http://www.bloomenergy.com/fuel-cell/solid-oxide/


http://www1.eere.energy.gov/hydrogenandfuelcells/

U.S. Energy Information Administration, Independent Statistics & Analysis

http://www.eia.gov/totalenergy/data/monthly/index.cfm#electricity


Institute for Energy and Research

http://www.instituteforenergyresearch.org/2013/06/18/the-bloom-is-off-bloom-energy/
The Science and Economics of the Bloom Box: Their Use as a Source of Energy in California

http://franke.uchicago.edu/bigproblems/Team4-1210.pdf

http://www.fuelcelltoday.com/about-fuel-cells/history

National Renewable Energy Laboratory

http://www.nrel.gov/learning/eds_hydro_fuel_cells.html

National Fuel Cell Research Center, UC-Irvine

http://www.nfrcrc.uci.edu/3/FUEL_CELL_INFORMATION/FCexplained/challenges.aspx

GreenExplored.com

http://www.greenexplored.com/search?q=fuel+cells


Things to think about...

Lindsey Leveen, a chemical engineer, reviewed Bloom’s permit application to the Delaware PSC.

**Bloom’s fuel cells emit 90 times more volatile organic compounds (VOCs) per day than a combined cycle natural gas power plant.** VOCs cause numerous adverse health effects, including headaches, nausea, and liver damage in humans and cancer in animals.

**Bloom Boxes produce more CO2 emissions than advanced natural gas facilities.**

**Bloom Boxes cost** more than **$200 per MWh** of electricity delivered to the grid and **emit 884 pounds** of CO2/MWh.

Advanced combined cycle natural gas plants cost **$65.60 per MWh** and emits only **730 pounds** of CO2 per megawatt-hour (Energy Information Administration)

http://www.instituteforenergyresearch.org/2013/09/23/the-bloom-energy-rip-off/
Bloom Fuel Cells came on the market in 2008

**California Public Utilities Commission (CPUC)**
As of June 25, 2013

<table>
<thead>
<tr>
<th>Type of Fuel Cell</th>
<th>Projects</th>
<th>Kilowatts</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Electric Only Fuel Cells</td>
<td>209</td>
<td>103,657</td>
<td>$349,867,856</td>
</tr>
<tr>
<td>All Bloom Fuel Cells</td>
<td>153</td>
<td>74,587</td>
<td>$257,310,790</td>
</tr>
<tr>
<td>Bloom Energy % of Total</td>
<td>73.20%</td>
<td>72.00%</td>
<td>73.50%</td>
</tr>
</tbody>
</table>
Commercial Sector Electricity Net Generation (1989-2012)
Commercial Sector Energy Consumption (1949-2012)

U.S. Energy Information Administration
January 30th, 2014

Commercial Sector Energy Consumption (1949-2012)

TRILLION BTU

Annual Total    Coal    Natural Gas    Petroleum    Total Fossil Fuels
Cost per Kilowatt hour for Bloom Fuel Cells as Gas Prices increase

The Science and Economics of the Bloom Box: Their Use as a Source of Energy in California
Institute of Energy Research 2013

Capital Costs of Selected Generating Technologies
(2012$ per KW)

http://www.instituteforenergyresearch.org/2013/05/03/eia-provides-updated-capital-cost-estimates-for-electric-generating-plants/
Fuel Cell Power Plant

- Produces electricity electrochemically without combusting fuel
- Gas enters fuel cell stack, reacts with oxygen to produce electricity, heat, H₂O and CO₂
- Thermal energy and water by-products can be recycled and reused in the fuel processor
- Fuel cells continue to generate energy as long as fuel is supplied
How do they work?

- Hydrogen fuel cells feed hydrogen-rich gas into an electrode that contains a catalyst, such as platinum, which helps to break up the hydrogen molecules into positively charged **hydrogen ions** (H⁺) and negatively charged **electrons** (e⁻). The electrons flow from the electrode to a terminal that connects to an external circuit, creating an electrical current.

- Electrons flow from the external circuit into this other electrode to complete the electrical circuit.

- Meanwhile, the hydrogen ions pass through an **electrolyte**—a conductive material—to reach the other electrode, where they combine with oxygen to form water.

- These "cells" are assembled together to form a "stack," which combines the voltage of the individual cells to form a high-voltage fuel cell.
Fuel Cell Power Section-continued

Fuel Cell Stack basics

1. Hydrogen fuel is channeled through field flow plates to the anode on one side of the fuel cell, while oxygen from the air is channeled to the cathode on the other side of the cell.

2. At the anode, a platinum catalyst causes the hydrogen to split into positive hydrogen ions (protons) and negatively charged electrons.

3. The Polymer Electrolyte Membrane (PEM) allows only the positively charged ions to pass through it to the cathode. The negatively charged electrons must travel along an external circuit to the cathode, creating an electrical current.

4. At the cathode, the electrons and positively charged hydrogen ions combine with oxygen to form water, which flows out of the cell.

#### Comparison of Fuel Cell Technologies

<table>
<thead>
<tr>
<th>Fuel Cell Type</th>
<th>Common Electrolyte</th>
<th>Operating Temperature</th>
<th>Typical Stack Size</th>
<th>Efficiency</th>
<th>Applications</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymer Electrolyte Membrane (PEM)</td>
<td>Perfluoro sulfonic acid</td>
<td>50-100°C 122-212° typically 80°C</td>
<td>&lt;1kW-100kW</td>
<td>60%</td>
<td>Backup power Portable power Distributed generation Transportation Specialty vehicles</td>
<td>Solid electrolyte reduces corrosion &amp; electrolyte management problems Low temperature Quick start-up</td>
<td>Expensive catalysts Sensitive to fuel impurities Low temperature waste heat</td>
</tr>
<tr>
<td>Alkaline (AFC)</td>
<td>Aqueous solution of potassium hydroxide soaked in a matrix</td>
<td>90-100°C 194-212°F</td>
<td>10-100 kW</td>
<td>60%</td>
<td>Military Space</td>
<td>Cathode reaction faster in alkaline electrolyte leads to high performance Low cost components</td>
<td>Sensitive to CO₂ in fuel and air Electrolyte management</td>
</tr>
<tr>
<td>Phosphoric Acid (PAFC)</td>
<td>Phosphoric acid soaked in a matrix</td>
<td>150-200°C 302-392°F</td>
<td>400 kW 100 kW module</td>
<td>40%</td>
<td>Distributed generation</td>
<td>Higher temperature enables CHP Increased tolerance to fuel impurities</td>
<td>Pt catalyst Long start up time Low current and power</td>
</tr>
<tr>
<td>Molten Carbonate (MCFC)</td>
<td>Solution of lithium, sodium, and/or potassium carbonates, soaked in a matrix</td>
<td>600-700°C 1112-1292°F</td>
<td>300 kW-3 MW 300 kW module</td>
<td>45-50%</td>
<td>Electric utility Distributed generation</td>
<td>High efficiency Fuel flexibility Can use a variety of catalysts Suitable for CHP</td>
<td>High temperature corrosion and breakdown of cell components Long start up time Low power density</td>
</tr>
<tr>
<td>Solid Oxide (SOFC)</td>
<td>Yttria stabilized zirconia</td>
<td>700-1000°C 1202-1832°F</td>
<td>1 kW–2 MW</td>
<td>60%</td>
<td>Auxiliary power Electric utility Distributed generation</td>
<td>High efficiency Fuel flexibility Can use a variety of catalysts Solid electrolyte Suitable for CHP &amp; CHHP Hybrid/GT cycle</td>
<td>High temperature corrosion and breakdown of cell components High temperature operation requires long start up time and limits</td>
</tr>
</tbody>
</table>
## Cost Breakdown

### Cost for Fuel Cell Energy Power plants

<table>
<thead>
<tr>
<th>Plant</th>
<th>Cost</th>
<th>$/kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>DFC-300</td>
<td>$1.7MM</td>
<td>$5,500</td>
</tr>
<tr>
<td>DFC-1500</td>
<td>$5.9MM</td>
<td>$4,200</td>
</tr>
<tr>
<td>DFC-3000</td>
<td>$10.0MM</td>
<td>$3,500</td>
</tr>
</tbody>
</table>

*Including installation*

<table>
<thead>
<tr>
<th>Plant</th>
<th>Cost</th>
<th>$/kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>DFC-1500 Operation &amp; Maintenance</td>
<td>$445,000/year</td>
<td>5 year cell stack life</td>
</tr>
</tbody>
</table>

### Opportunities for MCFC Cost Reduction (Fuel Cell Energy)

<table>
<thead>
<tr>
<th>Opportunity Area (year)</th>
<th>2020</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Gas Cleanup BOP</td>
<td>200</td>
<td>300</td>
</tr>
<tr>
<td>Volume Production of Module</td>
<td>440</td>
<td>600</td>
</tr>
<tr>
<td>Power Density Increase</td>
<td>330</td>
<td>330</td>
</tr>
<tr>
<td>BOP Volume Production</td>
<td>200</td>
<td>400</td>
</tr>
<tr>
<td>Conditioning and Installation</td>
<td>200</td>
<td>500</td>
</tr>
<tr>
<td>Total Potential Cost Reductions</td>
<td>1,370</td>
<td>2,130</td>
</tr>
</tbody>
</table>

### DFC-1500 Cost Breakdown

<table>
<thead>
<tr>
<th>Cost Component</th>
<th>$/kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Cell Module</td>
<td>2,400</td>
</tr>
<tr>
<td>Balance of Plant (BOP)</td>
<td>1,100</td>
</tr>
<tr>
<td>Conditioning, Installation &amp; Commissioning</td>
<td>700</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>4,200</strong></td>
</tr>
</tbody>
</table>

BOP costs include the gas cleanup system, a small pre-reformer, the process control system, all heat exchangers and water management systems, and the power conditioning section.

*Competitive Price for Electricity (2030)*: 2,000
Fuel Cell Energy
DFC-1500 Cost Reduction - competitive by 2030

Reduction in First Costs for DFC Units

- ADG/LFG Clean Up

Cost Reduction is a Combination of:
- Stack R&D
- BOP improvements
- Increased Volume
- Advances in fuel cleanup technology

<table>
<thead>
<tr>
<th>Year</th>
<th>MW/year</th>
<th>$/kW Installed</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>30</td>
<td>10,000</td>
</tr>
<tr>
<td>2020</td>
<td>100-200</td>
<td>7,000</td>
</tr>
<tr>
<td>2030</td>
<td>500-1000</td>
<td>4,000</td>
</tr>
</tbody>
</table>
Tulare County, California
38% of electricity from on-site green resources
$4 Million dollar incentive
$3 million City investment
Estimated savings of $570,000
~5 years to recoup costs