U.S. DEPARTMENT OF ENERGY

Fuel Cells for Distributed Generation (DG)

Fuel Cell Technologies Program

June 7, 2011

Boulder, CO

Fuel Cells: Technology Characteristics

Significant reduction in GHGs (~0.4 kg per kWh) and 95% reduction in other emissions relative to using electricity from the U.S. grid

- High electrical efficiencies, no transmission losses
- Heat can be recovered to displace natural gas boilers (DG in combined-heat-and-power mode)
- With credit for recovered heat, lower greenhouse gas emissions per kWh than most regional electric grids
- Virtual elimination of criteria pollutant emissions (NOx, SOx, particulates)
- Future: transition from using natural gas and existing biogas sources to using hydrogen from low-carbon sources (e.g., photo-biological).

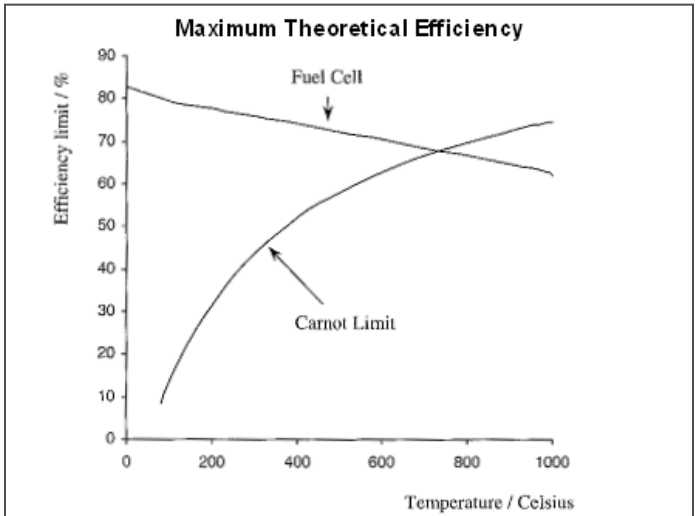
Fuel Cells vs. Combustion

Fuel cells are not heat engines, so their efficiency can exceed the Carnot efficiency

Conventional engines and turbines convert chemical energy into thermal energy prior to conversion to electrical energy. The efficiency of converting thermal energy to electrical energy is bounded by the Carnot efficiency.

$$\text{Carnot Efficiency} = \left(1 - \frac{T_C}{T_H}\right) \times 100\%$$

T_C = temperature at which waste heat is rejected
T_H = temperature of available heat



Adapted from Larminie and Dicks, Fuel Cell Systems Explained, 2000

Fuel cells convert chemical energy directly into electrical energy, bypassing inefficiencies associated with thermal energy conversion. The available energy is equal to the Gibbs free energy.

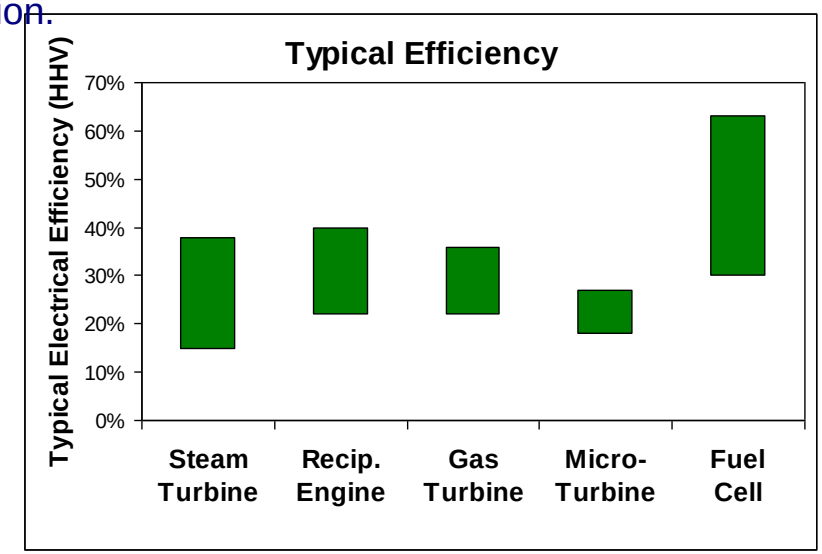
$$\text{Maximum Fuel Cell Efficiency} = \frac{\Delta G_f}{\Delta H_f} \times 100\%$$

ΔG_f = free energy of formation of H_2O from H_2 and O_2
ΔH_f = enthalpy of formation of H_2O from H_2 and O_2 (higher heating value)

Theoretical fuel cell voltage is directly proportional to ΔG_f.

$$V = \frac{\Delta G_f}{nF}$$

n = number of electrons transferred (2 for H_2)
F = Faraday constant



Source: EPA, Catalog of CHP Technologies, December 2008

Market Status for DG Fuel Cells

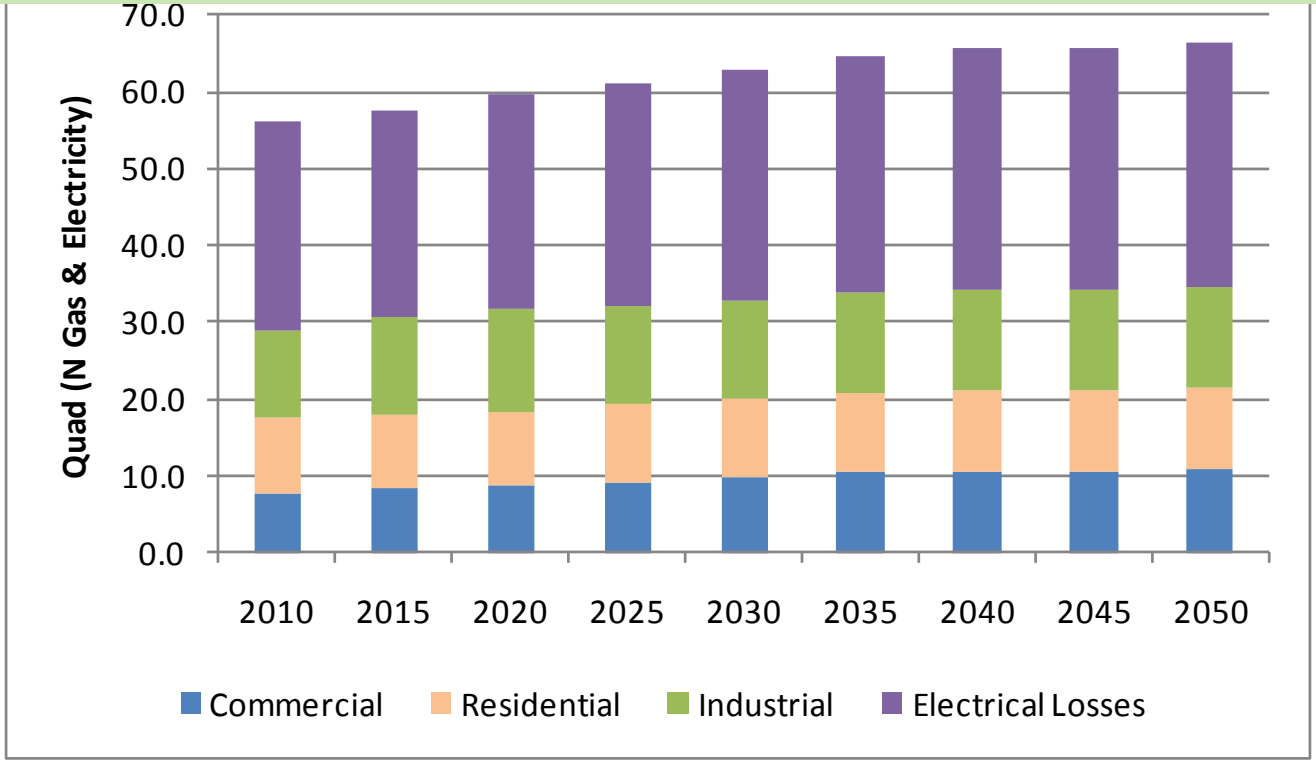
Rapid growth in recent years but incentives need to continue until the early 2020's

- Preliminary estimate of current installed capacity: 130-170 MW World, 50-70 MW in U.S.
- U.S. production for domestic and foreign markets: 2005: 10 MW; 2010: 68 MW
- Market value of world's annual production: 2010: $350 million; projected 2017: $ 9 billion

Sources: Pike Research, ORNL, industry reports

U.S. Energy Markets for Distributed Generation

- Electricity and thermal energy (based on natural gas) used in U.S.: over 50 quads per year (including electrical losses)
- Electric grid with 20% renewables will need 200 GW of peaking capacity
- DG fuel cells in CHP mode and fuel cells used for grid support can displace some of this energy consumption and meet part of the renewables support storage need.



Through 2035: Annual Energy Outlook 2011 by EIA; simple extrapolation from EIA beyond 2035

Market Landscape – Stationary (DG+backup power) Transport and Portable Fuel Cells

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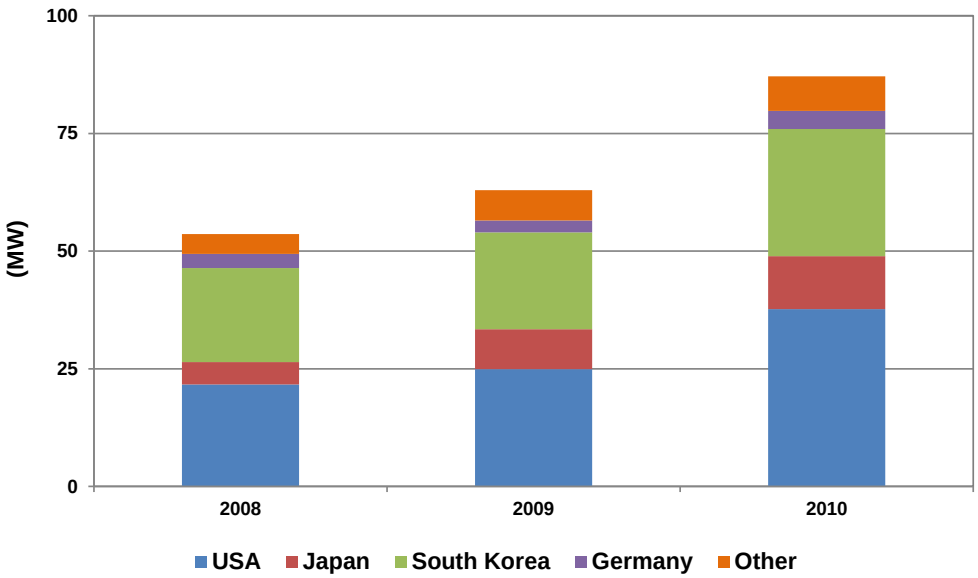
Fuel cell market continues to grow
- ~36% increase in global MWs shipped in 1 year
- ~50% increase in US MWs shipped

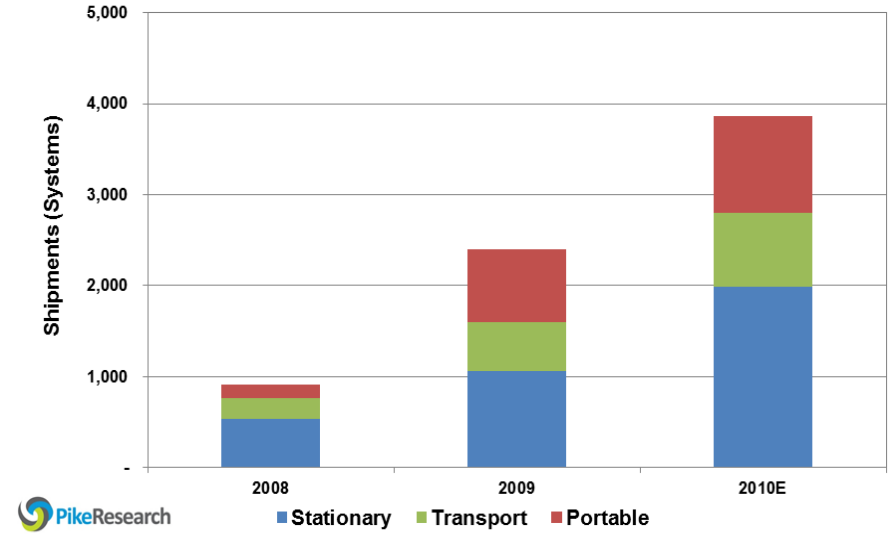
Megawatts Shipped, Key Countries: 2008-2010



FuelCell2000, Pike Research, Fuel Cell Today, ANL

In May 2011 POSCO Power (Korea) ordered 70 MW from a Connecticut fuel cell company for $130 M in hardware and services. POSCO will assemble the imported hardware into complete fuel cell systems. The POSCO plant has a capacity of 100 MW per year

North American Shipments by Application



http://www.fuelcells.org/BusinessCaseforFuelCells.pdf
http://www.fuelcells.org/StateoftheStates.pdf

Example of Early Market: the food industry is an emerging market for fuel cells

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Announced Supermarket Deployments: Nine Sites Include

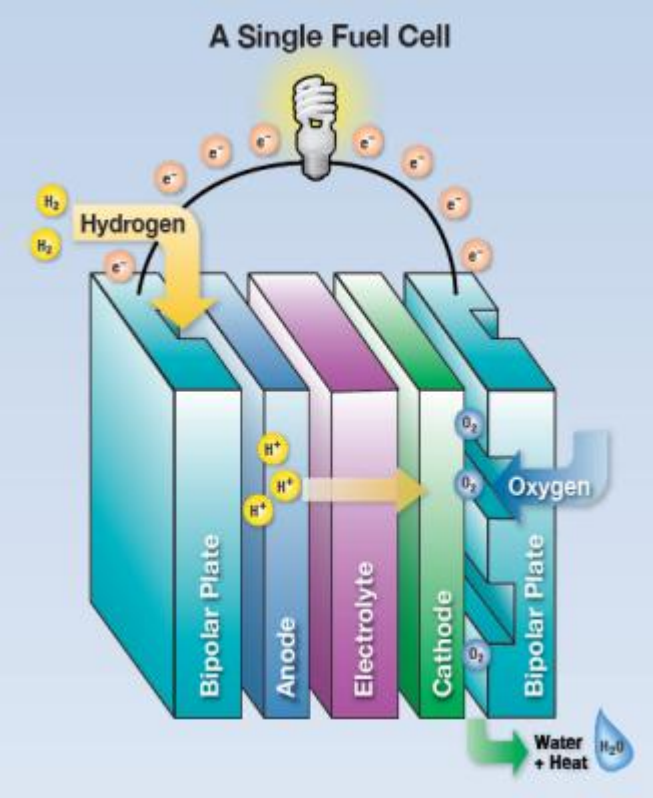
- **Whole Foods (CA,CT,MA)**
  - **3 sites, 400kW each**
- **Price Chopper (NY,CT)**
  - **3 sites, 400kW each**
- **SUPERVALU (MA,CA)**
  - **2 sites, 400kW each**
- **Ahold (CT, Stop & Shop)**
  - **1 site, 400kW**

Completed Food Producer Deployments:

- **Coca-Cola (NY, 800 kW) – another 800 kW under construction**
- **Gills Onions (CA, 600 kW)**
- **Pepperidge Farms (CT, 1.45 MW)**
- **Sierra Nevada Brewery (CA, 1 MW)**

A 400-kW fuel cell (grey box) meets 85 percent of the energy needs of this Price Chopper supermarket in Albany. The installation reduces the building's carbon footprint by 71 tons, provides energy security for perishable items, and saves more than 4 million gallons of water each year. *(Photo taken from the Executive Summary of the New York State Climate Action Plan Interim Report)*

Overview of Fuel Cell Technologies

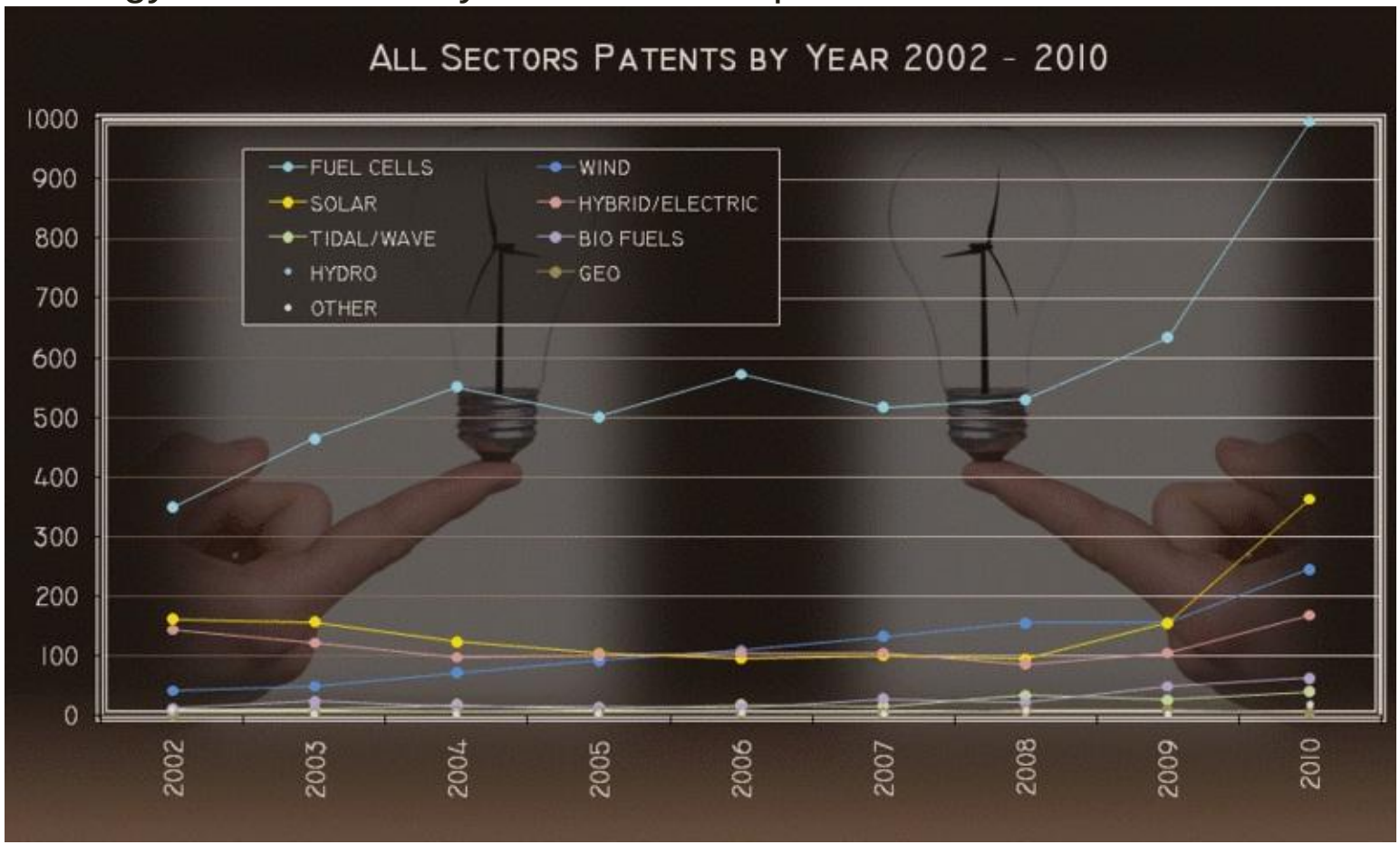


Types of Fuel Cells

- **Polymer Electrolyte Membrane (PEMFC)**
  - *Pros:* Low-temperature operation, quick start, and high power density
  - *Cons:* Expensive catalysts
  - *Applications:* Distributed generation, specialty vehicles, transportation, portable power
- **Phosphoric Acid Fuel Cell (PAFC)**
  - *Pros:* Low-temperature operation and high efficiency
  - *Cons:* Low current and power density
  - *Applications:* Distributed generation
- **Solid Oxide Fuel Cell (SOFC)**
  - *Pros:* High efficiency, multiple fuel feedstocks, usable waste heat, and inexpensive catalysts
  - *Cons:* Slow start-up and corrosion issues
  - *Applications:* Auxiliary Power Units (APUs) and distributed generation
- **Molten Carbonate Fuel Cell (MCFC)**
  - *Pros:* High efficiency, multiple fuel feedstocks, and usable waste heat
  - *Cons:* Slow start-up and corrosion issues
  - *Applications:* Distributed generation

Fuel Cell Patents in the Lead

Clean Energy Patent Growth Index: fuel cell patents lead in the clean energy field with nearly 1,000 fuel cell patents worldwide in 2010

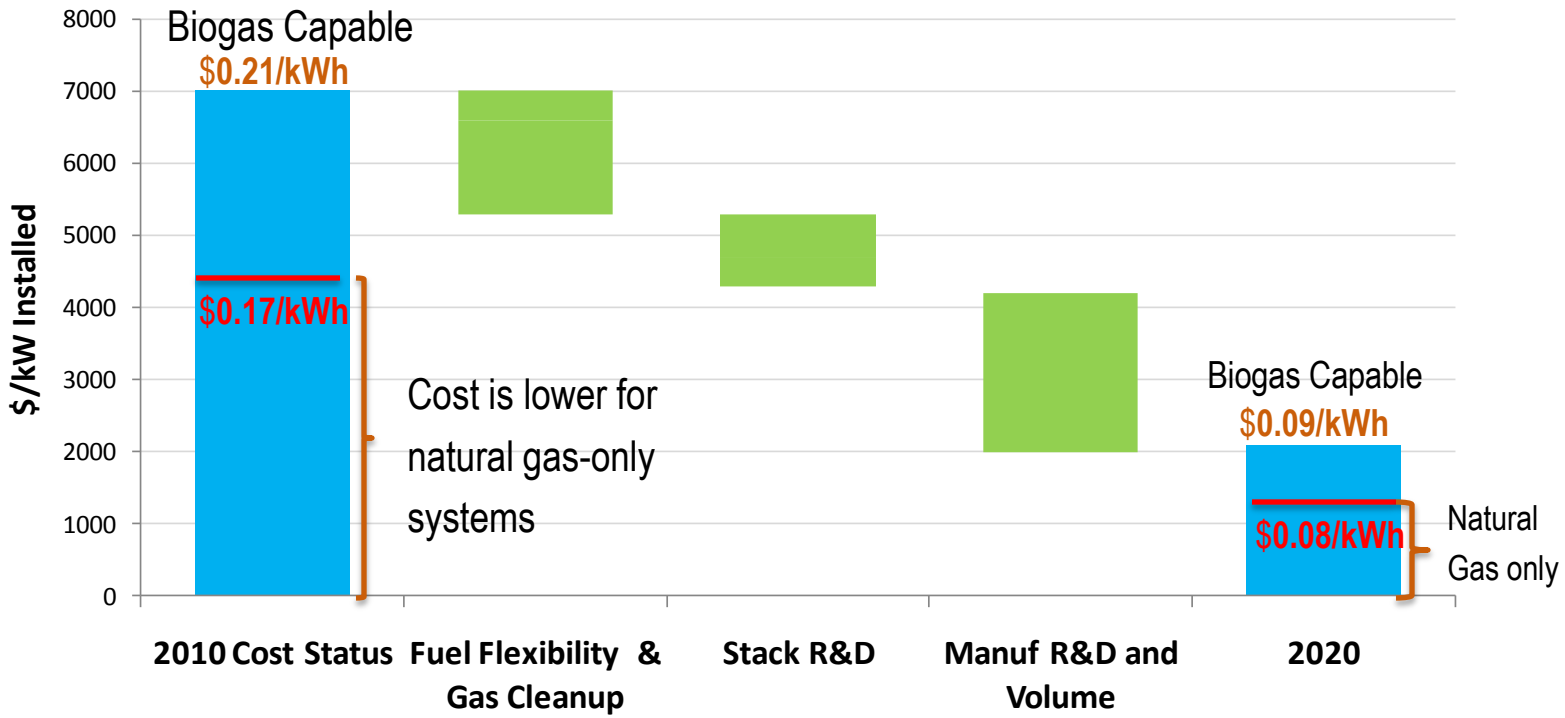


Cost Reduction Potential

- Durability could be increased by 50% to 100% for certain fuel cells (PEMFC, MCFC, SOFC) through R&D, resulting in electricity cost being reduced by up to 12%
- R&D on gas clean-up could reduce capital costs by up to 25% for biogas fuel cell systems
- Large volume production and manufacturing technology advances could reduce capital costs by over 50% from current production level and manufacturing technology
- Fuel cell stack: reducing platinum loading by 50% and improved manufacturing methods could bring system costs down by at least 10% for PEMFCs and PAFCs

Cost Targets for DG Fuel Cell Systems

Costs are expected to come down through R&D, scale, and advanced manufacturing technology.



Biogas contains impurities that must be removed before it can be used in fuel cells. The gas cleanup equipment and operation result in incremental costs beyond those associated with systems that use only natural gas

Portfolio of DG Fuel Cell Activities

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The FCT Program has a well balanced portfolio of RD&D activities

- Develop improved fuel cell catalysts and membrane electrolytes
- Identify degradation mechanisms and approaches for mitigating the effects
- Characterize and optimize transport phenomena improving membrane electrode assembly and stack performance
- Investigate and quantify effects of impurities on fuel cell performance
- Develop low-cost, durable system balance-of-plant components, including fuel processor sub-systems
- Develop advanced manufacturing technology and diagnostics
- Develop innovative concepts leading to a new generation of fuel cell technologies
- Develop and demonstrate compact fuel cell systems for micro-CHP applications

DOE and Performers' Potential Roles

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Pre-competitive research: typically national labs, universities and/or technology developers (Office of Science funds some of the work)

(other companies may opt to participate in a pre-competitive research initiative)

Stack & balance-of-plant components
Manufacturing process & diagnostics technology
Effect of impurities on performance
Innovative concepts

(companies may access these advances through arrangements such as licensing)

Cost-shares with fuel cell manufacturers: R&D on specific technology pathways

Improved durability & performance and reduced costs for proprietary fuel cell technologies

Fuel cell manufacturers have option to subcontract or partner with universities, national labs, or technology developers

National lab support for testing & validation

DOE activities re. outreach, codes & standards, & market transformation

Fuel cell manufacturers deliver fuel cells to technology end-users

In early deployment phase, national labs would support testing & validation (using DOE funds) and assist DOE in identifying additional R&D needs

Annual Merit Review with independent input allows DOE to decide on future funding of pathways, based on progress and national needs.

Additional Slides

Major Types of Fuel Cells: Operating Temperature Considerations

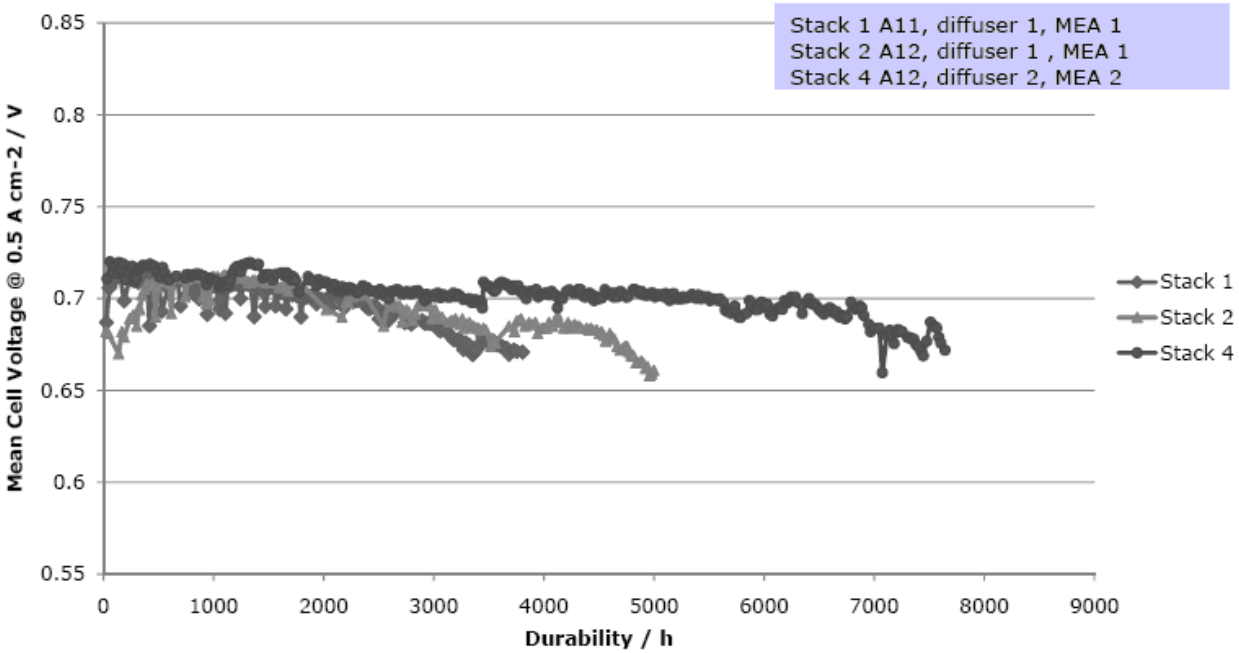
Higher temperature exhaust is more advantageous for displacing conventional natural gas boilers. However, very high temperatures can affect durability of fuel cell stack.

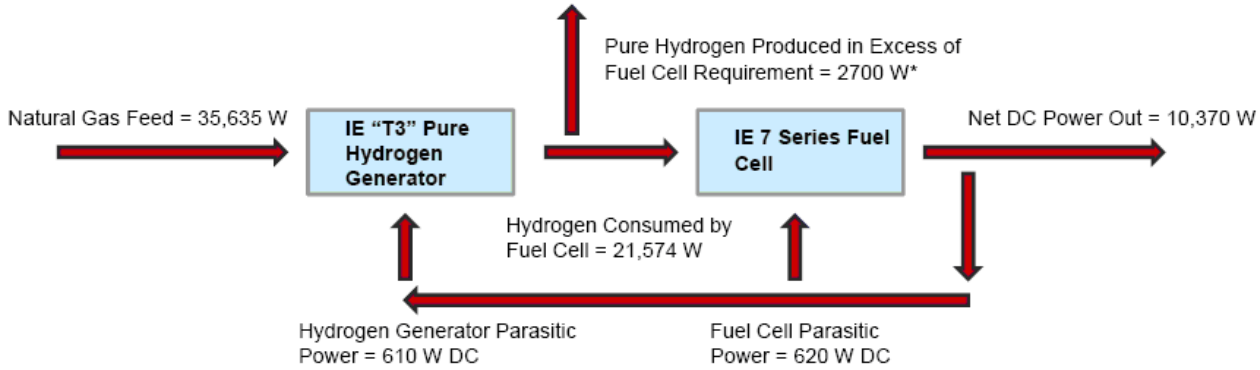
- Phosphoric acid fuel cells (PAFCs): 150° – 200°C
- Molten carbonate fuel cells (MCFCs): 600° – 700°C
- Polymer electrolyte membrane fuel cells (PEMFCs): 50° – 100°C
- Solid oxide fuel cells (SOFCs): 700 ^{o}- 1000 ^{o}C

Not considered for this QTR:

Alkaline fuel cells (highly susceptible to CO_2 poisoning) and microbial fuel cells (longer term; not enough data)

Example of Progress: Intelligent Energy improved durability and increased efficiency of PEMFC systems





- IE system uses reformer, pressure swing adsorption to supply pure H_2 to fuel cell stack
- 33% electrical efficiency and 61%CHP efficiency demonstrated in unoptimized system
- Implementation of adsorption-enhanced reformer expected to increase efficiency
- Over 7000 hours durability demonstrated in 20-cell stack

Durai Swamy et al., "Development and Demonstration of a New-Generation High Efficiency 1-10 kW Stationary Fuel Cell System"

Example of Progress: Industry improved performance and durability of SOFC systems

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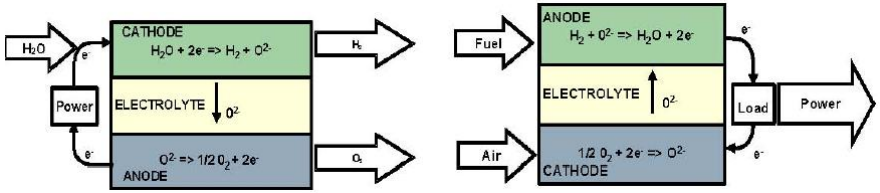
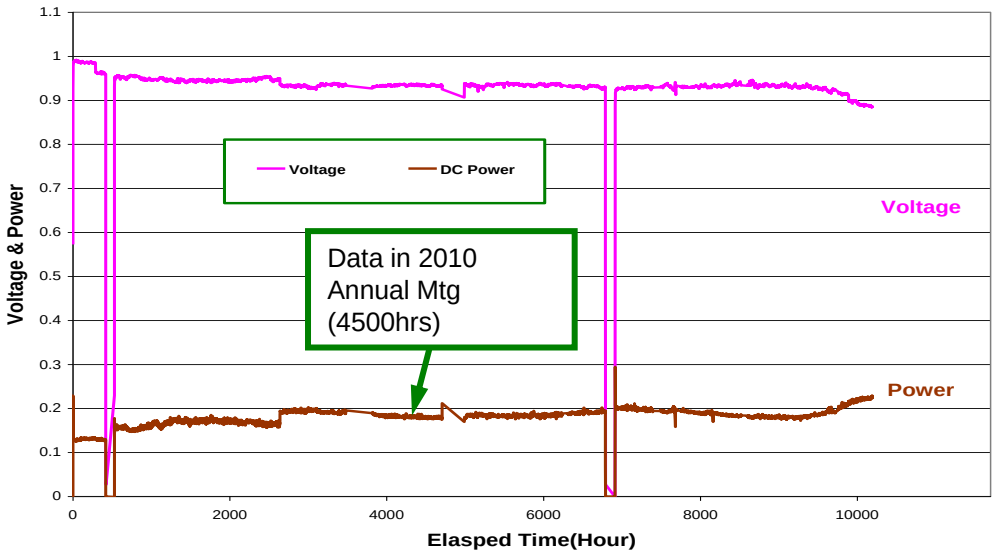
Reversible SOFCs under development at Versa Power Systems provide hydrogen generation and energy storage capability

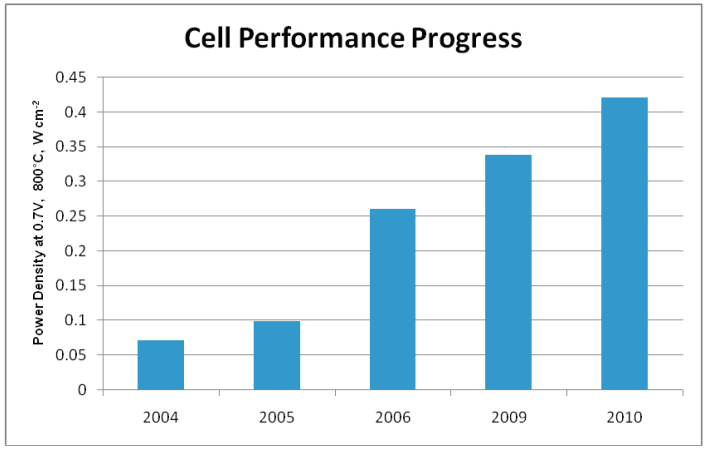


Metric	Target	Status
☑ **Performance** (Area specific resistance in both SOFC and SOEC operating modes)	< 0.3 Ω-cm²	0.223 Ω-cm² in SOEC 0.224 Ω-cm² in SOFC
☑ **Degradation** (Overall decay rate)	< 4% per 1000 hours	~1.5% per 1000 hours
☑ **Operating Duration**	> 1000 hours	1005 hours (as of Go/No-Go Decision)
☑ **Operating Current Density**	> 300 mA/cm²	500 mA/cm²

R. Petri et al., Versa Power Systems



Acumentrics achieved more than 10,000 hours operation of an SOFC in 2011 – more than double the 2010 durability



Cell power increased 6X from 2004 to 2010

N. Bessette et al., Acumentrics