Fuel Cells For a More Sustainable Energy Future

Calit2 - Clean Energy Challenge: Illuminating Environmentally Progressive Technologies

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Outline

• What makes a fuel cell different?
• How can fuel cells be used to increase sustainability?
• Recommended roles and convergence concept
• Summary
Traditional Energy Conversion RedOx Reactions

Traditional energy conversion device (combustion)

\[ \text{CH}_4 + 2 \text{O}_2 \rightarrow \text{CO}_2 + 2 \text{H}_2\text{O} \]

Reduction and Oxidation occur at the same place & time

-8 e⁻

Formal Valence:

\begin{align*}
\text{C:} & \quad -4 & +4 \\
\text{O:} & \quad 0 & -2 & -2
\end{align*}

High temperature
Heat energy
Pollutants

Random electron motion
Fuel Cell RedOx Reactions

Fuel cell energy conversion device

\[ \text{CH}_4 \rightarrow \text{O}_2 \rightarrow \text{Load} \]

Reduction and Oxidation separated in space:

Oxidation: \[ \text{CH}_4 + 2 \text{H}_2\text{O} \rightarrow \text{CO}_2 + 8 \text{H}^+ + 8 \text{e}^- \]

Reduction: \[ 2 \text{O}_2 + 8 \text{e}^- + 8 \text{H}^+ \rightarrow 4 \text{H}_2\text{O} \]

Formal Valence:
- $\text{C}$: $-4$ \hspace{2cm} + 4
- $\text{O}$: 0 \hspace{2cm} $-2$ \hspace{2cm} $-2$

Various temperatures
Electrical Work

Ordered electron flow – useful work
Fundamental Difference Leads to Benefits

Environment:
• Hydrogen fuel cells produce only water by-product
• Compared to HC combustion: NO\textsubscript{x}, SO\textsubscript{x}, CO, HC, CO\textsubscript{2}, lower
• Fuel cells, at same scale, are more energy efficient (use less fuel, less emissions per unit of useful work)
• Can contribute to energy sustainability (variety of fuels, including renewable fuels)

Energy Security, Independence:
• Fuel cells can operate on & hydrogen can be made from domestic sources of primary energy:
  • Natural gas
  • Electricity (renewable or grid)
  • Oil
  • Coal

Economics:
• Cheap sources of fuel (energy source and carrier) may be running out (~20-50 years)
• Capital cost of fuel cell today is the major barrier to widespread use
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GHG & Sustainability Depend on Primary Energy

Primary Energy: All We Use Comes from the Sun

- Millions of years
  - Fossil energy sources: Coal, natural gas, mineral oil

- Month / years
  - Biomass: Wood, vegetable oils, alcohol

- Weeks
  - Hydro-electro power

- Hours / days
  - Wind energy

- Direct
  - Solar heat, solar electricity

“Energy sustainability requires use of resources at the same rate at which they are naturally replenished on earth without externalities”

Courtesy: BMW Group, 2000
We should use more Solar and Wind Power!

Solar Power: PV, dish Stirling, solar-thermal
• Widely available “peaking” resource
• Challenges: COST, land use, water use, remote

Wind Power: becoming popular (tariffs, cost effective)
• Challenges: Intermittency and non-coincidence with peak demand, remote, aesthetics, bird kills

Figure 5.2: California ISO Wind Generation during the 2006 Heat Wave
Increasingly Require ‘Complementary’ Power

**Fuel Cell Stationary Power** – Commercially viable in many applications; continuous ‘dispatchable’ power; modular; low emissions; high efficiency; CHP; natural gas & renewable fuels

- CA State Northridge
- San Diego Sheraton, CA
- Sierra Nevada Brewery, California
- King County, WA
- Early DFC 1500®, Danbury, CT
- Santa Rita Jail, CA
Dynamic Renewable FC Power is Possible

Renewable Integrated Fuel Cell Systems

- Solar Residential
- Wind / Hydrogen fuel

Key Components:
- Hydrogen
- Hydrogen Production To Storage
- PEM Reversible Fuel Cell / Electrolyzer
- Zero-Emissions Dispatchable Power

System Breakdown:
- Hydrogen Storage
- PEM Reversible Fuel Cell / Electrolyzer
- Hydrogen to Power Generation
- Hydrogen

Power Generation Chart:
- PV Power
- 7.9 kW EZ Power (In)
- 4.2 kW FC Power (Out)
- Grid Power

System Performance:
- System Cost: $42,000.00
- H2 Produced: 50.9 kWh
- kW Peak RFC: 8.1 kW
- RFC Round Trip Eff.: 57%
- System Eff.: 71%

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Future FC Central Power

IGFC Cycle Enables CO₂ separation and Hydrogen Co-Production

100 MW class 65% mixed efficiency
We Also Need a Low GHG Transport Solution

Comparison of Alternative Fuels & Transport Options

Miles per Gallon (MPG) of Gasoline Equivalent

- RFG3, ICEV, 2002 CAFE MIX
- RFG3, IC Engine Vehicle
- RFG3, Hybrid EV
- RFG3, Lightweight, Small Hybrid EV
- RFG3, Plug-In Hybrid EV
- Ultra Low Sulfur Diesel, ICEV
- LPG, ICEV
- CNG, ICEV
- Ethanol 85%, ICEV
- Methanol 100%, Fuel Cell Vehicle
- cH2, Fuel Cell Vehicle
- Battery Electric Vehicle

From: Jackson, TIAx, 2003
So We Should Use More Electricity In Transport

Major Challenges (battery limitations):

- Low energy density compared to gasoline limits range
- Slow charging leads to long "refueling" time
- Lack of infrastructure
Perhaps Hybrid Technology Can Ease Transition

Current UCI Research on Plug-in Hybrid Electric Vehicles (PHEV)

• Toyota, Horiba, UCB, and CA Air Resources Board partners
• Testing two prototype plug-in Prius vehicles
• Vehicle emission standards (including grid emissions)
• Grid interaction/impacts
• Air quality impacts
Ultimately Some FC Use in Transport is Key

CO$_2$ Emissions (Gasoline Vehicle = 1)

Gasoline Vehicle
Diesel Vehicle
Gasoline HV
Gasoline HV Future
Diesel HV Future
FCHV (Natural gas $\rightarrow$ Hydrogen; current status)
FCHV (Natural gas $\rightarrow$ Hydrogen)
FCHV (Coal $\rightarrow$ Hydrogen)
FCHV ($\text{H}_2\text{O}$$\rightarrow\text{H}_2$ by Natural energy)
FCHV (Biomass)

Well to Tank CO$_2$
Tank to Wheel CO$_2$

Courtesy: Reinert, Toyota, May, 2003

Toyota’s Calculation; 10-15 mode, Hydrogen fueled FCHV

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Fortunately FC Vehicle Progress is Tremendous

Fuel Cells – All major auto manufacturers pursuing

GM_Opel Hydrogen 1
Mazda Premacy
Ford P2000 H2
Honda FCX Clarity

Honda FCX V3
Nissan FCV
Hyundai FCEV
GM HyWire

GM Sequel
Daimler FCell
Toyota Fine
Hyundai iBlue

GM Equinox
UCI
UCI
UCI

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Some Personally Tested Examples

Fuel Cell Vehicles


- Range: 350 miles (700 bar)
- Top Speed: 96 mph
- Fuel Cell: 90kW PEM
- Fueling Time: ~5-10 minutes

GM testing initiated in 2005
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Roles & Convergence Concept

1. Install more renewable power
2. Install more stationary fuel cells (complementary, dispatchable)
   - e.g., FuelCell Energy power plants operated on renewable fuel
3. Use more renewable power & green power from stationary fuel cells in transport by widespread use of BEV and PHEV
   - e.g., UCI’s ZEV-NET and PHEV programs
Third Rail Vehicle (TRV) idea

- All auto features desired by consumers (range, fast charge)
- Charge on major electrified roads ‘e-road’
- Functions like battery electric vehicle (BEV) off ‘e-road’
Roles & Convergence Concept

Plug-In Hybrid Fuel Cell Vehicle (PHFCV)

• Meet long range driving demands
• Fast refueling
• Small, cost-effective FC

![Diagram of FUEL CELL HYBRID VEHICLE]

- FC: Fuel Cell
- HYDROGEN
- FUEL CELL
- POWER CONTROL UNIT
- MOTOR
- SECONDARY BATTERY

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Roles & Convergence Concept

Energy Station Concept – locally co-produce H₂

Energy Station
- Electric Power Generation
- Thermal Power Generation
- Hydrogen Generation

“Renewable Energy Station”
- Green Electricity
- Green Thermal Power
- Renewable Hydrogen

2009: World’s First Renewable High Temperature Fuel Cell Hydrogen Co-Production Demonstration
Orange County Sanitation District, Fountain Valley, CA

UC Irvine H₂ Fueling Station
350 bar; 700 bar; liquid (future)
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• **Fuel Cells are fundamentally different from traditional energy conversion devices**
  - Electrochemistry, direct electric work production, separated streams, CO₂ sequestration, low emissions, high efficiency

• **Fuel Cells can substantially contribute to sustainability**
  - Stationary Power – continuous ‘dispatchable’ power; extremely low pollutant and GHG emissions; high efficiency; renewable & fossil fuels - compliment the relative intermittency of renewable power.
  - Transportation - Increase electrification *first, domestic H₂ fuel production, no GHG at vehicle, efficient, long range, fast fueling*

• **Convergence Concept**
  - Renewable power from fuel cells, wind, solar used first for stationary power and battery electric transport
  - Sustainability aided by high efficiency; use of renewable & waste fuels; efficient co-generation & co-production of hydrogen
  - Only small transport FC required in long-term
Thank you for your attention!