HYDROGEN — THE FUEL OF THE FUTURE

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California Hydrogen Business Council

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• MTU
• UTC Fuel Cells
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Overview

• The hydrogen economy - what is it? What is the long term perspective?
• Fuel cells - the cutting edge
• Hydrogen use in commercial and industrial buildings
• Renewable hydrogen: photovoltaics, wind and other renewables
• Hydrogen and pollution control
• Hydrogen Safety
• Hydrogen and fuel cell vehicles
The Hydrogen Economy

• What is the hydrogen economy?
  – The hydrogen economy is a vision
  – It consists of an economic system in which energy is supplied by renewable and regenerable resources

➤ In other words: Solar Energy

In this “economy” hydrogen is the medium of energy storage and transport
The Hydrogen Economy

• DOE 20-year vision
  – Timeline for development of key hydrogen energy systems

- Early renewable fuel cell/engine systems
- Broad-based renewable hydrogen systems
- Photobiological/photoelectrochemical systems
- Early renewable vehicle refueling stations
- Cost-effective natural gas fed distributed hydrogen production and electricity generation refueling stations
- Centralized hydrogen production with CO2 sequestration
- Demonstrate high-pressure and cryogenic storage
- Cost-effective hydride storage systems
- Carbon-based storage systems
- Wind/reversible fuel cells
- Early fuel cell systems for remote applications and villages
- Broad-based remote applications and village hydrogen systems
Hydrogen Economy

• National Vision to 2030 and Beyond*

  “There is general agreement that hydrogen could play an increasingly important role in America’s energy future. Hydrogen is an energy carrier that provides an energy solution for America. The complete transition to a hydrogen economy could take several decades.”

* “A NATIONAL VISION OF AMERICA’S TRANSITION TO A HYDROGEN ECONOMY — TO 2030 AND BEYOND” United States Department of Energy, February 2002
## National Vision

<table>
<thead>
<tr>
<th>Critical Issues</th>
<th>Achieved By</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen is economically produced from a variety of renewable energy sources (i.e. carbon-free sources) for transportation and distributed generation uses</td>
<td>2050</td>
</tr>
<tr>
<td>Total capital and infrastructure turnover</td>
<td>2100</td>
</tr>
<tr>
<td>Hydrogen is the dominant fuel for buses and fleets</td>
<td>2030</td>
</tr>
<tr>
<td>20 % hydrogen in the fuel mix</td>
<td>2030</td>
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</tbody>
</table>
National Vision

- Transition to a hydrogen economy
### Fuel Cells – The Cutting Edge

#### Fuel Cell Types

<table>
<thead>
<tr>
<th>Fuel Cell Type</th>
<th>Operating Temperature</th>
<th>Efficiency</th>
<th>Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal-air “half cells”</td>
<td>Ambient</td>
<td>?</td>
<td>Zn, Al</td>
</tr>
<tr>
<td>Polymer Electrolyte</td>
<td>80 °C</td>
<td>40 – 45 %</td>
<td>H₂</td>
</tr>
<tr>
<td>Direct Methanol</td>
<td>50 – 100 °C</td>
<td>30 – 40 %</td>
<td>MeOH</td>
</tr>
<tr>
<td>Phosphoric Acid</td>
<td>160 – 220 °C</td>
<td>40 – 45 %</td>
<td>H₂</td>
</tr>
<tr>
<td>Alkaline</td>
<td>120 – 250 °C</td>
<td>60 %</td>
<td>H₂</td>
</tr>
<tr>
<td>Molten Carbonate</td>
<td>600 – 650 °C</td>
<td>50 %</td>
<td>Syngas</td>
</tr>
<tr>
<td>Solid Oxide</td>
<td>700 – 1000 °C</td>
<td>50 – 55 %</td>
<td>CH₄, syngas</td>
</tr>
</tbody>
</table>
Pros and Cons of Fuel Cells

• Pros
  – High efficiencies
  – Good at part load
  – Low emissions
  – Good maintenance characteristics
  – Few moving parts
  – Low noise characteristics
  – Distributed power generation can be used with cogeneration

• Cons
  – Lifetimes unknown
  – Loss of efficiency with time
  – High investment costs
  – Low development status
  – Low availability
  – Few technology providers
  – Absence of fuel infrastructure for most applications
Low-Temperature Fuel Cells

- ~ 80 – 100 °C Operation
- Applications:

<table>
<thead>
<tr>
<th>Polymer Electrolyte Membrane Fuel Cells</th>
<th>Direct Methanol Fuel Cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Automobiles</td>
<td>- Automobiles</td>
</tr>
<tr>
<td>- Buses</td>
<td>- Personal Transportation</td>
</tr>
<tr>
<td>- Residential and small commercial distributed power generation</td>
<td>- Cell Phones</td>
</tr>
<tr>
<td>- Premium power</td>
<td>- Lap Tops</td>
</tr>
<tr>
<td>- Telecommunications</td>
<td>- PDAs</td>
</tr>
</tbody>
</table>
PEM Fuel Cell

- Ballard Nexa™ Power Module
  - 1200W, 26V output at full power
  - Backup or intermittent power
  - CSA, UL certified
Direct Methanol Fuel Cell

- Demonstration of MTI Fuel Cells DMFC powering a cell phone
Intermediate Temperature Fuel Cells

• ~ 200 °C operation

• Applications:

<table>
<thead>
<tr>
<th>Alkaline Fuel Cells</th>
<th>Phosphoric Acid Fuel Cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Space Power</td>
<td>• Baseload Power</td>
</tr>
<tr>
<td>• Personal Transportation</td>
<td>• Cogeneration</td>
</tr>
<tr>
<td>• Small Watercraft</td>
<td></td>
</tr>
<tr>
<td>• Utility Vehicles</td>
<td></td>
</tr>
<tr>
<td>• Fleet Vehicles</td>
<td></td>
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</tbody>
</table>
Alkaline Fuel Cell

• ZeTek
  – Alkaline fuel cell powered London taxi

• Astris Energi
  – Alkaline fuel cell-powered golf cart
  – 3.6 kW engine
  – 2 - 1 kW fuel cell stacks
  – 8 Nm³ compressed hydrogen
  – 6 – 7 hr range @ 25 mph
Phosphoric Acid Fuel Cells

- UTC Fuel Cells PC25™
  - 200 kW electrical
  - 900,000 Btu/hr thermal
  - 37% electrical efficiency
  - 87% overall efficiency
  - Installation shown is operating on digester gas in Portland, Oregon
High Temperature Fuel Cells

• ~ 600 – 1000 °C Operation
• Applications

<table>
<thead>
<tr>
<th>Molten Carbonate Fuel Cells</th>
<th>Solid Oxide Fuel Cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Baseload Power</td>
<td>• Baseload Power</td>
</tr>
<tr>
<td>• Cogeneration</td>
<td>• Small-scale Distributed Power</td>
</tr>
<tr>
<td>• Hybrid Power</td>
<td>• Cogeneration</td>
</tr>
<tr>
<td></td>
<td>• Hybrid Power</td>
</tr>
<tr>
<td></td>
<td>• Potential for Future Automotive use</td>
</tr>
</tbody>
</table>
Solid Oxide Fuel Cell

Tubular SOFC
- Typical Siemens-Westinghouse design
- Suitable for large scale installations

Planar SOFC
- Anode supported design on right
- Breakthrough approach by Global Thermoelectric
- Lower temperature operation
- Suitable for smaller systems

[Diagram of Single Cell Structure]

[Diagram of Tubular Solid Oxide Fuel Cell]
Solid Oxide Fuel Cell

- Siemens/Westinghouse
  - 220 kW SOFC/turbine hybrid
  - Installed at NFCRC in Irvine
  - 200 kW tubular fuel cell stack
  - 20 kW turbine
  - 55% electrical efficiency
  - Over 900 hours operational experience
  - Design targeted for eventual 60 – 70% electrical efficiency
Solid Oxide Fuel Cell

- **Global Thermoelectric**
  - Modular planar anode-supported SOFC stack
  - 85% overall efficiency in CHP mode
  - 750 °C operating temperature
  - 1.35 kW base module for residential use
Molten Carbonate Fuel Cell

- **MTU Hot Module™**
  - 250 kW output
  - 47% electrical efficiency
  - First high-temperature fuel cell installed and operating in a hospital
  - Selected for demonstration by LADWP
### Other Fuel Cell Technologies

#### Applications

<table>
<thead>
<tr>
<th>Zinc-air Fuel Cells</th>
<th>Aluminum-air Fuel Cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Automobiles</td>
<td>• Automobiles</td>
</tr>
<tr>
<td>• Hearing aids</td>
<td>• Large-scale Transportation</td>
</tr>
<tr>
<td>• Cell Phones</td>
<td></td>
</tr>
<tr>
<td>• Lap Tops</td>
<td></td>
</tr>
<tr>
<td>• PDAs</td>
<td></td>
</tr>
<tr>
<td>• Portable Power</td>
<td></td>
</tr>
<tr>
<td>• Portable Electronics</td>
<td></td>
</tr>
</tbody>
</table>

*These technologies present a challenge to the traditional concept of fuel cells as part of a hydrogen economy*
Hydrogen Use in Commercial and Industrial Buildings

- Baseload power
- Emergency backup power
- “Premium” power
- Load leveling
- Utility vehicles
- Fleet vehicles
Premium Power

- Value of power is greater than grid cost
  - Examples: banks, telecommunication, hospitals, financial industry
  - Provide uninterruptible power at “any cost”

- “Clean” Power
  - Examples: computer-intensive industries, sensitive electronic equipment
  - Install separate DC electrical system
    - Eliminates need for individual power conditioning equipment
    - Provides reliable ripple-free power to critical systems
Load Leveling

- Commonly applied at utility scale
- Takes advantage of off-peak power pricing
- Can be coupled with backup power systems
The ability to store hydrogen as an energy carrier is key to the viability of this concept.
Interesting Ways to Make and Use Hydrogen

• Renewable hydrogen:
  – PV-hydrogen
  – Direct Solar Hydrogen
  – Other Solar Hydrogen Production

• Hydrogen and pollution control
PV Hydrogen

- Stuart Energy Systems P3-1A Fleet Fuel Appliance
  - Installed at SunLine Transit Agency
  - PV system generates 18 kW of total 200 needed by electrolyzer (remainder of power is hydroelectric)
  - 1490 SCFH hydrogen produced at 4000 psig
  - 67% overall efficiency
  - Earlier system was installed at Xerox in El Segundo for refueling utility vehicles
PV Hydrogen

• The Energy Park at Agder College, Grimstad, Norway
  – 80 kW PV array
  – 50 kW electrolyzer
  – 20 kW PEM fuel cell
PV Hydrogen

• Honda Solar Hydrogen Refueling Station

  - Located at Torrance R&D facility
  - 8 kW PV array
  - Approx 7600 L/year hydrogen @ 250 atmospheres (ca. 125 kg)
  - About 30 fill-ups for one car
  - Electrolyzer capable of 4 – 5 x increase in capacity using grid electricity
Photoelectrochemical Hydrogen

- Direct electrochemical production of hydrogen induced by sunlight
- Potentially more efficient than PV electrolysis
- Still early in development
Photobiological H₂ Production

- Another potentially high efficiency technology for hydrogen production using solar energy
Reversible Fuel Cell

• Hydrogen replaces batteries used on conventional renewable energy systems
  - Higher storage energy density
  - Potentially higher efficiency
  - Eliminates “deep discharge”

• This looks very much like the earlier slide on load leveling
  - The distinction is replacement of the electrolyzer and fuel cell with a “reversible fuel cell
  - Efficiency is likely to be lower, but capital costs can in principle be reduced significantly
Hydrogen and Air Pollution

Data from Kirk Collier at NRG Tech (Reno, Nevada)

- Shows how blending hydrogen with compressed natural gas can reduce pollution
- NOx and CO emissions were reduced
- Adding 30 percent hydrogen by volume was almost as effective as burning pure hydrogen
- Vehicle driving range unaffected
- Engine horsepower increased by 23 %
Hydrogen and Air Pollution
EmeraChem EMx Process Diagram

Exhaust Gas In
Louvers Open

Exhaust Gas Out, Free of Pollutants
Louvers Closed

N₂ and H₂O Out
SCONOx™ Catalyst

NOx deposited on Catalyst

Hydrogen In
Hydrogen and Air Pollution

• Delphi Hydrogen Enrichment Concept

Reduced Pollution during Start up

Emissions of hydrocarbons and nitrogen oxides during cold start can account for 50% of total automobile pollution!
Hydrogen Safety

• The Zeppelin *The Hindenburg*

- Contained 7 million cu. ft. of hydrogen
- Burned and crashed in Lakehurst NJ on 6 May 1937
- 62 survivors
- 35 dead
  - One was burned
  - 34 jumped or fell

Cause of fire has now been attributed to the cellulose acetate/aluminum coating on the skin of the aircraft
## Hydrogen Safety

- Properties of hydrogen and other fuels

<table>
<thead>
<tr>
<th>Property</th>
<th>Gasoline</th>
<th>Methane</th>
<th>Hydrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flammability Limits In Air (vol)</td>
<td>1.0 - 7.6</td>
<td>5.3 - 15.0</td>
<td>4.0 - 75.0</td>
</tr>
<tr>
<td>Ignition Energy In Air (Mj)</td>
<td>0.24</td>
<td>0.29</td>
<td>0.02</td>
</tr>
<tr>
<td>Ignition Temperature (°C)</td>
<td>228 - 471</td>
<td>540</td>
<td>585</td>
</tr>
<tr>
<td>Flame Temperature In Air (°C)</td>
<td>2197</td>
<td>1875</td>
<td>2045</td>
</tr>
<tr>
<td>Explosion Energy (g-TNT/kJ)</td>
<td>0.25</td>
<td>0.19</td>
<td>0.17</td>
</tr>
<tr>
<td>Flame Emissivity (%)</td>
<td>34 - 43</td>
<td>25 - 33</td>
<td>17 - 25</td>
</tr>
</tbody>
</table>
Hydrogen Safety

• Hydrogen Storage Technology
  • Quantum Technologies Type IV, 10,000 psig gaseous fuel tank
    - Plastic lined
    - Carbon fiber wrapped
  • Lincoln Composites’ TuffShell™, 3600 psig gaseous fuel tank
    - Plastic lined
    - Carbon/glass fiber wrapped

*Polymer/composite designs necessary to prevent catastrophic failure*
Hydrogen Safety

• Effective detection also key to safe use of hydrogen

• Adequate sensor technology still lacking
  – Existing technology not specific to hydrogen
  – Detects other combustible gases
    • Carbon monoxide
    • Natural gas
    • Automobile exhaust
  – “false positive” readings

• Innovative new technologies offer promise
Hydrogen Safety

• New Hydrogen Sensor Technologies

  • DCH Technology Inc. H₂Scan
    • Platinum filament resistivity sensor
    • Highly selective to hydrogen

  • OptiSense HydroSafe optrodes
    • Transition metal complex embedded in porous glass matrix
    • Hydrogen-specific
    • Color change from yellow to blue

*New sensor technologies may be critical for both automotive and distributed power fuel cell introduction*
## Hydrogen and Fuel Cell Vehicles

### Current Automaker Programs

<table>
<thead>
<tr>
<th>Brand</th>
<th>Compressed H₂</th>
<th>Liquid H₂</th>
<th>Gasoline Reformer</th>
<th>Methanol Reformer</th>
</tr>
</thead>
<tbody>
<tr>
<td>GM</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>DaimlerChrysler</td>
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<tr>
<td>Ford</td>
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<td>Toyota</td>
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<td>Honda</td>
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<td>Hyundai</td>
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<td>Opel</td>
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<td>BMW</td>
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<td>Volkswagen</td>
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<td>Nissan</td>
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<td>Renault</td>
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<td>Suzuki</td>
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Hydrogen and Fuel Cell Vehicles
Hydrogen and Fuel Cell Vehicles

- Projected sales of FCVs in California
  - Based on CaFCP study, Ballard market research
Summary

- The hydrogen economy appears inevitable, but it will take some time.
- Advantages are clear – greater fuel efficiency and reduced environmental impact.
- Tremendous challenges remain – Especially in low-cost fuel cell technology, sensors, and hydrogen storage.
- Expect to see first inroads in high-value applications, convenience items, and displacement of low efficiency or low energy density technologies.