Why Hydrogen?
Building an Infrastructure

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What are the issues we trying to solve?

- Energy security – transportation’s dependence on petroleum
  - Increasing dependence on foreign oil, particularly from unstable regions
- Vulnerable domestic & international energy infrastructures
  - Oil and natural gas pipelines
  - Few and vulnerable ports of entry
- Urban air pollution
  - Criterion gas emission (NO$_x$, HC, PM, CO …)
- Threat of climate change
  - Atmospheric concentration of [CO$_2$], [CH$_4$] …
## Fuel Use by End Use Sector (Percent Share)

<table>
<thead>
<tr>
<th></th>
<th>Electricity</th>
<th>Transportation</th>
<th>Residential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>48</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oil</td>
<td>3</td>
<td>96</td>
<td>8</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>17</td>
<td>3</td>
<td>27</td>
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<tr>
<td>Hydro</td>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity</td>
<td>1</td>
<td></td>
<td>62</td>
</tr>
<tr>
<td>Renewable</td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Nuclear</td>
<td>19</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrogen</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Wind</td>
<td>2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Stabilizing Atmospheric CO$_2$
Concentrations …

- The residence time for CO$_2$ in the atmosphere is on the order of 120 years *
  - The concentration of CO$_2$ in the atmosphere is a result of cumulative net emissions **
    - From pre-industrial times to the indefinite future, by every economically developing country, everywhere on the planet … and with most emissions yet to come **

- Net Emissions must eventually decline to virtually ZERO . . . whatever the concentration target might be. **

** Stabilizing Atmospheric Carbon: The NCCTI Challenge, Jae Edmonds, John Clarke NCCTI Integration Group Measurement, Monitoring and Validation Workshop, September 26, 2001

CO₂ Emissions by Energy Sector

Source: AEO ‘99, USDOE OTT
U.S. Carbon Emissions

Source: DOE/EIA AEO 2001
Solutions

- Dependence on Petroleum
  - Hydrogen, natural gas, coal and/or bio-fuels

- Energy supply vulnerability
  - Use hydrogen as an energy carrier made from the broadest spectrum of domestic energy feed stocks
    - fossil fuels and coal (with CO₂ sequestration), renewables …

- Urban air quality (criterion gas emission)
  - Conventional fuels with after treatment
  - Natural gas fueled vehicles with after treatment
  - Hydrogen fueled vehicles with or without after treatment

- Climate change
  - Hydrogen and/or bio-derived energy carriers
“Hydrogen is America’s clean energy choice. Hydrogen is flexible affordable, safe, domestically produced, used in all sectors of the economy, and in all regions of the country.”
Major Findings

“… Widespread use of hydrogen will affect every aspect of the U.S. energy system from production through end-use. …”

Conversion

“… Conversion of hydrogen into useful forms of electricity and thermal energy involves the use of fuel cells, reciprocating engines, turbines, and process heaters. …“
Conversion

“... Government should assist in developing better information on the fundamental properties of hydrogen combustion and ... materials, electrochemistry, and interfaces for fuel cells.”

Applications

“... Ultimately, consumers should be able to use hydrogen energy for transportation, electric power generation, and portable electronic ...”
Hydrogen End-use

Hydrogen enables operating conditions not possible with hydrocarbon fuels – for example:

- Stable combustion at much higher dilution levels
  - Enables premixed dilute stable combustion to occur below the knee in the NO$_x$ curve
    - Reciprocating ICEs, Turbines, Process Heaters …

- Effective octane rating is high
  - Enables higher compression ratios and still operate spark ignited

- Enables fuel cells
Requirements on hydrogen conversion technologies for vehicular use

- Highly efficient energy conversion
- Power density must be sufficiently high to be packaged in a vehicle
- Environmentally benign
- Cost effective hardware
- Compatible with existing infrastructure
  - manufacturing, service, supplies, maintenance
  - refueling
- Energy storage density sufficiently high to provide acceptable range
What is possible for an optimized ICE?

- Measured peak efficiencies *
  - Indicated ~ 52%, brake ~ 37%

- H₂ ICEs are cost competitive with current gasoline ICE powertrains *

- HC, CO all near zero engine out emissions *
  - Trace amounts from lubricating oil
    - CO – O(1) ppm, HC – O(5) ppm for a reduction of a factor of 1000, 250 respectively compared to gasoline tailpipe emissions

- Engine out Dial-a-NOₓ value ~ 5-6 ppm

- With after treatment NOₓ values can be near zero **
  - Measured tailpipe NOₓ emissions equal to ambient levels of about 50 ppb

*SAE Papers #’s 2002-01-0240 thru 0243 and 2003-01-0631; Ford Research

**James Heffel, University of California, Riverside, College of Engineering – Center for Environmental Research and Technology (CE-CERT); Personal Communication
Under the technical guidance and contract to Sandia National Laboratories, funding from the Hydrogen Program Office; OPT
System Power Densities

Mass and space requirements for energy-conversion and energy-storage devices.
(Based on engine rated / max-power condition)

KEY:
- SI / L4  = 4-stroke spark ignition, Fe-block L4
- SI / 2S  = 2-stroke spark ignition, AL-block L3
- SI / V8  = 4-stroke spark ignition, AL-block V8
- CIDI = direct injection turbocharged diesel
- GT / R  = regenerative gas turbine, circa 1950-70
- GT / NR  = nonregenerative gas turbine, circa 1950
- STIR /'70-'80 = Stirling, circa 1970-80
- STIR /'90+ = Stirling (swash-plate), circa 1990
- BATT / EV  = current batteries for electric car
- BATT / EHV  = Pb-acid battery for hybrid vehicle
- FLYWHEEL = electro-mechanical battery
- U’CAP GOAL  = goal for ultracapacitor
- SFC  = Solid Oxide Fuel Cell (500ºC)
- H₂ ICE= Lean burn optimized ICE - AL block

DOE Goals are for the PEMFC system excluding the fuel processor

Original source: SAE International Magazine modified by Jay Keller, SNL
# Range and Mileage?

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Storage Mode</th>
<th>Internal Vol (l) *</th>
<th>H₂ (kg)</th>
<th>Mileage (mpgge)</th>
<th>Range (miles)</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ford Model U</td>
<td>10,000 psi</td>
<td>180</td>
<td>7</td>
<td>45</td>
<td>300</td>
<td>[1]</td>
</tr>
<tr>
<td>Ford P2000 – ICE</td>
<td>3600 psi</td>
<td>87</td>
<td>1.5</td>
<td>31.4/46.7</td>
<td>70</td>
<td>[2]</td>
</tr>
<tr>
<td>BMW 750hL – ICE</td>
<td>Liquid</td>
<td>140</td>
<td>9.9</td>
<td>22</td>
<td>218</td>
<td>[3]</td>
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<tr>
<td>Ford Focus FCV</td>
<td>5000 psi</td>
<td>186</td>
<td>4.3</td>
<td>47</td>
<td>200</td>
<td>[4]</td>
</tr>
<tr>
<td>Toyota FCHV</td>
<td>3600 psi</td>
<td>136</td>
<td>3.2</td>
<td>57</td>
<td>182</td>
<td>[5]</td>
</tr>
<tr>
<td>Honda FCX</td>
<td>5000 psi</td>
<td>157</td>
<td>3.8</td>
<td>45/58</td>
<td>170/220</td>
<td>[6,7]</td>
</tr>
<tr>
<td>Chrysler Natrium</td>
<td>NaBH₄</td>
<td>200</td>
<td>10</td>
<td>30</td>
<td>300</td>
<td>[6]</td>
</tr>
<tr>
<td>GM HydroGen3</td>
<td>Liquid</td>
<td>68</td>
<td>4.5</td>
<td>55</td>
<td>250</td>
<td>[6,7]</td>
</tr>
<tr>
<td>GM Hy-wire</td>
<td>5000 psi</td>
<td>88</td>
<td>2</td>
<td>40</td>
<td>80</td>
<td>[7]</td>
</tr>
</tbody>
</table>

* Does not include tank system volume
Where are we going?

Some FreedomCAR Technical Targets (2010)

Reciprocating H₂-ICE
- Cost - $45 / kW
- Peak brake engine efficiency of 45% and must meet or exceed all emissions standards

PEM Fuel Cell System
- Cost - $45 / kW
- Peak break thermal efficiency of 45% and must meet or exceed all emissions standards
  - Does not include vehicle traction
  - Includes FC BOP, fuel processor subsystems and auxiliaries
- 325 W/kg power density and 220 W/L specific power on hydrogen (not reformate!)
- 15-year life capable of 55 kW for 18 seconds and 30 kW continuous
Some Technical Challenges Today?

Reciprocating H$_2$-ICE
- Improve power density
  - while it is good some feel it is not good enough
- Improve efficiency
- Pre-ignition at low diluent levels
- Materials compatibility
- Lubricity

PEM Fuel Cell Systems
- Cost
  - DOE’s program is focusing on PEM Fuel Cell cost reduction
- Power density and specific power
- Catalysts loading – eliminate precious metal catalysts?
- System efficiency – BOP and power conditioning
- Manufacturability – Mass production
- *Low Temperature Starting/Operation – Water Freezes*
Remember This?
CO\textsubscript{2} Emissions by Energy Sector

Cannot just focus on PCs! That will not solve the problem!

Source: AEO ‘99, USDOE OTT
Gas Turbines are the fastest growing power production technology.

Drivers

- H₂-blended approach provides a solution to contemporary problems and provides a transition strategy to a carbon-free H₂ energy system
- Alternative low- and medium-heating value fuels containing H₂ could provide a significant source of cost-effective fuels
- Gas turbines are the fastest growing power production technology
- Gas turbines are responsible for about 15% of the U.S. CO₂ budget and are anticipated to grow to 28% in the next 20 years
- Fewer number of stationary turbines (compared to PCs) representing a larger impact on CO₂!
**Economic Analysis for Emissions Control**

**NO\textsubscript{x} abatement**
- Cost comparisons with Dry Low NO\textsubscript{x} combustors and Selective Catalytic Reduction showed 15% H\textsubscript{2} addition cost competitive
- Less than 3 ppm NO\textsubscript{x} achievable with 15% H\textsubscript{2} addition
- H\textsubscript{2} addition up to 20% offers NO\textsubscript{x} levels below 1 ppm

**NO\textsubscript{x} plus CO\textsubscript{2}**
- @ 65% H\textsubscript{2} addition resulting in less than 1 ppm NO\textsubscript{x} and a 65% reduction in CO\textsubscript{2} -- including emission credits
- H\textsubscript{2} addition is cost competitive for all turbine sizes analyzed (30 to 170 MW)
Some Technical Challenges Today?

Lean Combustion Systems

- Turbines
  - Acoustic instabilities
  - Flame stability
    - Flashback and Blow off
  - Robust systems capable of handling variable fuel properties
    - variable hydrogen concentration
  - Materials compatibility

- Process heaters and boilers
  - Acoustic instabilities
  - Flame stability
    - Flashback and Blow off
  - Materials compatibility
Challenges to Building an Infrastructure

- **Public education**
- **Safety**
  - Learn how to handle H₂ safely with the general public
  - Developing useful codes and standards for H₂ installations
  - Use H₂ safely in a wide variety of applications
    - Commercial, Residential, Utility, and Transportation
- **Production**
  - Distributed and centralized production (with carbon management if source is fossil fuels)
- **Storage**
  - Stationary -- Small and Large scale
  - Mobile -- Ground, water and air
Challenges of Building an Infrastructure

- Develop efficient end-use conversion technologies
  - Conventional combustion technologies, Advanced fuel cell technologies
- Delivery
  - Network of pipes and other ground transportation
- Personnel Training
  - Maintenance workers
  - Fire Marshals and Code Officials
- Maintenance network
  - Parts distribution
  - Repair facilities
- Etc.
- Oh Yeah – refueling stations for PCs
The building of an infrastructure
Make Everyone a Winner

- Evolutionary not revolutionary – driven by market forces (characteristic time > characteristic economic time scale – quasi-steady)
  - Introduce $\text{H}_2$ as an energy carrier into existing energy infrastructure preserving the installed capital base
    - Utilize conventional conversion devices modified for optimal hydrogen use in all energy sectors
  - Focus on high payoff applications for both $\text{CO}_2$ and for generating an energy market demand for $\text{H}_2$

- Introduce advanced $\text{H}_2$ under market conditions that provide a pull …

One Mans View - Mine
Gaining public acceptance

“We can start developing the hydrogen infrastructure as we perfect the fuel-cell car; and the internal combustion engine can run rather well on hydrogen …, the ICE hydrogen car is not the enemy of the fuel cell,”

“Indeed, if we were starting to deploy hydrogen-powered ICE cars tomorrow, it would hasten the day when fuel cells were viable because it would help bring the hydrogen infrastructure into place sooner rather than later.

- David Freeman
Chairman, California Power Authority
Presentation End