The end of the oil age?
A Transition to Hydrogen?

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Agenda

- Hydrogen Era
  - Motivation: reduce emissions
  - Efficiency of energy transformation
  - Why Hydrogen?

- Production and distribution of hydrogen
  - Sources
  - Production processes
  - Distribution

- Hydrogen utilization
  - Fuel cells: fundamentals
  - Fuel cells for vehicles
  - Fuel cells for power generation

- Conclusions
"The Stone Age didn't end because they ran out of stones; the Oil Age won't end because we run out of oil."

Don Huberts, Shell Hydrogen
The green house effect...

2010: 380ppm
1900: 280ppm
Energy utilization in 2009

- Commercial: 19%
- Industrial: 30%
- Residential: 22%
- Transportation: 29%


Cars production in the world (by year)

*Car produced*

<table>
<thead>
<tr>
<th>Year</th>
<th>1999</th>
<th>2001</th>
<th>2003</th>
<th>2005</th>
<th>2007</th>
<th>2009</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>30,000,000</td>
<td>35,000,000</td>
<td>40,000,000</td>
<td>45,000,000</td>
<td>50,000,000</td>
<td>55,000,000</td>
<td>60,000,000</td>
</tr>
</tbody>
</table>

Sexten, Monday, July 01, 2013- slide 5
Significant progress has been made in reducing local emissions and the focus is now shifting to Greenhouse Gases.

Future challenge: Reduce CO$_2$ while maintaining low regulated emissions.

Source: European Commission
Changes to transport fuels are required to meet sustainability challenges

- Need to balance the requirements of **affordable** mobility while **reducing local and global** environmental impacts
  - Cleaner Hydrocarbon Fuels enable more fuel efficient/low emission engine technology.
  - Renewable Biofuels - e.g. ethanol and vegetable oil esters
  - Radical new technologies - e.g. Fuel cells & Hydrogen

- Alternatives need to meet **economic** and **social** sustainability criteria as well as contributing to environmental objectives.

- Need to understand the challenge of **consumer acceptance**.
Well-to-Wheel Greenhouse Gases - US Study

- Gasoline
- Diesel
- ICE
- Fuel Cell HEV
- FT Diesel ICE
- Naphtha
- FT Naphtha FC HEV
- Liquid H2 FC HEV
- Methanol Fuel Cell HEV
- Gaseous H2 FC HEV
- Electrolysis
- GH2 FC HEV
- E-85 ICE
- Ethanol Fuel Cell HEV

ICE: internal combustion engine
HEV: hybrid electric vehicle
CNG: compressed natural gas
FT: Fisher Tropsch diesel
GTL: gas to liquid fuel
E-85: 85% ethanol and 15% gasoline

Tomorrow's Energy

Sexten, Monday, July 01, 2013 - slide 8
Shell’s Interpretation of existing Well-to-Wheel Studies

- **ICE hybrids** can deliver significant further benefits (benefit bigger for gasoline).
- **Fuel cell vehicles have potential** for further gains but dependent on how Hydrogen produced.
- **Methanol fuel cell** vehicles **do not offer** a worthwhile GHG advantage vs. gasoline/naphtha fuel cell vehicles. On board reforming gives relatively little benefit versus ICE hybrids (main value as a transition pathway).
- **CNG does not** on average offer GHG benefit vs. conventional fuels for internal combustion engine (ICE) vehicles (depending on gas source assumed). No benefit for H2 in ICE.
- **GTL broadly comparable with conventional diesel** on a full systems basis.
- **Renewable fuels** offer the lowest greenhouse gas emissions.
Hydrogen Economy........ a compelling vision

Hydrogen Economy

- Electricity from Renewable Sources
- Electrolysis
- Biomass
- Reformer

Packaging of Hydrogen

Pure Hydrogen

Natural H₂O - Cycle

User

Truncated CO₂ - Cycle
The Hydrogen age: the transition is uncertain...

THE PAST
Internal Combustion Engine led to the Oil Age

THE TRANSITION IS UNCERTAIN

THE FUTURE

The Fuel Cell can lead to the Hydrogen Age

Underlying Decarbonisation

Product Performance vs. Time

Coal: 1.5 : 1
Oil: 1 : 2
Gas: 1 : 4
Hydrogen: 0 : 1
Hydrogen is not prohibitively expensive to get started today.

(Sources: British Petroleum, Hoffmann, Ogden, and Bossel/Eliasson.)

<table>
<thead>
<tr>
<th>Hydrogen Production Method</th>
<th>Cost ($/GJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Central Production</strong></td>
<td></td>
</tr>
<tr>
<td>Natural Gas</td>
<td>5-8</td>
</tr>
<tr>
<td>Coal</td>
<td>9-12</td>
</tr>
<tr>
<td>Electrolysis of Water</td>
<td>20</td>
</tr>
<tr>
<td>Gasified Biomass</td>
<td>8-13</td>
</tr>
<tr>
<td><strong>Distributed Production</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Onsite</strong></td>
<td></td>
</tr>
<tr>
<td>Natural Gas</td>
<td>8-15</td>
</tr>
<tr>
<td>Electrolysis (hydroelectric)</td>
<td>10-20</td>
</tr>
<tr>
<td>Electrolysis (wind)</td>
<td>20-40</td>
</tr>
<tr>
<td>Electrolysis (solar/thermal)</td>
<td>40-60</td>
</tr>
<tr>
<td>Electrolysis (photovoltaic)</td>
<td>50-100</td>
</tr>
</tbody>
</table>

Relative Costs of Energy
(Hydrogen from Natural Gas)

With Gas priced at $3/MBTU
Technology efficiencies

- Biomass
- Geothermal
- Photovoltaic
- Wind
- Nuclear
- Gas turbine
- Coal
- Fuel cell
- Gas combined cycle
- Hybrid fuel cell
- Hydro

(*) DER efficiencies improve with heat recovery
The next 10 years will see a wider range of technologies and fuel types, especially in the developed world.

One possible view of the future - not a forecast.
Timeline for Hydrogen Economy

**Transitional Phases**

**PHASE I**
- **Technology Development**
  - Research to meet customer requirements and establish business case leads to a commercialization decision.
  - **RD&D**

**PHASE II**
- **Initial Market Penetration**
  - Portable power and stationary/transport systems begin commercialization; infrastructure investment begins with governmental policies.
  - **Transition to the Marketplace**

**PHASE III**
- **Infrastructure Investment**
  - H₂ power and transport systems commercially available; infrastructure business case realized.
  - **Expansion of Markets and Infrastructure**

**PHASE IV**
- **Fully Developed Market and Infrastructure Phase**
  - H₂ power and transport systems commercially available in all regions; national infrastructure.
  - **Realization of the Hydrogen Economy**

**Timeline**
- **2010**
- **2020**
- **2030**
- **2040**

**Strong Government R&D Role**
- **Strong Industry Commercialization Role**

*Today's Energy*
The Power of Innovation

- Heavier-than-air flying machines are impossible,...
  - Lord Kelvin, President Royal Society, 1895

- I think that there is a world market for maybe five computers
  - Thomas Watson, chairman of IBM, 1943

- Computers in the future may weigh no more than 1.5 tons
  - Popular mechanics, 1949

- There is no reason anyone would want a computer in their home
  - Ken Olson, President, Chairman, and founder of Digital Equipment Corp., 1977

- 64K ought to be enough for anybody
  - Bill Gates, 1981
Time Taken to achieve 25% access in the US

- The Original Gasoline Automobile: > 55 years
- Electricity: c. 40 years
- The Microwave: 18 to 20 years
- The PC: 15 years
- The Web: 7 years
- Facebook: .......
A new source of power...called gasoline has been produced by a Boston engineer. Instead of burning the fuel under a boiler, it is exploded inside of the cylinder of an engine.... The dangers are obvious. Stores of gasoline in the hands of people interested primarily in profit would constitute a fire and explosive hazard of the first rank. Horseless carriages propelled by gasoline might attain speeds of 14, or even 20 miles per hour. The menace to our people of this type hurdling through our streets and along our roads and poisoning the atmosphere would call for prompt legislative action even if the military and economic implications were not so overwhelming....

The cost of producing [gasoline] is far beyond the capacity of private industry...

In addition the development of this new power may displace the use of horses, which would wreck our agriculture.
So Why Hydrogen?

- Hydrogen Combustion:
  - \( \text{H}_2 + \frac{1}{2} \text{O}_2 \rightarrow \text{H}_2\text{O} \quad \Delta H = -57.8 \text{ kcal/mole} \)
- \( \text{H}_2 \) is an energy carrier, is converted to water which has minimal environmental impact.
- \( \text{H}_2 \) is a non-polluting fuel for transportation vehicles and power production
- Currently road vehicles emit about the same quantity of \( \text{CO}_2 \) as power production in developed economies.
- \( \text{H}_2 \) can be produced from fossil fuels with \( \text{CO}_2 \) capture and storage or from renewables
In the long run, hydrogen has the potential to be the ultimate fuel.
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  - Sources
  - Production processes
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  - Fuel cells: fundamentals
  - Fuel cells for vehicles
  - Fuel cells for power generation

- Conclusions
CO₂ Capture and Storage: Hydrogen Production from Fossil Fuels

- H₂ production from fossil fuels will predominate
- H₂ for transportation fuel only makes sense if CO₂ is captured and stored
## Production of Hydrogen Options

<table>
<thead>
<tr>
<th>Method</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photolysis</td>
<td>catalytic-water splitting</td>
</tr>
<tr>
<td>Electrolysis</td>
<td>water</td>
</tr>
<tr>
<td>Power for electrolyser</td>
<td>ambient → high temperature</td>
</tr>
<tr>
<td></td>
<td>ambient → high pressure</td>
</tr>
<tr>
<td>Thermal splitting</td>
<td>water</td>
</tr>
<tr>
<td></td>
<td>high temperature</td>
</tr>
<tr>
<td>Fossil fuel Conversion</td>
<td>Heat, water, oxygen, catalytic</td>
</tr>
<tr>
<td>Far Future</td>
<td>Non fossil fuel alternatives based on sunlight, renewables and nuclear</td>
</tr>
<tr>
<td>Present</td>
<td>Fossil fuels</td>
</tr>
</tbody>
</table>
Renewable Hydrogen Production via Electrolysis

Typical 2 MW Turbine gives 100 tonnes/year Hydrogen.
# Production of Hydrogen: Reactions

## Reforming With Steam - Catalytic

<table>
<thead>
<tr>
<th>Natural gas and light hydrocarbons</th>
<th>CH(_4) + H(_2)O ↔ CO + 3H(_2) + ΔH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CO + H(_2)O ↔ H(_2) + CO(_2) - ΔH</td>
</tr>
</tbody>
</table>

## Partial Oxidation - Non Catalytic

<table>
<thead>
<tr>
<th>Any hydrocarbon or carbonaceous feedstock</th>
<th>C + ½O(_2) → CO - ΔH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CO + H(_2)O ↔ CO(_2) + H(_2) - ΔH</td>
</tr>
</tbody>
</table>

## Thermal Decomposition

<table>
<thead>
<tr>
<th>Only limited application as co-product in carbon black manufacture</th>
<th>CH(_4) → 2H(_2) + C +ΔH</th>
</tr>
</thead>
</table>
Production of Hydrogen: Process Characteristics

- **Open Systems**
  - External heating of a catalytic reactor
  - Combustion products vented to atmosphere

50,000 Nm³/hr Steam Natural Gas Reformer
Production of Hydrogen: Process Characteristics

- **Closed Systems**
  - Pressurised reactors with heat supplied by direct oxidation with oxygen
  - No venting of combustion products

**Partial Oxidation**
- Natural Gas
- Oxygen

**Autothermal Reformer**
- Natural Gas
- Oxygen
- Steam
- POX Catalyst
Worldwide Market Scenario in 2020

- Transit Buses*
  - 130,000-150,000 buses in service

- Light Duty Vehicles*
  - 17-80 million vehicles in service

- Hydrogen Required†
  - 2.5 - 9 million tonnes per year

- Current Largest Merchant H₂ Plant
  - 100,000 tonne/year

- HUGE INFRASTRUCTURE TO BE BUILT
Agenda

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  - Sources
  - Production processes
  - Distribution

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  - Fuel cells: fundamentals
  - Fuel cells for vehicles
  - Fuel cells for power generation

- **Conclusions**
Fuel cells: Power station & Automotive
What is a fuel cell?

- DC Voltage Source with low emissions
- Makes electricity chemically
- Like a battery, but doesn’t run down
- Emits only water vapor
- High fuel-to-electric efficiency
- Low noise
- No moving parts

Are they the microchip of the hydrogen age?

48 V dc 7.5 kW Fuel Cell
A fuel cell system

For top efficiency, you must use the heat! Ultimately, hydrogen is needed!
Electricity

- Electrical current is the flow of electrons.
- Need a source of electrons, a medium in which they can flow, and a driving force.

**Electrons Produced**
- Anode (-)
- low E (V)

**Electrons consumed**
- Cathode (+)
- high E (V)

**Source of Electrons**

**Sink for Electrons**

\[ \Delta E (V) \]
Oxidation and Reduction

Electrons are produced and consumed in oxidation and reduction reactions.

Oxidation is loss (OIL) of electrons:

- Fe → Fe²⁺ + 2e⁻
- Ca → Ca²⁺ + 2e⁻
- Na → Na⁺ + e⁻
- H₂ → 2H⁺ + 2e⁻

Reduction is gain (RIG) of electrons:

- Cl₂ + 2e⁻ → 2Cl⁻
- Ag⁺ + e⁻ → Ag
- Ni³⁺ + e⁻ → Ni²⁺
- Br₂ + 2e⁻ → 2Br⁻
Half Reactions

- Individual oxidation and reduction reactions are half reactions.
- Must occur together to make an overall oxidation-reduction reaction.

EX. \[ \text{Mg (s) } \rightarrow \text{Mg}^{2+} + 2 \text{ e-} \]
+ \[ \text{Cl}_2 (g) + 2 \text{ e-} \rightarrow 2 \text{ Cl-} \]

\[ \text{Mg (s) } + \text{Cl}_2 (g) \rightarrow \text{MgCl}_2 (s) \]
Reduction Potential

- Each half-reaction has a characteristic *reduction potential* ($E^\circ$).
  - $E^\circ$ is a *relative* measure of energy released by adding electrons.

**EXAMPLE.**

\[
2H^+ + 2e^- \rightarrow H_2 (g) \quad E^\circ = 0.000 \text{ V}
\]

\[
4H^+ + O_2 (g) + 4e^- \rightarrow 2H_2O \quad E^\circ = +1.23 \text{ V}
\]

- Positive $E^\circ$ indicates that energy is obtained by adding electrons.
  - $\Delta G = -n F E^\circ$
  - $F$ = Faraday’s constant; $n$ = n. of electrons
Overall Reaction

For hydrogen and oxygen:

\[
\text{OX: } 2\text{H}_2 (g) \rightarrow 4\text{H}^+ + 4e^- \quad E^\circ = 0.00 \text{ V}
\]

\[
\text{RED: } \text{O}_2 (g) + 4\text{H}^+ + 4e^- \rightarrow 2\text{H}_2\text{O}_2 (g) \quad E^\circ = 1.23 \text{ V}
\]

\[
\text{TOTAL: } 2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O} \quad \Delta E^\circ = +1.23 \text{ V}
\]

Large, positive \( \Delta E^\circ \rightarrow \) more energy
Fuel Cells

Fuel and oxidant react to produce electricity directly without combustion.

- **Oxidation:** $2 \text{H}_2(g) \rightarrow 4 \text{H}^+ + 4 \text{e}^-$
- **Reduction:** $\text{O}_2(g) + 4 \text{H}^+ + 4 \text{e}^- \rightarrow 2 \text{H}_2\text{O}$
- **Overall:** $2 \text{H}_2 + \text{O}_2 \rightarrow 2 \text{H}_2\text{O}$, $\Delta E^\circ = +1.23$ V

How does this happen without combustion occurring or H$_2$ and O$_2$ coming into contact with each other?
## Combustion vs. Electron Transfer

- Chemical reactions are the same!
- Reaction rate and types of energy produced are different.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Chemical Products</th>
<th>Energy Produced</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combustion</td>
<td>CO₂, H₂O</td>
<td>Noise, heat, light</td>
<td>Fast</td>
</tr>
<tr>
<td>Electron Transfer</td>
<td>CO₂, H₂O</td>
<td>Electrical, some heat</td>
<td>Slow</td>
</tr>
</tbody>
</table>
Basic Operation of Fuel Cells

- Fuel and oxidant are separated.
- Ions conducted through electrolyte, electrons carried through external circuit.
- Electrodes are catalysts that facilitate the reactions.

\[
\begin{align*}
\text{Anode:} & \quad H_2 &\rightarrow 2H^+ + 2e^- \\
\text{Cathode:} & \quad O_2 + 4H^+ + 4e^- &\rightarrow 2H_2O \\
\text{Overall:} & \quad 2H_2 + O_2 &\rightarrow 2H_2O
\end{align*}
\]

\(H_2 \text{ and } O_2 \text{ never come into contact, only } H^+ \text{ and } O^{2-}!!\)
Fuel Cell

Anode

Cathode

Proton Exchange Membrane

Oxygen from Air

Hydrogen from Tank

Exhaust

Electrical Current

© Schatz Energy Research Center
Basic Electrochemistry for Fuel Cell

- Chemical Energy = Electrical Energy – Energy losses
- $\Delta G_{\text{rxn}} = \text{Current}\times\text{Voltage}\times\text{time} – \text{Energy losses}$
- $\Delta G_{\text{rxn}} = V\times(\text{charge passed}) – \text{Energy losses}$
  - As current $\to 0$ the energy losses $\to 0$
- $\Delta G_{\text{rxn}} = V\times(\text{charge passed})$
  - $= V\times(\text{moles reacted})\times(\text{electrons transferred per molecule})\times(\text{coulombs per mole})$
  - $= V\times n\times F$
- For $\text{H}_2+\text{O}_2 \rightarrow \text{H}_2\text{O}$ $\Delta G=240 \text{ kJ/mol H}_2$, $n=2$ electrons/H$_2$
- $V=240 \text{ kJ/mol / (2}*96485 \text{ coulomb/mol)} = 1.23 \text{ Volt}$

Advantages of Fuel cells

- Fuel cells can be made very tiny.
  - $\mu$m, nm instead of mm, cm.
- Power the product of current (I) and potential difference (V)
  - $P = I\times V$ so $\uparrow I$ and/or $\uparrow V$ means $\uparrow P$,
  - Higher fuel and oxidant flows increase I.
  - Stacking of fuel cells increases V.
Ideal (Nernst) potential as a function of T

\[ H_2 + \frac{1}{2} O_2 \rightarrow H_2O(g) \]

Table 2-3 Ideal Voltage as A Function of Cell Temperature

<table>
<thead>
<tr>
<th>Temperature</th>
<th>25°C (298K)</th>
<th>80°C (353K)</th>
<th>100°C (273K)</th>
<th>205°C (478K)</th>
<th>650°C (923K)</th>
<th>800°C (1073K)</th>
<th>1100°C (1373K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell Type</td>
<td>PEFC</td>
<td>AFC</td>
<td>PAFC</td>
<td>MCFC</td>
<td>ITSOFC</td>
<td>SOFC</td>
<td></td>
</tr>
<tr>
<td>Ideal Voltage</td>
<td>1.18</td>
<td>1.17</td>
<td>1.14</td>
<td>1.03</td>
<td>0.91</td>
<td>0.91</td>
<td></td>
</tr>
</tbody>
</table>
Basic Principles

Thermodynamics
\[ \Delta G = -n F V \]

Theoretical Efficiency
\[ \eta = \frac{\Delta G}{\Delta H} \sim 0.83 \]

Actual Efficiency (best conditions) \( \sim 0.5 \)
Energy Losses

- **Activation Polarization**
  - Energy barrier associated with catalytic reactions at the electrodes

- **Ohmic Polarization**
  - Resistive losses of proton transport through the electrolyte

- **Mass Transfer Polarization**
  - Limit of getting the reactants to the active catalyst surface
Voltage – current relationships
Fuel utilization
First Fuel Cell

Basic principle developed in 1839 by William Grove. Reversal of current after turning off water electrolysis.

Fuel cell stack sketched by Grove in 1843.
Brief History

- 1839 William Grove demonstrates principle of fuel cell operation
- 1894 Ostwald initiates efforts to replace heat engine with a carbon fuel cell operating at 1100°C
- 1938 Baur demonstrates coal fuel cell with oxygen ion conducting electrode
- 1923 Schmid develops gas diffusion electrode
- Post WWII Attention directed towards indirect cells using H2, CO and alcohols
# Fuel Cell Types & Efficiencies

<table>
<thead>
<tr>
<th>Fuel Cell Type</th>
<th>Operating Temp. (°C)</th>
<th>Projected Efficiency</th>
<th>Suitable Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkaline (AFC)</td>
<td>80-100</td>
<td>60%</td>
<td>Space, Automotive</td>
</tr>
<tr>
<td>Molten Carbonate (MCFC)</td>
<td>600-650</td>
<td>45-60%</td>
<td>Large Stationary</td>
</tr>
<tr>
<td>Phosphoric Acid</td>
<td>200-220</td>
<td>40-45%</td>
<td>Large Stationary</td>
</tr>
<tr>
<td>Proton Exchange Membrane (PEMFC)</td>
<td>70-80</td>
<td>35-45%</td>
<td>Small Stationary, Automotive, Portable</td>
</tr>
<tr>
<td>Solid Oxide (SOFC)</td>
<td>800-1000</td>
<td>50-65%</td>
<td>Stationary, Automotive</td>
</tr>
</tbody>
</table>
Alkaline Fuel Cell

- **Electrolyte:**
  - 85%wt KOH @ ~250°C
  - 35 to 50%wt KOH @ <120°C

- **Catalyst:** Ni, Ag, metal oxides, spinels, and noble metals

- **Advantages:**
  - Excellent Performance on H₂ and O₂ compared to other due to its active O₂ electrode kinetics
  - flexibility to use wide range of electro-catalyst

- **Disadvantages:**
  - Sensitive to CO₂ and CO
  - Needs pure H₂
  - CO₂ must be removed if ambient air is used
Molten Carbonate Fuel Cell

- **Electrolyte**: combination of alkali carbonates retained in a ceramic matrix of LiAlO$_2$
- **Electrodes**: Nickel & nickel oxide
- **Advantages**:
  - No expensive electro-catalysts needed
  - Both CO & certain hydrocarbon can be used as fuel
  - High temperature waste heat allows use of bottoming cycle to increase system efficiency
- **Disadvantages**:
  - Very corrosive electrolyte
  - Material problems, affecting mechanical stability and stack life.
  - Large size & weight and slow start-up times
Phosphoric Acid Fuel Cell

- Electrolyte: 100% Phosphoric Acid retained by silicon carbide
- Catalyst: Platinum
- Electrodes: Porous Carbon

Advantages:
- Less Sensitive to CO, ~1% tolerance
- Relatively low temperature to use common construction materials
- Waste heat can be used in cogeneration/bottoming cycle application

Disadvantages:
- Cathode-side oxygen reduction is slower than AFC
- Use of expensive materials in the stack (especially the graphite separator plates) due to corrosive phosphoric acid.
Proton Exchange Membrane

- **Electrolyte**: Ion Exchange Membrane (fluorinated sulfonic acid polymer or similar)
- **Electrodes**: Porous Carbon
- **Catalyst**: Platinum

**Advantages:**
- Solid electrolyte resistant to gas crossover
- Rapid start-up
- Absence of corrosive constituents, exotic materials are not required.
- High current densities of over 2kW/l & 2 W/cm²

**Disadvantages:**
- Difficult to use rejected heat.
- Must balance sufficient hydration of electrolyte against flooding
- Higher catalyst loading (platinum)
- Anode is easily poisoned by CO
Solid Oxide Fuel Cell

Electrolyte: Solid, non porous metal oxide $\text{Y}_2\text{O}_3$-stabilized $\text{ZrO}_2$.

Advantage:
- Solid electrolyte enable casting of the cell in various shapes, such as tubular, planar, or monolithic.
- Solid ceramic construction alleviates any corrosion problems.
- Fast kinetics and CO is directly usable as fuel.
- No requirement for CO$_2$ at the cathode and resistant to sulfur.
- Modest cost materials.
- High temperature allows use of waste heat for cogeneration or bottoming cycle and internal reforming of fuel.

Disadvantage:
- Thermal expansion mismatches among materials and sealing between cells is difficult in the flat plate configurations.
- Slow startup.
Effect of temperature
Types of fuel cells

Fuel used

- Hydrogen: \[2 \text{H}_2 (g) + \text{O}_2 (g) \rightarrow 2 \text{H}_2\text{O} (g)\]
- Methanol: \[\text{CH}_3\text{OH} (g) + \text{O}_2 (g) \rightarrow \text{CO}_2 (g) + \text{H}_2\text{O} (g)\]
- Propane: \[\text{C}_3\text{H}_8 (g) + 5 \text{O}_2 (g) \rightarrow 3 \text{CO}_2 (g) + 4 \text{H}_2\text{O} (g)\]

Configuration

Planar Configuration

Tubular Configuration
Typical Fuel Cell Vehicles
**Direct Hydrogen Fuel Cell Vehicle**

1. Hydrogen is supplied to the fuel cells.

2. Air is supplied to the fuel cells by the air compressor.

3. Oxygen from the air combines with hydrogen in the fuel cell to generate electricity, which is sent to the traction inverter module (TIM).

4. The traction inverter module converts the electricity for use by the motor/transaxle. The motor/transaxle converts the electric energy into the mechanical energy which turns the wheels.

5. Water vapor/droplets is/are the only byproduct of this process.

Graphic: Ford Motor Company
Commercial Hydrogen Fuelling Installations

Supplied to major oil companies

Air Products’ Hydrogen Fuelling Systems

BP, Singapore

Shell, Washington, DC, USA
The Process

Fig. 3. Shows a schematic diagram of one type of combined heat and power (CHP) fuel cell system (FCS) using a proton exchange membrane (PEM) fuel cell and a fuel processing system for the delivery of hydrogen fuel. The thick solid line represents gas flow of products and reactants; the thin solid line represents electricity flow; and the thick dashed line indicates heat flow.
Process: simplified version (external reformer)
Internal reforming

Diagram:

- Internal Reforming Carbonate Fuel Cell Power Plant System
- CH₄ + Steam
- Cleanup
- Anode
- Fuel Cell Stack
- Cathode
- Final Super Heater
- DC/AC Converter
- Oxidizer
- Supplementary Fuel

Chemical reactions:

- CH₄ + H₂O ⇌ CO + 3H₂
- CO + H₂O ⇌ CO₂ + H₂

Electrolyte matrix:

- Anode (Ni)
- Electrolyte matrix (γ-LiAlO₂ / α-Al₂O₃)
- Cathode (NiO)

Current generation:

- I_{cell}
- V

Exhaust gas:

- CO₂
- CO

Temperature:

- T = 600 °C
Energy from waste (Ansaldo)
Agenda

- Hydrogen Era
  - Motivation: reduce emissions
  - Efficiency of energy transformation
  - Why Hydrogen?

- Production and distribution of hydrogen
  - Sources
  - Production processes
  - Distribution

- Hydrogen utilization
  - Fuel cells: fundamentals
  - Fuel cells for vehicles
  - Fuel cells for power generation

- Conclusions
The Alternative to a Hydrogen Future

Type:
Horse Front Drive

Specifications:
- bio-propulsion displacement: 15 ccm
- fuel economy: 0 l
- horsepower: 1 hp
- $V_{\text{max}}$: 20 mph
- cruising range: 20 miles

Options:
- navigation system
- full air conditioning

Emissions:
- $\text{CO}_2 = 380 \text{ g/mile}$
- $\text{CH}_4 = 1,6 \text{ g/mile}$
- particles $= 800 \text{ g/mile}$
- low-emission
Modeling fuel cells

Steady state and dynamic modeling of fuel cells: Molten carbonate Fuel Cell MCFC
Modeling MCFC

Goals

- Develop a dynamic model for the MCFC
  - Bi-dimensional geometry cross-flow
  - Density and chemical reaction distributed
  - Considers conduction and convention
  - Solids are considered with their physical properties
  - Anode and Cathode are independent
- Check steady state and dynamic cell behavior
  - Sensitivity analysis
- Develop a steady state simulation of the process
  - Simplified model for the cell (based on the rigorous model)
  - Sensitivity analysis

Topics covered

- The cell model
- The Results of the cell steady state and dynamic simulation
- The plant model and the sensitivity analysis
MCFC simulation: model equations development

- The cell: a Molten carbonate Fuel Cell – second generation
- Assumptions of the model
- Flow and reaction scheme
- Equations of change
- Electrochemical equations
- Balances and boundary conditions at cathode
- Balances and boundary conditions at anode
- Balances and boundary conditions at electrolyte
- Physical properties
  - From Aspentech™ Data base (except for Nu)
  - From Literature correlations (electrolytic properties)
Assumptions and Input data (1)

- **Anode feed**: vectors of stoichiometric coefficients for the electrochemical and water gas shift reaction
- **Cathode feed**: vector of stoichiometric coefficients
- **Electrolyte composition**: potassium, sodium and lithium carbonates are considered.
- **Ideal gases**: mixture effects on densities are ignored; the ideal gas law is assumed and the activities are assumed to be equal to partial pressures.
- **Adiabatic system**: no heat exchanged perpendicularly to the overall flow; electrolytes do not exchange heat with the borders.
- **Reaction rate**: full Butler-Volmer equation is applied (quasi equilibrium reaction and negligible ion conduction resistance of the electrolyte)

Flow and reaction scheme

Separator Plate [stainless steel]

Hydrogen

Anode [porous Ni]

Matrix [aluminates] + Elettrolyte [carbonates]

Cathode [porous NiO]
Assumptions (2)

- **Thick channel** distribution on the cell plane
- **Plug flow**: parabolic profiles on different channels are approximated by a velocity on a single direction ($v_x$ for cathode and $v_y$ for anode).
- **Perfect mixing**: negligible diffusion flow.
- **Bi dimensional model**:
  - velocities and their derivatives along the $z$-axis are neglected
  - characteristic dimension for calculating the fluxes along the $z$-axis is the geometric mean of the bi-dimensional extensions
- **Equal current distribution at the electrodes**, due their negligible thickness.
- **Nitrogen effects**: nitrogen oxides at the cathode and ammonia at the anode are ignored.
- **Nusselt number** is function of Prandtl number, Reynolds number and geometrical factor: Brinkman and Grashof numbers are neglected.


Tomorrow’s Energy
Equations of change: application to anode

\[
\frac{D\rho}{Dt} = -\rho \left( \nabla \cdot \vec{v} \right) + r
\]
\[
\rho \frac{D\vec{v}}{Dt} = -\nabla \cdot \vec{\tau} - \nabla P
\]
\[
\rho c_v \frac{DT}{Dt} = -\left( \nabla \cdot \vec{q} \right) - T \left( \frac{\partial P}{\partial T} \right)_V \left( \nabla \cdot \vec{v} \right) - \left( \vec{\tau} : \nabla \vec{v} \right) + S
\]

Example: anode

\[
\begin{cases}
\nu_y = 0 \\
\tau_{xx,i} = -2 \mu_i \frac{\partial v_x}{\partial x} + \frac{2}{3} \mu_i \frac{\partial v_x}{\partial x} = -\frac{4}{3} \mu_i \frac{\partial v_x}{\partial x} \\
\tau_{yy,i} = -\mu_i \frac{\partial v_x}{\partial y} \\
q_{y,i} = -k_i \frac{\partial T_i}{\partial y} \\
q_{x,i} = -k_i \frac{\partial T_i}{\partial x} \\
\frac{\partial \rho_i}{\partial t} + v_x \frac{\partial \rho_i}{\partial x} + \rho_i \frac{\partial v_x}{\partial x} = (n_y \tilde{\nu} + n_{WGS} \tilde{\nu}_{WGS}) M_i \\
\rho_i \left( \frac{\partial v_x}{\partial t} + v_x \frac{\partial v_x}{\partial x} \right) = -\frac{\partial P_i}{\partial x} - \left( \frac{\partial \tau_{xx,i}}{\partial x} + \frac{\partial \tau_{yy,i}}{\partial y} \right) \\
S_{R,i} = \frac{h_i}{L} (T_E - T_A) \\
\rho_i c_v \left( \frac{\partial T_i}{\partial t} + v_x \frac{\partial T_i}{\partial x} \right) = -\frac{\partial q_{y,i}}{\partial y} - \frac{\partial q_{y,i}}{\partial x} - P_i \frac{\partial v_x}{\partial x} - \left( \tau_{xx,i} \frac{\partial v_x}{\partial x} + \tau_{yy,i} \frac{\partial v_x}{\partial y} \right) + S_{R,i}
\end{cases}
\]

Electrochemistry equations

- **Nerst equation**

\[ \eta = R_e + \eta_A + \eta_C \]

\[ \Downarrow \]

\[ V = V_0 - \eta i \]

- **Polarization equation**

- **Butler – Volmer equation**

\[ V_0 = E_0 + \frac{RT}{nF} \ln \frac{a_1^{\pi} a_2^{\kappa}}{a_1^{\psi} a_2^{\xi}} \]

\[ \eta = \eta_0 + \eta_A + \eta_C \]

\[ \Downarrow \]

\[ i_0 = i_0 \left( i_0^0, P_{O_2}, P_{CO_2} \right) \]

\[ \Downarrow \]

\[ i = i_0 \left( e^{\beta nF \eta i / RT} - e^{(1-\beta) nF \eta i / RT} \right) \]
### Degrees of freedom analysis

<table>
<thead>
<tr>
<th>Variables</th>
<th>Equations</th>
<th>Fixed</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>(29n_x n_y + 3n_x + 8)</td>
<td>(29n_x n_y + 3n_x + 3)</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>((24 + n_{\text{Comp}<em>A}) n_x n_y + (4 + n</em>{\text{Comp}<em>A}) n_y + 2n</em>{\text{Comp}_A} + 24)</td>
<td>((24 + n_{\text{Comp}<em>A}) n_x n_y + (4 + n</em>{\text{Comp}<em>A}) n_y + n</em>{\text{Comp}_A} + 6)</td>
<td>16 + n_{\text{Comp}_A}</td>
<td>2</td>
</tr>
<tr>
<td>((19 + 2n_{\text{Comp}<em>A}) n_x n_y + n</em>{\text{Comp}_A})</td>
<td>((19 + 2n_{\text{Comp}<em>A}) n_x n_y + n</em>{\text{Comp}_A})</td>
<td>4 + n_{\text{Comp}_A}</td>
<td></td>
</tr>
<tr>
<td>((8 + n_{\text{Comp}<em>C}) n_x n_y + (4 + n</em>{\text{Comp}<em>C}) n_x + 2n</em>{\text{Comp}_C} + 10)</td>
<td>((8 + n_{\text{Comp}<em>C}) n_x n_y + (4 + n</em>{\text{Comp}<em>C}) n_x + n</em>{\text{Comp}_C} + 6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>((17 + 2n_{\text{Comp}<em>C}) n_x n_y + n</em>{\text{Comp}_C})</td>
<td>((17 + 2n_{\text{Comp}<em>C}) n_x n_y + n</em>{\text{Comp}_C})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(9n_x n_y + n_x + 1)</td>
<td>(9n_x n_y + n_x + 1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(4n_x n_y + 5n_{\text{Comp}_E} + 2)</td>
<td>(4n_x n_y + 4n_{\text{Comp}_E} + 2)</td>
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<td></td>
</tr>
</tbody>
</table>

- Method Of LINES
- Variable Step Implicit EULER
- Fast NEWTON
Aspen Custom Modeler™
### Base Case and Sensitivity analysis

<table>
<thead>
<tr>
<th>Input variables</th>
<th>BASE CASE</th>
<th>v(0.27,1.7)</th>
<th>T(840,830)</th>
<th>P(2.5,3.5)</th>
<th>i(1.7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>v(x,0) – m/s</td>
<td>0.33</td>
<td>0.27</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>v(0,Y) – m/s</td>
<td>1.52</td>
<td>1.70</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T(x,0) - K</td>
<td>870.0</td>
<td>840.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T(0,y) - K</td>
<td>860.0</td>
<td>830.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P(x,0) - bar</td>
<td>3.500</td>
<td>3.380</td>
<td>2.500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P(0,y) - bar</td>
<td>3.500</td>
<td>3.378</td>
<td>3.500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>i - kA/m²</td>
<td>1.500</td>
<td></td>
<td></td>
<td></td>
<td>1.700</td>
</tr>
</tbody>
</table>

| Output Variables | U H₂ - %     | 75.000      | 82.279      | 75.132      | 89.450  | 80.746  |
|                 | U O₂ - %     | 30.000      | 28.041      | 30.955      | 30.812  | 34.780  |
|                 | Tₐ out - K   | 930.3       | 930.2       | 909.5       | 936.1   | 946.3   |
|                 | Tₖ out - K   | 952.9       | 954.1       | 932.4       | 963.6   | 974.4   |
|                 | Tₑ av. - K   | 938.9       | 940.8       | 919.7       | 948.5   | 957.8   |
|                 | l₀ - kA/m²   | 0.024       | 0.025       | 0.015       | 0.029   | 0.027   |
|                 | V av. - V    | 1.092       | 1.081       | 1.069       | 1.083   | 1.076   |
|                 | W av. - kW/m²| 1.636       | 1.620       | 1.599       | 1.625   | 1.827   |

Base case distributions

Electrolyte Temperature [K]

Current [kA/m²]

Overpotential [mV]

WGS Reaction [mol/m³/h]
Results of dynamic open-loop simulation

- **Input:** Pressure perturbation
  - Anode pressure perturbation
  - Step input (1 bar)

- **Output:** Temperature profile at anode
  - Inverse response
  - Fast phenomena (P prop T)
  - Slow response (heat of reaction)

- **Output:** Voltage distribution
  - Inverse response
  - Fast phenomena: potential rises as $V \sim \ln(P_A - 1) \sim P_A^{-1}$
  - Slow phenomena: decrease of $E_0$ with decreasing $T$ dominates
Dynamic Results: temperature effect

- Temperature perturbation
  - Anode and Cathode
  - Semi - sinusoidal ramp (different time)

The power generation process

Based on simplified model of MCFC
Fig. 3. Shows a schematic diagram of one type of combined heat and power (CHP) fuel cell system (FCS) using a proton exchange membrane (PEM) fuel cell and a fuel processing system for the delivery of hydrogen fuel. The thick solid line represents gas flow of products and reactants; the thin solid line represents electricity flow; and the thick dashed line indicates heat flow.
Process: simplified version (external reformer)
Internal reforming
A conceptual diagram of 50 MW MCFC power generation plant
Steady state process simulation

Steady State Process Simulation: details

Electrochemical model

Modular Integrated Reformer
Steady State process simulation

Fuel cells efficiency defined as the ratio of electric power produced by the stack and chemical power of the fuel actually consumed.

\[
\frac{P_{\text{turbine}} - P_{\text{compressor}}}{P_{\text{chemical}} - P_{\text{stack}}}
\]

Input specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell solid temperature (°C)</td>
<td>650</td>
</tr>
<tr>
<td>Fuel utilisation (%)</td>
<td>75</td>
</tr>
<tr>
<td>Oxygen utilisation (%)</td>
<td>30</td>
</tr>
<tr>
<td>Pressure (bar)</td>
<td>3.5</td>
</tr>
<tr>
<td>Steam/methane ratio</td>
<td>3</td>
</tr>
<tr>
<td>Steam temperature (°C)</td>
<td>170</td>
</tr>
</tbody>
</table>

Base Case & Sensitivity analysis

### Base case results

- **CH₄ plant feed rate (kg/h)**: 82
- **Stack power (kW)**: 505.6
- **Bottling cycle power (kW)**: 77.5
- **Thermal cogeneration power (kW)**: 261
- **Reforming temperature (°C)**: 688
- **CH₄ conversion (%)**: 79.3
- **Stack efficiency (%)**: 60.3
- **Cell voltage (V)**: 0.769
- **Bottling cycle efficiency (%)**: 12.2
- **Global process electrical efficiency (%)**: 51.1
- **Cogenerative efficiency (%)**: 74

### Sensitivity analysis on H₂O / CH₄

<table>
<thead>
<tr>
<th>H₂O/CH₄</th>
<th>3</th>
<th>4</th>
<th>4.5</th>
<th>5.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical plant efficiency</td>
<td>54.8</td>
<td>56.3</td>
<td>57.1</td>
<td>57.7</td>
</tr>
<tr>
<td>Stack efficiency</td>
<td>59.7</td>
<td>58.8</td>
<td>58.3</td>
<td>57.5</td>
</tr>
<tr>
<td>Cell voltage</td>
<td>0.761</td>
<td>0.748</td>
<td>0.741</td>
<td>0.730</td>
</tr>
<tr>
<td>CH₄ conversion</td>
<td>88.7</td>
<td>92.3</td>
<td>94</td>
<td>96.6</td>
</tr>
<tr>
<td>Bottling cycle efficiency</td>
<td>13.2</td>
<td>14.3</td>
<td>14.8</td>
<td>16.2</td>
</tr>
<tr>
<td>Cogenerative efficiency</td>
<td>75.6</td>
<td>71.8</td>
<td>69.8</td>
<td>65.8</td>
</tr>
</tbody>
</table>

**Base Case:**

In accordance with 500 kW MCFC from ANSALDO
Fuel cell module sensitivity analysis


Fig. 5. Pressure effect on fuel cell.
Process simulation sensitivity analysis

Electrical plant efficiency (%)

Air flow rate (Kg/hr)

Fig. 7. Air flow rate sensitivity analysis.

Pressure sensitivity analysis

Electrical plant efficiency (%)

Pressure (bar)

Fig. 6. Pressure sensitivity analysis.

Energy from biomass

MCFC based process
Energy from waste (Ansaldo)
Biomass gassification and MCFC

Biomass → Pre treatment → Gasification → Gas Clean-up → Reforming → Burner

Pre treatment ↪ Evaporator ↪ Pre heating ↪ Co generation

Gasification ↪ Gas Clean-up

Reforming

Biomass ↪ Pre heating

Air/Oxygen ↪ Evaporator ↪ Pre heating

An. Cath.

Pre heating ↪ Co generation

Evaporator ↪ Gas Clean-up

Reforming ↪ Co generation

Turbine

Compr

Air

Air/Oxygen
Biomass gassification

Literature

Ultimate analysis

Proximate analysis

Model

Steam

Oxidant

Biomass

Gassification

Gas
- Mole fraction
- Temperature
- Pressure

Data fitting

Steam

Oxidant

Biomass

Gassification

Model

Gas
- Mole fraction
- Temperature
- Pressure
Simulation strategy

Flow rate of biomass under investigation

Model Input
- I
- Fuel conversion (CO + H₂ 75%)
- Boundary conditions
- ...

Number of cells in the stack

Original modified

Flexibility of the tool

N of cells (different for different biomasses)

Gassification Model

- I
- n. of cells
- Boundary conditions
- ...

Sexten, Monday, July 01, 2013 - slide 100
Different biomass investigated

- Sugarcane bagasse (BG): residue from sugar cane treatment
- Switchgrass (SW)
- Nut shells (NT): mix 20% nut shell, 40% hazel nut shell, 40% wood

<table>
<thead>
<tr>
<th>Proximate analysis</th>
<th>bg</th>
<th>sw</th>
<th>nt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ash</td>
<td>6,99</td>
<td>5,24</td>
<td>2,38</td>
</tr>
<tr>
<td>Volatile Subst.</td>
<td>80,06</td>
<td>80,09</td>
<td>76,28</td>
</tr>
<tr>
<td>C residual</td>
<td>12,95</td>
<td>14,67</td>
<td>21,34</td>
</tr>
<tr>
<td>HHV (MJ/kg)</td>
<td>17,77</td>
<td>18,62</td>
<td>19,80</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ultimate analysis</th>
<th>bg</th>
<th>sw</th>
<th>nt</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>46,46</td>
<td>47,73</td>
<td>48,51</td>
</tr>
<tr>
<td>H</td>
<td>5,4</td>
<td>5,56</td>
<td>5,65</td>
</tr>
<tr>
<td>N</td>
<td>0,18</td>
<td>0,67</td>
<td>0,77</td>
</tr>
<tr>
<td>S</td>
<td>0,06</td>
<td>0,01</td>
<td>0,01</td>
</tr>
<tr>
<td>Ash</td>
<td>8,5</td>
<td>5,24</td>
<td>3,07</td>
</tr>
<tr>
<td>O</td>
<td>39,36</td>
<td>40,68</td>
<td>41,98</td>
</tr>
<tr>
<td>Cl</td>
<td>0,04</td>
<td>0,11</td>
<td>0,01</td>
</tr>
</tbody>
</table>

Source: Gas Technology Institute, 2002
Comparison of biomass feeds for constant conversion in the cell

\[ R = \frac{(kg_{H_2} + kg_{CO})_{out}}{(kg_{\text{biomassa}})_{in}} \]

<table>
<thead>
<tr>
<th>biomass</th>
<th>bg</th>
<th>sw</th>
<th>nt</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>0.24</td>
<td>0.34</td>
<td>0.38</td>
</tr>
</tbody>
</table>

| Humidity | 20 % | 12 % | 12.5 % |

<table>
<thead>
<tr>
<th>Type of Biomass</th>
<th>Electrical Efficiency (%)</th>
<th>Cogeneration Efficiency (%)</th>
<th>Biomass Flow rate Kg/h</th>
<th>Total Electrical Power kW</th>
<th>Gasifier efficiency %</th>
<th>Conversion at anode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bg</td>
<td>36.5</td>
<td>68.4</td>
<td>1900</td>
<td>2739</td>
<td>76.5</td>
<td>75%</td>
</tr>
<tr>
<td>Sw</td>
<td>40.3</td>
<td>69.1</td>
<td>1550</td>
<td>2841</td>
<td>82.2</td>
<td>75%</td>
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<tr>
<td>nt</td>
<td>40.2</td>
<td>69.9</td>
<td>1450</td>
<td>2802</td>
<td>84.5</td>
<td>75%</td>
</tr>
</tbody>
</table>
Agenda

- Hydrogen Era
  - Motivation: reduce emissions
  - Efficiency of energy transformation
  - Why Hydrogen?

- Production and distribution of hydrogen
  - Sources
  - Production processes
  - Distribution

- Hydrogen utilization
  - Fuel cells: fundamentals
  - Fuel cells for vehicles
  - Fuel cells for power generation

- Conclusions
Summary - Conclusions

- **Environmental legislation** will continue to tighten.
- The next 3 decades will see a *multitude of fuels* and technologies employed on a regional basis.
- Automotive development will **improve the efficiency** of use of remaining fossil fuels.
- The necessary technology for a viable H$_2$ infrastructure of **production, distribution** and **storage** already *exists*.
- Hydrogen production from fossil fuels with **CO$_2$ capture and storage** is likely to provide the bulk of hydrogen required in the next 30-50 years.
- R&D should concentrate on **cost reduction** for production, transport and storage alternatives, and demonstration projects.
The Alternative to a Hydrogen Future

Type:
Horse Front Drive

Specifications:
- bio-propulsion displacement: 15 ccm
- fuel economy: 0 l
- horsepower: 1 hp
- $V_{\text{max}}$: 20 mph
- cruising range: 20 miles

Options:
- navigation system
- full air conditioning

Emissions:
- $\text{CO}_2$: 380 g/mile
- $\text{CH}_4$: 1,6 g/mile
- particles: 800 g/mile
- low-emission