Prospects and Challenges for Fuel Cell Cars for Tomorrow’s mobility
Dr. Peter Treffinger / Prof. Horst E. Friedrich / Dr. Karelle Couturier

DLR - sites and employees
The DLR - German Aerospace Research Center

5,100 employees working in 27 research institutes and facilities
- at 8 sites
- in 7 field offices.


fields of research:
- aeronautics, space, transport, energy
Outline

- Bench mark liquid fuel
- Tomorrow’s vehicle concepts?
  - Fuel consumption
  - Development routes
- Tomorrow’s fuels?
- Fuel cell cars and hydrogen storages
  - Operation conditions
  - Safety
  - Cost
- Summary
Bench mark – Storage of conventional liquid fuels

- Almost free shapable
- Volumetric efficiency (Volume of Storage / package space) ≈ 90 %
- Gravimetric efficiency (Mass of fuel / Mass of empty storage) ≈ 4,0
- Gravimetric energy density ≈ 9,5 kWh/kg_{System weight}
Vehicle Concepts

- Honda IMA
- Lexus RX400h
- Toyota Prius
- GM Sequel
- Touran Hy-Motion
- DLR - Hylite
- Audi Q7 hybrid
- BMW
- GM
- Two-Mode Hybrid
- DaimlerChrysler
- F-Cell
- HyperCar
- A-Klasse B-Klasse
- Lexus
- RX400h
- Audi Q7 hybrid
- Bora Hy-Power

Institute of Vehicle Concepts
Fuel consumption

CO$_2$-emissions
different generic drive trains

reference gasoline middle class
- vehicle
- fuel production
- urban operation
- highway operation

gasoline start/stop
- vehicle
- fuel production
- urban operation
- highway operation

gasoline micro hybrid
- vehicle
- fuel production
- urban operation
- highway operation

gasoline mild hybrid
- vehicle
- fuel production
- urban operation
- highway operation

gasoline full hybrid
- vehicle
- fuel production
- urban operation
- highway operation

FC vehicle H2 ex Coal
- vehicle
- fuel production
- urban operation
- highway operation

FC vehicle H2 ex CNG
- vehicle
- fuel production
- urban operation
- highway operation

FC vehicle H2 ex CleanCoal
- vehicle
- fuel production
- urban operation
- highway operation

FC vehicle H2 ex REG
- vehicle
- fuel production
- urban operation
- highway operation

CO$_2$ reduction potentials

Cost optimized mix of technologies

- Lightweight construction, integral, electro hybrid
- Lightweight construction, integral, gasoline engine
- Full hybrid
- Mild hybrid
- Optimization gasoline engine, second stage
- Aerodynamic resistance, long term
- Aerodynamic resistance, short term
- Red. of rolling resistance
- Optimization gasoline engine, third stage
- Efficient gearbox
- Lightweight construction, first stage
- Stop/start, extern
- Optimization gasoline engine, first stage

New cars in Germany 2004 (source: ifeu/KBA)

ACEA goal for 2008 (KAMA 2009)

EU goal for 2012

CO$_2$ emissions of new vehicles in g/km (NEFZ)

- 2012
- 2020
- 2030

80 100 120 140 160 180
Roadmap towards sustainability

- H₂ combustion engine
- H₂APU
- cryogen storage
- H₂ combustion based propulsion
- variable compression
- HCCI/CSS
- downsizing
- opt. supercharging
- cylinder deactivation
- direct injection/gasoline
- variable valve control

Technology:
- fuel cell system
- high pressure storage
- "advanced Storage"
- power split
- power assist
- recuperation
- start/stop
- plug-in-hybrid (EV)
- full hybrid
- mild hybrid
- μ-hybrid

Fuel Sources:
- gasoline
- diesel
- natural gas
- GTL
- Ethanol
- FlexFuel
- BTL
- H₂
Fuel scenario for Germany
High-efficient vehicles & liquid bio fuels

Kilometers traveled
Mrd. Veh-km
PC 750 75
HT

Reduction of fuel consumption
by efficient vehicle concepts
70

Reduction of CO2 Emissions
by alternative power trains/fuels
65

Diversification
60

Quelle: DLR
Fuel cell vehicle
Example Mercedes-Benz F-600 Hygenius

- Permanent excited Synchronous motor (85 kW, 350 Nm)
- Wasser-cooled Lithium-Ionen-Battery
- Fuel cell stack (60 kW)
- Compressed hydrogen (700 bar)
- Electrical compressor
- New Humidification device
- Range: 400 km
- Max speed: 170 km/h

The following data is based on our estimation:
- Fuel cell stack operation temperature: ~ 80 °C
- Challenge heat rejection (Have a look on front area of vehicle)
- Hear more on that issue in presentation of VW
## Data of fuel cell stacks

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>DaimlerChrysler</th>
<th>Ballard</th>
<th>Nuvera</th>
<th>GM</th>
<th>Honda</th>
<th>Toyota</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labeling</td>
<td></td>
<td>Mark 902</td>
<td>Andromeda II</td>
<td>St – 18</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stack Type</td>
<td>PEM</td>
<td>PEM</td>
<td>PEM</td>
<td>PEM</td>
<td>PEM</td>
<td>PEM</td>
</tr>
<tr>
<td>Development date (approx.)</td>
<td>2006</td>
<td>2003</td>
<td>2004</td>
<td>2005</td>
<td>2003</td>
<td>-</td>
</tr>
<tr>
<td>Power</td>
<td>16,5 kW</td>
<td>85 kW</td>
<td>85 kW</td>
<td>93 kW</td>
<td>43 kW</td>
<td>90 kW</td>
</tr>
<tr>
<td>Number of cells</td>
<td>100</td>
<td>440</td>
<td>384</td>
<td>440</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Pressure (abs.)</td>
<td>ca. 1,6 bar</td>
<td>3 bar</td>
<td>1,6 bar</td>
<td>ca. 1,7 bar</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Temperature</td>
<td>ca. 70-80°C</td>
<td>65 - 80 °C</td>
<td>70 – 85 °C</td>
<td>ca. 85 °C</td>
<td>max. 95 °C</td>
<td>-</td>
</tr>
<tr>
<td>BPP Material</td>
<td>Metal</td>
<td>Graphite</td>
<td>Metal</td>
<td>Metal</td>
<td>Metal</td>
<td>-</td>
</tr>
<tr>
<td>Dimensions</td>
<td>-</td>
<td>805x375x250 mm³ (75 l)</td>
<td>864x486x200 mm³ (84 l)</td>
<td>-</td>
<td>(33 l)</td>
<td>-</td>
</tr>
<tr>
<td>Weight</td>
<td>-</td>
<td>96 kg</td>
<td>140 kg</td>
<td>-</td>
<td>48 kg</td>
<td>-</td>
</tr>
<tr>
<td>spez. Weight</td>
<td>ca. 1 kW/kg</td>
<td>0,9 kW/kg</td>
<td>0,6 kW/kg</td>
<td>-</td>
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**Sources:** Gathered from several sources, publications, web-sites, might be not consistent.
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### Challenge desorption temperature:
- If the “HT-PEM” does not happen we would rely on a temperature level for desorption of approx. 90 °C

<table>
<thead>
<tr>
<th>Pressure (abs.)</th>
<th>ca. 1.6 bar</th>
<th>3 bar</th>
<th>1.6 bar</th>
<th>ca. 1.7 bar</th>
<th>-</th>
<th>-</th>
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<td>Metal</td>
<td>Metal</td>
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<td>48 kg</td>
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</tr>
<tr>
<td>spez. Weight</td>
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<td>0.6 kW/kg</td>
<td>-</td>
<td>0.9 kW/kg</td>
<td>-</td>
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</table>

Sources: Gathered from several sources, publications, web-sites, might be not consistent.
Example HyLite® fuel cell system package
Safety concept and hydrogen storage

H₂-Sensor 3 in the Passenger Compartment
H₂-Sensor 2
PEFC-Stack Case
H₂-Sensor 1
H₂-Component Compartment
Ambient
H₂-Storage Compartment 1

H₂-Storage Compartment 2

H₂-Sensor 2 in the Passenger Compartment
Example HyLite® fuel cell system package
Safety concept and hydrogen storage

- Components/function needed
  - Storage (material + heat exchanger + vessel); storing hydrogen
  - Charging line with safety equipment; provide mass flow; operating pressure
  - Hydrogen supply line to fuel cell stack with safety equipment
  - Heating and cooling circuit for desorption and adsorption
  - Eventually: Cold start device

⇒ System mass must consider all components required to fulfill the functions
Challenge charging of storage

- 35 kJ/mol: 5 kg $H_2 \rightarrow 90$ MJ
- 5 min: ca. 300 kW
Challenge charging of storage

- 35 kJ/mol: 5 kg H₂ → 90 MJ
- 5 min: ca. 300 kW

The station should provide cooling power of several 100 kW
I personally believe not on concepts replacing of storages; warranty!

\[
\Delta H = -40 \text{ kJ/mol}
\]

\[
\Delta H = -35 \text{ kJ/mol}
\]

\[
\Delta H = -30 \text{ kJ/mol}
\]

\[
\Delta H = -25 \text{ kJ/mol}
\]

\[
\Delta S = -130 \text{ J/mol.K}
\]

Temperature 1000/T [1/K]
Pressure P [bar]

\[
\ln(P) = \frac{\Delta H - \Delta S}{RT} - \frac{\Delta S}{R}
\]

\[
\Delta S = -130 \text{ J/mol.K}
\]
Experiments on charging of technical solid state storages

- Variety of storage tanks
  - 40 to 400 Nl H₂ capacity
  - Charge/discharge at constant pressure or constant mass flow
  - External cooling/heating system (2.25 kW)

- Lab scaled tank
  - 125 cm³ geometric volume
  - Fulfilled with variety of low temperature metal hydride (AB₅, AB₂, etc…)
  - Temperature profile and pressure drop in the hydride bed

- Commercially available storage tank as bench mark
  - AB₅ with annular geometry (300 Nl H₂ capacity)
  - Storage of JSW compatible to HyLite vehicle
Experiments on charging of technical solid state storages

Variety of storage tanks
- H₂ loading in a LaNi₅ Storage tank: 40 L H₂, T=25°C, P=10 bar
- 40 to 400 Nl H₂ capacity

Temperature profile and pressure drop in the hydride bed

Commercially available storage tank as bench mark
- AB₅ with annular geometry (300 Nl H₂ capacity)
- Storage of JSW compatible to HyLite vehicle

Sources: DLR, Institute of Technical Thermodynamics, Institute of Vehicle Concepts
Challenge dynamic operation

- Dynamic operation
  - Understand heat and mass transfer
  - Develop effective heat and mass transfer employing light weight heat exchange devices

Dynamic operation

Understand heat and mass transfer

Develop effective heat and mass transfer employing light weight heat exchange devices

Source: DLR, Institute of Technical Thermodynamics
## Challenge cost

### DLR cost investigation of fuel cell stacks

**DLR (2007) cost consider material cost only**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Membrane</td>
<td>4.36 €</td>
<td>165.20 €</td>
</tr>
<tr>
<td>Electrodes</td>
<td>52.08 €</td>
<td>205.42 €</td>
</tr>
<tr>
<td>GDL’s</td>
<td>3.43 €</td>
<td>51.36 €</td>
</tr>
<tr>
<td>Bipolar plates</td>
<td>8.98 €</td>
<td>85.26 €</td>
</tr>
<tr>
<td>Gaskets</td>
<td>2.32 €</td>
<td>10.05 €</td>
</tr>
<tr>
<td><strong>Summe</strong></td>
<td>71.17 €</td>
<td>517.29 €</td>
</tr>
</tbody>
</table>

### DLR cost model for Li-Ion batteries

#### High-Energy Cell

<table>
<thead>
<tr>
<th>Component</th>
<th>Gewicht (kg)</th>
<th>Volumen (l)</th>
<th>Fläche (dm²2)</th>
<th>Spannung (V)</th>
<th>Masse</th>
<th>Nische</th>
</tr>
</thead>
<tbody>
<tr>
<td>LiNi0.3Co0.33Mn0.3O2</td>
<td>0.143</td>
<td>0.062</td>
<td>45.071</td>
<td>3.9</td>
<td>2.46</td>
<td>3.29</td>
</tr>
<tr>
<td>Graphit</td>
<td>0.063</td>
<td>0.042</td>
<td>45.071</td>
<td>-0.22</td>
<td>1.26</td>
<td>1.88</td>
</tr>
<tr>
<td>Separator</td>
<td>0.005</td>
<td>0.015</td>
<td>99.156</td>
<td>0.32</td>
<td>0.43</td>
<td></td>
</tr>
<tr>
<td>PVdF (Kathode)</td>
<td>0.007</td>
<td>0.003</td>
<td></td>
<td>0.18</td>
<td>0.26</td>
<td></td>
</tr>
<tr>
<td>PVdF (Anode)</td>
<td>0.003</td>
<td>0.002</td>
<td></td>
<td>0.08</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td>Acetylschwarz</td>
<td>0.007</td>
<td>0.003</td>
<td></td>
<td>0.13</td>
<td>0.16</td>
<td></td>
</tr>
<tr>
<td>LiBF4</td>
<td>0.005</td>
<td>-</td>
<td></td>
<td>1.53</td>
<td>1.91</td>
<td></td>
</tr>
<tr>
<td>Dimethylcarbonat</td>
<td>0.054</td>
<td>0.050</td>
<td></td>
<td>0.08</td>
<td>0.07</td>
<td></td>
</tr>
<tr>
<td>Aluminium</td>
<td>0.009</td>
<td>0.003</td>
<td></td>
<td>0.18</td>
<td>0.18</td>
<td></td>
</tr>
<tr>
<td>Kupfer</td>
<td>0.020</td>
<td>0.002</td>
<td></td>
<td>0.40</td>
<td>0.44</td>
<td></td>
</tr>
<tr>
<td><strong>Hülle</strong></td>
<td>0.032</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Kathodendicke</strong></td>
<td>150 μm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Gesamtkosten</strong></td>
<td>0.348 kg</td>
<td>0.132 l</td>
<td>0.07 kWh</td>
<td>3.68 V</td>
<td>7.88</td>
<td>10.27</td>
</tr>
</tbody>
</table>

*Structure of Lithium-ion Battery*
Challenge cost

- Cost issue of fuel cell
- Cost issue of traction batteries
- Cost issue of solid state storage?

<table>
<thead>
<tr>
<th>Component</th>
<th>DLR (2007) cost model for Li-Ion batteries</th>
</tr>
</thead>
<tbody>
<tr>
<td>GDL’s</td>
<td>3.43 €</td>
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<tr>
<td><strong>Summe</strong></td>
<td>71.17 €</td>
</tr>
</tbody>
</table>

DLR (2007) cost consider material cost only

### Zellebene

<table>
<thead>
<tr>
<th>Komponent</th>
<th>Bedarf</th>
<th>Technik</th>
<th>Kosten/Zeile €</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIN0.33Co0.33Mn0.33O2</td>
<td>0.143</td>
<td>45.071</td>
<td>2.46, 3.29</td>
</tr>
<tr>
<td>Graphit</td>
<td>0.063</td>
<td>45.071</td>
<td>1.26, 1.88</td>
</tr>
<tr>
<td>Separator</td>
<td>0.005</td>
<td>99.156</td>
<td>0.32, 0.43</td>
</tr>
<tr>
<td>PVdF (Kathode)</td>
<td>0.007</td>
<td>99.156</td>
<td>0.19, 0.26</td>
</tr>
<tr>
<td>PVdF (Anode)</td>
<td>0.003</td>
<td>99.156</td>
<td>0.08, 0.11</td>
</tr>
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<td>Acetylschwarz</td>
<td>0.007</td>
<td>99.156</td>
<td>0.13, 0.18</td>
</tr>
<tr>
<td>LIBF4</td>
<td>0.005</td>
<td>-</td>
<td>1.53, 1.91</td>
</tr>
<tr>
<td>Dimethylcarbonat</td>
<td>0.054</td>
<td>99.156</td>
<td>0.08, 0.07</td>
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<tr>
<td>Hülle</td>
<td>0.032</td>
<td>150 μm</td>
<td>1.29, 1.52</td>
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**Kathodendicke:** 150 μm

**Total:** 0.348 kg, 0.132 l, 0.07 kWh, 3.68 V, 7.88, 10.27
Summary

- Liquid fuel tank is tough benchmark
- Multiple power train technologies are in development the race is going on …
- Hydrogen competes with other fuels also in long term
  - Bio fuels
  - Electricity
- Solid state storage faces a lot of challenges
  - Reversible capacity of material
  - Cyclability
  - Adjustment to operation conditions of fuel cell system (T and p)
  - Refueling efforts
  - Is gravimetric energy density kept when considering all components needed in real operation
  - and finally what’s about the cost …

- We should discuss today and then go back to work immediately …
Thank you very much for your attention!