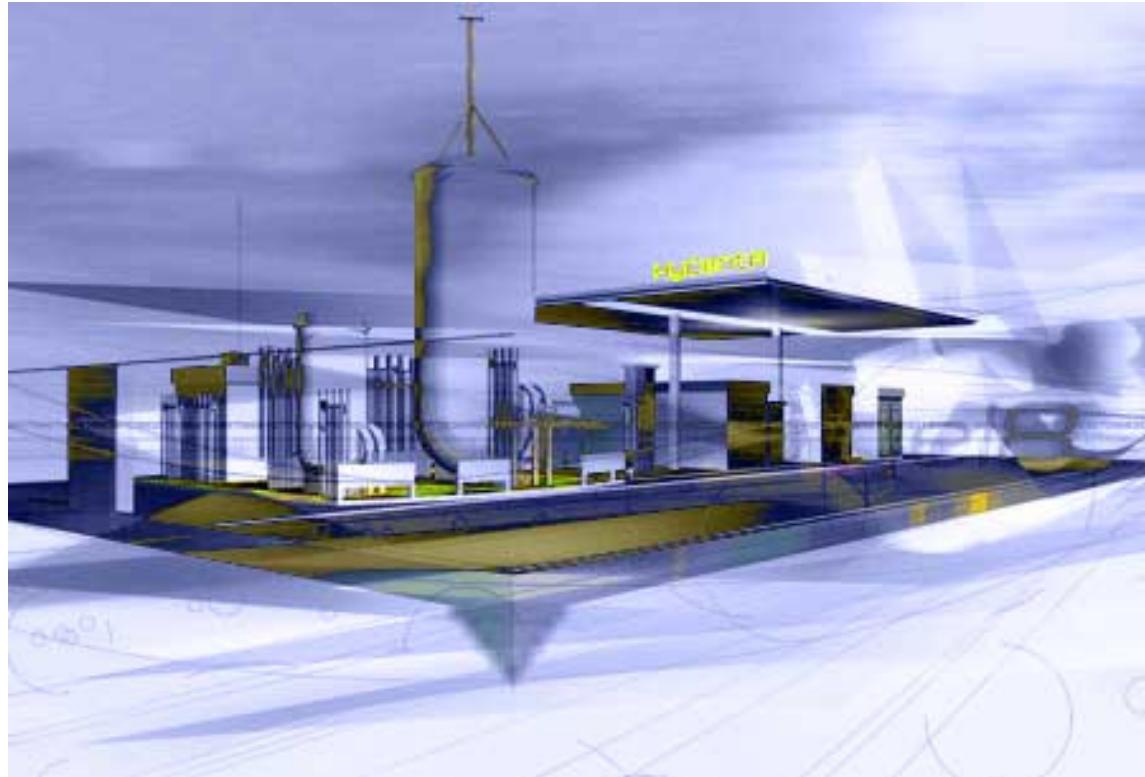


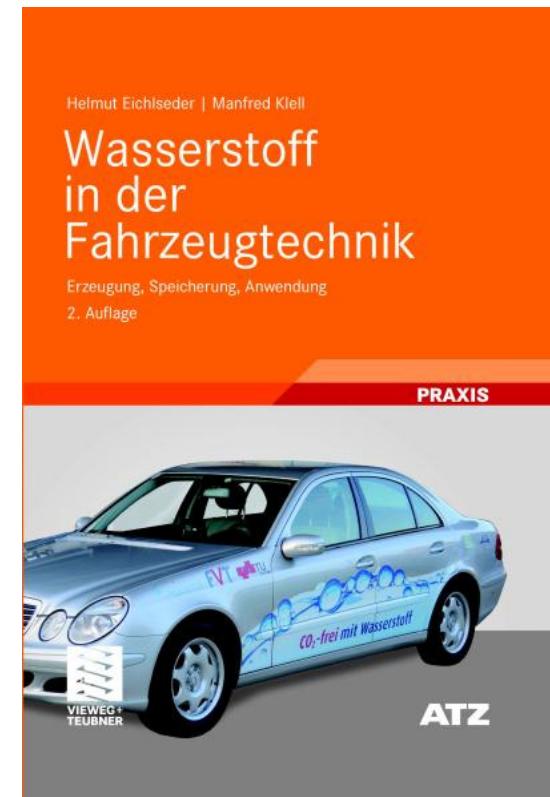
# Hydrogen – Potentials and Perspective



**Dr. Manfred Klell  
HyCentA Research GmbH, Graz  
A3PS, Vienna, 18. November 2010**

- Motivation
- Properties
- Production
- Storage
- Application

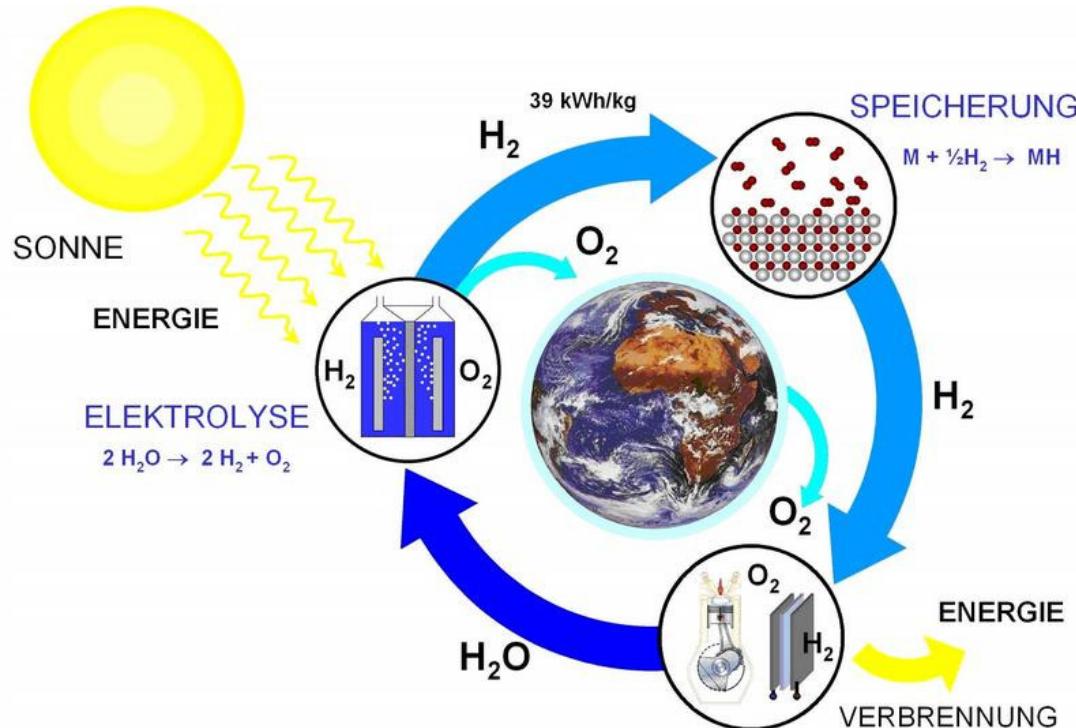
Internal Combustion Engine  
Turbine  
Fuel Cell



# Hydrogen Economy

Hydrogen provides a sustainable energy cycle with closed loop feedstock:  
**Production** from water through electrolysis with electricity from water power  
**Storage** as compressed gas, liquified or in compounds  
**Combustion** in fuel cells, turbines or internal combustion engines emitting water

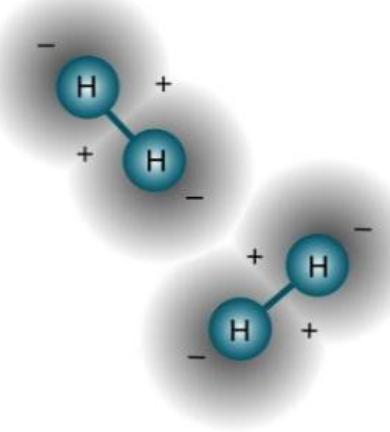
## Motivation



Source: Züttel 2010

# H(ydrogenum)

## Properties



Hydrogen H is the most abundant element, more than 90 % of all atoms are hydrogen, main component and main energy source of stars, simplest atom, one proton and one electron only, very reactive, combines to the molecule  $H_2$ , in inorganic ( $H_2O$ ,  $NH_3$ ) and organic compounds (hydrocarbons, alcohols, acids, proteins).

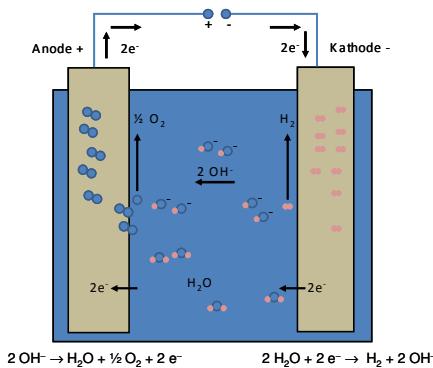
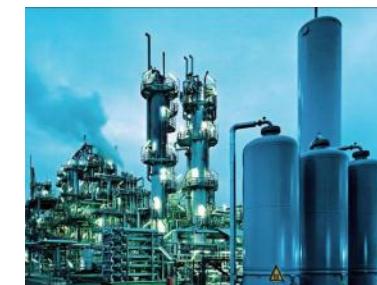
Hydrogen  $H_2$  is a colorless, odorless gas with no toxic effects, lowest density, high diffusion and heat transfer coefficients, low melting and boiling points, explosive atmosphere with air in a wide range of mixtures, high flame speed, high adiabatic combustion temperature.

# Production

## Production

Annual production: 600 Mrd. Nm<sup>3</sup>,  
6,5 EJ/year (1,5 % of primary energy consumption)  
In chemistry (NH<sub>3</sub>), refining & metallurgic processes

- 40 % by-product (Chlor-Alkali-Electrolysis)
- 50 % **Reforming** ( $\eta$  to 80 %)
- 10 % **Electrolysis** ( $\eta$  to 70 %)
- Gasification ( $\eta$  to 50 %)
- Chemical water splitting (lab scale)
- Biochemical methods (lab scale)



# Compressed Gas CGH2

## Compressed gaseous hydrogen CGH2:

compressed gas at ambient temperature and pressures of 200 – 700 bar

compression consumes 10 - 15 % of energy content  $H_u$

issue: safety of storage system

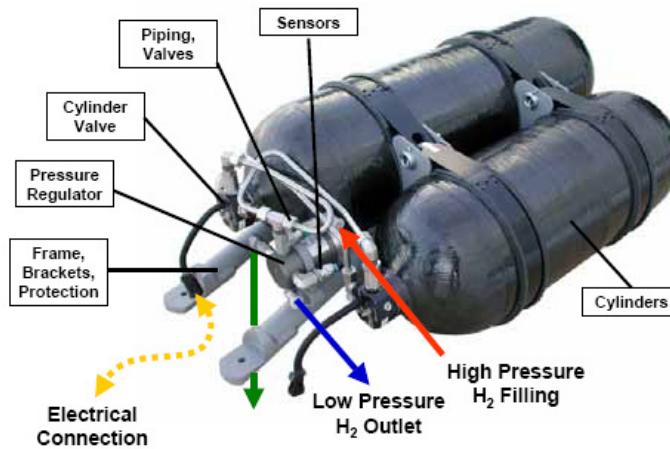
gravimetric storage capacity: pure: 33.3 kWh/kg

system 700 bar: 1 kg H<sub>2</sub>/ 20 kg tank (5 mass%), 1.7 kWh/kg

volumetric storage capacity 700 bar: pure 1.3 kWh/dm<sup>3</sup>

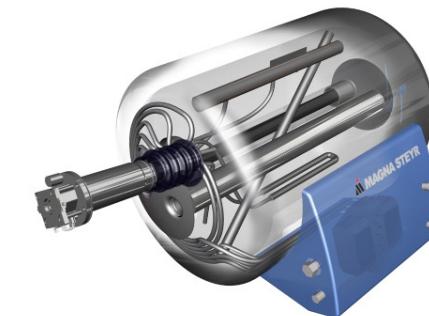
system 700 bar: 0.02 kg H<sub>2</sub>/dm<sup>3</sup>, 0.7 kWh/dm<sup>3</sup>

## Storage



# Cryogenic Liquid LH2

## Storage



# Storage in compounds

## Storage

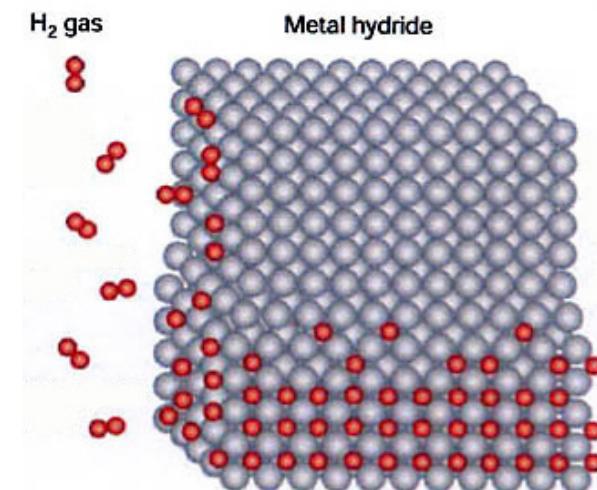
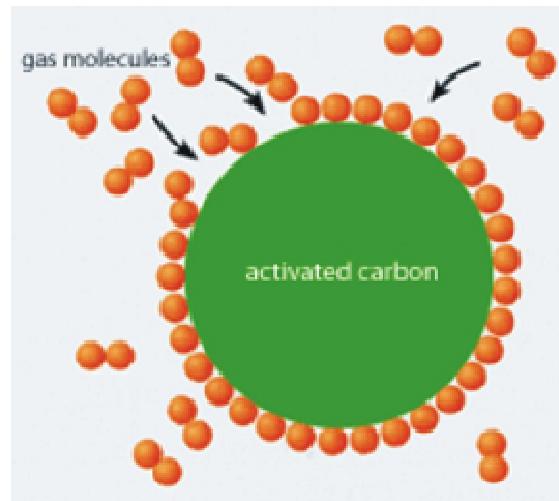
### Physical adsorption and chemical absorption:

$H_2$  molecules are bound on the surface, e. g. of carbon (nanotubes, microspheres) or are bound in the atomic lattice of metals (Mg, Al, Na, Li) or in liquids (alcohol, gasoline, oil, diesel,  $NH_3$ )

high theoretical energy densities

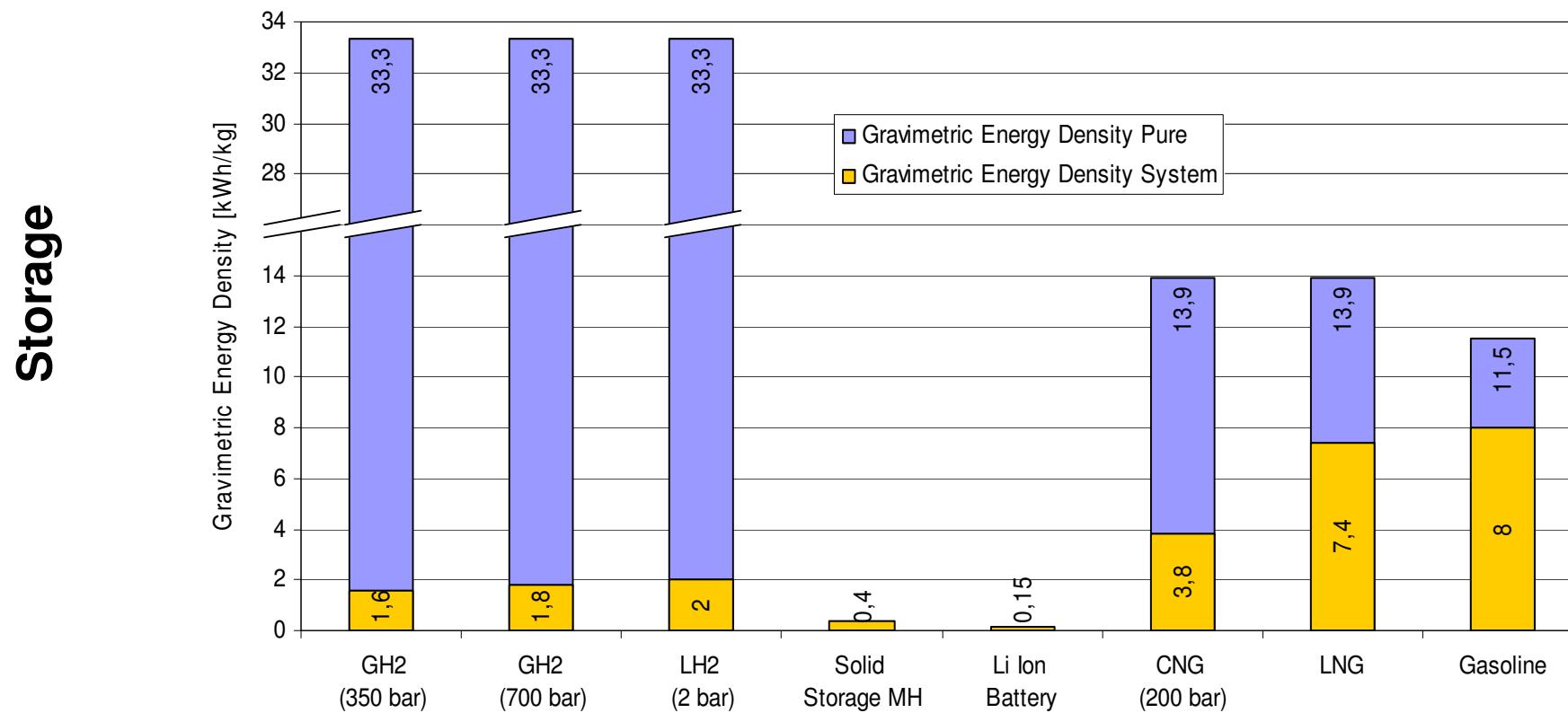
practically difficult conditions for charging and decharging  
(high or low temperatures, high pressures, long time, irreversible)

at lab scale



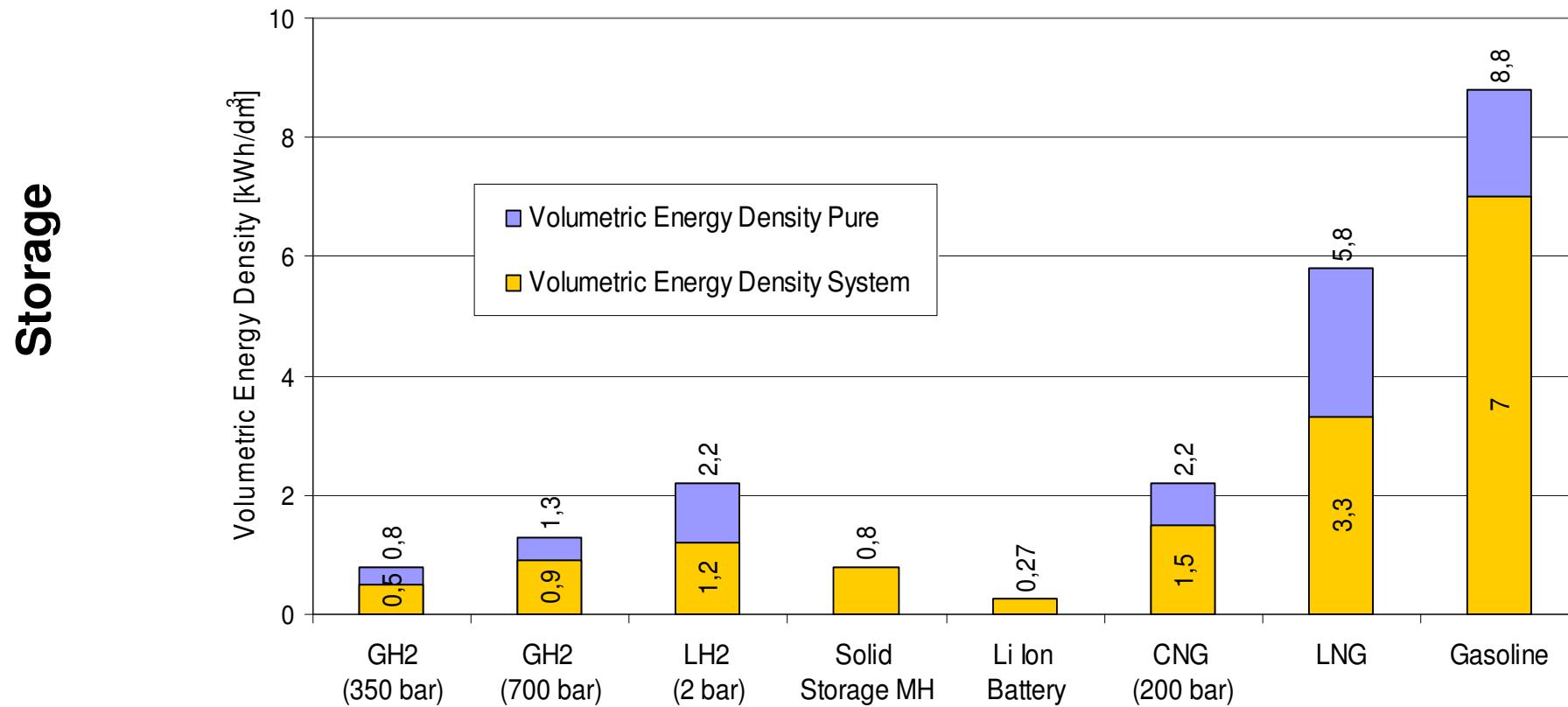
# Gravimetric Energy Density

1 kg gasoline ≈ 0,36 kg H<sub>2</sub>, 1 kg H<sub>2</sub> = 2,77 kg gasoline



# Volumetric Energy Density

1 l (dm<sup>3</sup>) gasoline = 3,84 dm<sup>3</sup> LH2 = 6,95 dm<sup>3</sup> GH2 bei 700bar



# Internal Combustion Engine

## Internal Combustion Engine

over 1 billion internal combustion engines worldwide

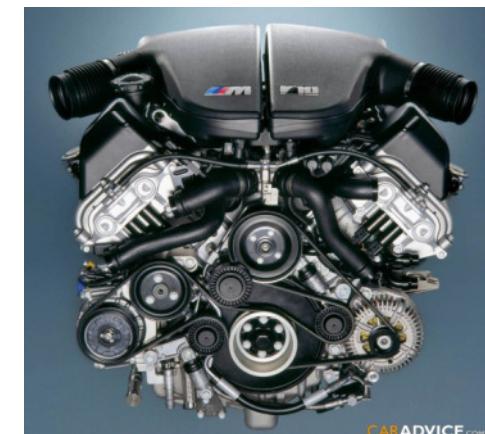
### Advantages:

- simple, robust and cheap (€ 30/kW)
- high energy density (of engine and fuel)
- multi fuel ability (liquid, gaseous)



### Disadvantages:

- low efficiency (Carnot)
- emissions (pollutants and noise)



### Combustion engine with hydrogen:

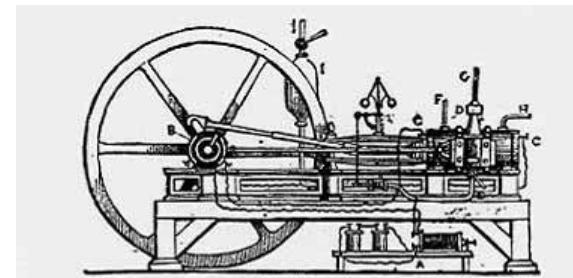
- + no emissions except NOx
- no H<sub>2</sub> Infrastrukture

# History

## Internal Combustion Engine

**1807 Francois de Rivaz** built the first vehicle with a simple internal combustion engine with hydrogen

**1860 Etienne Lenoir** built the first commercially available internal combustion engine with hydrogen that he also used in a vehicle



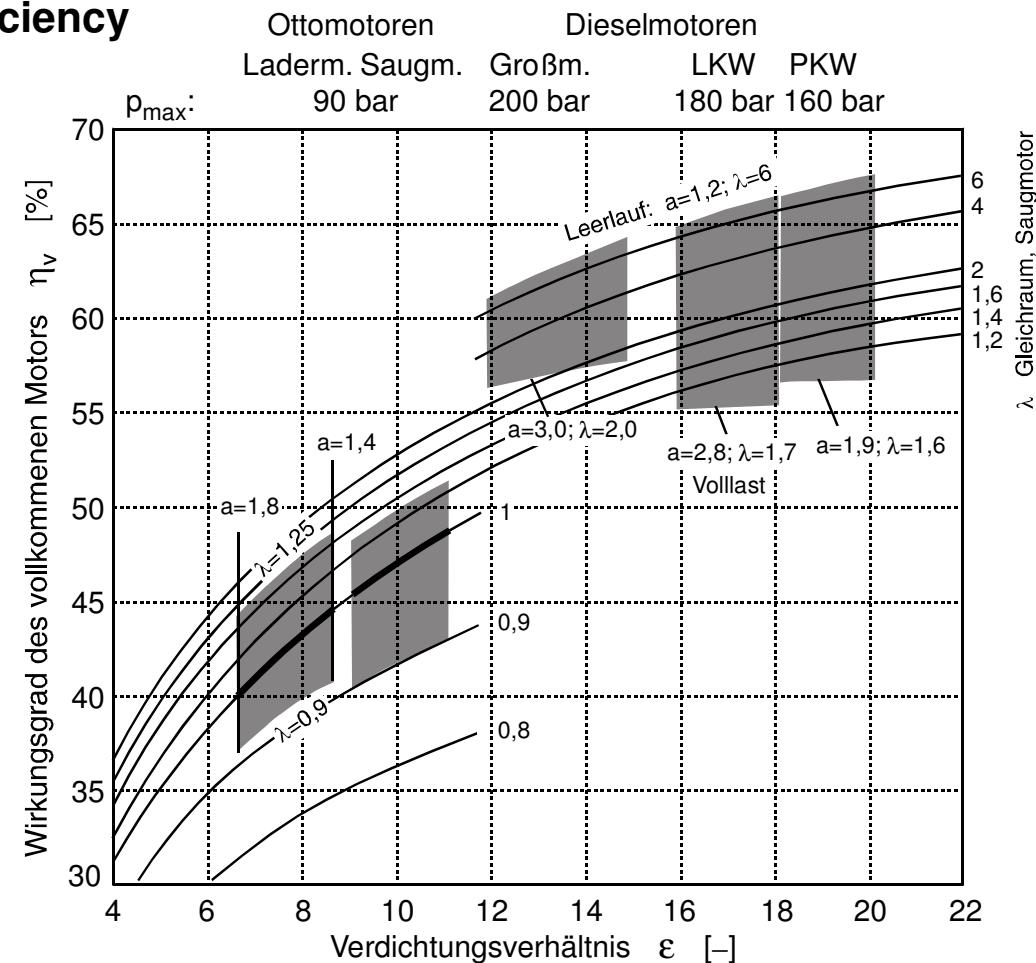
# Efficiency

## Internal Combustion Engine

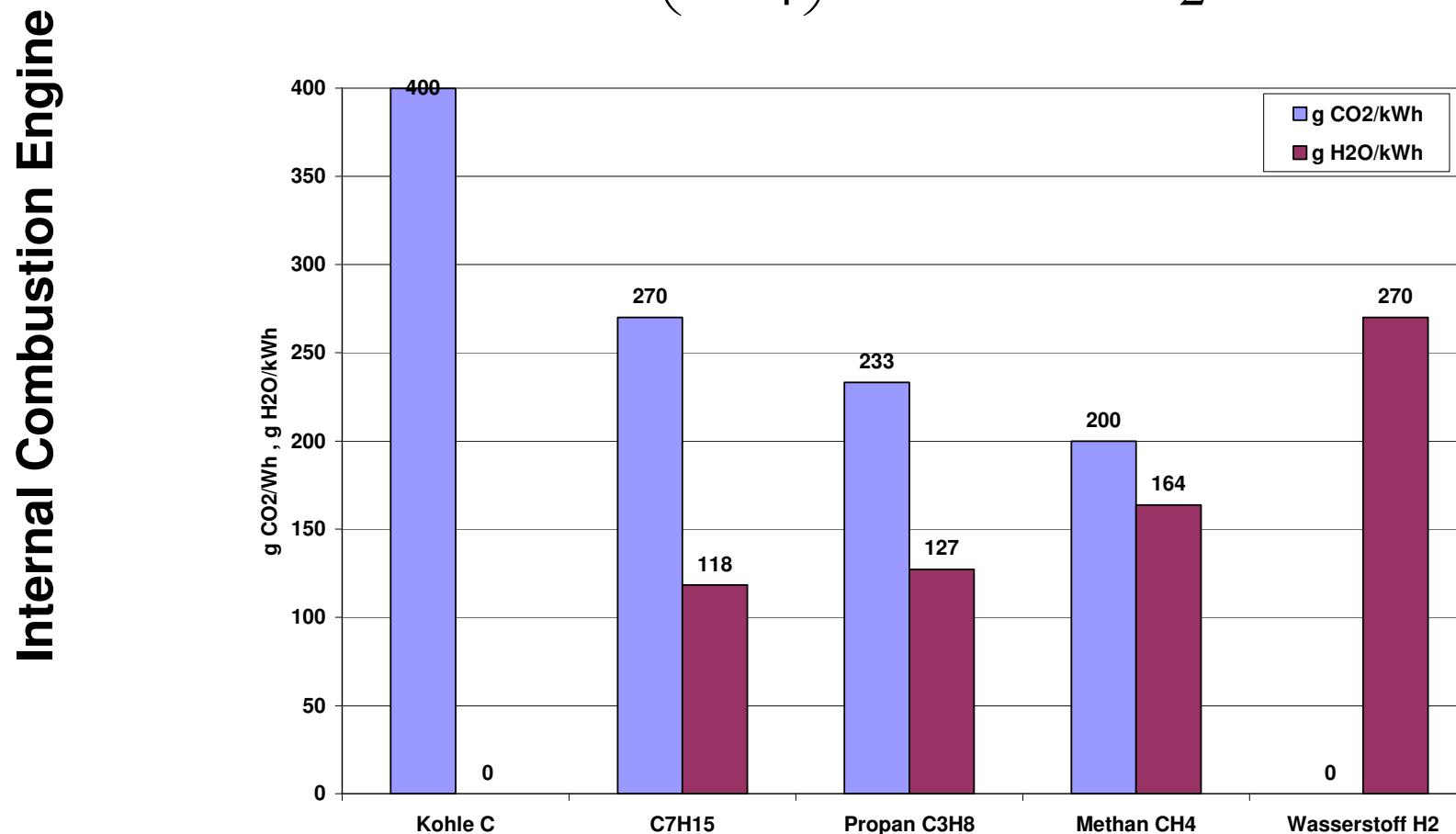
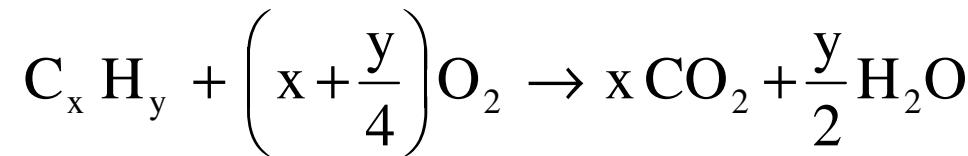
The efficiency of internal combustion engines is limited by the **Carnot-efficiency** for the conversion of heat into mechanical energy.

Efficiency increases with **combustion ratio** and **air/fuel ratio**.

Efficiency of hydrogen engines reaches values between gasoline and diesel engines.



# Ideal Combustion

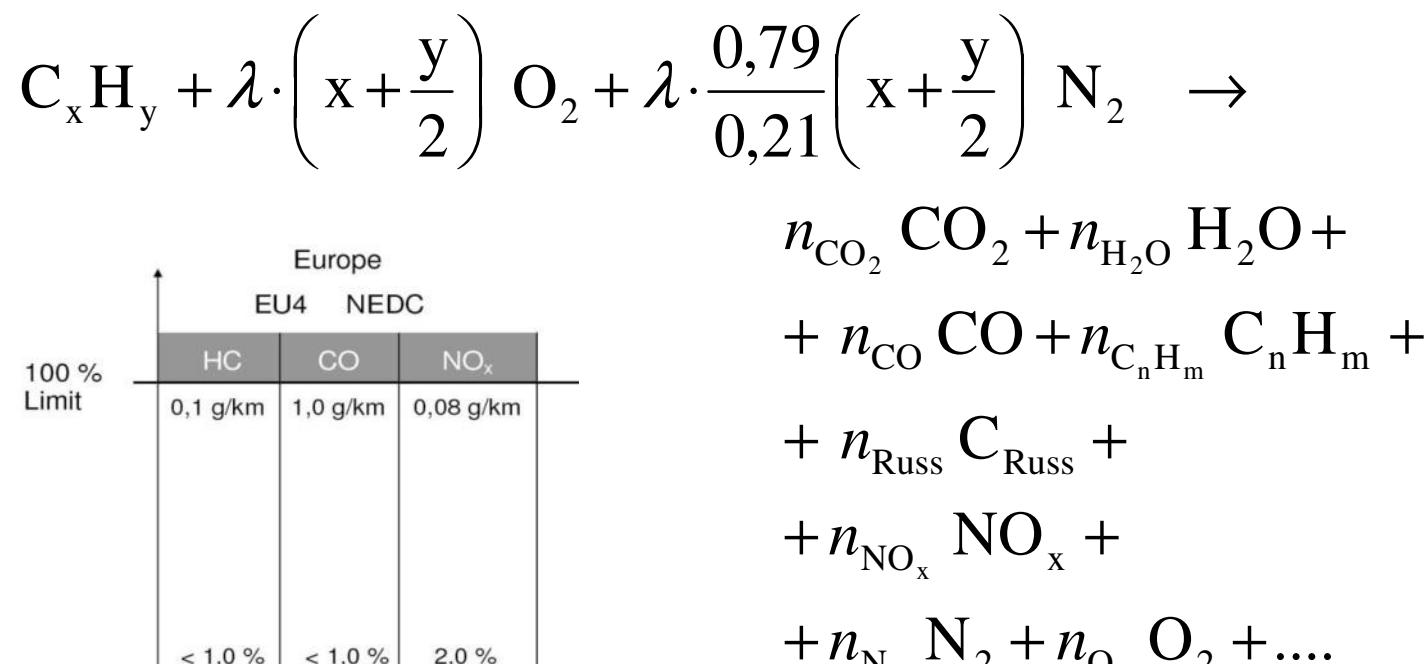


# Real Combustion

## Internal Combustion Engine

Depending on the air/fuel ratio  $\lambda$ , real combustion produces a number of pollutants apart from water and carbondioxide:

incomplete combustion with local deficiency of air produces carbonmonoxide, hydrocarbons and carbon as basis for soot and particulate matter, high temperatures cause formation of nitronoxides



# Mixtures hydrogen - methane

Vehicles with internal combustion engines for **gasoline / methane** (natural gas, biogas) / **hydrogen** / **mixtures** of methane and hydrogen are regarded as bridging technology:

conventional functionality is combined with the option of CO<sub>2</sub>-free mobility

### Advantages:

- proven, tested and cheap engines
- use of existing production facilities
- use of existing infrastructure
- gradual introduction of a new infrastructure
- reduction of carbon based pollutants

CO, CO<sub>2</sub>, CH

synergy effects with components,  
infrastructure and customer acceptance



# Multi-Flex-Fuel Vehicle

## Internal Combustion Engine



Prototype by	IVT TU Graz, HyCentA <b>SAE paper 2009-01-1420</b> <b>IJVD 45 2 2010</b>
Model	Mercedes E, CNG
Fuel	gasoline, natural gas, hydrogen
Swept volume	1796 cm <sup>3</sup>
Power gasoline/hydrogen	120 kW / 70 kW
Tank gasoline/hydrogen	65 l / 2 kg at 350 bar
Range gasoline/hydrogen	700 km / 125 km

## Internal Combustion Engine

# BMW Hydrogen 7



OEM	BMW
Model	760 h
Fuel	gasoline and hydrogen
Swept volume	5972 cm <sup>3</sup>
Power gasoline/hydrogen	191 kW
Tank gasoline/hydrogen	75 l / 8 kg cryo
Range gasoline/hydrogen	500 km / 200 km

Source: BMW AG

## Internal Combustion Engine

# Mazda 5 RE & RX-8 Hy



OEM	Mazda
Model	Premacy
Fuel	hydrogen / electricity
Swept volume	2 x 654 cm <sup>3</sup>
Power	110 kW
Tank	2,5 kg / 350 bar
Range	200 km



Source : MAZDA Motor Corporation

# Turbine

Also in gas turbines, hydrogen allows for carbon-free combustion.

To avoid nitrogen oxides:

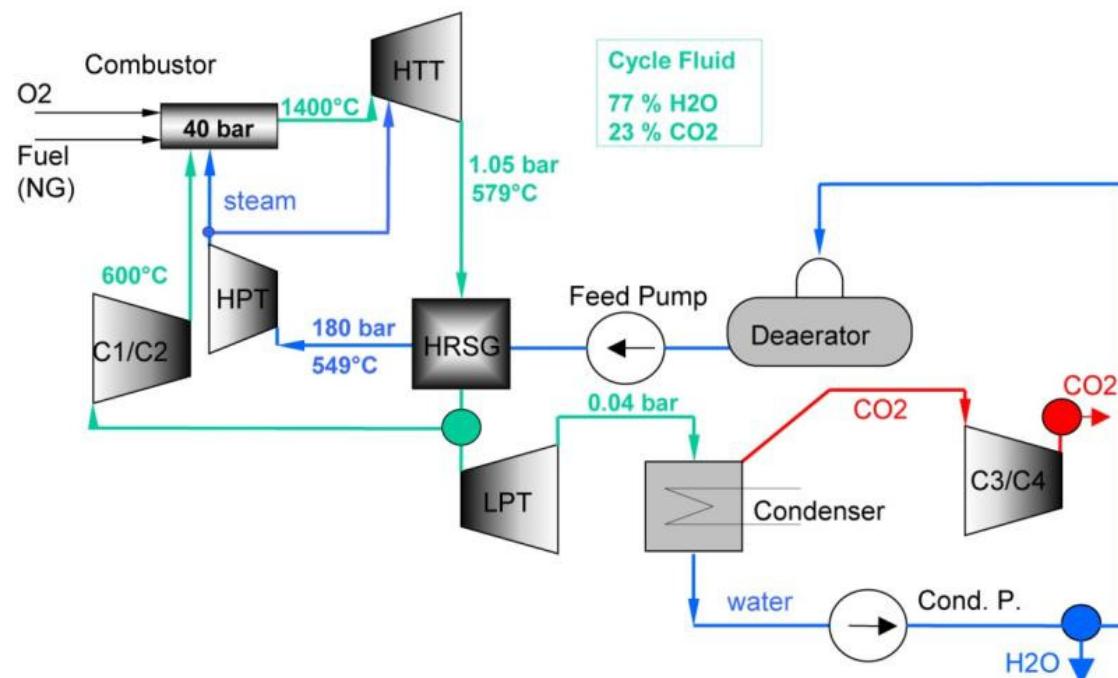
Pure oxygen instead of air (**Graz Cycle**)

## Advantages:

no emissions  
high efficiency

## Disadvantages:

high costs  
high temperatures



Source : Jericha

# Fuel Cell

## Fuel Cell

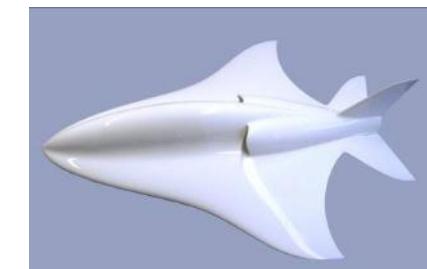
### Advantages:

- high theoretical efficiency
- no emissions tank to wheel
- no moving parts
- wide variety of applications



### Disadvantages:

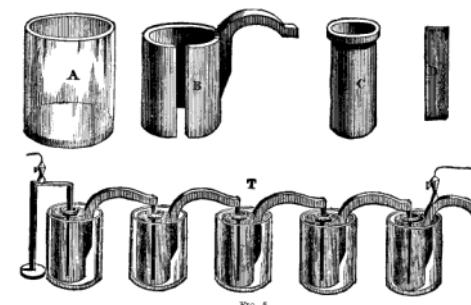
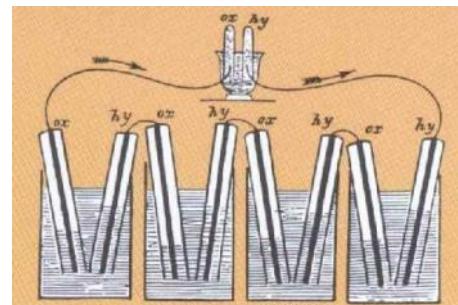
- high costs (catalyst)
- no H<sub>2</sub> infrastructure
- durability ??



# History

## Fuel Cell

1838 Friedrich Schönbein discovered the polarisation effect, the electrochemical production of electricity from water and oxygen in an electrolyte,  
Based on this discovery William Grove 1839 built the first fuel cell

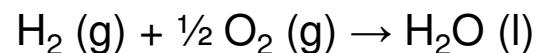


First vehicles with fuel cells were built 1966 by General Motors and 1970 by Karl Kordesch



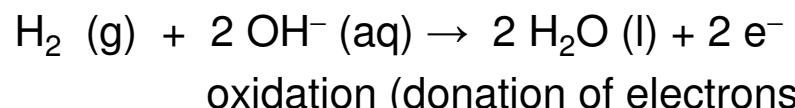
# Principle

The reaction of hydrogen and oxygen yields electricity in a “cold combustion”

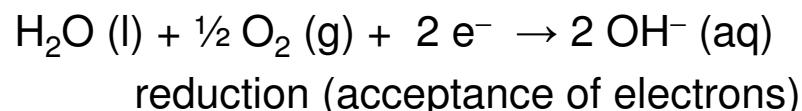


$$\Delta_{\text{R}}H = -286 \text{ kJ/mol}$$

Anode (-):



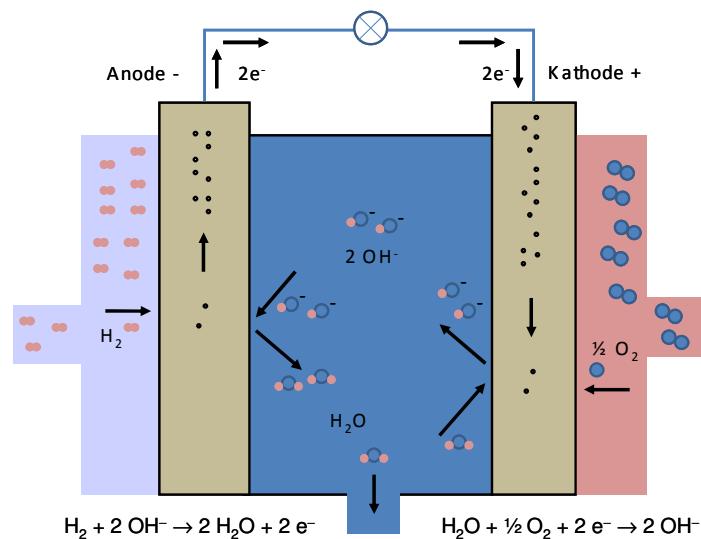
Kathode (+):



## Fuel Cell

As the voltage of a fuel cell is low, many cells have to be combined to form a stack

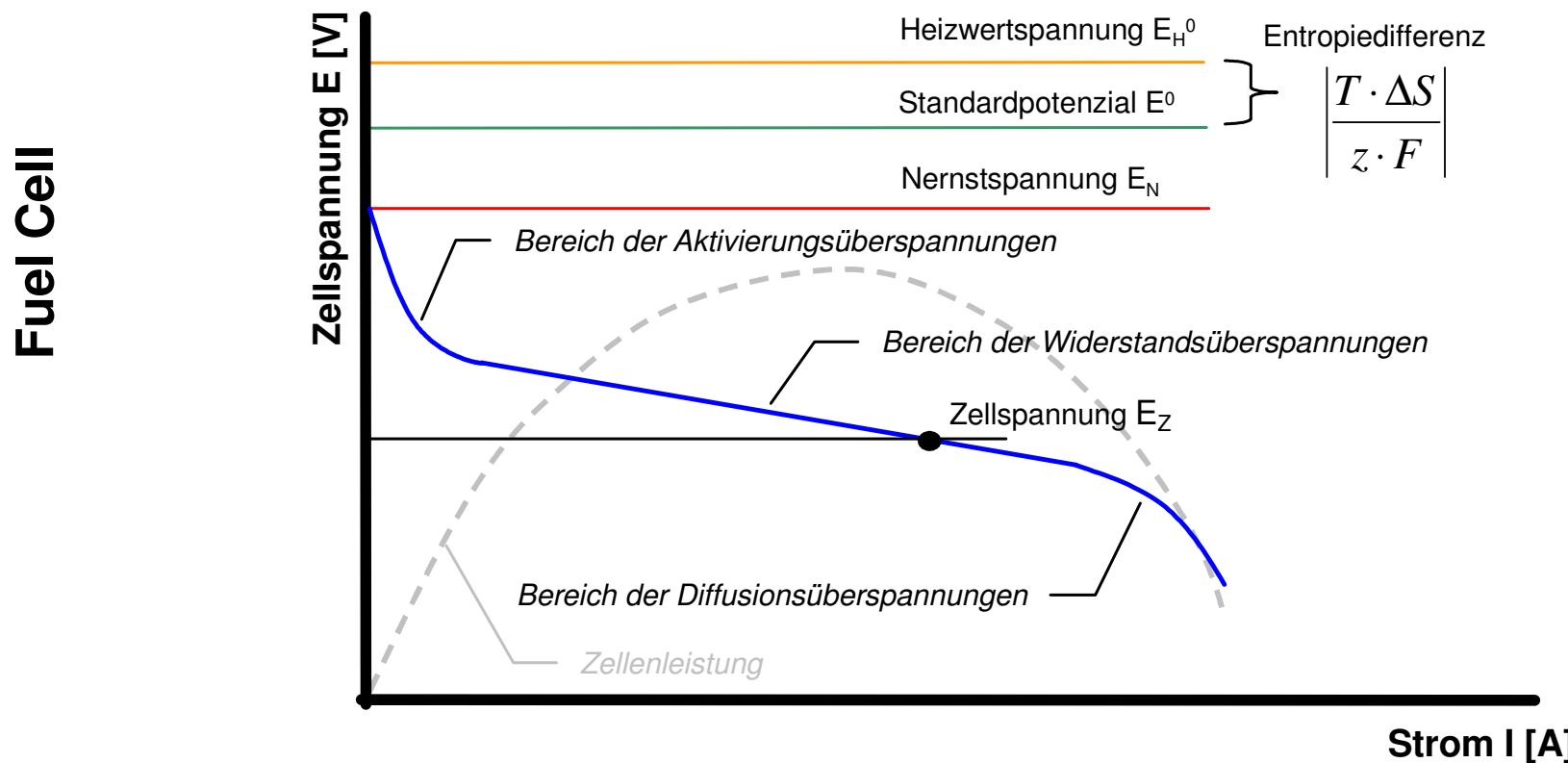
$$E^0 = -\frac{\Delta_{\text{R}}H_m^0}{z \cdot F} = -\frac{-286 \cdot 10^3 \text{ J/mol}}{2 \cdot 96485 \text{ As/mol}} = 1,48 \text{ V}$$



# Efficiency

$$\eta_{\text{th}} = \frac{\Delta G}{\Delta H}$$

The theoretical high efficiency of the fuel cell is decreased by a number of electrochemical processes, practically efficiencies of a cell range from 60 to 80 %, of a stack from 40 to 60 %.



# Application

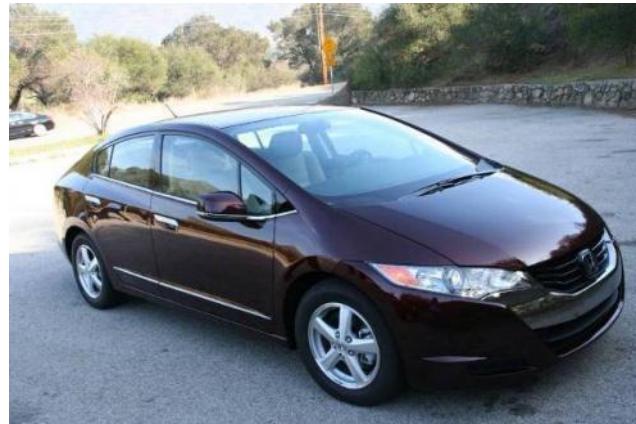
## Fuel Cell

Brennstoffzelle	Leistung [kW]	el. Wirkungsgrad [%]	Anwendung
AFC	10-100	Zelle 60-70, System: 60	Raumfahrt, Fahrzeuge
PEMFC	0,1-500	Zelle 50-70, System 30-50	Raumfahrt, Fahrzeuge
DMFC	0,01-1	Zelle 20-30	Kleingeräte
PAFC	bis 10.000	Zelle 55, System 40	Kleinkraftw.
MCFC	bis 100.000	Zelle 55, System 50	Kraftwerke
SOFC	bis 100.000	Zelle 60-65, System 55-60	Kraftwerke und APU



# Honda Clarity FCX

## Fuel Cell



OEM	Honda
Model	Clarity FCX
Battery	Lithium-Ionen Akku
Electric motor	100 kW
Fuel cell	100 kW
Hydrogen tank	4,1 kg / 350 bar
Range	430 km

**Green Car of the Year 2009**

Source : HONDA Motor

# Daimler f-Cell

## Fuel Cell



OEM	Daimler
Model	B Klasse
Battery	Lithium-Ionen Akku
Electric motor	100 kW
Fuel cell	100 kW
Hydrogen tank	3,5 kg / 700 bar
Range	400 km

Source : Daimler AG

# Mercedes Benz Citaro

## Fuel Cell

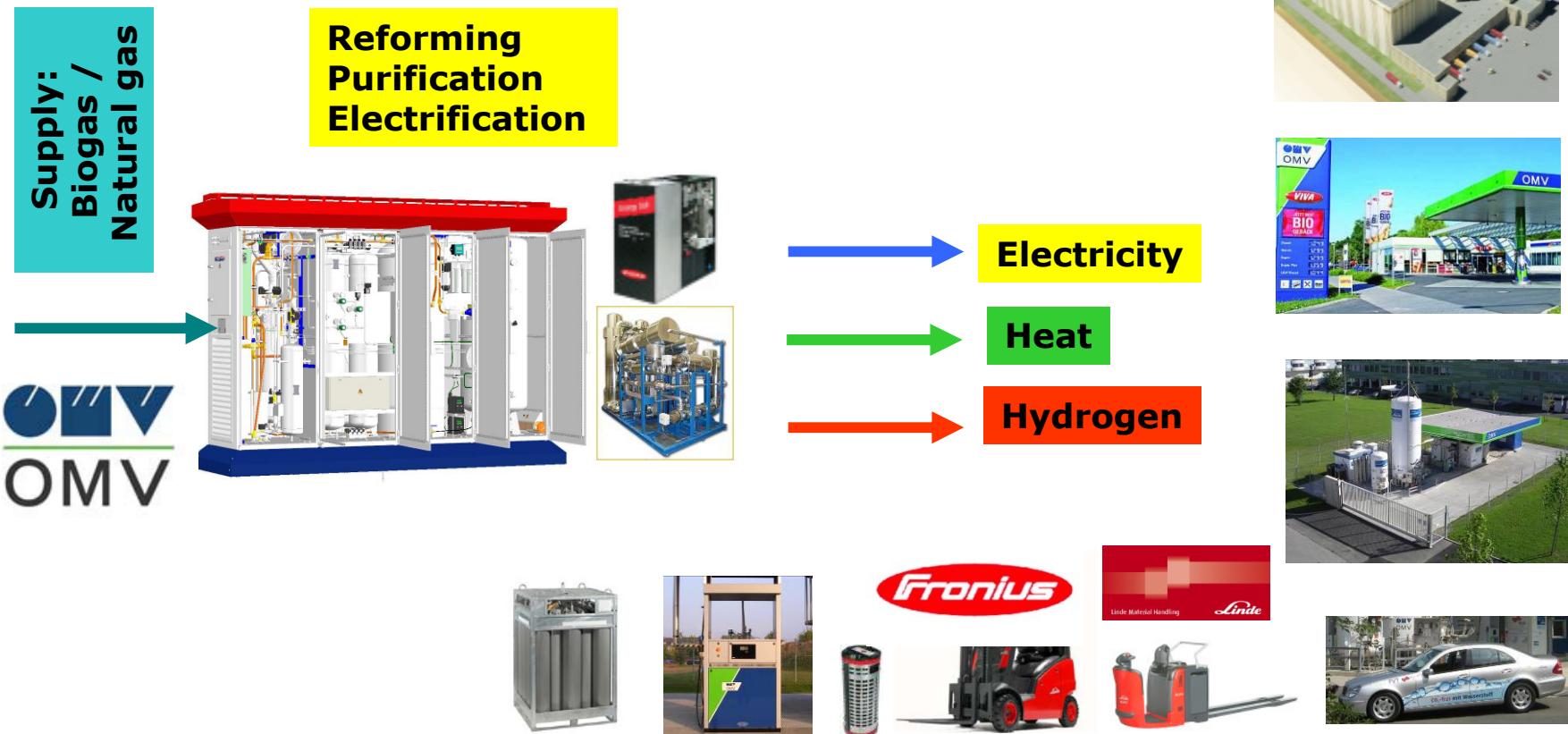


OEM	Daimler AG
Model	Citaro FC Hybrid
Battery (A123)	Lithium-Ionen Akku 26 kWh
Electric hub motor	2 x 80 kW
Fuel cell (AFCC)	2 x 60 kW
Hydrogen tank	7 x 205 l, 35 kg / 350 bar
Range	250 km

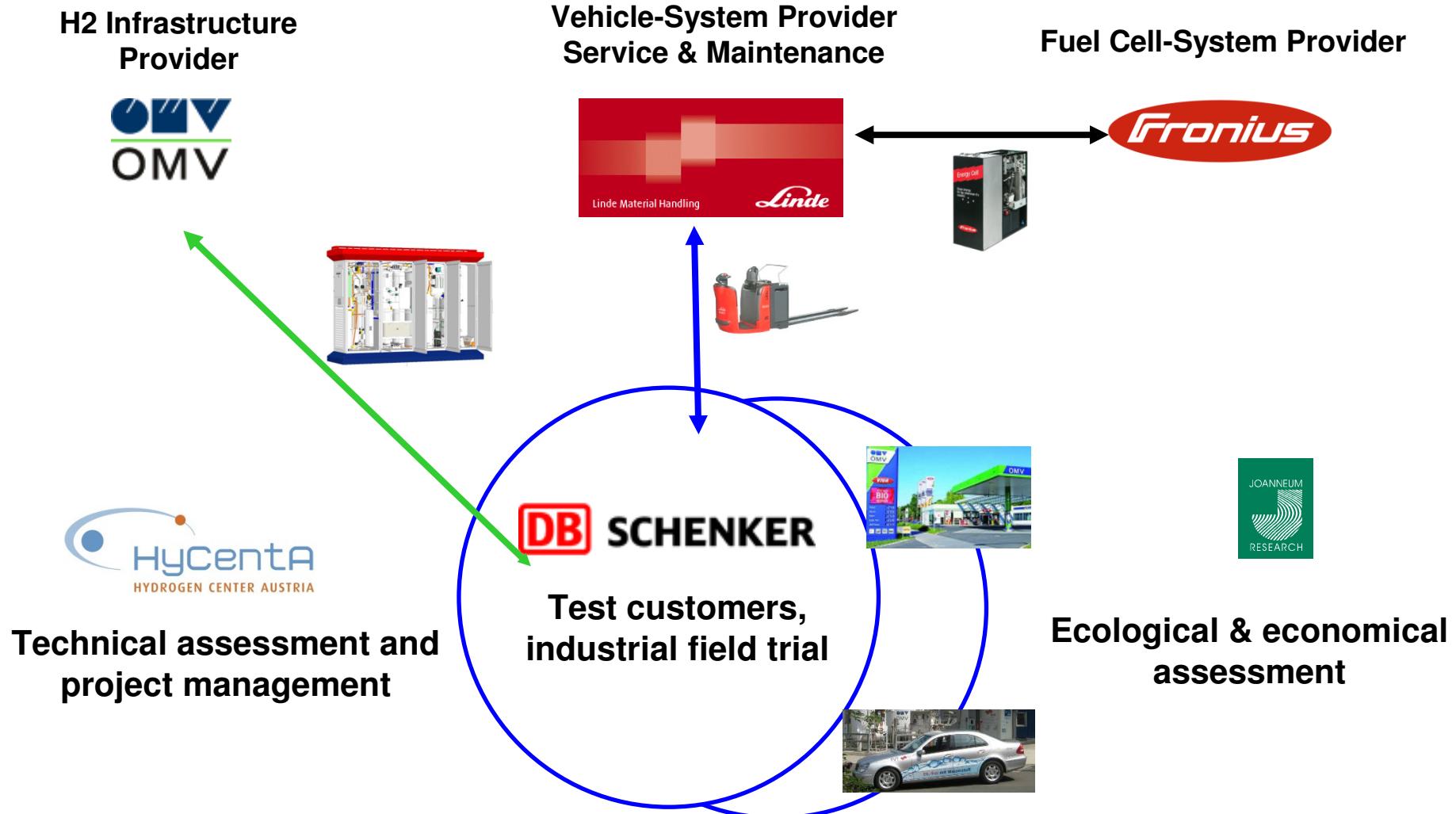
Source : Daimler AG

# Project BioEnergie

Local production of electricity, heat and fuel (hydrogen) from biogas/natural gas



# Project E-LOG-BioFleet



# Potentials and Perspective

Hydrogen permits a CO<sub>2</sub>-free sustainable closed energy cycle:

- produced from water by electrolysis using electricity from alternative sources (sun, wind, water)
- stored as compressed gas at medium energy densities at acceptable technical complexity
- combustion in internal combustion engines as bridging technology, especially in mixtures with (bio)methane
- combustion in fuel cells at high efficiencies, with high vehicle driving ranges and short filling times

Expensive and sophisticated technology

Political support necessary (CO<sub>2</sub>-tax)