Hydrogen and its Storage for Mobility, a Challenge, not only for Materials Science and Technology

Louis Schlapbach \(^1\), Andreas Züttel\(^1,2\)

\(^1\) Empa – Materials Science and Technology, Switzerland
\(^2\) Physics Dept., University of Fribourg, Switzerland

louis.schlapbach@empa.ch

Supported by Swiss DOE and EU-Projects
“The primal element of all things is water
all things come from water and all things
return to water.”

Thales of Miletus (circa 625 – 547 BC.)
WORLD ENERGY CONSUMPTION

![Graph showing world energy consumption over time, with categories for Renewables, Nuclear, Hydroelectric, Natural gas, Crude oil, Coal, and Biomass. The graph illustrates a significant increase in energy consumption from 1860 to 2000.]
WORLD CLIMATE CHANGE

Spektrum der Wissenschaft Mai 2001, pp. 90-91
Energy for Mobility (fuel and its storage)

globalisation: mobility of persons
transport of goods
emissions, greenhouse gases, CO₂
global warming, more breathing problems

We have a problem!
Statistics related to energy consumption
## WORLD ENERGY ECONOMY

<table>
<thead>
<tr>
<th>Energy carrier</th>
<th>Demand</th>
<th>Reserve [years]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fossil</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crude Oil</td>
<td>32.7 %</td>
<td>41</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>19.5 %</td>
<td>63</td>
</tr>
<tr>
<td>Coal</td>
<td>21.4 %</td>
<td>218</td>
</tr>
<tr>
<td><strong>Renewable</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydropower</td>
<td>6.7 %</td>
<td></td>
</tr>
<tr>
<td>Biomass</td>
<td>11.6 %</td>
<td></td>
</tr>
<tr>
<td>Others</td>
<td>2.0 %</td>
<td></td>
</tr>
<tr>
<td><strong>Nuclear</strong></td>
<td>6.1 %</td>
<td>100</td>
</tr>
</tbody>
</table>

### Average Power Consumption per Person kW

- World = 2 kW/person
- for 2 Bil. = 0 kW

20th Century

<table>
<thead>
<tr>
<th>Year</th>
<th>Milestone</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980</td>
<td>80</td>
</tr>
<tr>
<td>1975</td>
<td></td>
</tr>
<tr>
<td>1970</td>
<td></td>
</tr>
<tr>
<td>1965</td>
<td></td>
</tr>
<tr>
<td>1960</td>
<td></td>
</tr>
<tr>
<td>1955</td>
<td></td>
</tr>
</tbody>
</table>
International comparison of energy consumption 1998

Source: International Energy Agency 2001
Why hydrogen?

Why not already today?
## Energy is linked to forces

<table>
<thead>
<tr>
<th>Natural forces</th>
<th>Ratio</th>
<th>Example</th>
<th>Store technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravitation</td>
<td>$10^0$</td>
<td>Mechanical</td>
<td>Hydropower</td>
</tr>
<tr>
<td>Weak Nuclear</td>
<td>$10^{33}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>$10^{38}$</td>
<td>Chemical</td>
<td>Hydrogen synthetic fuel, Electric battery</td>
</tr>
<tr>
<td>Strong Nuclear</td>
<td>$10^{40}$</td>
<td>Nuclear fission, fusion</td>
<td>Nuclear fuel</td>
</tr>
</tbody>
</table>
Hydrogen

<table>
<thead>
<tr>
<th>Atomic Number</th>
<th>Symbol</th>
<th>Atomic Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>H</td>
<td>1.0079</td>
</tr>
</tbody>
</table>

Boiling Point [K]: 20.288
Melting Point [K]: 14.025
Density [g/cm³] at 300K: 0.0899

1s¹
Hydrogen

Isotopes
- Hydrogen
- Deuterium
- Tritium

HYDROGEN on EARTH

2H₂O ⇌ 2H₂ + O₂
Properties of hydrogen

- non toxic, C-free gas, unlimited available as H₂O
- simplest element of periodic table
- best ratio of valence electrons to nucleons: 1e⁻ per 1 proton, high binding energy 13.5 eV
- isotopes D deuterium, T tritium for nuclear fission and fusion reaction
- molecular gas H₂, liquid T< 21 K, solid T< 14K
- transforms @ high pressure from molecular insulating solid into atomic metallic solid
- high temperature superconductor?
Use of Hydrogen

Store hydrogen, convert it CO₂ free into heat, electric or mechanical power

\[
\begin{align*}
H₂ + \frac{1}{2} O₂ &\rightarrow H₂ O + \text{heat} & \text{(combustion)} \\
H₂ + \frac{1}{2} O₂ &\rightarrow H₂ O + \text{electricity} & \text{(fuel cell)}
\end{align*}
\]
# PROPERTIES OF FUELS

<table>
<thead>
<tr>
<th>Properties</th>
<th>Hydrogen ((\text{H}_2))</th>
<th>Methane ((\text{CH}_4))</th>
<th>Gasoline ((-\text{CH}_2-))</th>
</tr>
</thead>
<tbody>
<tr>
<td>lower <strong>heating value</strong> ([\text{kWh} \cdot \text{kg}^{-1}])</td>
<td>33.33</td>
<td>13.9</td>
<td>12.4</td>
</tr>
<tr>
<td>self ignition temperature ([\text{°C}])</td>
<td>585</td>
<td>540</td>
<td>228-501</td>
</tr>
<tr>
<td>flame temperature ([\text{°C}])</td>
<td>2045</td>
<td>1875</td>
<td>2200</td>
</tr>
<tr>
<td><strong>ignition limits in air</strong> ([\text{Vol}%])</td>
<td>4 - 75</td>
<td>5.3 - 15</td>
<td>1.0 - 7.6</td>
</tr>
<tr>
<td>minimal ignition energy ([\text{mWs}])</td>
<td>0.02</td>
<td>0.29</td>
<td>0.24</td>
</tr>
<tr>
<td>flame propagation in air ([\text{m} \cdot \text{s}^{-1}])</td>
<td>2.65</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>detonation limits ([\text{Vol}%])</td>
<td>13 - 65</td>
<td>6.3 - 13.5</td>
<td>1.1 - 3.3</td>
</tr>
<tr>
<td>detonation velocity ([\text{km} \cdot \text{s}^{-1}])</td>
<td>1.48 - 2.15</td>
<td>1.39 - 1.64</td>
<td>1.4 - 1.7</td>
</tr>
<tr>
<td>explosion energy ([\text{kg TNT} \cdot \text{m}^{-3}])</td>
<td>2.02</td>
<td>7.03</td>
<td>44.22</td>
</tr>
<tr>
<td><strong>diffusion coefficient</strong> in air ([\text{cm}^2 \cdot \text{s}^{-1}])</td>
<td><strong>0.61</strong></td>
<td>0.16</td>
<td>0.05</td>
</tr>
</tbody>
</table>
HYDROGEN CYCLE

Sun

Dissociation of water

H₂ O₂

Transport Storage

H₂

Photovoltaics
Hydropower
Nuclear

O₂

Combustion

H₂O

ENERGY

Andreas Züttel, University of Fribourg, 8/29/2006
Is Hydrogen a Safe Energy Carrier?
**LZ 129 “Hindenburg”**

New York / Lakehurst, May 6\textsuperscript{th} 1937, 6 pm

**Accident:**
While the airship was landing she has got on fire about 80 meters above ground level and crashed.

**Fatalities:**
- 13 of 36 passengers,
- 22 of 60 crew members
- 1 member of 228 ground staff holding the ship.
Cause of fire

New investigation: The inflammable skin of the Hindenburg was ignited by an electric discharge arc between the electrostatic charged skin and the grounded metallic frame.

FUEL LEAK SIMULATION

Before ignition $t = 0 \text{ s}$

Hydrogen powered vehicle on the left.
Gasoline powered vehicle on the right.

Ignition $t = 3 \text{ s}$

Ignition of both fuels occur.
Hydrogen flow rate 2100 SCFM (0.18 m$^3$/min.)
Gasoline flow rate 680 cm$^3$/min.

Ref.: Michael R. Swain, University of Miami, Coral Cables, FL 33124, USA
FUEL LEAK SIMULATION

$t = 60 \text{ s}$

Hydrogen flow is subsiding, view of gasoline vehicle begins to enlarge

$t = 90 \text{ s}$

Hydrogen flow almost finished. View of gasoline powered vehicle has been expanded to nearly full screen.

Ref.: Michael R. Swain, University of Miami, Coral Cables, FL 33124, USA
Why do we use hydrocarbons instead of hydrogen?

hydrogen is an ideal gas @ ambient conditions
1 mol $H_2 = 2g = 22,4l = 284$ kJ = 80 Wh

compacting by 1000 needed
PRIMITIVE PHASE DIAGRAM OF HYDROGEN

Figure 5. Hydrogen passes through several transformations as the pressure is increased. In the fluid phase (a) $\text{H}_2$ molecules are dispersed randomly and at low density. The solid phase formed at 54 kilobars (b) has a hexagonal close-packed structure; further increases in pressure up to well beyond a megabar drive the molecules closer together but do not alter the fundamental structure (c). In this phase the molecules remain randomly oriented. Viewed classically, the axis defined by the bond between hydrogen atoms can point in any direction, and indeed the molecules are continually tumbling. With further pressure increases hydrogen may enter a phase with orientational order; four candidate structures are shown (d–g), although none of them has been confirmed experimentally at very high pressures. The ultimate fate of hydrogen, as the pressure continues to rise, must be to form an atomic metal (h), where the $\text{H}_2$ molecules have ceased to exist.
Hydrogen storage

Storage Media  Volume  Mass  Pressure  Temp.

Hydrogen gas  
(298 K, 25°C)  
0.01 mol H₂·cm⁻³  
at 200 bar

Liquid hydrogen  
(21 K, -252°C)  
0.0708 g·cm⁻³  
0.0354 mol H₂·cm⁻³  
at 1 bar

Absorbed hydrogen  
(298 K, 25°C)  
e.g. LaNi₅H₆  
0.05 mol H₂·cm⁻³  
at 2 bar

Adsorbed hydrogen  
(65 K, -208°C)  
0.01 mol H₂·cm⁻³  
at 70 bar
VOLUME OF HYDROGEN STORAGE MEDIA

4 kg hydrogen = 560 MJ_{\text{therm.}}

Mg_2FeH_6  \quad \text{LaNi}_5H_6  \quad \text{H}_2 (\text{liquid})  \quad \text{H}_2 (200 \text{ bar})

3 l gasoline / 100 km = 9 kWh_{\text{mech.}} / 100 km = 32 MJ_{\text{mech.}} / 100 km

Ref.: L. Schlapbach & A. Züttel, NATURE, 414, 2001, 353-358
LIQUID HYDROGEN AS FUEL FOR CARS

BMW 745i refilled with liquid hydrogen

Liquid hydrogen tank
**High pressure vessels**

**Assumptions**
- gas pressure \( p = 1000 \text{ bar} = 100 \text{ MPa} \)
- tensile strength \( \sigma = 3000 \text{ MPa} \) (modern composites)
- cylinder diameter \( D = 0.1 \text{ m} \)
- \( \rightarrow \) wall thickness \( d = \frac{P}{20 \cdot D} = \frac{100}{6000} \) \( 0.1 \text{ m} = 1.4 \text{ mm} \)
- composite density \( \rho = 3 \text{ g/cm}^3 \)
- length \( L = 1 \text{ m} \)
- gas volume \( V = 8 \text{ l} \)

\( 1.5 \text{ kg container} \)
\( 0.5 \text{ kg H}_2 \)

\( \rightarrow 25 \text{ mass}\% \text{ H}_2 \)
1. Radiator
2. Air supply
3. Electric motor
4. System module
5. Fuel cell module (stack)
6. Power distribution unit
7. Hydrogen tanks
8. Battery
Hydrogen condensation in and on nanotubes

![Graph showing hydrogen mass fraction vs. nanosheet count and nanometer thickness]
Solution and metal hydride formation

pressure composition isotherms
thermodynamics
kinetics, diffusion
electronic structure
Hydrogen absorption mechanism

**H₂ gas phase**

1) Physisorption of H₂ molecules
2) Dissociation (activation barrier)
3) Chemisorption of H-atoms
4) Diffusion of H-atoms
5) Intercalation

**Alkaline electrolyte**

1) Physisorption of H₂O molecules
2) Electron transfer (desorption of OH⁻)
3) Chemisorption of H-atoms
4) Diffusion of H-atoms
5) Intercalation
Phase Diagram of Metal Hydrides (LaNi5)

\[ R \cdot T \cdot \ln \left( \frac{p}{p_0} \right) = \Delta H - T \cdot \Delta S \]
\[ H_2 + 2H_{\text{abs}} \]

CRYSTAL STRUCTURE

LATTICE EXPANSION

ELECTRONIC STRUCTURE

\[ \text{PROTON: ATTR.POT., for } e^- \]

\[ \rightarrow \text{lowering of states} \]

\[ \rightarrow \text{H-induced bonding band} \]

H ELECTRON

\[ \rightarrow \text{shift of } E_F \]

\[ \rightarrow \text{charge transfer} \]

H-H INTERACTION

PHONONS \[ \rightarrow \text{harder} \]

\[ H_2O + e^- \rightarrow H_{\text{abs}} + OH^- \]
Slater-Koster density of states for Pd
And total and partial wave
Analysis of the DOS of PdH
(D. Papaconstantopoulos)
UPS, BIS and XPS Spectra of Pd hydride
Intermetallic compounds for reversible hydride formation

- hexagonal: \( \text{AB}_5, \text{LaNi}_5, \)  
- cubic: \( \text{AB}, \text{FeTi}, \text{AB}_2, \text{Mg}_2\text{Ni}, \text{AB}_2, \text{Zr}_2\text{Ni}, \text{Mn}_2\text{Ni}, \)  

**AB\text{\_}5, \text{AB, AB}_2** type hydrides:  
Reversible cycling 10 000 times  
Safe room temperature operation  
Compact, but very heavy (1.5 -3 w% H) and expensive
Other materials to adsorb or intercalate hydrogen

layered structures

<table>
<thead>
<tr>
<th>Type</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>hexagonal</td>
<td>Al B₂</td>
</tr>
<tr>
<td>trigonal</td>
<td>Ca Si₂</td>
</tr>
<tr>
<td>orthogonal</td>
<td>Ru B₂</td>
</tr>
<tr>
<td>hexagonal</td>
<td>Re B₂</td>
</tr>
<tr>
<td>hexagonal</td>
<td>W B₂</td>
</tr>
</tbody>
</table>

high surface area nanostructures

<table>
<thead>
<tr>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li Al O₂</td>
</tr>
</tbody>
</table>

high (open) porosity nanostructures

<table>
<thead>
<tr>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>zeolites</td>
</tr>
</tbody>
</table>


Some metal hydrides discovered and/or characterized at the Uni Geneva (Klaus Yvon)

<table>
<thead>
<tr>
<th>compound</th>
<th>space group</th>
<th>structure</th>
<th>H density (wt %)</th>
<th>T_{des} (1 bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Complex transition metal hydrides</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BaReH₉</td>
<td>P6₃/mmc</td>
<td>[ReH₉]²⁻ttp</td>
<td>2.7</td>
<td>134</td>
</tr>
<tr>
<td>Mg₂FeH₆</td>
<td>Fm-3m</td>
<td>[FeH₆]⁴⁻oct</td>
<td>5.5</td>
<td>150</td>
</tr>
<tr>
<td>Ca₄Mg₄Fe₃H₂₂</td>
<td>P-43m</td>
<td>[FeH₆]⁴⁻oct</td>
<td>5.0</td>
<td>122</td>
</tr>
<tr>
<td><strong>Intermetallic hydrides</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zr₂CoH₅</td>
<td>P4/ncc</td>
<td>new type</td>
<td>2.0</td>
<td>123</td>
</tr>
<tr>
<td>Zr₆FeAl₂H₁₀</td>
<td>P-62c</td>
<td>filled Fe₂P</td>
<td>1.5</td>
<td>80</td>
</tr>
<tr>
<td><strong>Saline hydrides</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ca₄Mg₃H₁₄</td>
<td>P-62m</td>
<td>new type</td>
<td>5.7</td>
<td>98</td>
</tr>
<tr>
<td>Ba₆Mg₇H₂₆</td>
<td>C2/m</td>
<td>Ba₆Zn₇H₂₆</td>
<td>2.6</td>
<td>82</td>
</tr>
</tbody>
</table>
MOLECULAR CONTAINERS Developing suitable storage media for hydrogen is critical to capitalizing on the gas's potential benefits as an energy carrier. Among other candidates, this metal-organic framework compound—MOF-177, composed of zinc clusters (blue) and 1,3,5-benzenetri benzoate units—is being studied for gas uptake because of its large pore volume (yellow spheres).
### Complex hydrides

Hydrogen generation by the hydrolysis of alkaline borohydrides

<table>
<thead>
<tr>
<th>MH complex</th>
<th>Mol. mass (mass%)</th>
<th>H-content (mass%)</th>
<th>H-generated (mass%) (Hydrolysis)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LiAlH$_4$</td>
<td>37.93</td>
<td>10.53</td>
<td>10.82</td>
</tr>
<tr>
<td>LiBH$_4$</td>
<td>17.85</td>
<td>22.41</td>
<td>14.86</td>
</tr>
<tr>
<td>KAlH$_4$</td>
<td>70.08</td>
<td>5.71</td>
<td>7.54</td>
</tr>
<tr>
<td>KBH$_4$</td>
<td>53.91</td>
<td>7.42</td>
<td>8.90</td>
</tr>
<tr>
<td>NaAlH$_4$</td>
<td>53.97</td>
<td>7.41</td>
<td>8.89</td>
</tr>
<tr>
<td>NaBH$_4$</td>
<td>37.70</td>
<td>10.61</td>
<td>10.85</td>
</tr>
</tbody>
</table>
NEUTRON DIFFRACTION OF LiBD₄

A. Züttel et al., J. of Alloys and Compounds 356–357 (2003), 515–520
STRUCTURE OF LiBH$_4$ AT 408K (135°C)

hexagonal symmetry
space group: P6$_3$mc (#186)

a = 4.27631(5) Å

$\text{c} = 6.94844(8)$ Å

Vol: 110.041 Å$^3$, Z = 2

<table>
<thead>
<tr>
<th>Atom</th>
<th>x</th>
<th>y</th>
<th>z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li</td>
<td>0.3333</td>
<td>0.6666</td>
<td>0.0000</td>
</tr>
<tr>
<td>B</td>
<td>0.3333</td>
<td>0.6666</td>
<td>0.553</td>
</tr>
<tr>
<td>H$_1$</td>
<td>0.3333</td>
<td>0.6666</td>
<td>0.370</td>
</tr>
<tr>
<td>H$_2$</td>
<td>0.172</td>
<td>0.344</td>
<td>0.624</td>
</tr>
</tbody>
</table>

THERMAL DESORPTION OF $\text{H}_2$ FROM OF LiBH$_4$

Polymorphic transformation

50% of $\text{H}_2$ desorption

1.5 mol $\text{H}_2$

LiH + B

THERMAL H₂ DESORPTION FROM LiBH₄ into vacuum

- **Catalyzed**
- **Pure**

Graphical representation showing the desorption of H₂ at different temperatures and times.
REVERSIBILITY OF LiBH$_4$
HYDROGEN DENSITY

Ref: A. Züttel, “Materials for hydrogen storage”, materialstoday, September (2003), pp. 18-27
Future Developments

- H storage by light weight metal alloys
- Kinetics: nanosized particles (short diffusion path) however: high thermal conductivity
- Thermodynamics: include side reactions which balance $\Delta H$
- Catalysts to lower reaction temperature (3d, 4d metals with high DOS@$E_F$)
- Alkaline and alkaline earth metals and their compounds (borides, alanates,...)
- Adsorption on other nanoporous structures
- *Accept and use more efficient energy technologies*
Mehr Intelligenz, weniger Verbrauch.
HY-LIGHT®

- A purpose designed vehicle
- Curb Weight: 850 kg
- 4 seats + trunk
- Acceleration 0-100 km/h: < 12 Sek.
- Range (@ 80 km/h const.): 400 km
- Consumption: < 25 kWh/100km compressed H₂
- Electrical damping and steering
- Advanced wheel motors 30 kW per wheel
- Fuel storage integrated in the vehicle structure
- Fuel cell stack: 30 kW, based on H₂ and O₂
- Supercaps: 32-45 kW @ 17 s
- The vehicle participated at the **Challange Bibendum 2004** in Shanghai

A collaboration between Michelin and PSI:
PSI contributed the fuel cell system and the supercap-module
F600 HY Genius

(Mercedes-Benz Research Vehicle)
Zero emission compact class car
Fuel cell–Li battery–electric motor hybrid car

Hydrogen Reservoir:
4 kg 700 bar

Fuel Cell:
with air turbocharger

Li-ion Battery:
30/55 kW

Electric Motor:
60/85 kW const/peak
Torque 250-350 Nm

Range, Consumption:
400 km, eq. 2.9 l diesel/100 km
Hydrogen interactions with materials

Metal semiconductor transition of Rare Earth hydrides

Valence fluctuation in Yb hydride

Hydrogen induced defects on graphitic carbon
VB spectra of rare earth hydrides, metal-semiconductor transition
VB spectra of Ce hydride at low temperature
Individual hydrogen defects on graphite

Localized structural changes induced by the interaction with hydrogen species lead to long-ranged (~5 nm) electronic effects

Current image (STM)

Topography (AFM)

Tight Binding Calculation
by M. Franco and F. Zerbatti
University of Bologna

Hydrogen chemisorption on sp$^2$-bonded carbon

Local change of the hybridization from sp$^2$ to sp$^3$
Armchair \((n,n)\) SWNT are always (in principle) metallic, because the band going through the \(\Gamma\)-point (origin of the \(k\)-space) always goes through a Fermi-point!
Local modification of the electronic properties of CNT
Formation of symmetric states in the gap of semiconducting SWNT

LT-STM measurement @ 77 K
Local modification of the electronic properties of CNT by hydrogen induced defects: Band Gap Engineering

Sharp (FWHM < 30 meV) twin state in the bandgap of a semiconducting tube. May be active as radiative recombination centers => Point photon source.

LT-STM @ 5 K
What is so interesting with defects and SWNT?

(*single walled carbon nanotube SWNT*)
Again: Is working with hydrogen safe?
LAVOISIER

JEAN-PIERRE POIRIER

Préface de
ALAIN PEYREFITTE
de l'Académie française
Chronologie des travaux de physique et de chimie de Lavoisier

1765: Mémoire «Sur l'analyse du gypse».
1772: Expériences sur la calcination; pli cacheté à l'Académie.
1773: Calcination du plomb et de l'étain dans des cornues.
1774: Opuscules physiques et chimiques.
1777: Mémoire «Sur la respiration des animaux»;
      mémoire «Sur la combustion en général».
1780: Expériences sur les acides.
1781: Travaux sur la chaleur (en coll. avec Laplace).
• 1783: Mémoire «Sur la composition de l'eau»; «Réflexion sur le phlogistique».
1785: Grande expérience de synthèse et analyse de l'eau.
1787: Mémoire «Sur la nécessité de réformer et de perfectionner la nomenclature chimique».
• 1789: Traité élémentaire de chimie; premier volume des Annales de chimie.
1792: Travaux pour le système métrique.
ANTOINE LAURENT LAVOISIER.
Fermier Général, né à Paris le 16 août 1743.
Juge le 16 févr. an 2.

Selon l'opinion d'un acteur, en présence de tous les humains, que les tous, les vertus accroissent la vénération, les humains de leurs contemporains et de la postérité. Il est dit que notre propre beaucoup plus humaine, qui est en effet plus conciliante humaine aussi, plus du monde que des vertus.

Selon la postérité, les humains pendant plusieurs siècles, jusqu'à l'époque de la Révolution, où la Révolution a porté l'indépendance, la Révolution a porté l'indépendance, la Révolution a porté l'indépendance.
Mittelalterlicher Stadtplan von Paris.
Remaining Challenges e.g. Mobility

Goal: Safe, comfortable and fast transport of 1 or a few persons

2.5 ton vehicle as mid-size car (US DOE)?

Introduce mass ratio „brain to car“ as a quality criteria? Or „mass CO₂/km“
Incremental increase of storage capacity of 2.5 ton cars or new concepts for efficient cars?
F600 HY Genius

(Mercedes-Benz Research Vehicle)
Zero emission compact class car
Fuel cell–Li battery–electric motor hybrid car

Hydrogen Reservoir:
4 kg  700 bar

Fuel Cell:
with air turbocharger

Li-ion Battery:
30/55 kW

Electric Motor:
60/85 kW const/peak
Torque 250-350 Nm

Range, Consumption:
400 km, eq. 2.9 l diesel/100 km
Availability of energy is a product of nature, science, technology, culture, not of economics, nor politics or war.

Ethical behaviour respects energy and its efficient use.