Science and technology of hydrogen in metals

Ronald Griessen
Vrije Universiteit, Amsterdam
2008

Energy and Power: what is that ?

- Missing energy intuition because:
  - Energy is ubiquitous in the industrialized nations
  - There is a zoo of units
  - Energy and Power are mixed up
  - Energy is far too cheap

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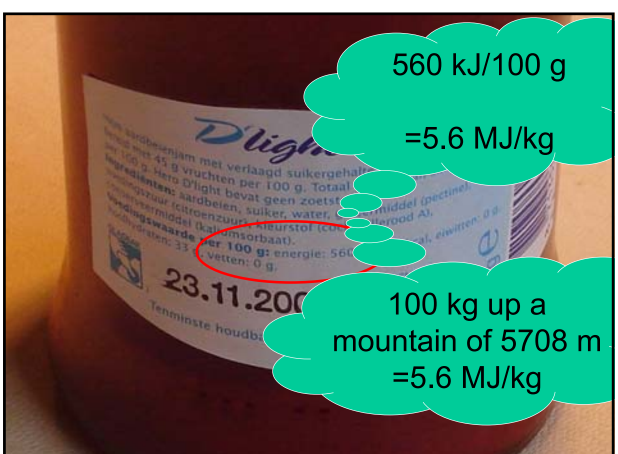
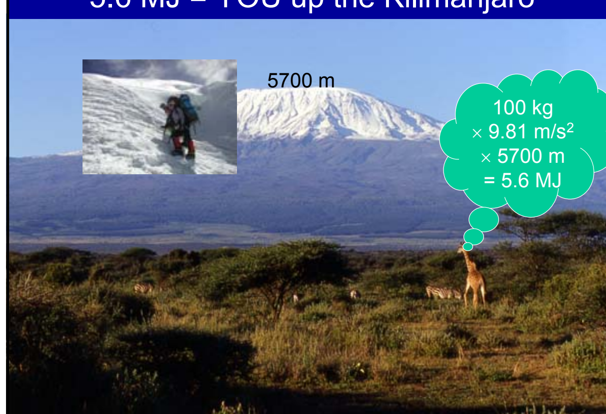


5.6 MJ = YOU up the Kilimanjaro



Comparison of energy densities

5.6 MJ/kg

Gasoline 44.5 MJ/kg

Methane 50 MJ/kg

Hydrogen 120 MJ/kg

How much energy do you need for a bath?

7 x 5.6 MJ

37.8 MJ

Comparison of energy densities

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Methane 50 MJ/kg

Hydrogen 120 MJ/kg

Energy and Power: what is that ?

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General Conversion Factors for Energy

To: / From:	TJ	Gcal	Mtoe	MBtu	GWh
	multiply by:				
TJ	1	238.8	2.388×10^{-5}	947.8	0.2778
Gcal	4.1868×10^{-3}	1	10^{-7}	3.968	1.163×10^{-3}
Mtoe	4.1868×10^{4}	10^{7}	1	3.968×10^{7}	11630
MBtu	1.0551×10^{-3}	0.252	2.52×10^{-8}	1	2.931×10^{-4}
GWh	3.6	860	8.6×10^{-5}	3412	1

For example:
1 *toe* to be equal to 41.868 GJ or 11.630 MWh
1 GJ=10^9 J giga
1 TJ=10^{12} J tera
1 PJ=10^{15} J peta
1 EJ=10^{18} J eta

General Conversion Factors for Volumes

To:	gal U.S.	gal U.K.	bbl	ft³	l	m³
From:	multiply by:					
U.S. Gallon (gal)	1	0.8327	0.02381	0.1337	3.785	0.0038
U.K. Gallon (gal)	1.201	1	0.02859	0.1605	4.546	0.0045
Barrel (bbl)	42.0	34.97	1	5.615	159.0	0.159
Cubic foot (ft³)	7.48	6.229	0.1781	1	28.3	0.0283
Litre (l)	0.2642	0.220	0.0063	0.0353	1	0.001
Cubic metre (m³)	264.2	220.0	6.289	35.3147	1000.0	1

1 G=10^9 giga
1 T=10^{12} tera
1 P=10^{15} peta
1 E=10^{18} eta

Energy and Power: what is that ?

- Missing energy intuition because:
  - Energy is ubiquitous in the industrialized nations
  - There is a zoo of units
  - Energy and Power are mixed up

What are kW and kWh ?

[Force]= Newton	$1N = 1\ kg \times 1\frac{m}{s^2}$
[Energy]= Joule	$1J = 1\ N \times 1m$
[Power]= Watt	$1W = 1\ \frac{J}{s}$

$$1kW = 1000\frac{J}{s} = 1\frac{kJ}{s}$$

$$1kWh = 1\frac{kJ}{s} \times 3600s = 3.6MJ$$

Energy and Power: what is that ?

- Missing energy intuition because:
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  - Energy and Power are mixed up
  - Energy is far too cheap

Energy costs in NL (2008)

1 kWh costs:

- Continu 0.0927 €
- BTW 19%

Average price 0.09 €

1 m^3 gas (8.8 kWh) costs:

- Gas 0.25 €
- Transport 0.05 €
- BTW 19%

Average price 0.44 €/m^3

Energy per € in NL

1 kWh costs: 0.09 €

1 kWh=3.6 MJ

$$\frac{3.6}{0.09}\frac{MJ}{€} = 40\frac{MJ}{€}$$

1 m^3 gas costs: 0.44 €

1 m^3 = 35.17 MJ

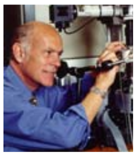
(Groningen-gas-equivalent)

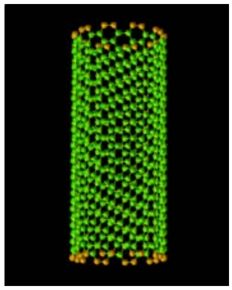
$$\frac{35.17}{0.44}\frac{MJ}{€} = 80\frac{MJ}{€}$$

Why a lecture on metal-hydrogen systems ?

- Societal reason:
  - Global warming

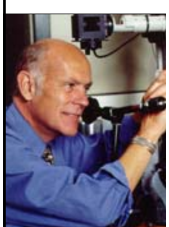
Smalley’s Nobel prize





Smalley’s conclusions

1. **ENERGY**
2. Water
3. Food
4. Environment
5. Poverty
6. Terrorism and war
7. Disease
8. Education
9. Democracy
10. Population



www.mrs.org/publications/bulletin

MATERIAL MATTERS

Future Global Energy Prosperity: The 50 Terawatt Challenge

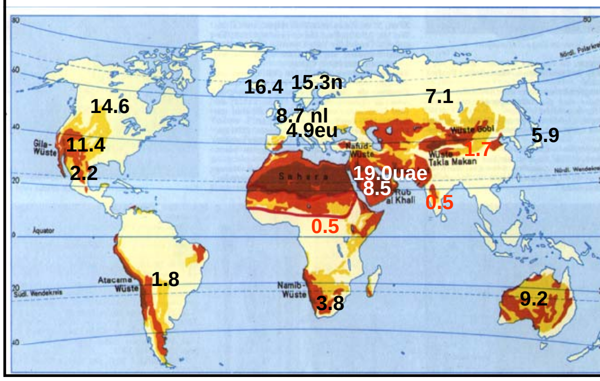
Richard E. Smalley

The following article is an edited transcript based on the Symposium X—Frontiers of Materials Research presentation given by Richard E. Smalley of Rice University on December 2, 2004, at the Materials Research Society Fall Meeting in Boston.

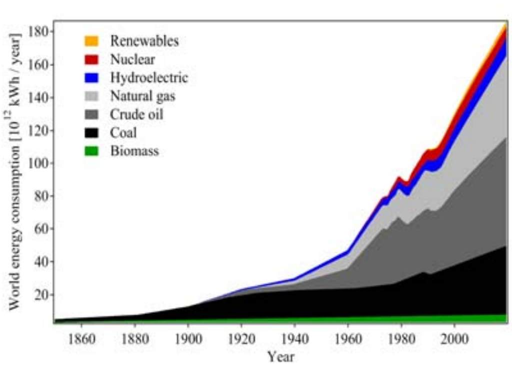
MRS Bulletin 30 (2005) 412

Primary Power Consumption (kW) per Capita (2005)

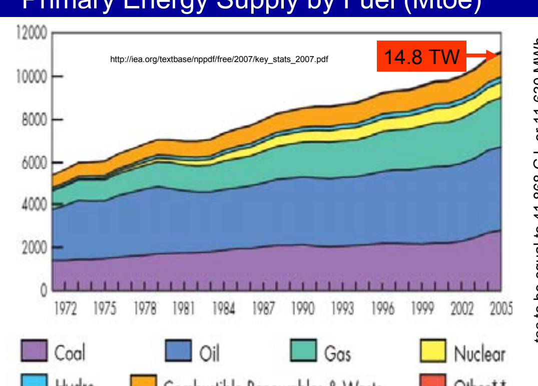
World = **2.41 kW/person;** for 2 billion = **0 kW**



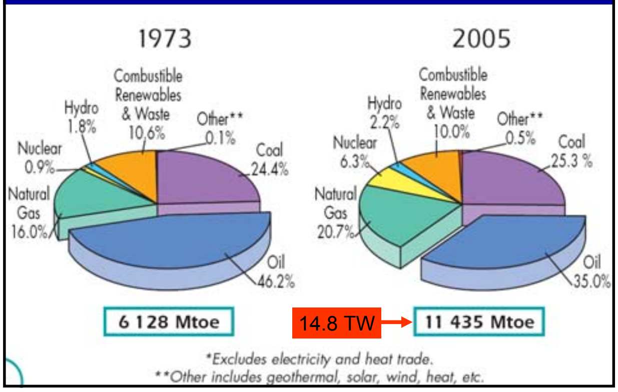
World Energy Consumption



Evolution from 1971 to 2005 of World Total Primary Energy Supply by Fuel (Mtoe)



Fuel shares of World Total Primary Energy Supply



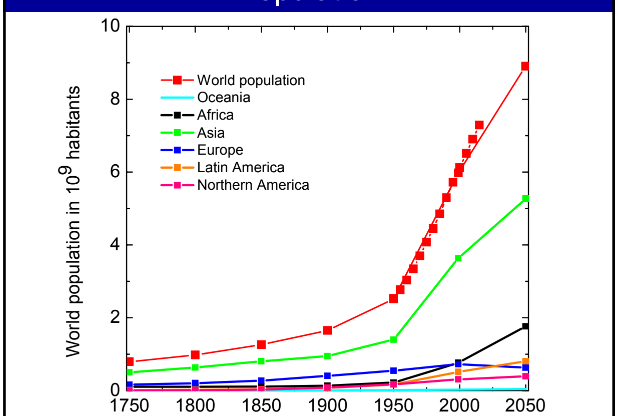
Tonne of Oil Equivalent

The 30 member countries of the OECD are: Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Korea, Luxembourg, Mexico, the Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland, Turkey, United Kingdom, United States.

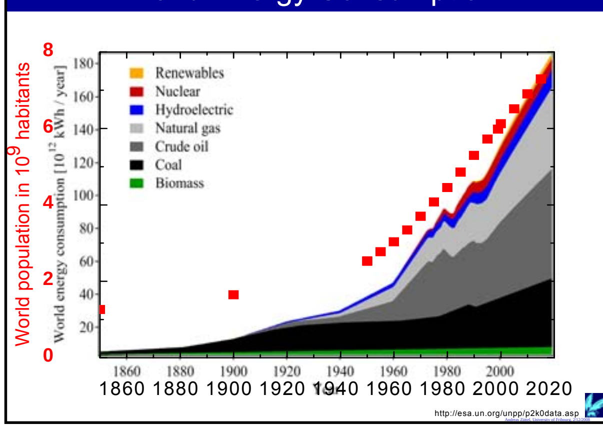
The IEA/OECD define one *toe* to be equal to 41.868 GJ or 11.630 MWh.

1 t diesel = 1.01 toe
1 m^3 diesel = 0.98 toe
1 t petrol = 1.05 toe
1 m^3 petrol = 0.86 toe
1 t biodiesel = 0.86 toe
1 m^3 biodiesel = 0.78 toe
1 t bioethanol = 0.64 toe
1m^3 bioethanol = 0.51 toe

Population



World Energy Consumption



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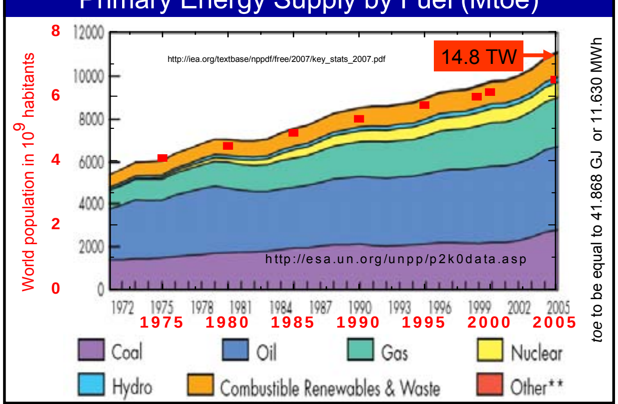
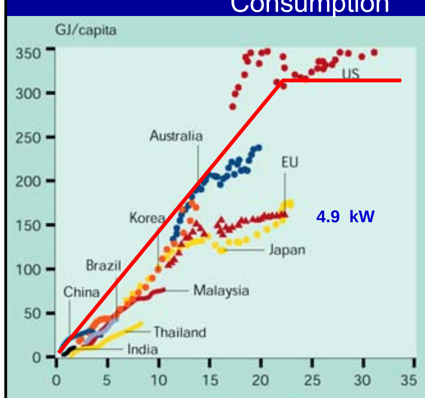


Relation between Wealth and Energy Consumption



Energy consumption increases until a certain level of wealth is reached

Holdren, Harvard University

Smalley's conclusions

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3. Food
4. **ENVIRONMENT**
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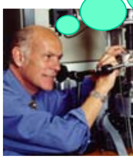
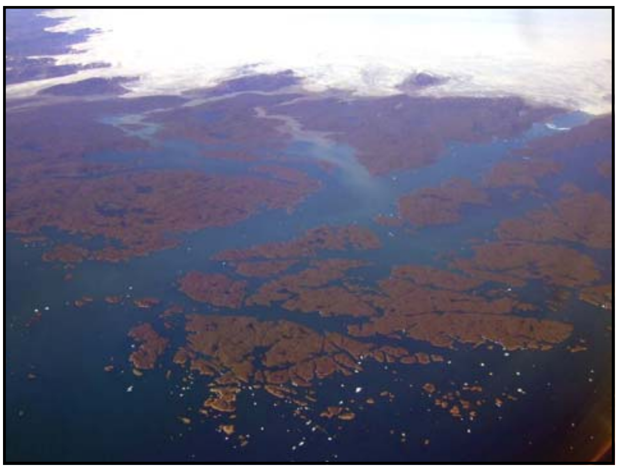
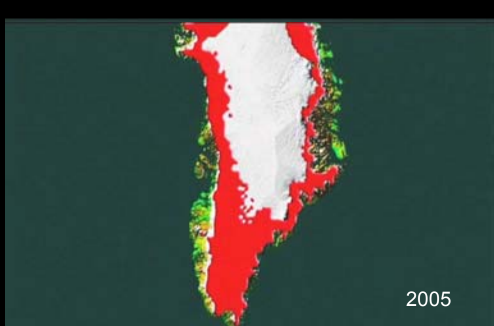


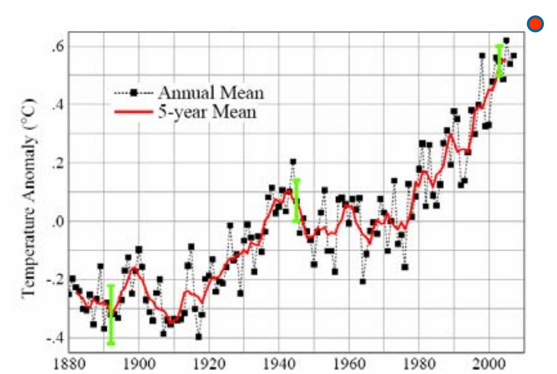


Greenland ice melts fast



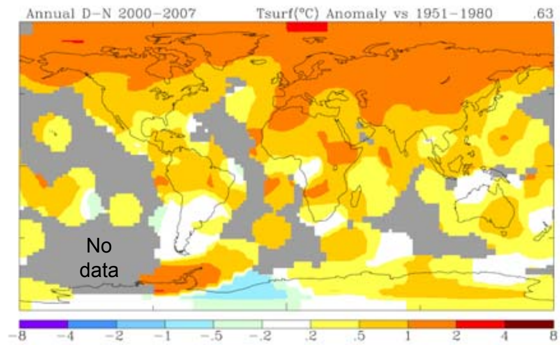
When Greenland ice melts

Global Temperature (Land + Ocean)

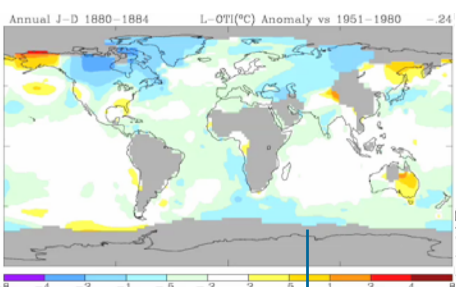


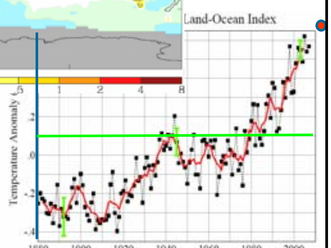
http://data.giss.nasa.gov/gistemp/maps/

Temperature anomaly map: Average warming 0.63 ºC



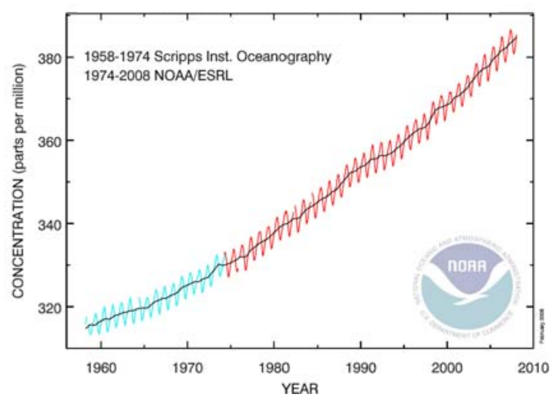
http://data.giss.nasa.gov/gistemp/maps/



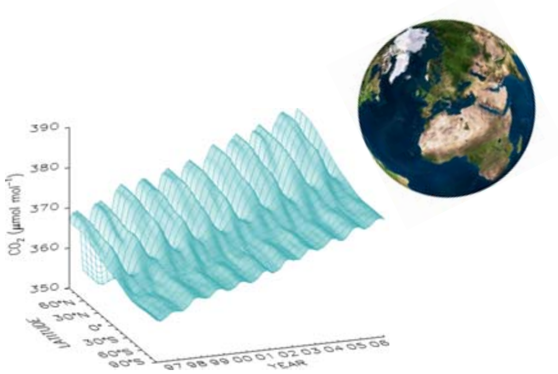


Temperature anomalies

Atmospheric CO_2 at Mauna Loa Observatory

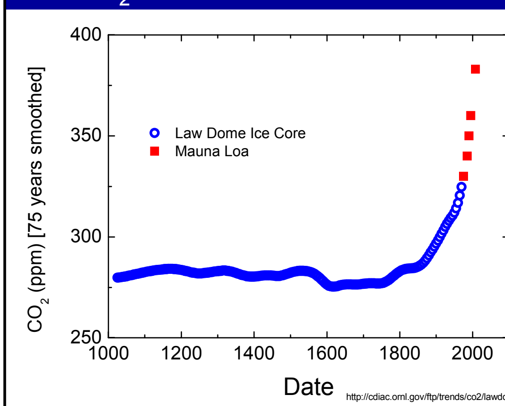


CO_2 Latitude dependence



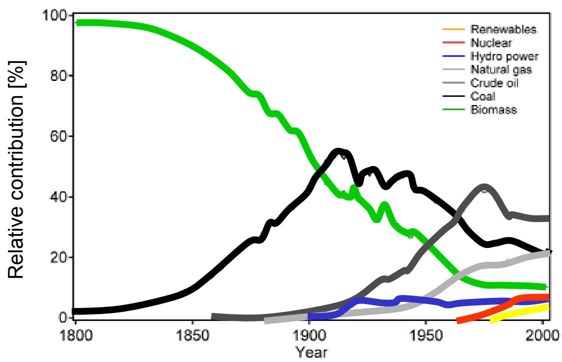
http://www.esrl.noaa.gov/gmd/ccgg/globalview/gv_extension.html

CO_2 from the Law Dome Ice Cores



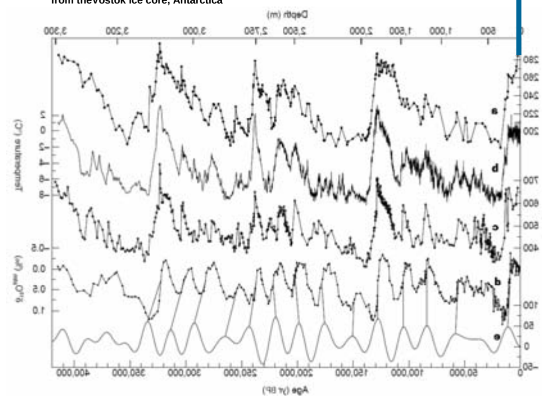
http://cdiac.ornl.gov/ftp/trends/co2/lawdome.combined.dat

ENERGY VECTORS

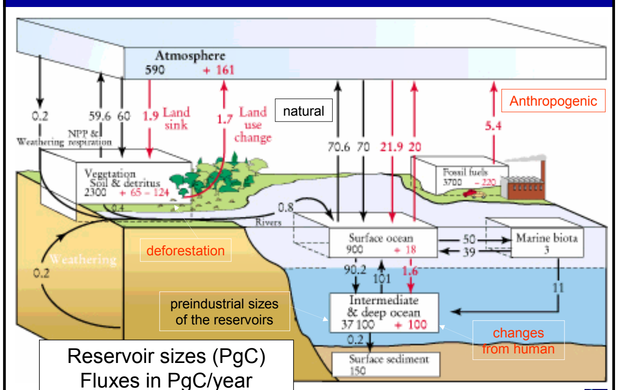


NATURE 399 (1999) 429

Climate and atmospheric history ofthe past 420,000 years from theVostok ice core, Antarctica

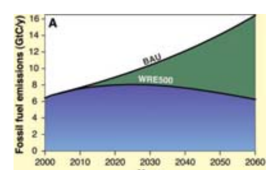


CARBON CYCLE: Fluxes in PgC/yr Reservoir sizes in PgC



Options to reduce 14 GtC/year BAU

1. Efficient vehicles
2. Reduced use of vehicles
3. Efficient buildings
4. Efficient baseload coal plants
5. Gas baseload power for coal baseload power
6. Capture CO2 at baseload power plant
7. Capture CO2 at H2 plant
8. Capture CO2 at coal-to-synfuels plant
9. Nuclear power for coal power
10. Wind power for coal power
11. PV power for coal power
12. Wind H2 in fuel-cell car for gasoline in hybrid car
13. Biomass fuel for fossil fuel
14. Reduced deforestation, plus reforestation
15. Conservation tillage

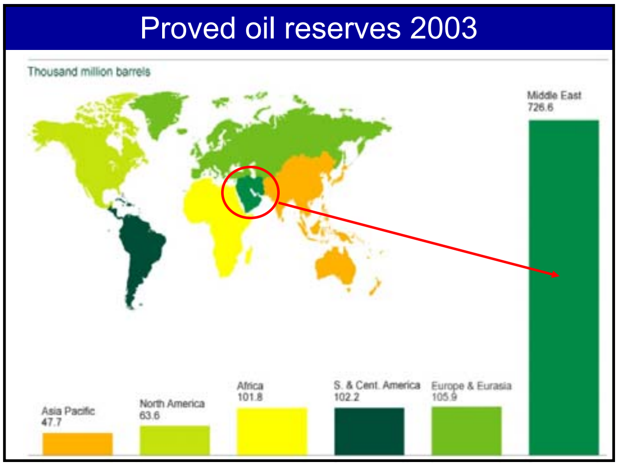


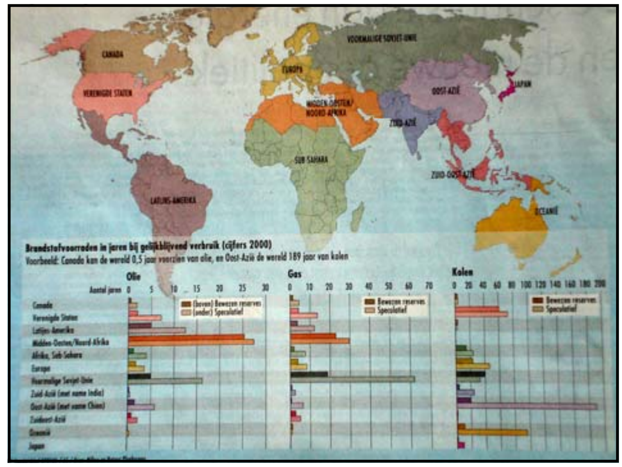
http://www.sciencemag.org/cgi/reprint/305/5686/968.pdf

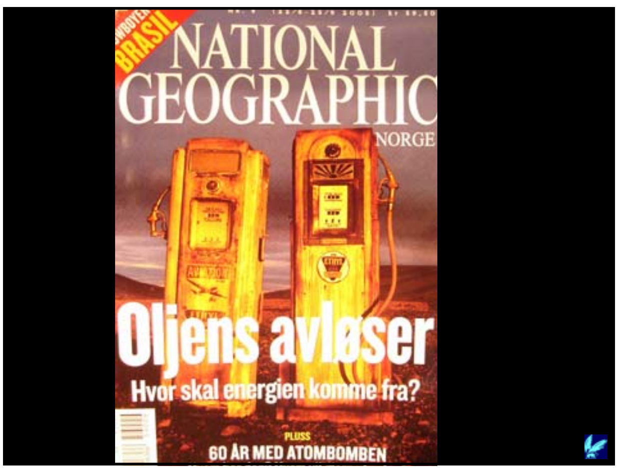
Arrows show the fluxes (in petagrams of carbon per year) between the atmosphere and its two primary sinks, the land and the ocean, averaged over the 1980s. Anthropogenic fluxes are in red; natural fluxes in black. The net flux between reservoirs is balanced for natural processes but not for the anthropogenic fluxes. Within the boxes, black numbers give the preindustrial sizes of the reservoirs and red numbers denote the changes resulting from human activities since preindustrial times. For the land sink, the first red number is an inferred terrestrial land sink whose origin is speculative; the second one is the decrease due to deforestation. Numbers are slight modifications of those published by the Intergovernmental Panel on Climate Change. NPP is net primary production.

Why a lecture on metal-hydrogen systems ?

- Societal reason:
  - Global warming
  - Moral responsibility for sustainability

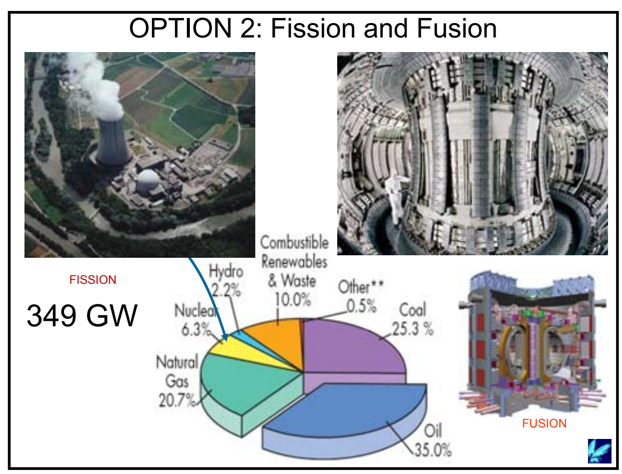

Proved oil reserves 2003
Thousand million barrels
Middle East
726.6
Asia Pacific
47.7
North America
63.6
Africa
101.8
S. & Cent. America
102.2
Europe & Eurasia
105.9


CANADA
VERENIGDE STATEN
LATIJNS-AMERIKA
EUROPA
VOORMALIGE SOVJET-UNIE
MIDDEN-OOSTEN/NOORD-AFRIKA
SUB SAHARA
ZUID-AZIË
OOST-AZIË
JAPAN
ZUID-OOST-AZIË
OCEANIË
Brandstofvoorraden in jaren bij gelijkblijvend verbruik (cijfers 2000)
Olie
Gas
Kolen

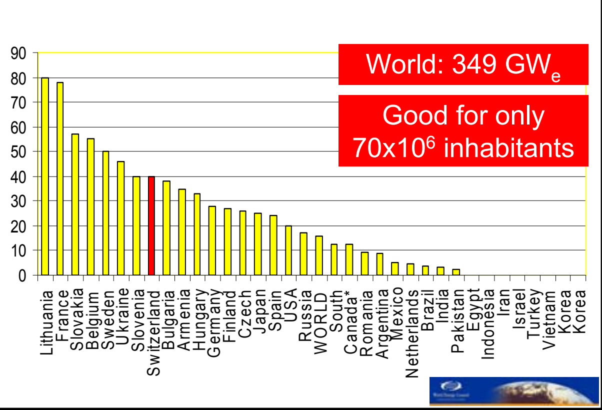

NATIONAL GEOGRAPHIC
NORGE
Oljens avløser
Hvor skal energien komme fra?
PLUSS
60 ÅR MED ATOMBOMBEN


OPTION 1: The American Way

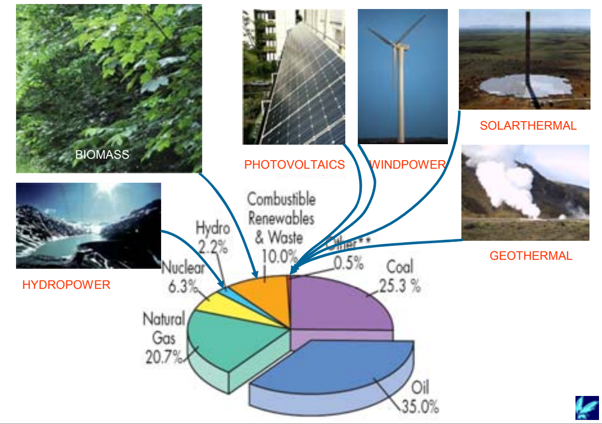

Brandstof voor de macht

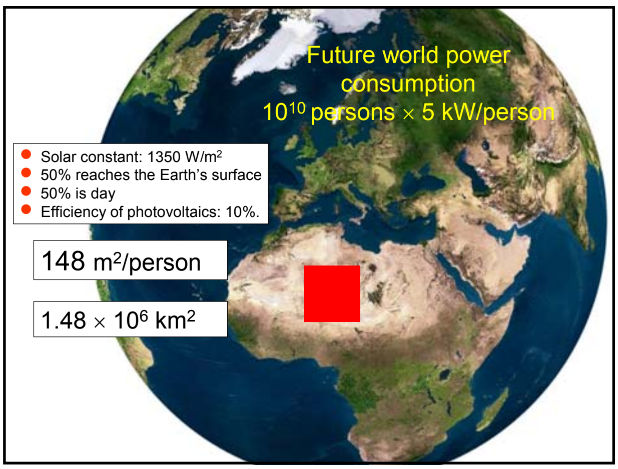

OPTION 2: Fission and Fusion
FISSION
349 GW
Hydro
2.2%
Combustible Renewables & Waste
10.0%
Other**
0.5%
Coal
25.3 %
Nuclear
6.3%
Natural Gas
20.7%
Oil
35.0%
FUSION

Nuclear Power in % of national electricity production



OPTION 3: Renewable Energy





Why a lecture on metal-hydrogen systems ?

- Societal reason:
  - Global warming
  - Moral responsibility for sustainability
- Technological reason:
  - Clean energy sources and carriers

Consequence

- CO_2 reduction
- Inherently fluctuating renewable energy sources
- Nuclear power generation

⇒ New energy carrier

Why a lecture on metal-hydrogen systems ?

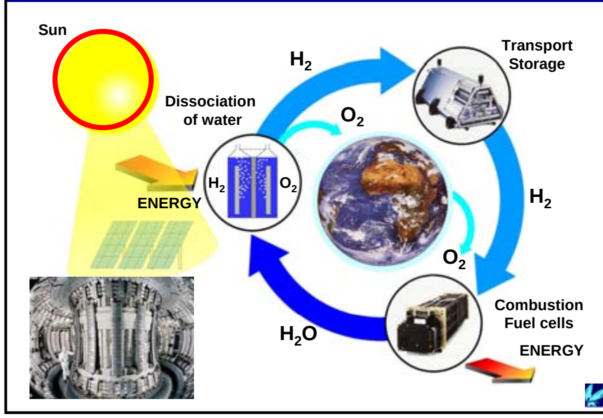
- Societal reason:
  - Global warming
  - Moral responsibility for sustainability
- Technological reason:
  - Clean energy sources and carriers
  - Hydrogen is an attractive energy carrier

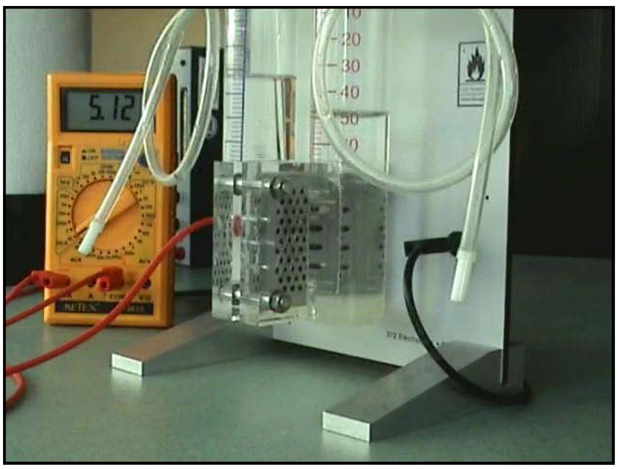
Why hydrogen ?

Because hydrogen is:

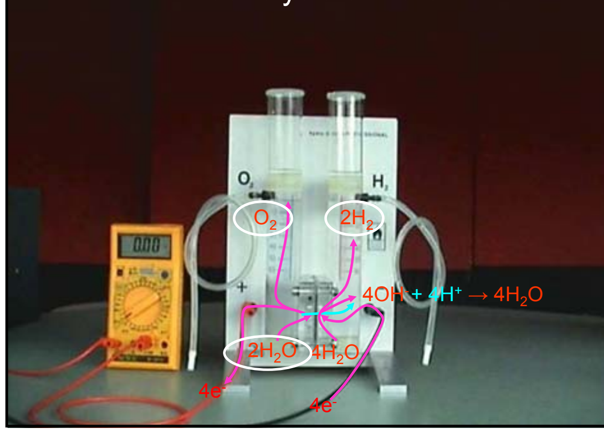
- a closed loop energy carrier
- clean
- transportable over long distances
- much more easily stored than electrons
- interconvertible with electricity

Hydrogen cycle: electrolysis

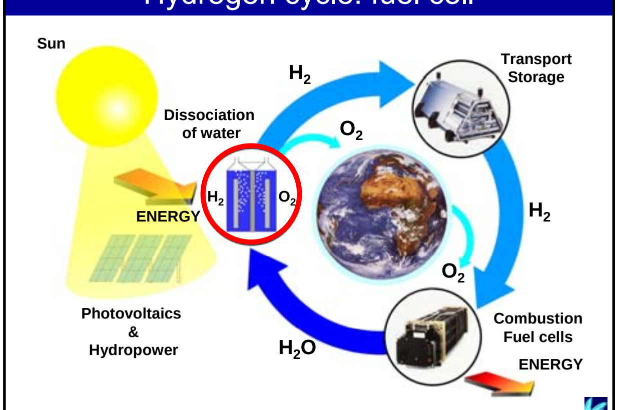


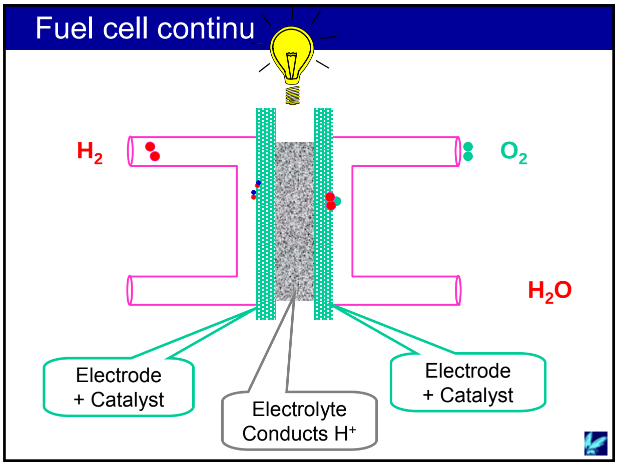


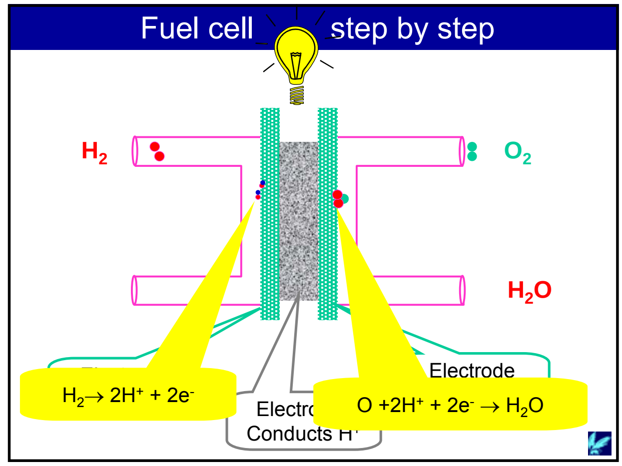
Electrolysis of water

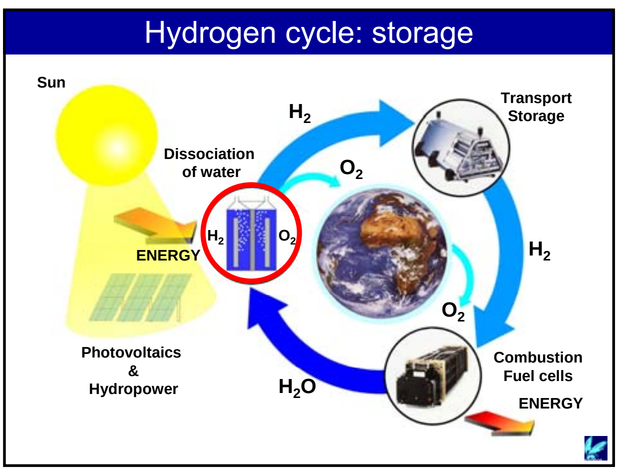


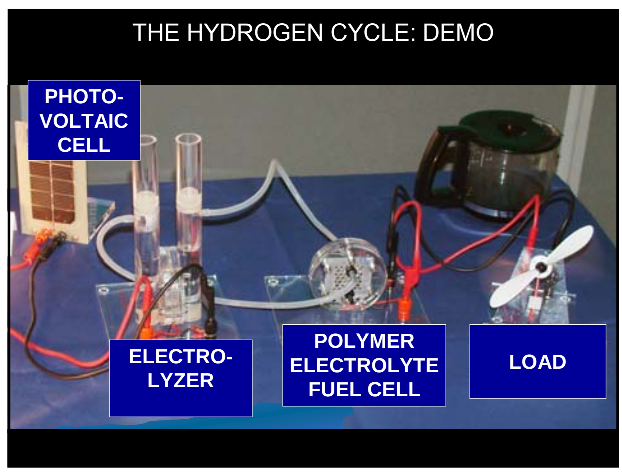
Hydrogen cycle: fuel cell




Fuel cell continu
H_2
O_2
H_2O
Electrode
+ Catalyst
Electrolyte
Conducts H^+
Electrode
+ Catalyst


Fuel cell step by step
H_2
O_2
H_2O
$H_2 \rightarrow 2H^+ + 2e^-$
Electrode
$O + 2H^+ + 2e^- \rightarrow H_2O$
Conducts H^+


Hydrogen cycle: storage
Sun
Dissociation
of water
H_2
O_2
Transport
Storage
ENERGY
H_2
O_2
H_2
O_2
Photovoltaics
&
Hydropower
H_2O
Combustion
Fuel cells
ENERGY


THE HYDROGEN CYCLE: DEMO
PHOTO-
VOLTAIC
CELL
ELECTRO-
LYZER
POLYMER
ELECTROLYTE
FUEL CELL
LOAD


Electrolyser
Efficiency: 75%

Compressed hydrogen gas

HYDROGEN FROM FOSSIL FUELS

$-CH_2- + H_2O \longrightarrow 2\,H_2 + CO$
$\Delta H = 194$ kJ $\cdot mol^{-1}$

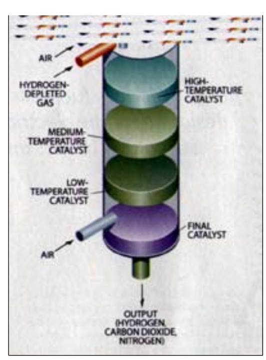
$CO + H_2O \longrightarrow H_2 + CO_2$
$\Delta H = 2$ kJ $\cdot mol^{-1}$

$H_2 + 0.5\,O_2 \longrightarrow H_2O$
$\Delta H = -285$ kJ$\cdot mol^{-1}$

Process	raw material	T [ºC]	p [bar]	catalyst	gas components
steam reforming	$-CH_2-$, H_20	> 850	25	NiO	H_2, CO
plasma reforming	$-CH_2-$, H_20	> 1350	3	-	H_2, CO
partial oxidation	$-CH_2-$, H_20, O_2	> 1200	10-100	-	H_2, CO
coal gasification	C, H_20, O_2	800-1200	1-40	-	H_2, CO
CO conversion	CO, H_20	200-500	3	Fe_2O_3, Cr_2O_3	H_2, CO_2

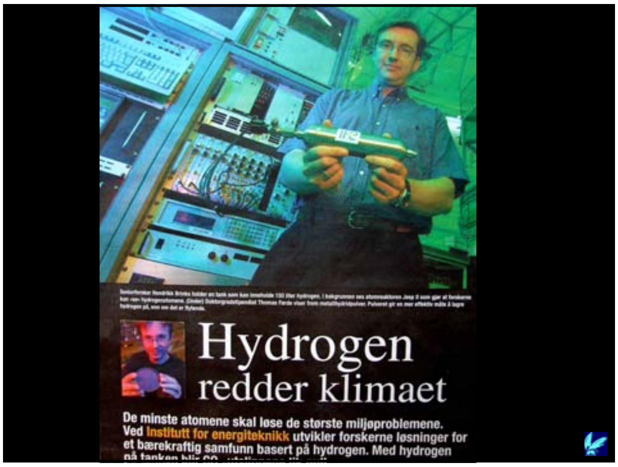
Andreas Züttel, University of Fribourg, 19. 05. 2001

FOSSIL FUEL REFORMING



Multifuel Processor converts gasoline or methanol to a hydrogen-rich gas mixture for fuel cells.

$-CH_2- + 2\,H_2O \longrightarrow 3\,H_2 + CO_2$
$\Delta H = 196$ kJ$\cdot mol^{-1}$

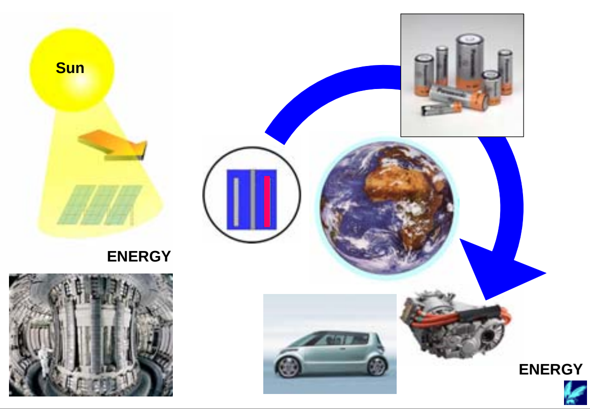


Why hydrogen ?

Because hydrogen is:

- a closed loop energy carrier
- clean
- transportable over long distances
- much more easily stored than electrons
- interconvertible with electricity

The electrical cycle



Electrons — Hydrogen now

Battery Toyota Prius
0.12 MJ/kg

Li-ion battery
0.84 MJ/kg

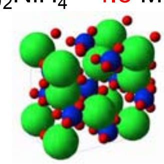
H in modified Prius “$LaNi_5H_6$”
1.9 MJ/kg

Electrons — Hydrogen tomorrow

Battery Toyota Prius
0.12 MJ/kg

Li-ion battery
0.84 MJ/kg

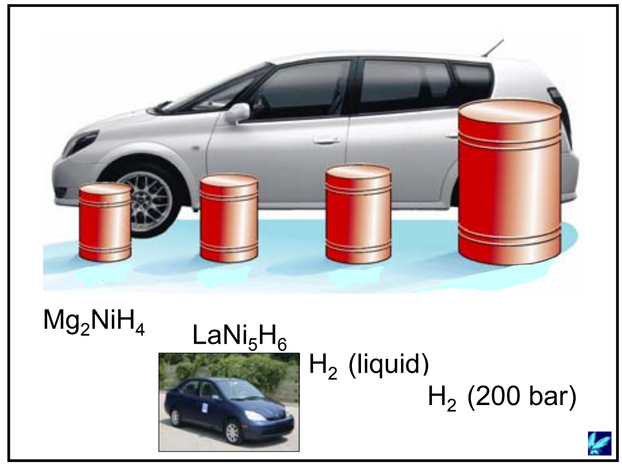
Mg_2NiH_4 4.5 MJ/kg

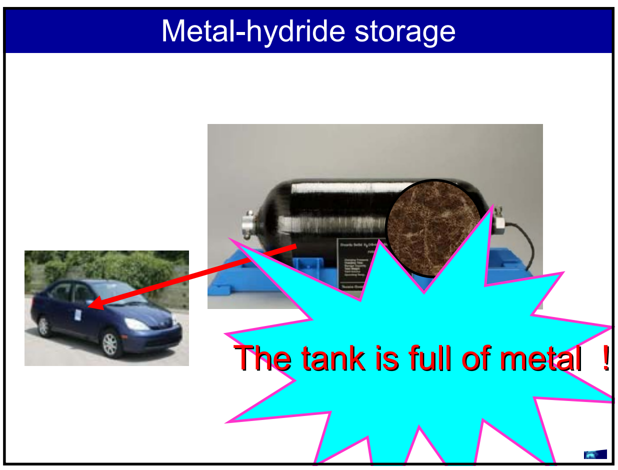


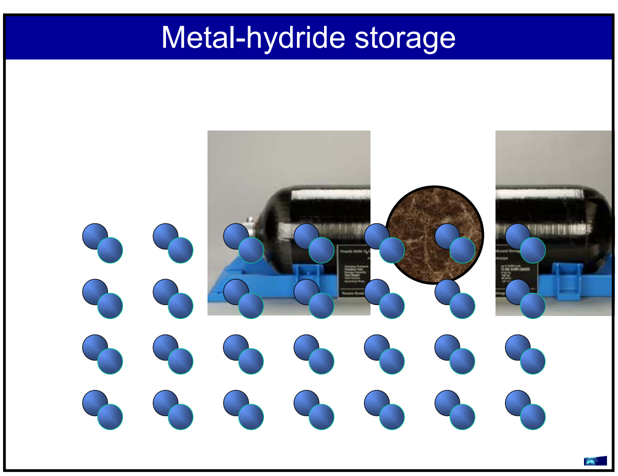
$NaAlH_4$	9 MJ/kg
$Ti(AlH_4)_4$	11 MJ/kg
$LiAlH_4$	12 MJ/kg
$LiBH_4$	22 MJ/kg
$Al(BH_4)_3$	24 MJ/kg

Why a lecture on metal-hydrogen systems ?

- Societal reason:
  - Global warming
  - Moral responsibility for sustainability
- Technological reason:
  - Clean energy sources and carriers
  - Hydrogen is an attractive energy carrier
  - Metal-hydrides are attractive storage systems







Why a lecture on metal-hydrogen systems ?

- Societal reason:
  - Global warming
  - Moral responsibility for sustainability
- Technological reason:
  - Clean energy sources and carriers
  - Hydrogen is an attractive energy carrier
  - Metal-hydrides are attractive storage systems
- Scientific reason: hydrogen in metals is fascinating
  - Experimentally and
  - Theoretically

Properties of metal-hydrogen systems

- Large quantities of hydrogen in transition metals and intermetallic compounds
- Wide solubility range
- Easy preparation by electrolytic charging or by hydrogen gas loading
- Very high diffusion coefficient
- Largest (anomalous) isotope effects
- Switchable metal-hydride films (optical properties, metal-insulator transition)
- Switchable metal-hydrides films (ferro-antiferromagnetic switching)
- Superconductivity

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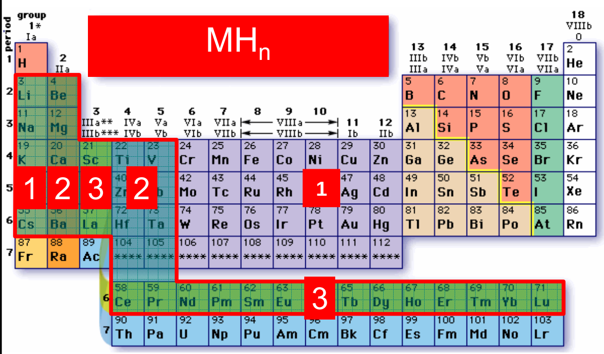
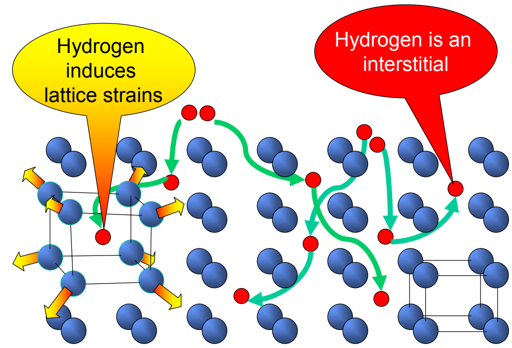
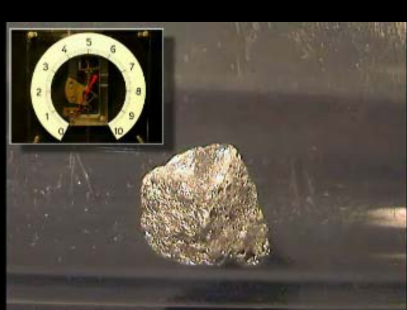
The Periodic Table of the Elements



Absorption of hydrogen by a metal

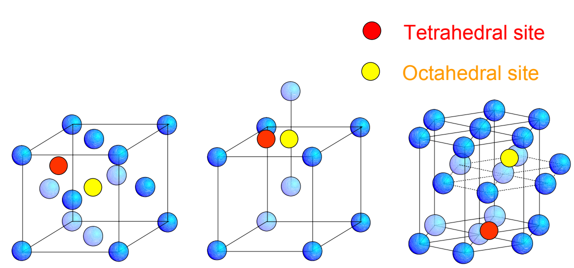


First hydrogenation of Zr-Mn

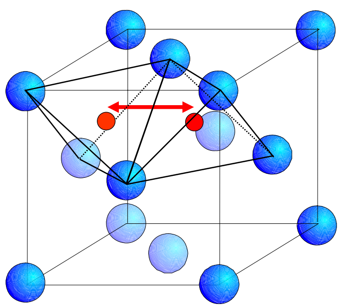


Andreas Zuettel, EMPA

Interstitial sites in FCC, BCC and HCP lattices



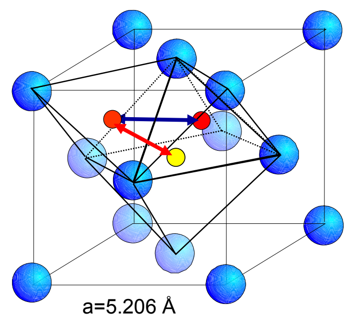
Westlake's criteria



$r_H > 0.4$ Å

$d_{H-H} > 2.1$ Å

YH_2 and YH_3



a=5.206 Å

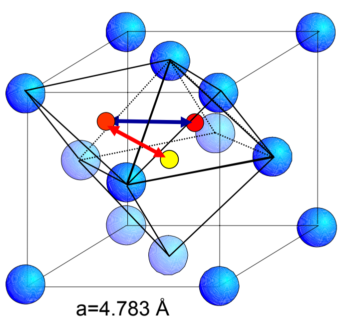
$r_T = 0.41$ Å

$d_{T-T} = 2.60$ Å

$d_{O-T} = 2.25$ Å

$r_O = 0.76$ Å

ScH_2 and NO ScH_3



a=4.783 Å

$r_T = 0.38$ Å

$d_{T-T} = 2.39$ Å

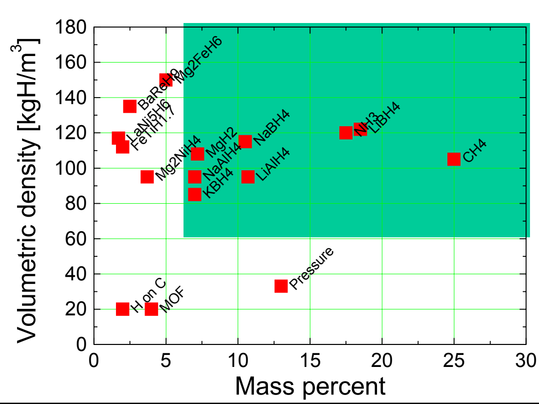
$d_{O-T} = 2.07$ Å

$r_O = 0.70$ Å

Substance	ρ [kg m^{-3}]	N_H [10^{28} m^{-3}]	[illegible]	[illegible]
H_2O	1000	6.		
H_2SO_4	1841	2.2		
liq CH_4	425	6.3		
liq H_2	71	4.2	1	
TiH_2	3800	9.2	.0	153
ZrH_2	5610	7.3	2.1	122
YH_2	3958	5.7	2.2	95
LaH_2	5120	4.4	1.4	73
LaH_3	5350	6.5	2.1	108
$LaNi_5H_6$	6225	5.3	1.4	88
$TiFeH_{1.95}$	5470	6.2	1.9	101
$Mg_{0.97}Ni_{0.03}H_{1.85}$	1800	7.9	7.3	132
NbH_2	8400	10.9	2.2	181
VH_2	6100	14.4	4.0	240
PdH	12000	6.8	0.9	113

More H atoms per m^3 than in pure liquid H_2

Hydrogen content of complex metal-hydrides



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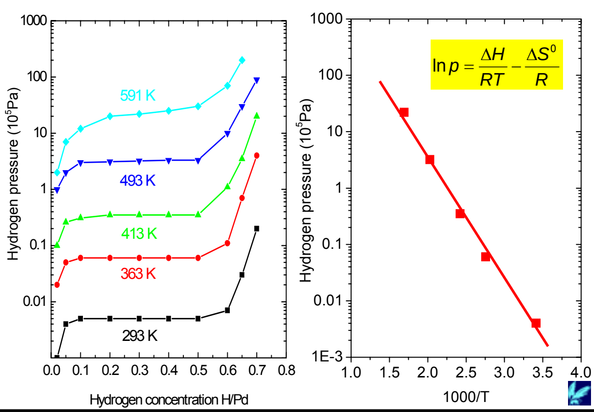
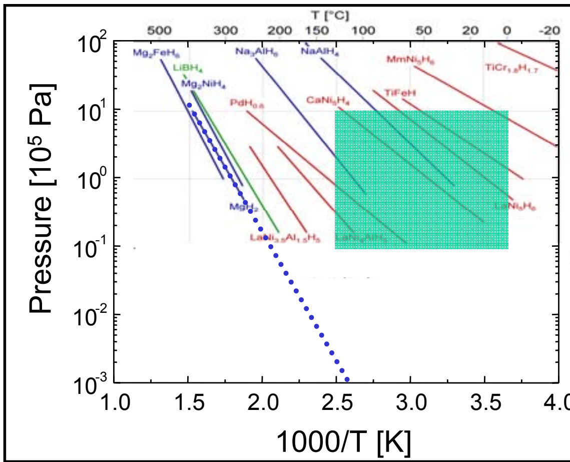
Pressure-composition isotherms of PdH_x





The standard metal-hydride storage materials

$LaNi_5H_6$ | $FeTiH_2$

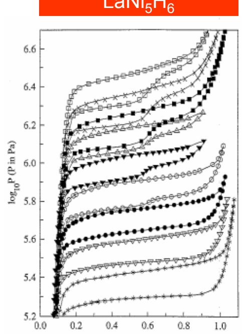


Fig. 2. Hysteresis loops conducted at T = 30° (*), 40°C (▽), 50°C (●), 60°C (○), 70°C (▼), 80°C (△), 90°C (■), 100°C (x) and 110°C (□).

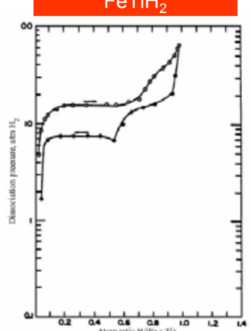


Figure 11
Hydrogen absorption-desorption loop at 40 °C for TiFe-H.

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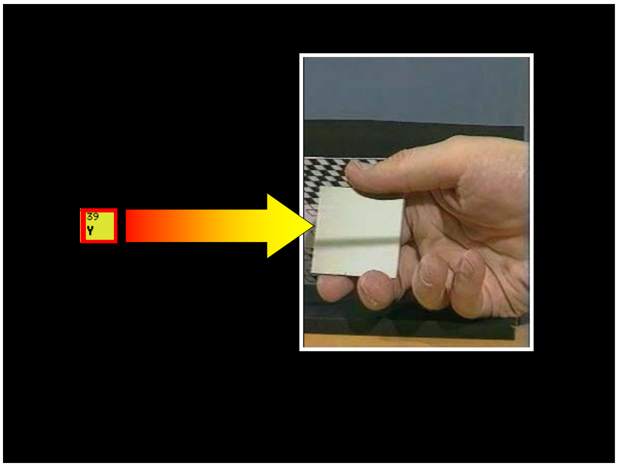
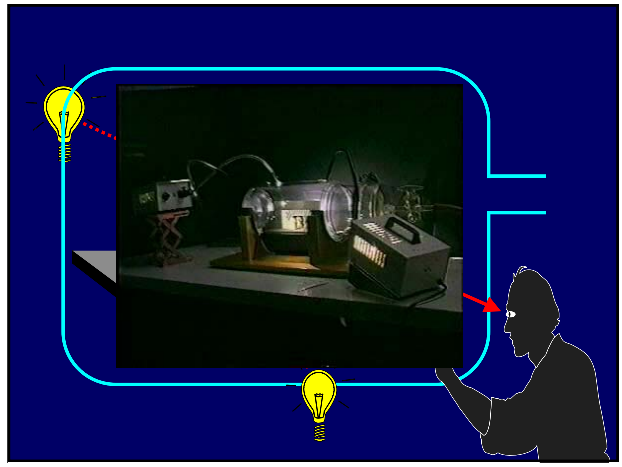
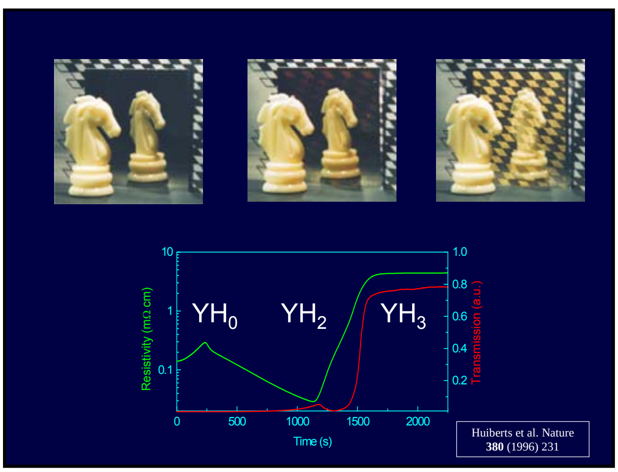
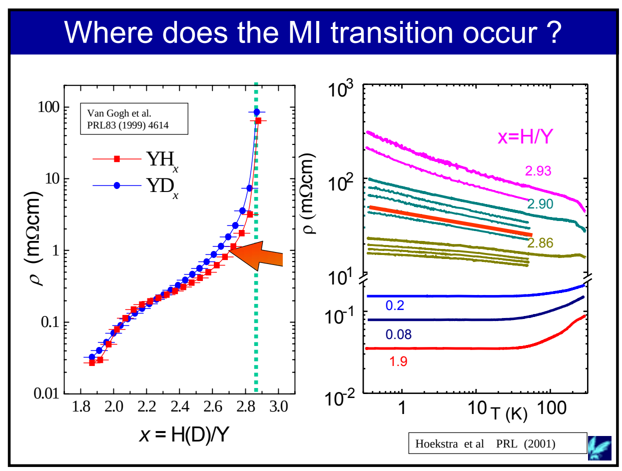
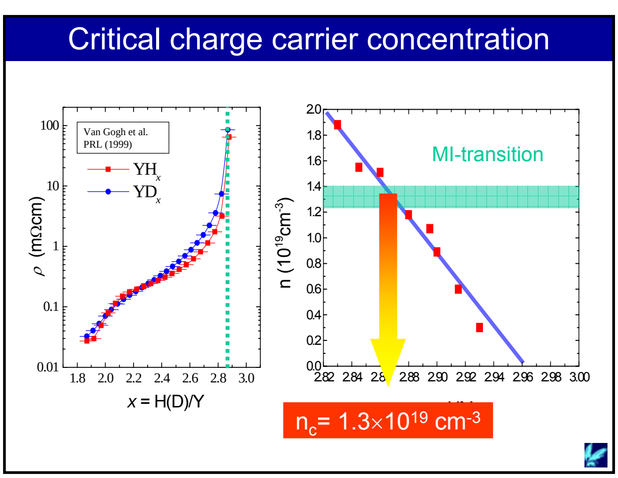
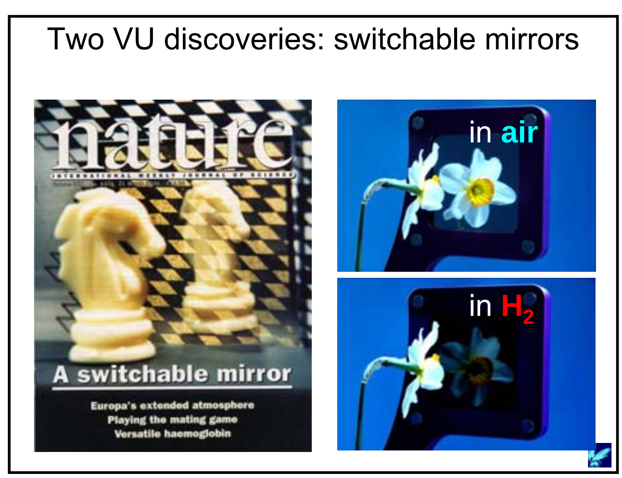

39
Y




YH0
YH2
YH3
Resistivity (mΩ cm)
Transmission (a.u.)
Time (s)
Huiberts et al. Nature
380 (1996) 231


Where does the MI transition occur ?
Van Gogh et al.
PRL83 (1999) 4614
YHx
YDx
ρ (mΩcm)
x = H(D)/Y
x=H/Y
2.93
2.90
2.86
0.2
0.08
1.9
T (K)
Hoekstra et al PRL (2001)


Critical charge carrier concentration
Van Gogh et al.
PRL (1999)
YHx
YDx
ρ (mΩcm)
x = H(D)/Y
n (10^19cm^-3)
MI-transition
nc= 1.3×10^19 cm^-3


Two VU discoveries: switchable mirrors
nature
A switchable mirror
Europa's extended atmosphere
Playing the mating game
Versatile haemoglobin
in air
in H2

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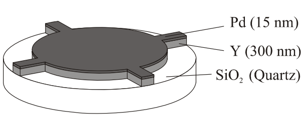
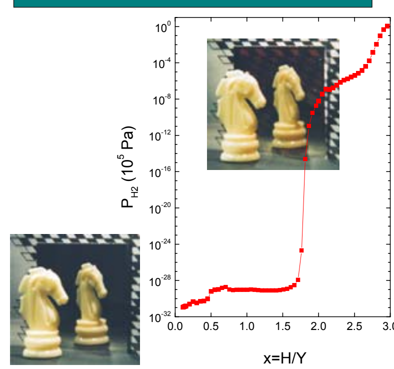


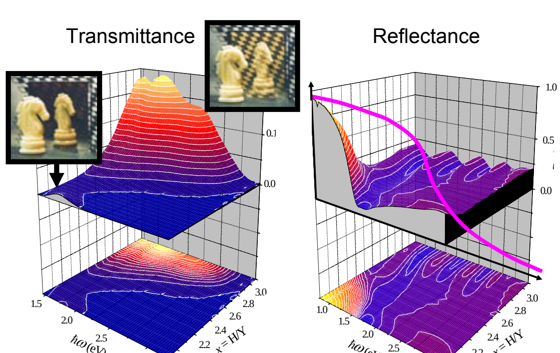
E.S. Kooij, A.T.M. van Gogh, and R. Griessen, J. Electrochem. Soc. **146**, 2990 (1999)

Pressure-composition isotherm of YH_x at T=293 K

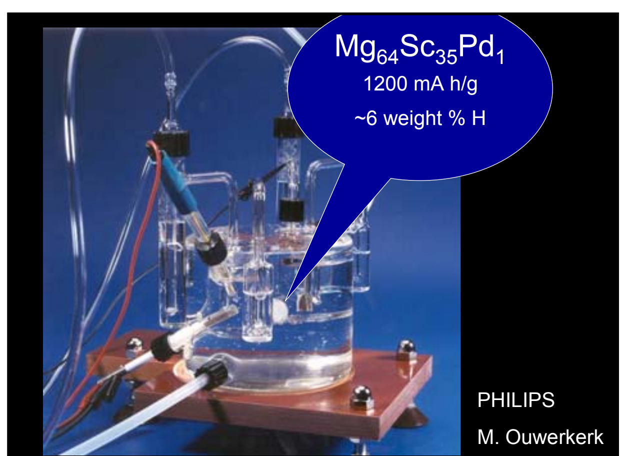


E.S. Kooij, A.T.M. van Gogh, and R. Griessen, J. Electrochem. Soc. **146**, 2990 (1999)

The optical switching occurs in the visible



Kooij et al. PRB62 (2000) 10088



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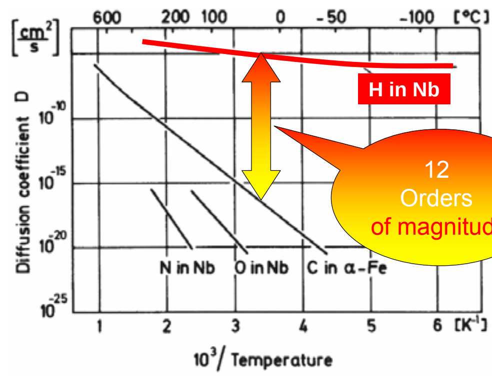
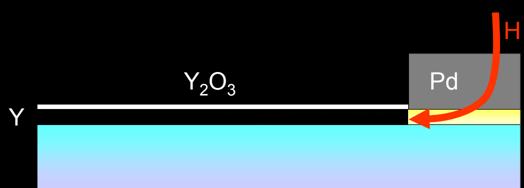
Diffusion coefficients of various interstitials

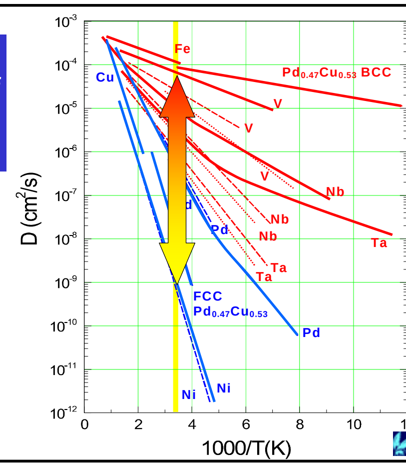


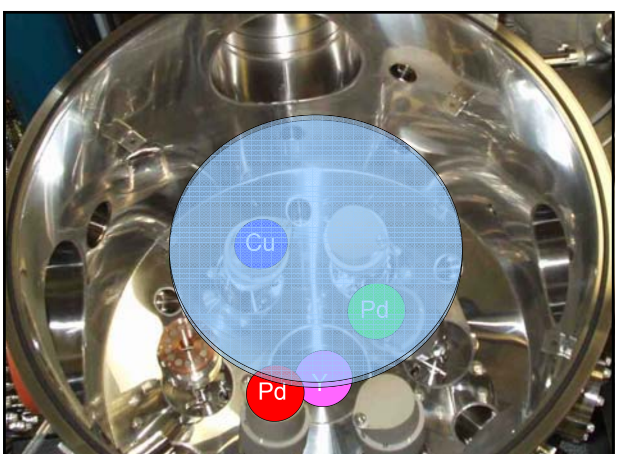
H diffusion in Y

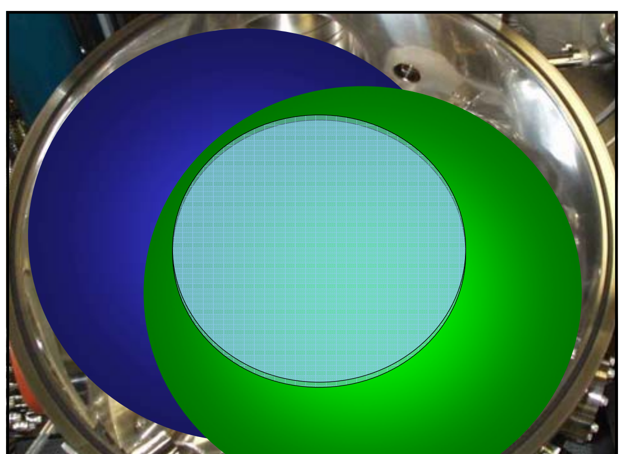


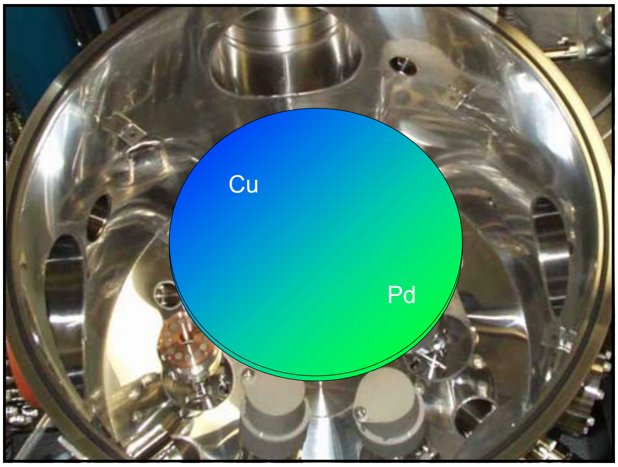
Den Broeder, van der Molen et al, Nature 394 (1998) 656

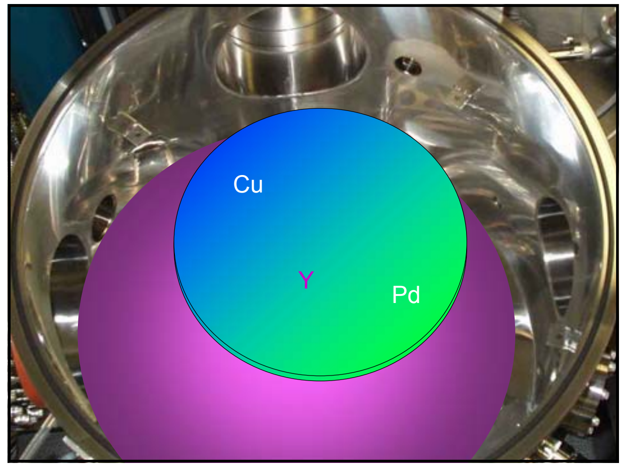
Diffusion coefficients of various interstitials

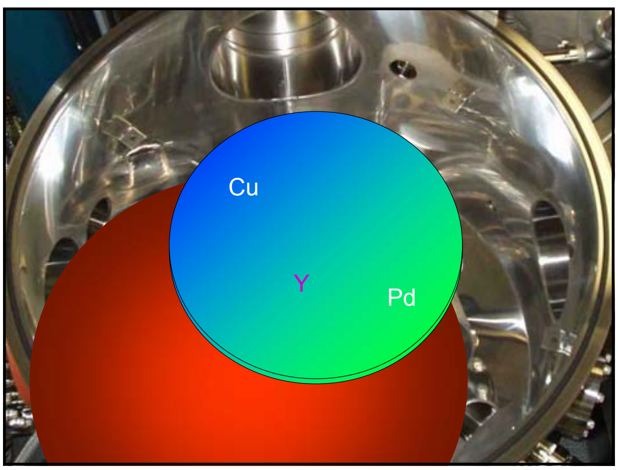


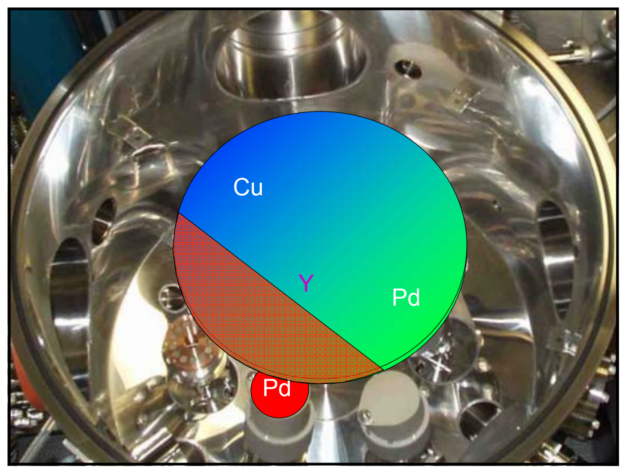


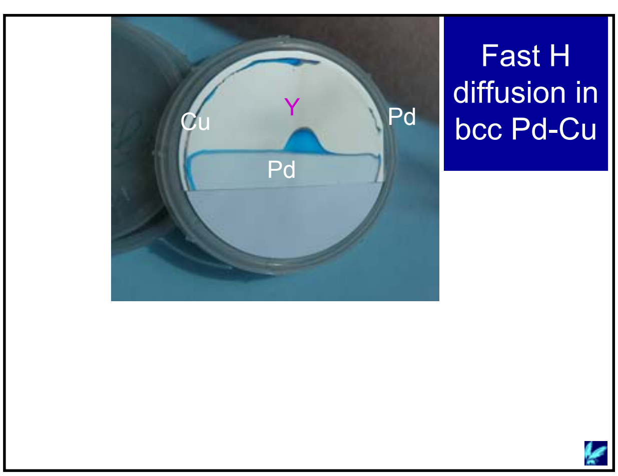


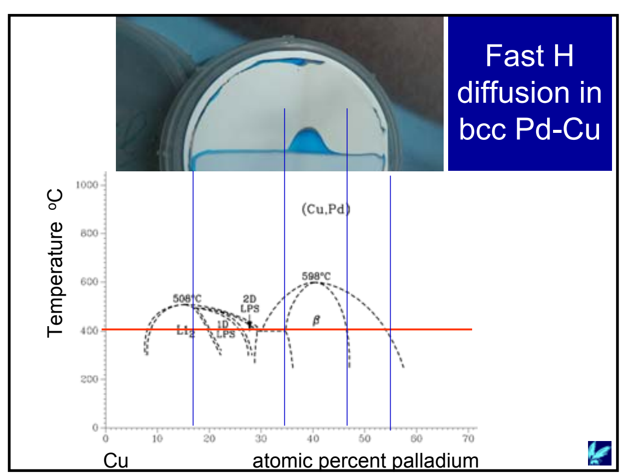

Cu
Pd


Cu
Y
Pd


Cu
Y
Pd

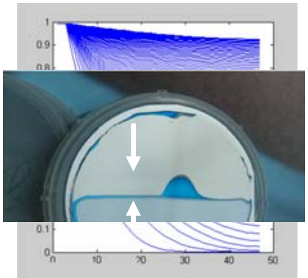

Cu
Y
Pd
Pd


Cu
Y
Pd
Pd
Fast H diffusion in bcc Pd-Cu


Fast H diffusion in bcc Pd-Cu
Temperature °C
(Cu,Pd)
598°C
508°C
Cu
atomic percent palladium

Diffusion length

$$D\frac{\partial^2 c}{\partial x^2}-\frac{\partial c}{\partial t}=0 \text{ with } c(0,t)=1 \qquad c=1-erf\left(\frac{x}{2\sqrt{Dt}}\right)$$

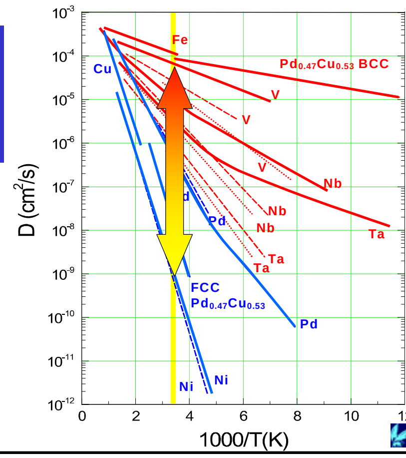


$$x^2 \cong Dt$$

In 10^4 s we have $x \cong 1$ cm

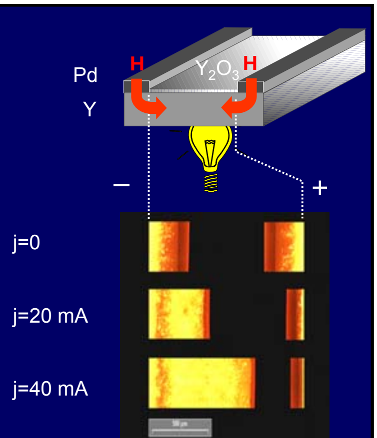
Thus $D=10^{-4}$ cm^2/s

Diffusion coefficients of various interstitials



Electromigration

Den Broeder, van der Molen et al. Nature 394 (1998) 656



H behaves like a negative ion in Y

Effective charge of H from electromigration

Metal	Z*	T[K]	Reference
Y	-1	350	van der Molen et al. (1999)
	-1	1025	Carlson et al.(1966)
V	1.54...1.33	276...527	Verbruggen et al. (1986)
Nb	2.04...1.30	276...522	Verbruggen et al. (1986)
Ta	0.38...0.61	377...518	Verbruggen et al. (1986)
Mo	0.29...1.05	289...767	
Pd	0.80	373	Pietrzak (1991)
Cu	-20		

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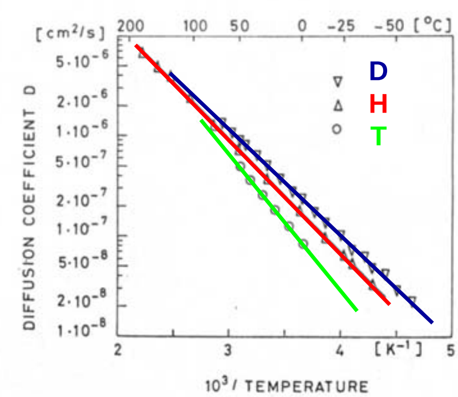
Anomalous isotope effect in diffusion



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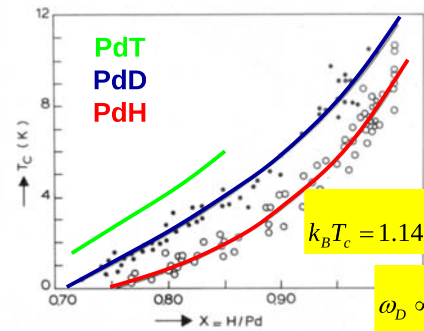
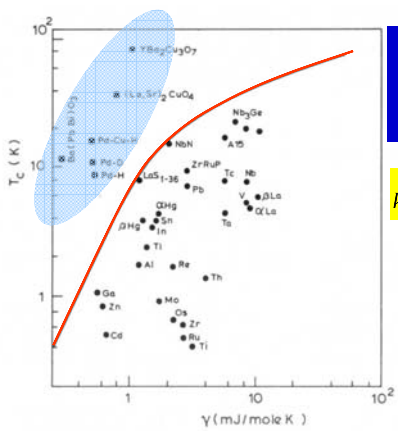
Superconductivity PdH, PdD, PdT



$$k_B T_c = 1.14 \hbar \omega_D e^{\left(-1/VN(E_F)\right)}$$

$$\omega_D \propto \sqrt{\frac{K}{M}}$$



High T_c and low density of states

$$k_B T_c = 1.14 \hbar \omega_D e^{\left(-1/VN(E_F)\right)}$$

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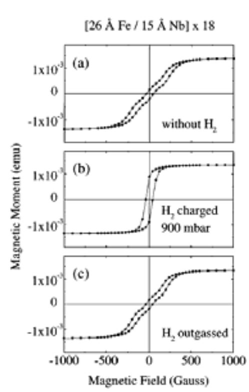
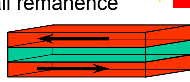
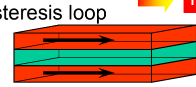
Reversible change in magnetic coupling



Linear slope
Small remanence → Antiferro



Nearly "square" hysteresis loop → Ferro

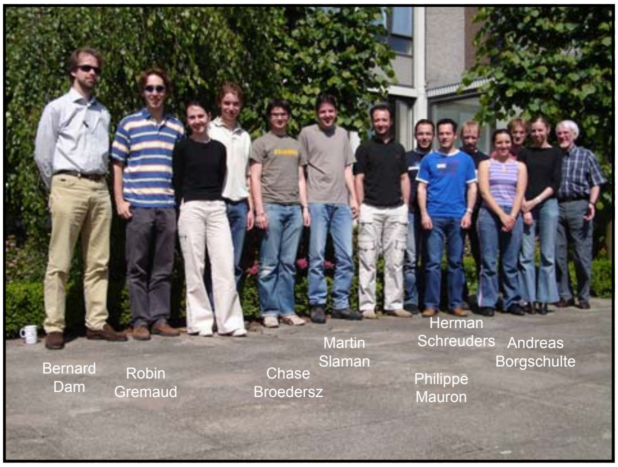


F. Klose et al. PRL78 (1997)1150

Properties of metal-hydrogen systems

- Large quantities of hydrogen in transition metals and intermetallic compounds
- Wide solubility range
- Easy preparation by electrolytic charging or by hydrogen gas loading
- Very high diffusion coefficient
- Largest (anomalous) isotope effects
- Switchable metal-hydride films (optical properties, metal-insulator transition)
- Switchable metal-hydrides films (ferro-antiferromagnetic switching)
- Superconductivity

Sensitivity to defect structure



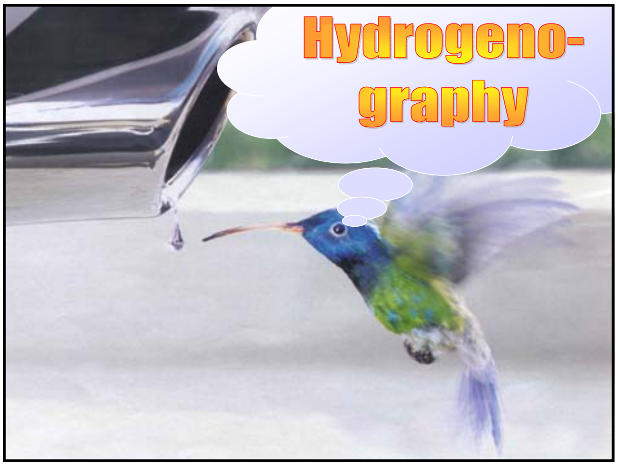
Mg_2NiH_4

?

$LaNi_5H_6$

H_2 (liquid)

H_2 (200 bar)



Tentative schedule 2008

Date	Subject	Lecturer
February 12, 2006 Tuesday	Introduction: Energy, Environment & Sustainability	
February 15, 2006 Friday	Review of H, H2, Van der Waals gasses	Griessen
February 19, 2006 Tuesday	Thermodynamics (self-study and werkcollege)	Griessen
February 22, 2006 Friday	Thermodynamics	Griessen
February 26, 2006 Tuesday	Critical behaviour and H-H interaction	Griessen
February 29, 2006 Friday	Elasticity	Griessen
March 4, 2006 Friday	Band structure of transition metals/ effect of H on electronic states	Griessen
March 7, 2006 Tuesday	Band structure of complex hydrides	Griessen
March 11, 2006 Friday	Practicum: Fuel cell, Electrolyser, Photovoltaic cell	Heeck
March 18, 2006 Tuesday	Hydrogen storage in various systems (metals, borohydrides, MOF's, graphite,....)	Zuettel
March 21, 2006 Friday	Complex hydrides/ Sustainability and safety /	Zuettel
March 25, 2006 Tuesday	Transport properties (diffusion, electromigration)	Griessen
March 28, 2006 Friday	Correlation effects; Outlook	Griessen

	A	B	C	D
1) How many 1 GW nuclear power plant are required to produce the energy corresponding to all the kerosene used by the planes landing/departing from Schiphol. To answer this question you need : o The energy content of kerosene o The amount of kerosene used at Schiphol per day or per year	1 power plant	2 power plants	5 power plants	22 power plants
2) Which area of the Earth is needed to produce photovoltaically the same power as the one used presently on a world scale ? To answer this question you need : o The efficiency of a standard photovoltaic cell o The world energy consumption o The solar energy reaching the ground	Area of NL	Area of France	Whole Earth	3 times the area of the Earth
3) What are the efficiencies of the following devices: a) A diesel engine	10%	25%	35%	42%
b) An electric engine	50%	75%	86%	98%
c) A thermal solar collector (producing warm water)	30%	40%	50%	65%
d) Name a device with an efficiency higher than 100% and explain how this is possible.				
4) Photovoltaic and thermal solar collectors panels are becoming increasingly popular. a) How large was the total installed photovoltaic power in 2006?	1 GW	6 GW	33 GW	120 GW
b) How much thermal solar power was available in the same year ? Some information can be found in the Sarasin report matthias.fawer@sarasin.ch	3 GW	25 GW	100 GW	155 GW
5) In 2020 one expects that 10% of the total energy demand will be supplied by photovoltaic solar energy. What does this imply for the amount of **silicon** to be produced ?	3 times present world producti on	5 times present world producti on	6 times present world producti on	10 times present world producti on
What does this imply for the amount of **silver** to be produced ? For this you need to know a) the solar cell efficiency with respect to its peak output b) the amount of silver and silicon used in a 100 Wp system.	3 times present world producti on	5 times present world producti on	6 times present world producti on	10 times present world producti on
6) Estimate the CO_2 emission budget per person in 2050 if we want to limit the CO_2 atmospheric content to 500 ppm and compare this with the present emissions in the Western countries, Asia, Africa. The requested data can be found in the Stern report.	800 kg CO_2 per person per year	1200 kg CO_2 per person per year	1600 kg CO_2 per person per year	2500 kg CO_2 per person per year

1) On the internet you can find many companies that offer to compensate your CO_2 emission by planting trees for a certain amount of money. For example www.treesfortravel.nl plants 125 trees to compensate the emission per person for a flight to the USA at a cost of € 34. How much surface area needs to be covered with trees per year to compensate the yearly **increase** (not the total yearly production) of the energy related CO_2 emission.	Area of Australia	Area of NL	Area of France	Whole Earth
2) The efficiency of an electric power plant is defined as the ratio between "the amount of electric power produced per second" (in Watt = J/s) and "the energy content of the fuel consumed by the power plant per second". For a power plant running on fossil fuels the latter number is the combustion energy of that fuel consumed per second. a) What is the efficiency of a (state-of-the art) gas fired electric power plant?	33 %	42%	50%	60%
b) Idem: a coal fired electric power plant?	30%	40%	52%	66%
c) What is the efficiency of an average gasoline car (tank-to-wheel)?	15%	25%	33%	40%
d) Calculate the well-to-wheel efficiency of a gasoline car.	15%	20%	30%	45%
3) CO_2 sequestration (i.e. storage of CO_2 outside the atmosphere) offers a route to keep using fossil fuels for the time required to transform society's energy system into a more sustainable one. How long does one at least have to store CO_2 to minimize the effect on the climate?	25 years	100 years	200 years	>200 years
4) Apart from CO_2 also water is a product from the combustion of fossil fuels. Why does water play only a minor role in current climate change discussion?	A. There is water everywhere			
	B. Water is non-polluting			
	C. Water cools the atmosphere			
5) Assume that the currently estimated total world oil reserve of one tera barrels of oil is burned all at once. Give an estimate of the effect of this process on the total world atmospheric oxygen mass. More specifically can oxygen requiring organisms like animals and humans survive such a massive oil fire? Neglect likely dust particle production and its possible effects.	They will survive	They will NOT survive	They will barely survive	
6) Give an estimate of the "virtual power" (in W =J/sec) going through your hands when you fill: a) the gasoline tank of a regular car at a regular gas station?	11 MW	33 MW	44 MW	65 MW
b) a tank of a Formula 1 racing car in the pit street during a Grand Prix race?	33 MW	170 MW	250 MW	420 MW