Renewable Energy

- Outline:

    Hydrogen as an energy vector:

    1.   **Motivation**

    2.   **Properties**

    3.   **Production**

    4.   **Storage**
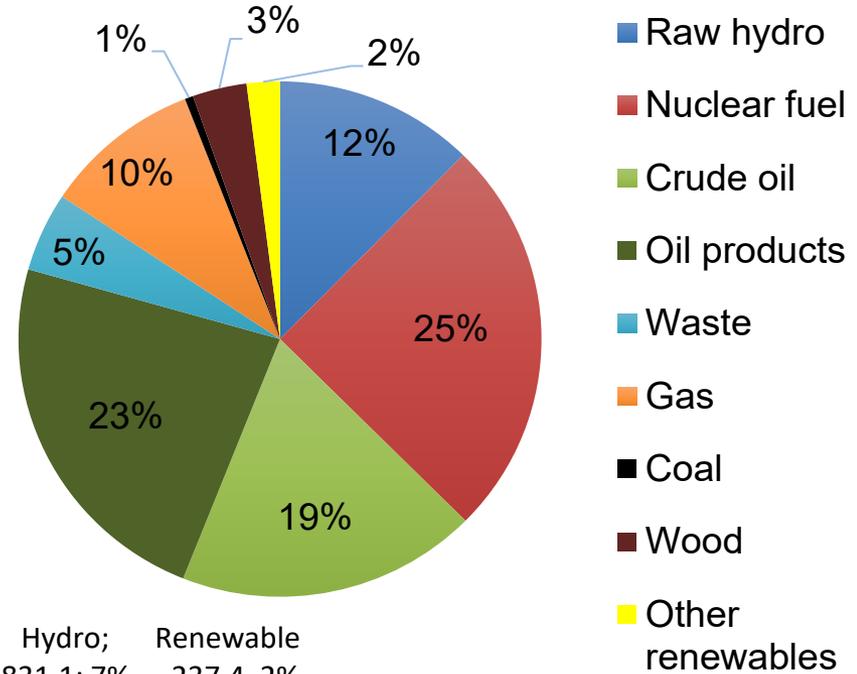
    5.   **Distribution**

    6.   **Application**

Learning outcomes of todays lecture

- Hydrogen as an energy vector
  - What is hydrogen and what makes it special
  - Why using hydrogen as an energy vector, alternatives
  - How can hydrogen be generated, how renewable
  - How can hydrogen be stored
  - How can hydrogen be transported/distributed
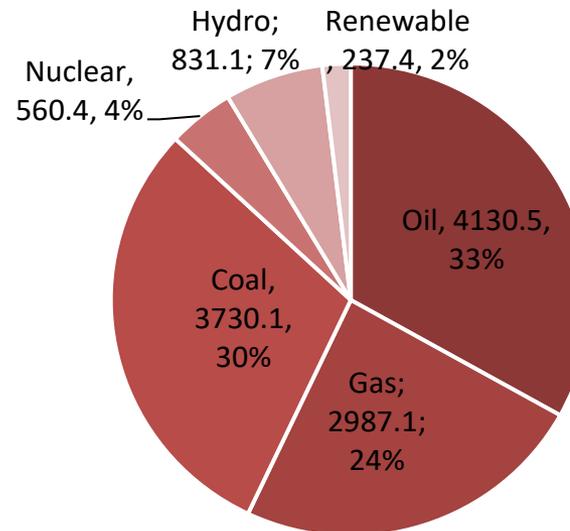 - Where and how is hydrogen used as an end product

Motivation

- Current society is largely based on the use of fossil fuels
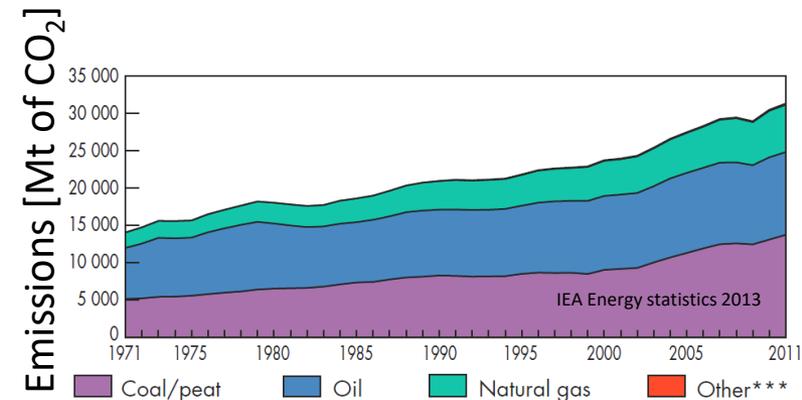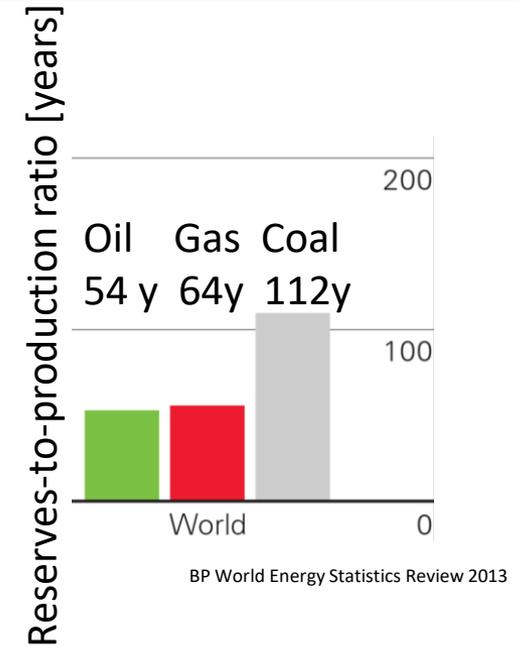 - Switzerland: 56% (oil, gas, coal)

Legend: Raw hydro, Nuclear fuel, Crude oil, Oil products, Waste, Gas, Coal, Wood, Other renewables

Switzerland pie chart values: 12%, 2%, 3%, 1%, 10%, 5%, 23%, 19%, 25%

  - Global: 87% (oil, coal, gas)

Global pie chart: Oil, 4130.5, 33%; Gas; 2987.1; 24%; Coal, 3730.1, 30%; Nuclear, 560.4, 4%; Hydro; 831.1; 7%; Renewable, 237.4, 2%

EPFL

Motivation

- This is not sustainable:

    - Finite reserves (economy)

    - Pollution and climate change (environment)
        - Emissions: CO_2, CH_4, N_2O, particles, NO_x, SO_2, F-gases, heavy metals (Hg, As)
        - Health issues: smog (winter and summer-smog), ozon layer depletion
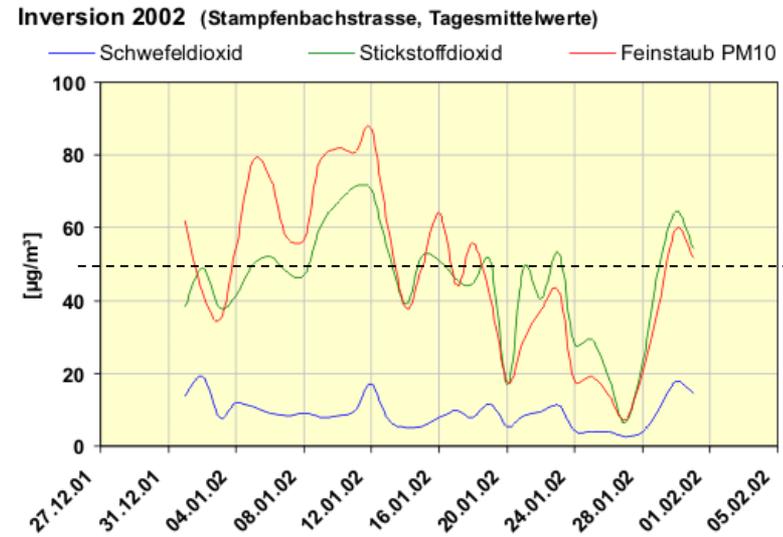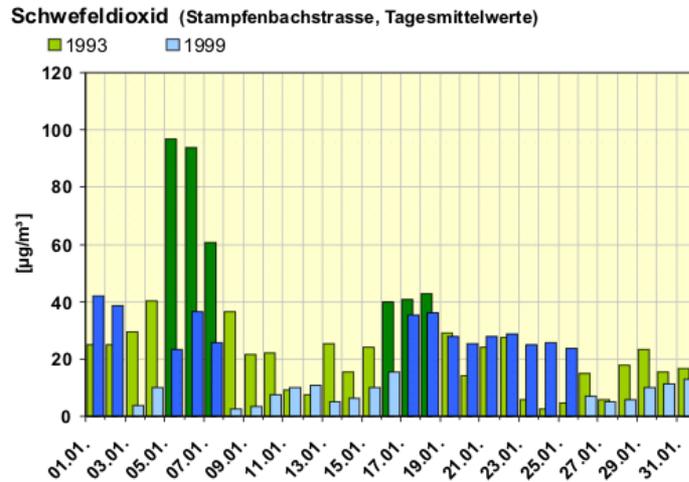   - Climate change: temperature, precipitation, snow cover, sea level, etc.*

BP World Energy Statistics Review 2013

*See IPCC report: https://www.ipcc.ch/report/ar5/
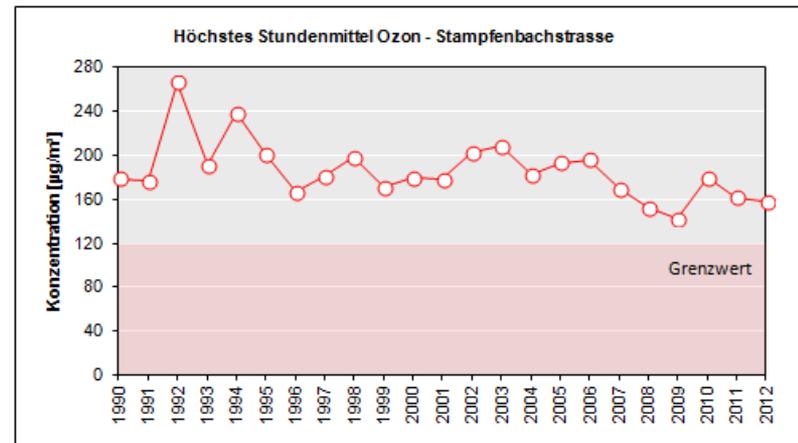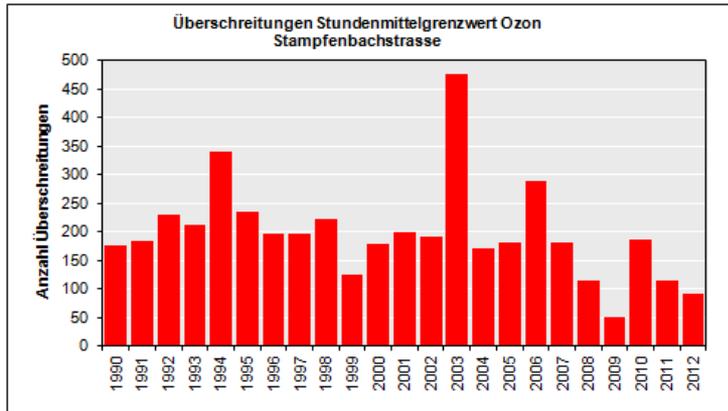

IEA Energy statistics 2013

- Geopolitical tensions over resources (security)

Motivation

- Winter smog in Zürich:

- Summer smog Zürich:

Motivation

- Increase of renewable energy sources, but issues with
  - Storage
  - Transport, distribution

- Introduction of an energy vector:

  An energy vector allows to transfer, in space and time, a quantity of energy.

  ... energy vectors allow to make energy available for use at a distance of time and space from the source, [independent of] the point of availability of the primary resource in nature.

  Orecchini, The era of energy vectors, IJHE, 31, 2006.

Motivation

- Various energy vectors:
  - Hydrogen
  - Synthetic fuels
  - Fossil fuels
  - Electricity
  - …

Table 1
Energy vectors key attitudes

Energy vector	Transfer attitude	Storage attitude
Fossil fuels	Short, medium, long range	Yes, short, medium, long term.
Hydrogen	Short, medium, long range	Yes, short, medium, long term. (Cryogenic exception)
Heat exchanging fluids	Short range	Yes, short term
Electricity	Short and medium range	No (indirect methods)
Mechanical, oil-dynamic and pressure-dynamic transmissions	Short range	Yes
Radiation	Very long range in space Short range in atmosphere	No

Orecchini, The era of energy vectors, IJHE, 31, 2006.

Motivation

- Hydrogen has been identified as a possible energy vector and alternative to hydrocarbon-based fuels:

  - Sustainable and environmentally acceptable (produced from water, production/storage/transport can be almost GHG and pollutant free)

  - Independent from crude oil

  - Available from different energy sources

  - Storable in gas, liquid, or metal-hydride form

  - Alternative production technologies

  - Versatile conversion (can be converted in variety of other forms) and application

  - Efficient direct conversion to/from electricity via fuel cells/electrolyzer

  - Almost pollutant free combustion (only NO_x)

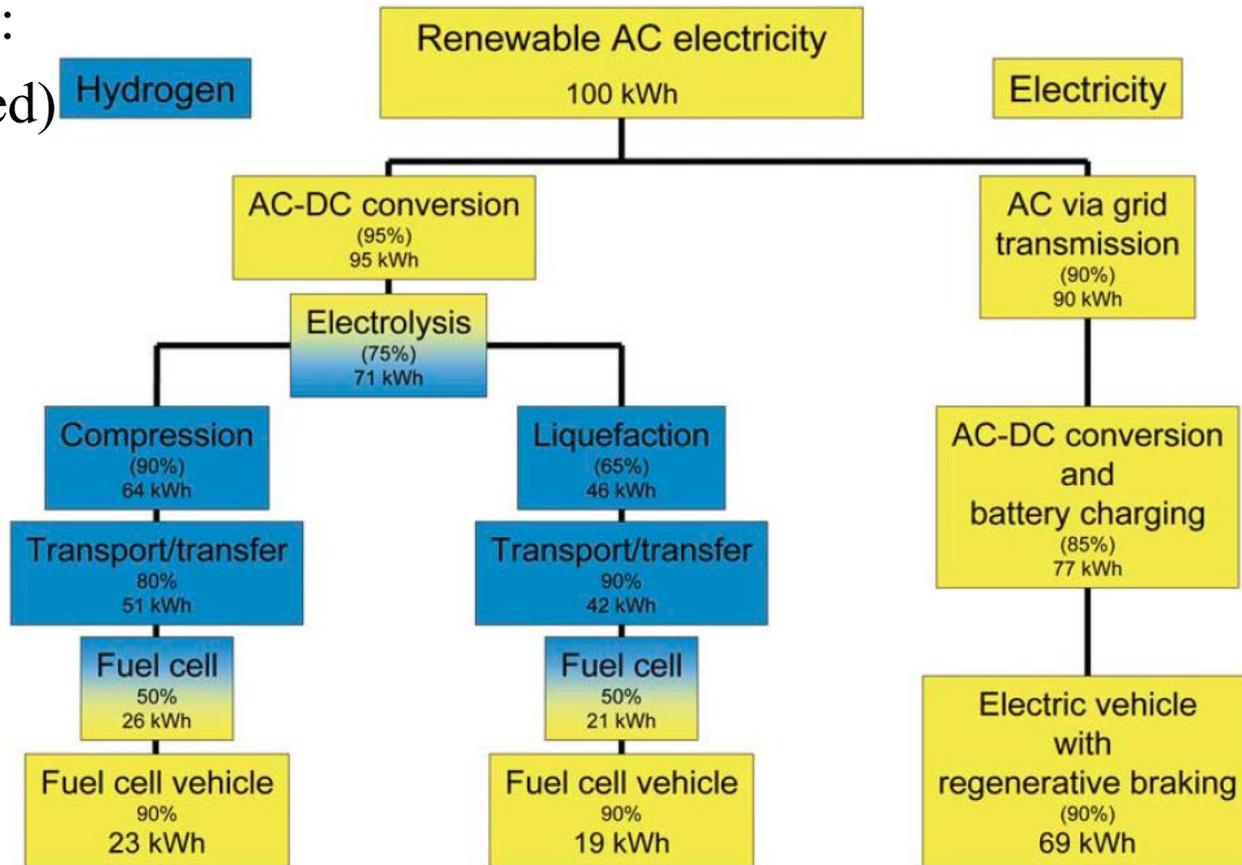 - Large market potential

Motivation
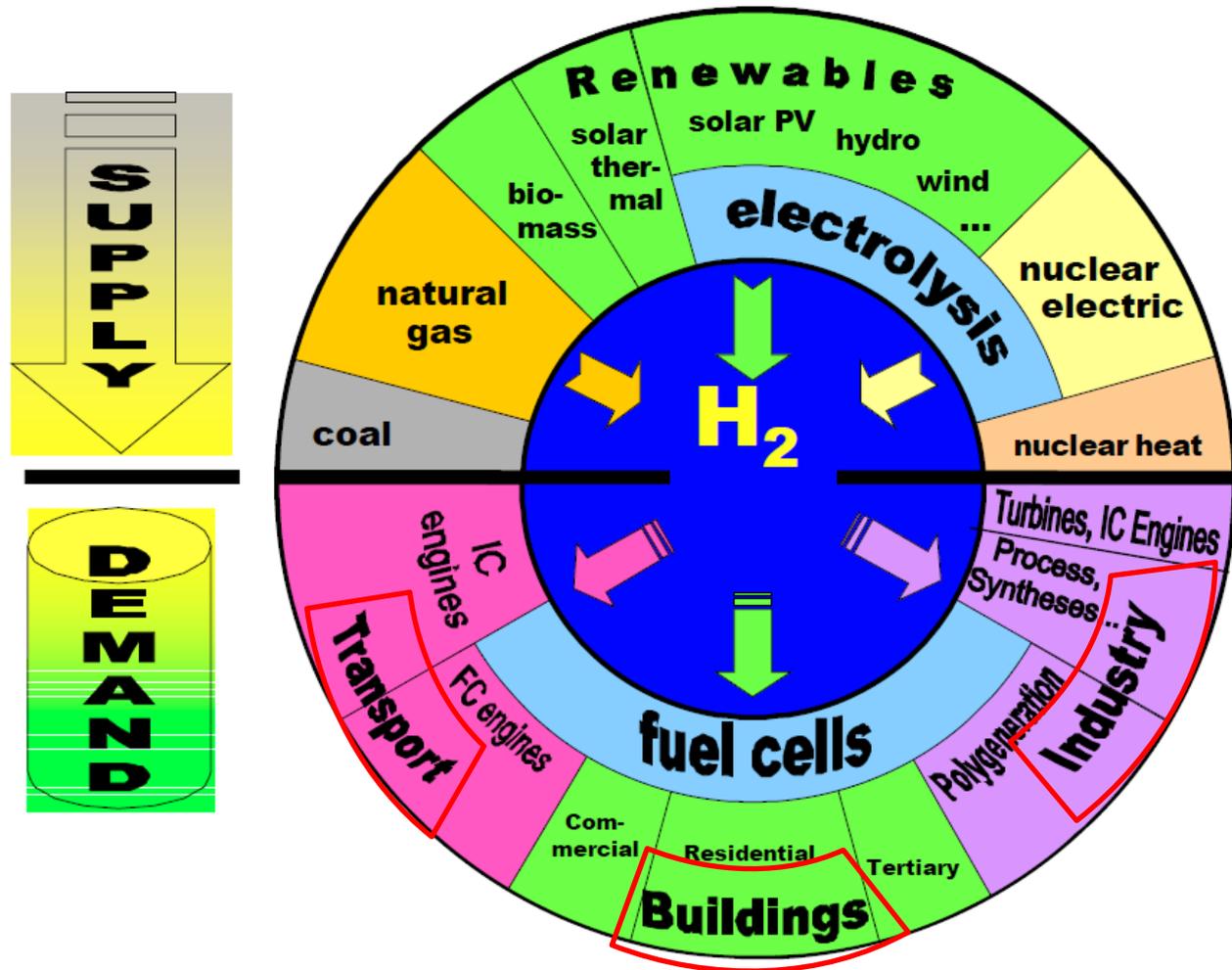
- Hydrogen is an energy carrier not an energy source!

Motivation

- Hydrogen vs. electricity:

  (both renewably produced)

Bossel, Does a hydrogen economy make sense?, Proceedings of the IEEE, vol. 94, no. 10, October 2006.

- But:
  - Charging time of batteries, reliability, range, weight, toxicity
  - Versatility of electricity limited (hydrogen can also be used in ICE, or as chemical commodity)

# Renewable Energy

- Outline:

Hydrogen as an energy vector:

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2. **Properties**

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EPFL

Hydrogen properties

- Lightest, most abundant element
  - 90 wt% of the universe
  - 4th most abundant on earth
    (highly reactive - mainly found
    in water and hydrocarbons)

- Colorless, odorless, tasteless
- Non-toxic and non-corrosive
- Low viscosity
  ($0.89 \cdot 10^{-5}$ Pa·s @ 293 K, 1 atm)
- Low density
  (0.08345 kg/m^3 @ 293 K, 1 atm)
- Gaseous to 20 K (-253 °C)
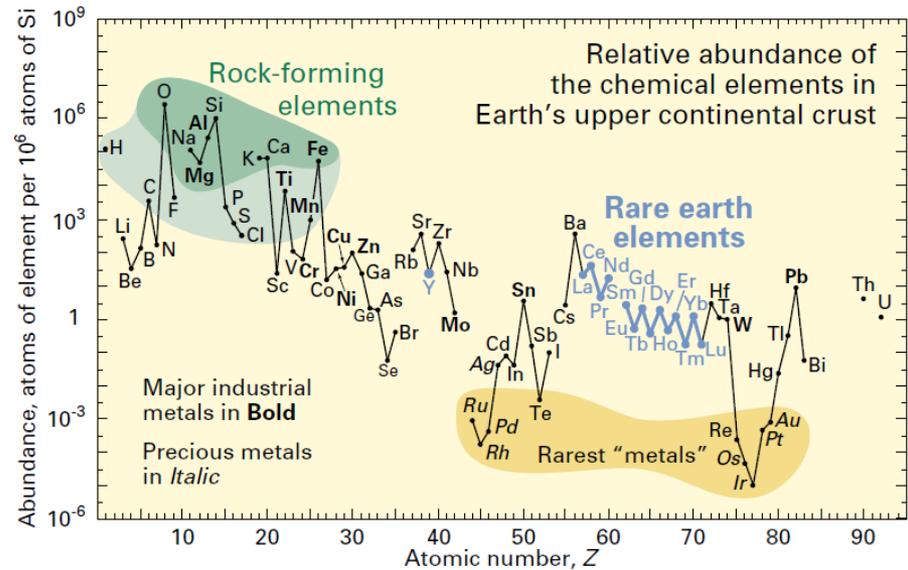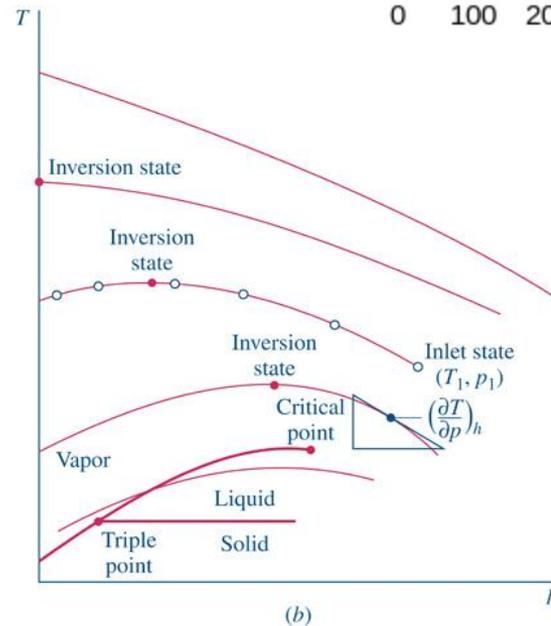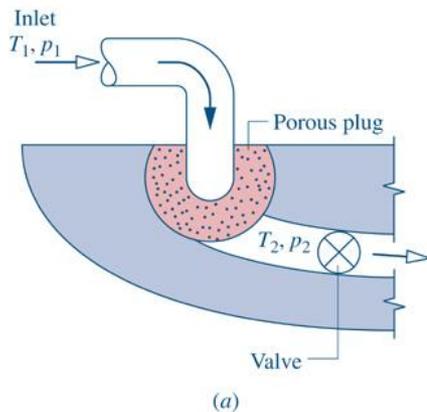

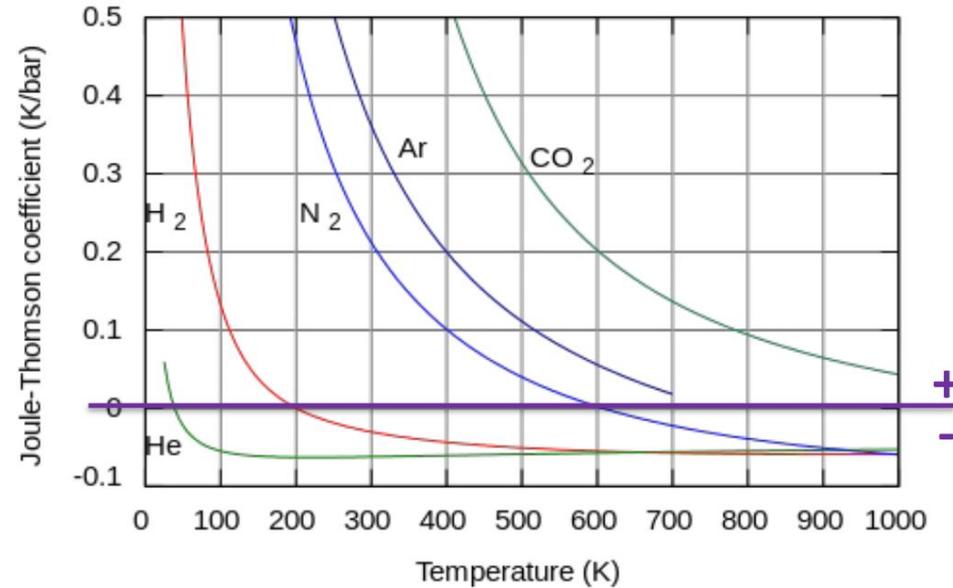US Geological Survey, Fact sheet, 2002.
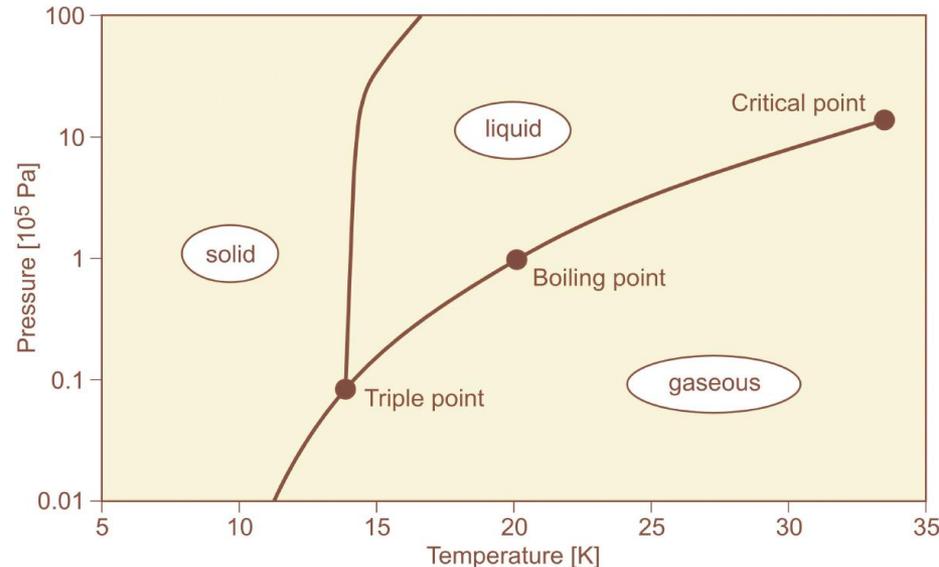
Hydrogen properties

- Negative Joule-Thompson coefficient above inversion (inversion 193 K):

$$\mu_J = \left(\frac{\partial T}{\partial p} \right)_h$$

- Determined experimentally in
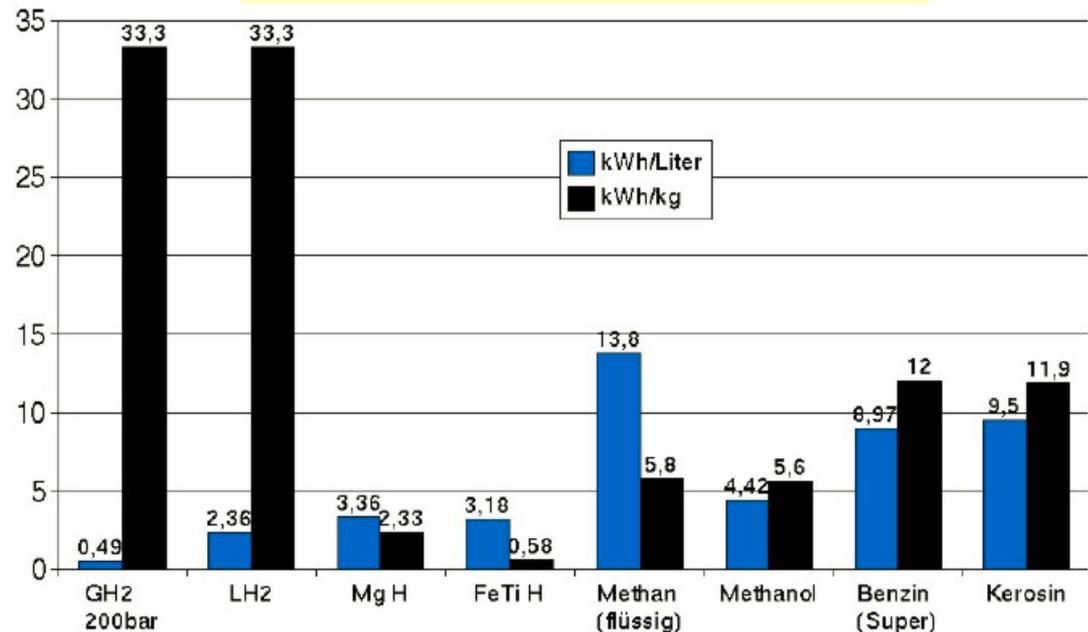- an enthalpic expansion process

Hydrogen properties

- Highly diffusive (diffusion coeff. $0.61 \cdot 10^{-4}$ m^2/s): rapid mixing

- High solubility: leads to steel embrittlement, enhanced with higher pressure and temperature

- Most energy per unit mass:
  - Hydrogen: 120 MJ/kg
  - Biomass 18 MJ/kg
  - Gasoline 43 MJ/kg

Hydrogen properties

- Safety:
  - Light: rises quickly and disperses
  - High diffusivity: less easy built up of flammable mixtures
  - Small and low viscosity: easily leaks and doesn't accumulate but can also diffuse in metals and embrittle them
  - Small volumetric energy density: holds less energy than gasoline
  - Concentration limits of flammable fuel/air mixture 5-76 vol% (gasoline 1-7 vol%)
  - Autoignition temperature 853 K (gasoline 533 K)
  - Non-toxic
  - Odorless: odorants such as thiole ($R-S_{\diagdown H}$) can be added (already done for natural gas)
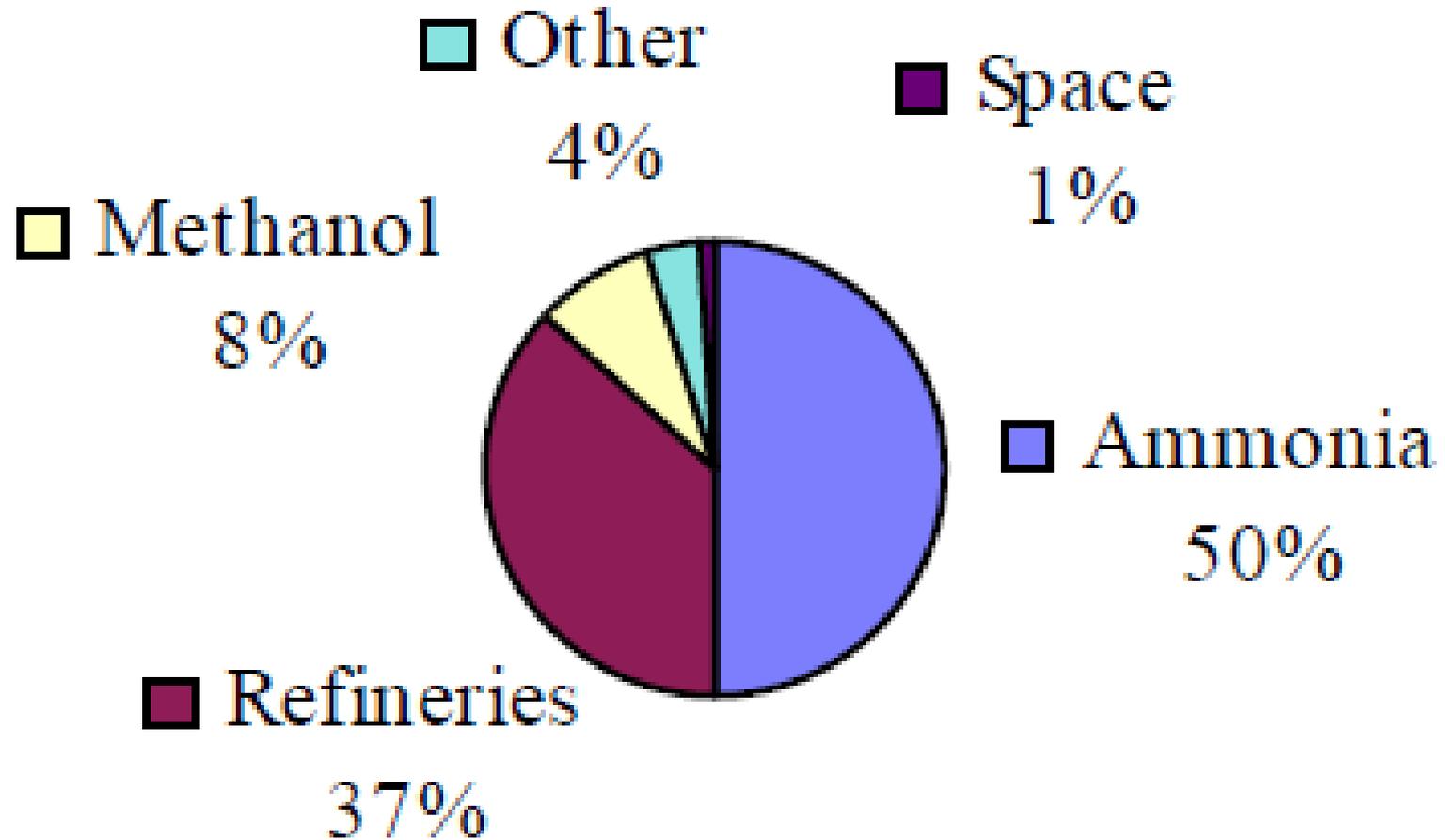
Hydrogen properties

- Properties in comparison to other gases and liquids:

Property	Hydrogen	Methane	Propane	Gasoline
Molecular weight (u)	2.02	16.04	44.06	~107
Density (kg/m^3) at normal conditions	0.084	0.651	1.87	4.4
Buoyancy (density with respect to air)	0.07	0.55	1.52	3.4 to 4.0
Diffusion coefficient (cm^2/s)	0.61	0.16	0.12	0.05
Lean flammability limit in air (% by volume)	4.1	5.3	2.1	1.0
Rich flammability limit in air (% by volume)	75	15	10	7.8
Minimum ignition energy (mJ)	0.02	0.29	0.26	0.24
Minimum self-ignition energy (K)	858	813	760	501 to 744
Lean detonability limit in air (% by volume)	18	6.3	3.1	1.1
Rich detonability limit in air (% by volume)	59	13.5	7.0	3.3
Explosion energy (kg equivalent TNT per m^3 of vapor)	2.02	7.02	20.2	44.2

^ Selected physical properties of hydrogen, methane, propane and gasoline.

Hydrogen use

- Current yearly world production ~75 mio tons and used for:

Other 4%

Space 1%

Methanol 8%

Ammonia 50%

Refineries 37%
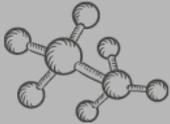
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Colors of Hydrogen

Production

- Production of hydrogen:

Electrolysis, 1%

Oil, 23%

Natural gas and coal, 76%

Technology	Hydrogen source	Energy source
Steam reforming	Natural gas	Combustion, solar
Gasification	Coal, carbonaceous material, biomass	Combustion, solar
Thermal cracking	Natural gas, oil	Combustion, solar
Thermal dissociation	Water	Solar
Thermochemical cycles	Water	Solar, nuclear
Photoelectrochemical	Water	Solar
Electrolysis	Water	Electricity from renewable, nuclear, fossil

Production

- Steam reforming: uses light hydrocarbon feedstock, usually methane, reacts it at elevated temperatures with steam and catalytically converts the feed into hydrogen
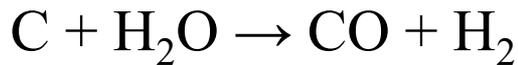
$$CH_4 + H_2O \rightarrow CO + 3H_2 \quad (\Delta H = 206 \text{ kJ/mol})$$
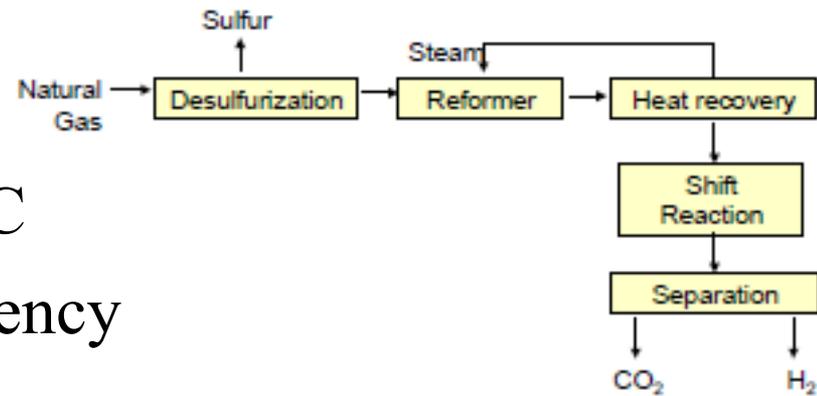
  – Operates around 700 – 925°C
  – Can achieve 65 – 75% efficiency

water gas shift: $CO + H_2O \rightarrow CO_2 + H_2 \quad (\Delta H = -41 \text{ kJ/mol})$
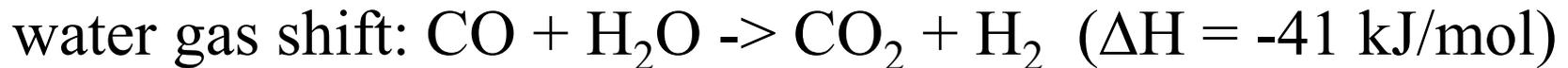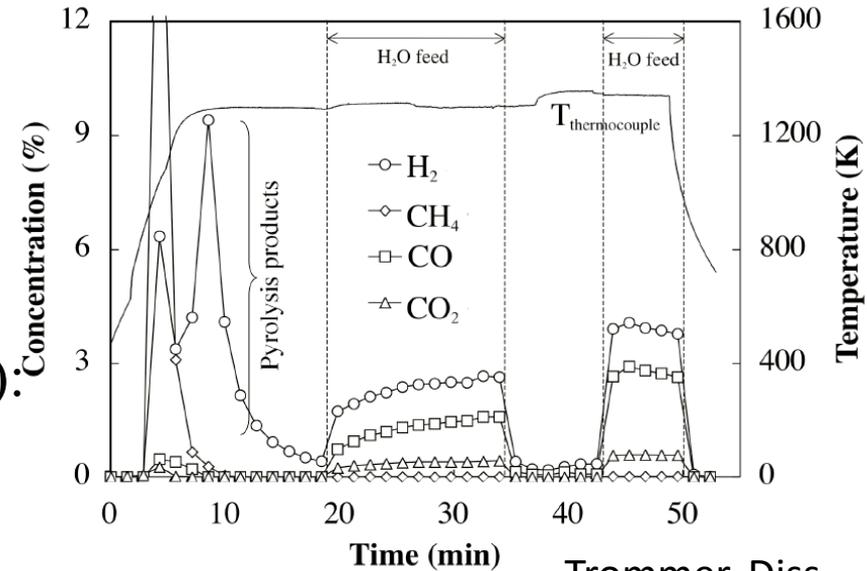
Production

- Gasification: uses carbonaceous materials, reacts it at high temperatures (>700 °C), without combustion, with a controlled amount of steam, oxygen, and/or CO_2. Results in CO, H_2, and CO_2.

$$C + H_2O \rightarrow CO + H_2$$

Trommer, Diss ETH, 2006.

- Consists of (sequential or simultaneous):
  - Dehydration
  - Pyrolysis (thermal decomposition in the absence of O_2, devolatilization)
  - Gasification (heterogeneous gas-solid reaction of pyrolysis residue with reactive gas)
  - Combustion
  - Water-gas-shift

Production

- Thermal cracking: complex organic molecules such as heavy hydrocarbons are broken down into simpler molecules such as light hydrocarbons, by the breaking of carbon-carbon bonds in the precursors at high temperatures and by using catalysts
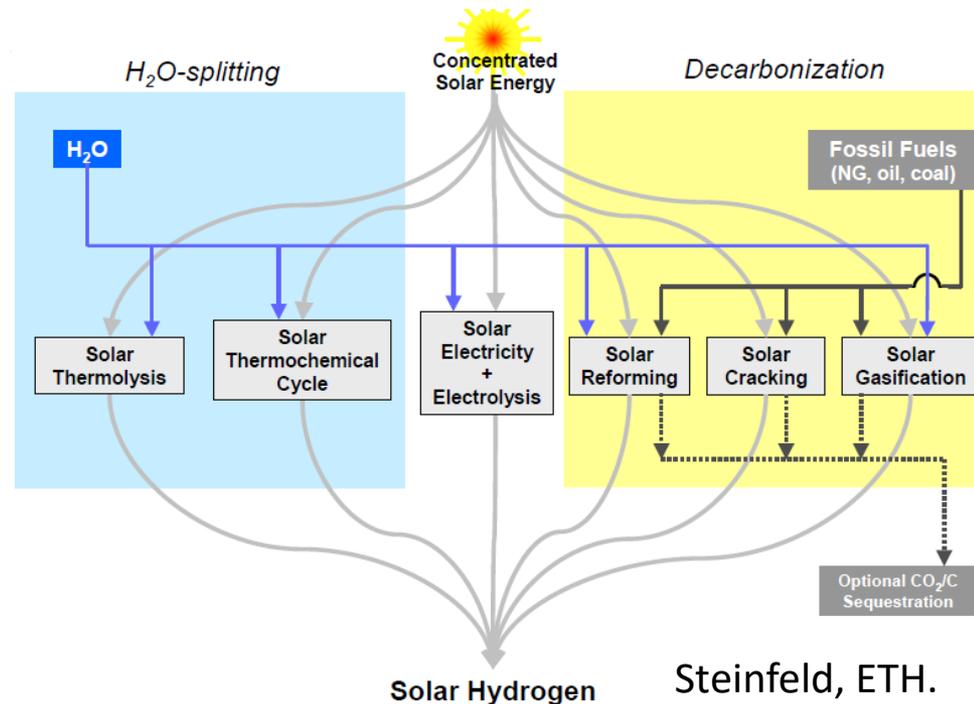
$$CH_4 \rightarrow C + 2H_2 \ (\Delta H = 74.85 \text{ kJ/mol})$$

Production

- Hydrogen derived from fossil fuels has many impurities:
  - From combustion: CO_2, CO, N_2
  - From the feedstock: sulfur

- Purification:
  - Desulfurization for gaseous feedstock: calcium-based slurries (SO_2 to sulfites and sulfates)
  - Desulfurization from solid/liquid feedstock: via catalysts into H_2S
  - CO_2 removal:
    - temperature swing adsorption (solubility variation of CO_2 with temperature)
    - pressure swing adsorption (pressure dependent absorption of e.g. zeolites)
    - special membranes (cellulose)
  - CO removal from H_2 mixture: Hydrogen-permeable membranes made of metals (palladium)

Production

- Heat for steam reforming, gasification, or cracking can be produced via:

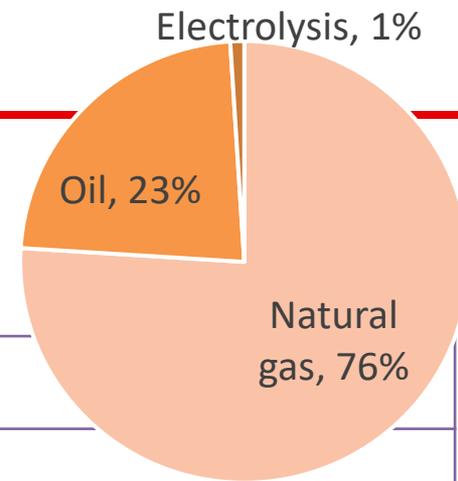 - Autothermal processes (partial combustion of the feedstock)

    Combustion: $C_xH_y + (x+y/4)O_2 \rightarrow xCO_2 + y/2H_2O$
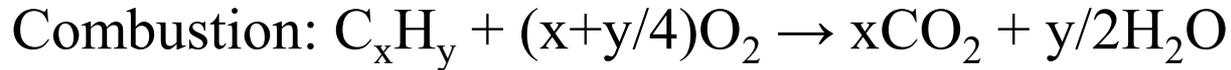
  - Any other heat source such as solar or nuclear:

Steinfeld, ETH.

EPFL

Production

- Production of hydrogen:

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Oil, 23%

Natural gas, 76%

| Technology	Hydrogen source	Energy source
Steam reforming	Natural gas	Combustion, solar
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Electrolysis	Water	Electricity from renewable, nuclear, fossil

EPFL

Production

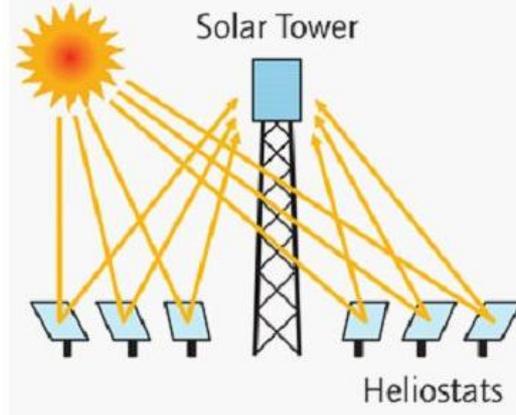- Thermal and thermochemical approaches:
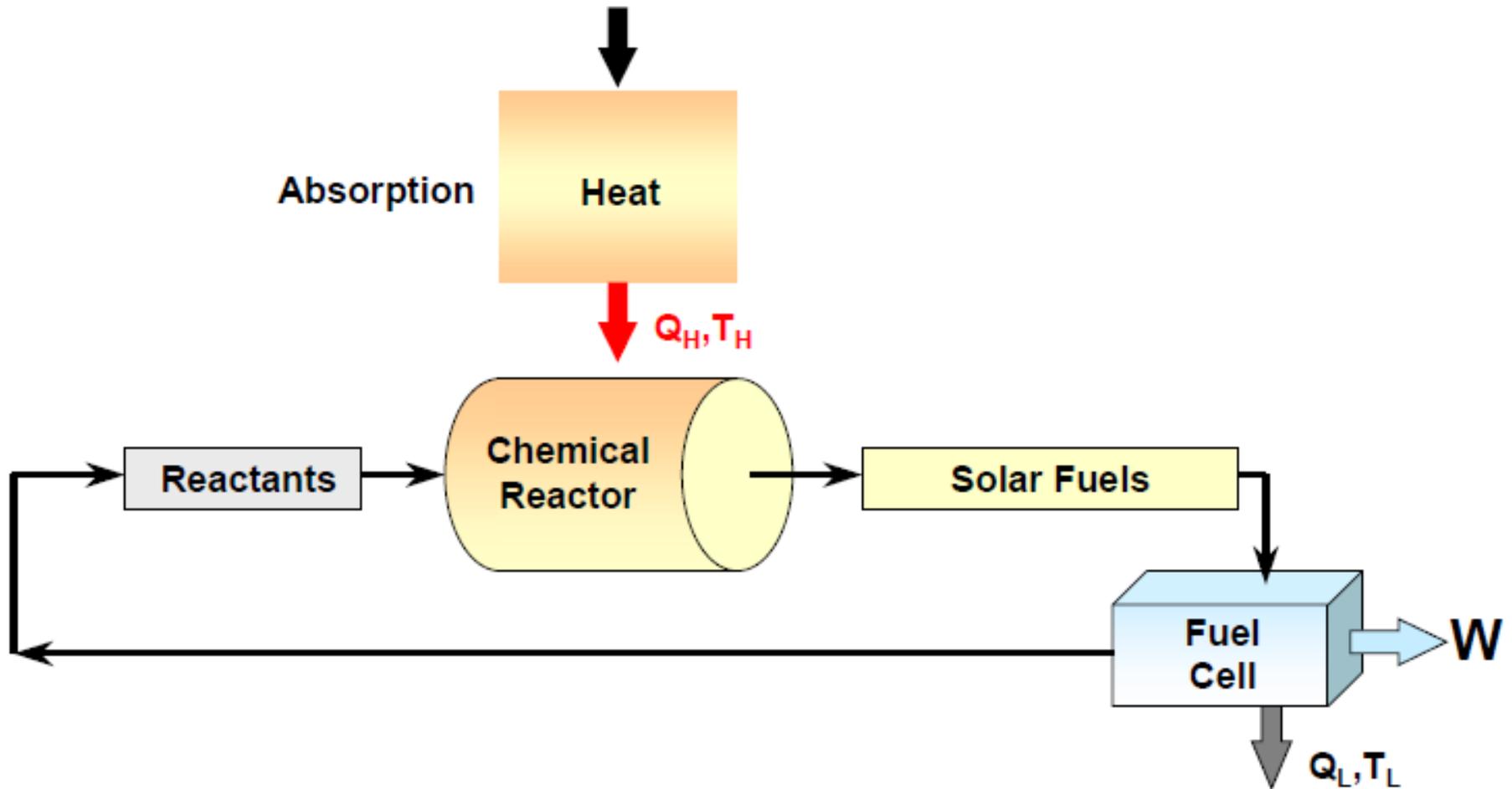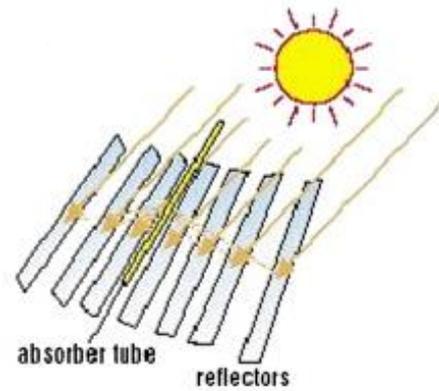
Production

- Thermochemical cycles – solar: concentrating technologies
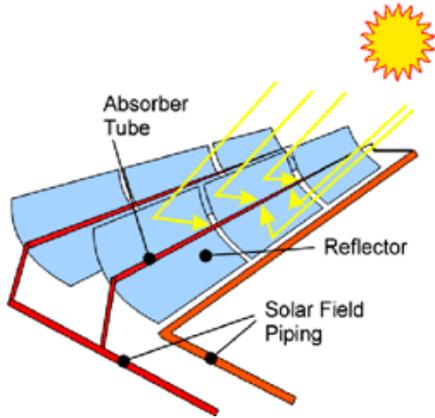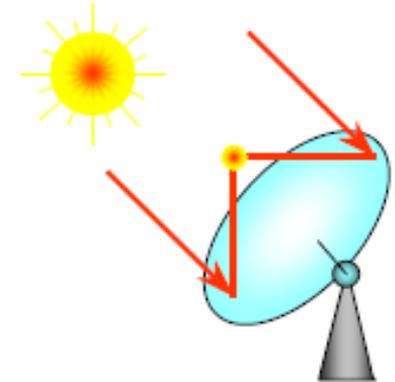

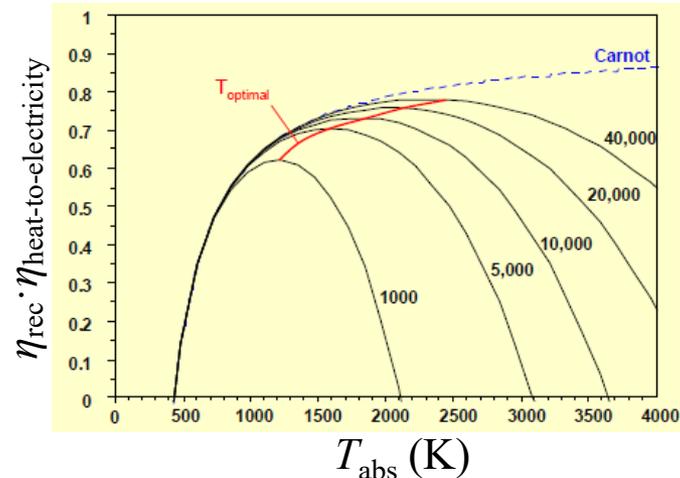Parabolic through   Solar tower   Fresnel   Dish

- Temperatures reachable:

$$\eta_{\text{rec}} = \frac{q_{\text{use}}}{q_{\text{sol,in}}} = \frac{q_{\text{use}}}{CI} = \alpha - \sigma\varepsilon\frac{T_{\text{abs}}^4 - T_{\text{amb}}^4}{CI}$$

$$\eta_{\text{heat-to-electricity}} = \frac{T_{\text{abs}} - T_{\text{amb}}}{T_{\text{abs}}}$$
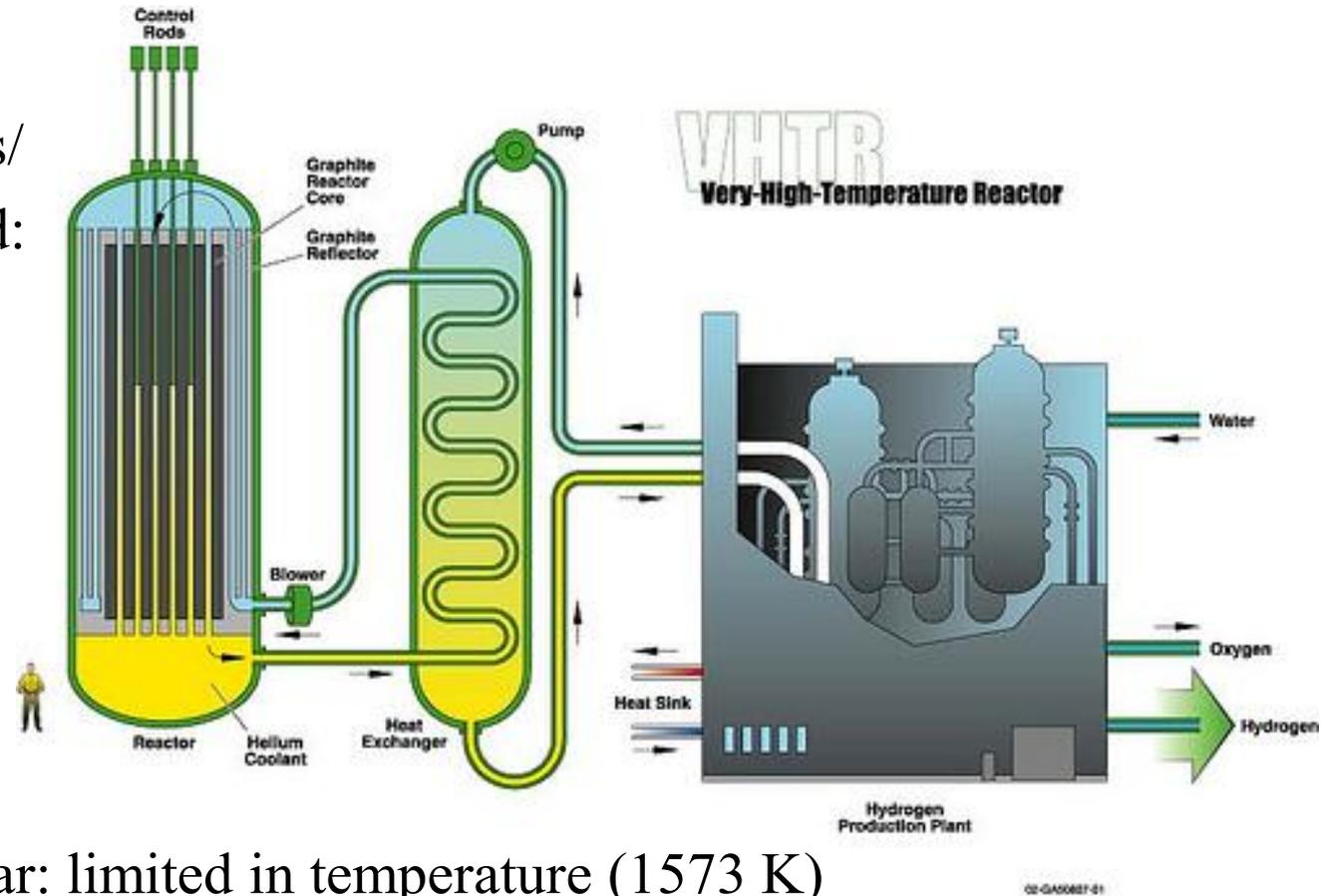
Production

- Thermochemical cycles – nuclear:

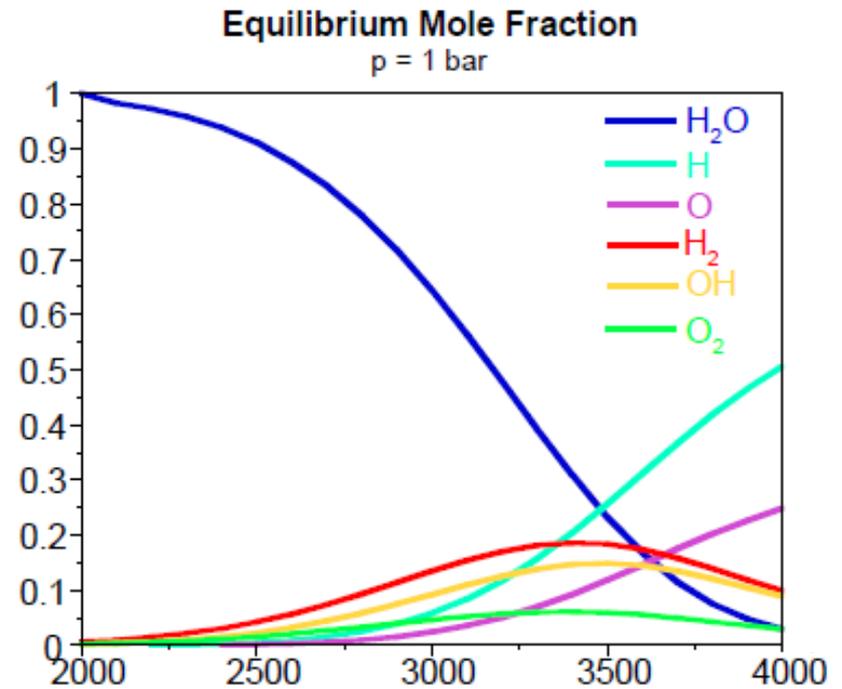 - Possible coolants/
    heat transfer fluid:
    - Molten-salt
    - Gases (e.g. He)
    - Heavy metals

  - Compared to solar: limited in temperature (1573 K)

- Thermal dissociation:

$$H_2O \rightarrow 1/2 O_2 + H_2$$
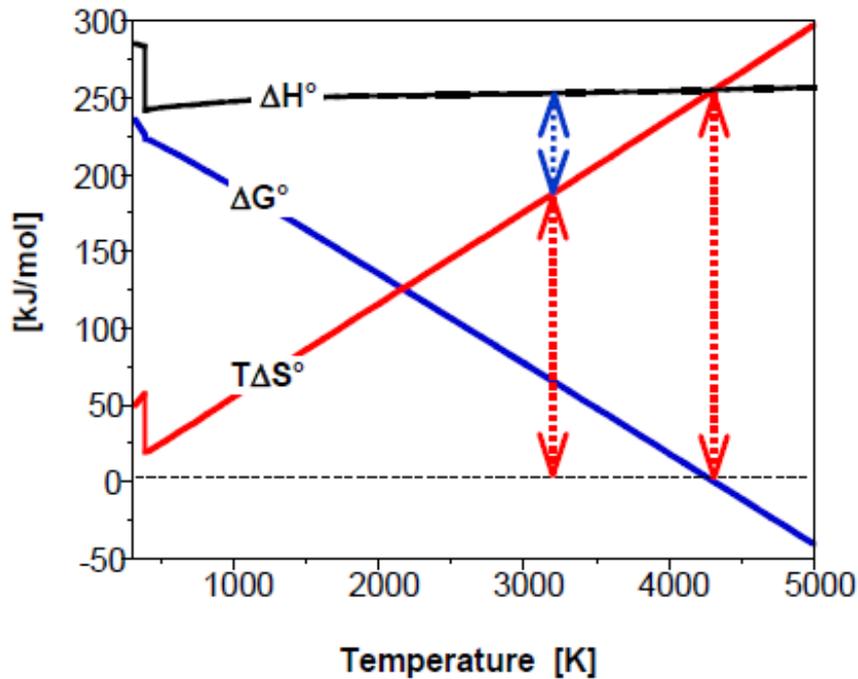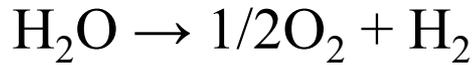
Production

- Multi-step water-splitting cycles

$$MeO \longleftrightarrow Me+1/2O_2 \qquad \rightarrow 1/2O_2$$
$$H_2 \longleftarrow MeO+H_2 \longleftrightarrow Me+H_2O \longleftarrow H_2O$$
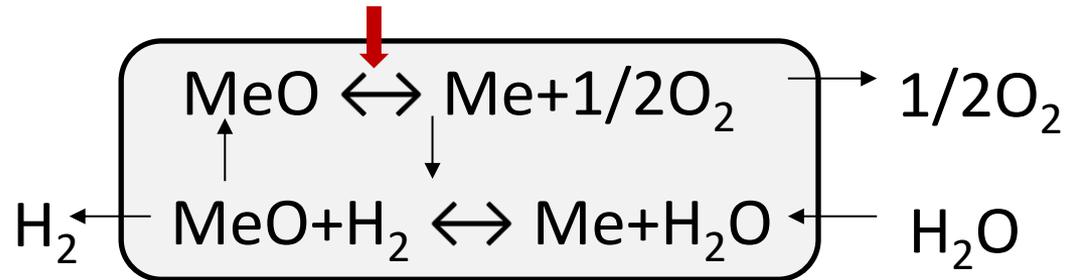
- reduce required temperatures
- omit explosive H_2/O_2 mixture

EPFL
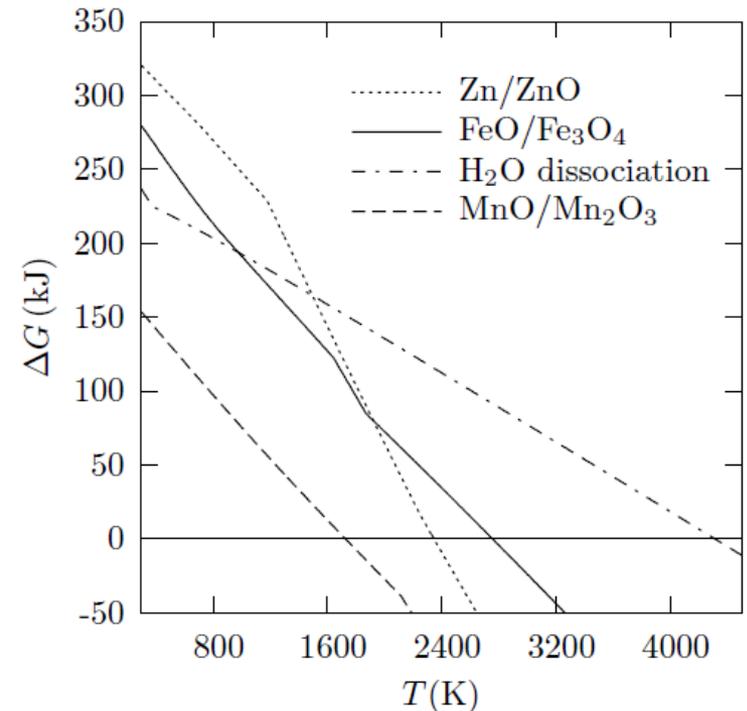
Production

- Possible redox pairs for two-step cycles:

Cycle	Reactions	Cycle	Reactions
Zn/ZnO	$ZnO \rightarrow Zn + O_2$ $Zn + H_2O \rightarrow ZnO + H_2$	SoO_2/SiO	$SiO_2 \rightarrow SiO + 1/2\ O_2$ $SiO + H_2O \rightarrow SiO_2 + H_2$
Fe_3O_4/FeO	$Fe_3O_4 \rightarrow 3\ FeO + \frac{1}{2}\ O_2$ $3\ FeO + H_2O \rightarrow Fe_3O_4 + H_2$	W/WO_3	$WO_3 \rightarrow W + 3/2\ O_2$ $W + 3H_2O \rightarrow WO_3 + 3H_2$
In_2O_3/In_2O	$In_2O_3 \rightarrow In_2O + 1/2\ O_2$ $In_2O + 2H_2O \rightarrow In_2O_3 + 2H_2$	Hg/HgO	$Hg + H_2O \rightarrow HgO + H_2$ $HgO \rightarrow Hg + 1/2O_2$
SnO_2/Sn	$SnO_2 \rightarrow Sn + O_2$ $Sn + 2H_2O \rightarrow SnO2 + 2H_2$	Cd/CdO	$Cd + H_2O \rightarrow CdO + H_2$ $CdO \rightarrow Cd + 1/2O_2$
$MnO/MnSO_4$	$MnSO_4 \rightarrow MnO + SO_2 + 1/2O_2$ $MnO + H_2O + SO_2 \rightarrow MnSO_4 + H_2$	CO/CO_2	$CO + H_2O \rightarrow CO_2 + H_2$ $CO_2 \rightarrow CO + 1/2O_2$
$FeO/FeSo_4$	$FeSO_4 \rightarrow FeO + SO_2 + 1/2O_2$ $FeO + H_2O + SO_2 \rightarrow FeSO_4 + H_2$	Ce_2O_3/CeO_2	$CeO_2 \rightarrow Ce_2O_3$ $Ce_2O_3 + H_2O \rightarrow 2CeO_2 + H_2$
$CoO/CoSO_4$	$CoSO_4 \rightarrow CoO + SO_2 + 1/2O_2$ $CoO + H_2O + SO_2 \rightarrow CoSO_4 + H_2$	Mg/MgO	$MgO \rightarrow Mg + 1/2O_2$ $Mg + H_2O \rightarrow MgO + H_2$
$Fe_3O_4/FeCl_2$	$Fe_3O_4 + 6HCl \rightarrow 3FeCl_2 + 3H_2O + 1/2O_2$ $3FeCl_2 + 4H_2O \rightarrow Fe_3O_4 + 6HCl + H_2$	$SnO/SnO2$	$SnO_2 \rightarrow SnO + 1/2O_2$ $SnO + H_2O \rightarrow SnO_2 + H_2$
Mo/Mo_2	$MoO_2 \rightarrow Mo + O_2$ $Mo + 2H_2O \rightarrow MoO_2 + 2H_2$		

Production

- Production of hydrogen:

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Photoelectrochemical	Water	Solar
Electrolysis	Water	Electricity from renewable, nuclear, fossil

Production

- Photoelectrochemical:

$H_2O \rightarrow 2H^+ + 2e^- + 1/2 O_2$

electrolyte

h^+

H^+

e^-

absorber

$2H^+ + 2e^- \rightarrow H_2$
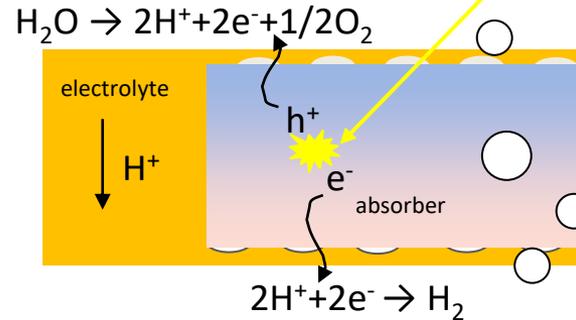
- Stringent material requirements:
  - band gap size
  - suitable band edge position
  - high chemical stability in the dark and under illumination, as well as under highly acidic or base conditions
  - efficient charge transport in the semiconductor
  - selective and efficient electrochemical reactions
  - earth-abundance and low costs

Solution pH=1

Production

- Production of hydrogen:

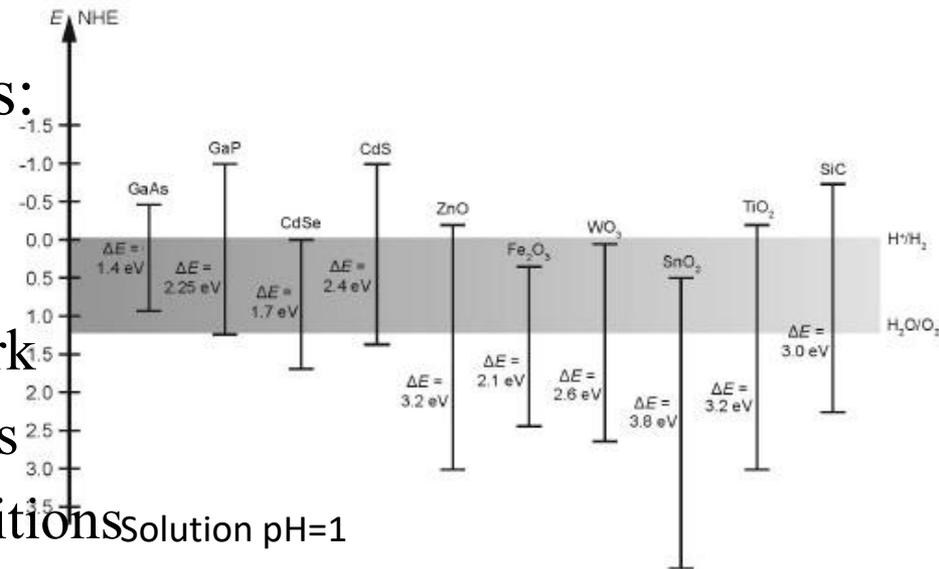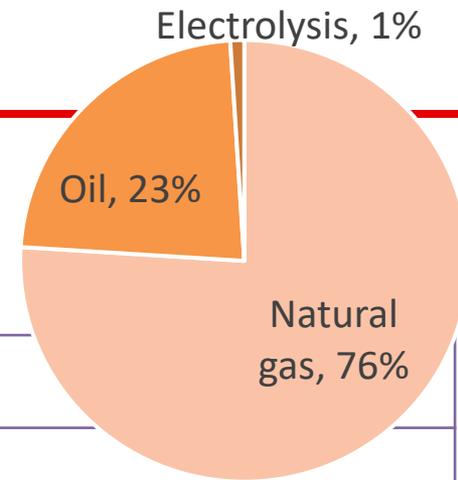Electrolysis, 1%

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Steam reforming	Natural gas	Combustion, solar
Gasification	Coal, carbonaceous material, biomass	Combustion, solar
Thermal cracking	Natural gas, oil	Combustion, solar
Thermal dissociation	Water	Solar
Thermochemical cycles	Water	Solar, nuclear
Photoelectrochemical	Water	Solar
Electrolysis	Water	Electricity from renewable, nuclear, fossil

Production

- Electrolysis, e.g. SPE

$$H_2O \rightarrow 1/2 O_2 + H_2 \quad (\Delta G = 237 \text{ kJ/mol})$$
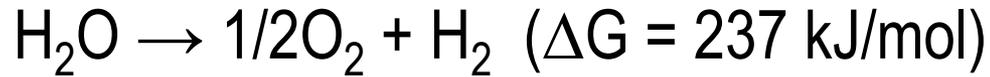
- At standard conditions (25 °C and 1bar)

$$\Delta G = nFV_{rev} \rightarrow V_{rev} = \Delta G / (nF) = 1.23V$$

- Practical:

$$V = V_{rev} + \eta_a + \left|\eta_c\right| + \eta_\Omega$$

Overpotential due to electrochemical reactions and ohmic losses

$$\eta_{a,c} = a + b\log(i) \quad \text{Tafel relation}$$

water

Current collector

oxygen

Membrane

hydrogen

Diffusion media   **Catalyst**
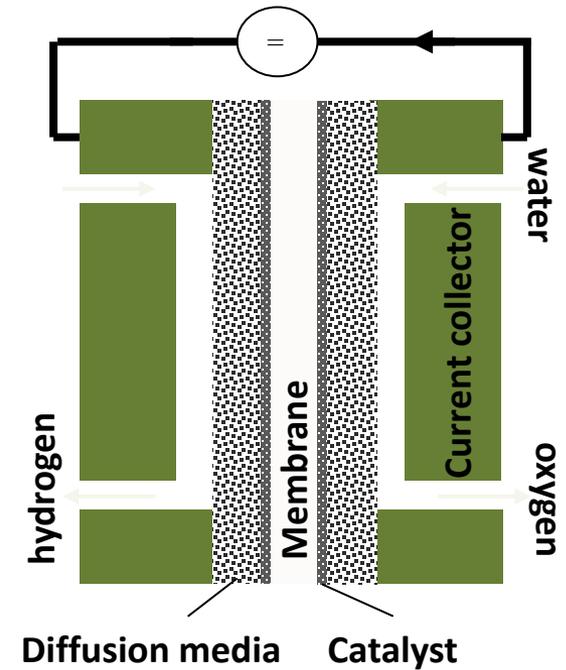
Production

- Alkaline electrolyzer: uses high pH electrolytes (KOH, NaOH)

Anode: $2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^-$

Cathode: $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$
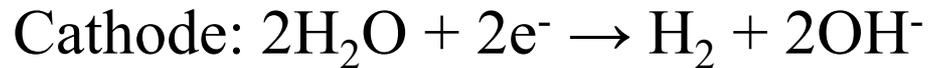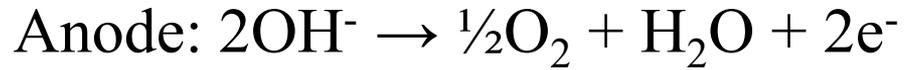
NEL-Hydrogen: 50-485 Nm^3 H_2/h
25% KOH aqueous solution, 80°C

Production

- Solid polymer electrolyzer: polymeric electrolyte

  PEM fuel cell:

  Anode: $H_2O \rightarrow \frac{1}{2}O_2 + 2H^+ + 2e^-$ Cathode: $2H^+ + 2e^- \rightarrow H_2$

- Sulfonated tetrafluoroethylene:

  - Semi-permeable for products
  - Withstand large pressure differentials
  - Proton conducting (10 S/m)
  - Not conducting for electrons
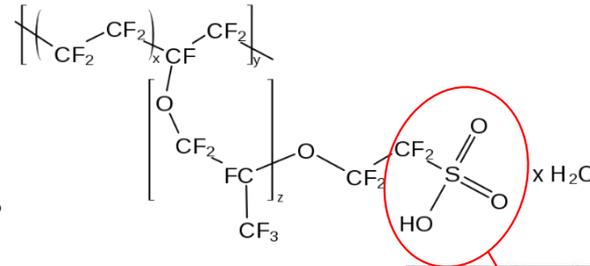
- Membrane is usually only 150-300 μm thick

- Commonly uses rare metals as catalysts (Pt, Ir, Ru)

- Gas diffusion layers:

  - Electrical conducting
  - Gas diffusing, permeable
  - Mechanical stable
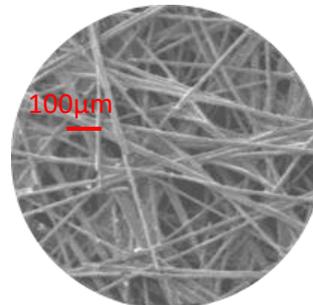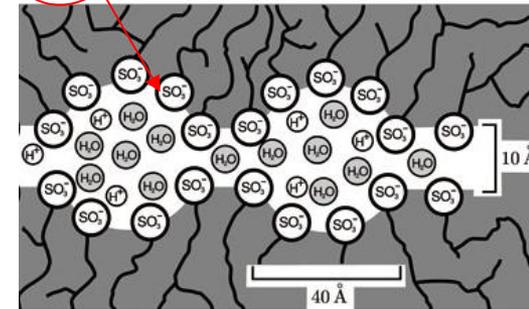
- Solid oxide electrolyzers: operate at very high temperatures (~700-1000°C)

Anode: $O^{2-} \rightarrow 1/2 O_2 + 2e^-$

Cathode: $2H_2O + 2e^- \rightarrow H_2 + O^{2-}$

= Electrical demand

= Heat demand
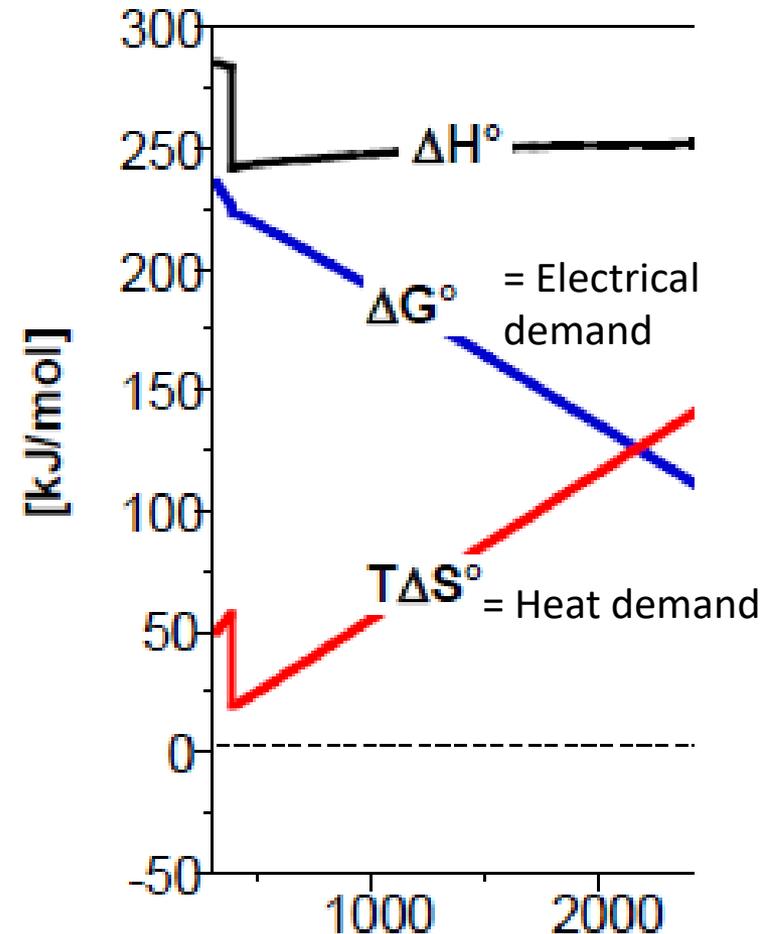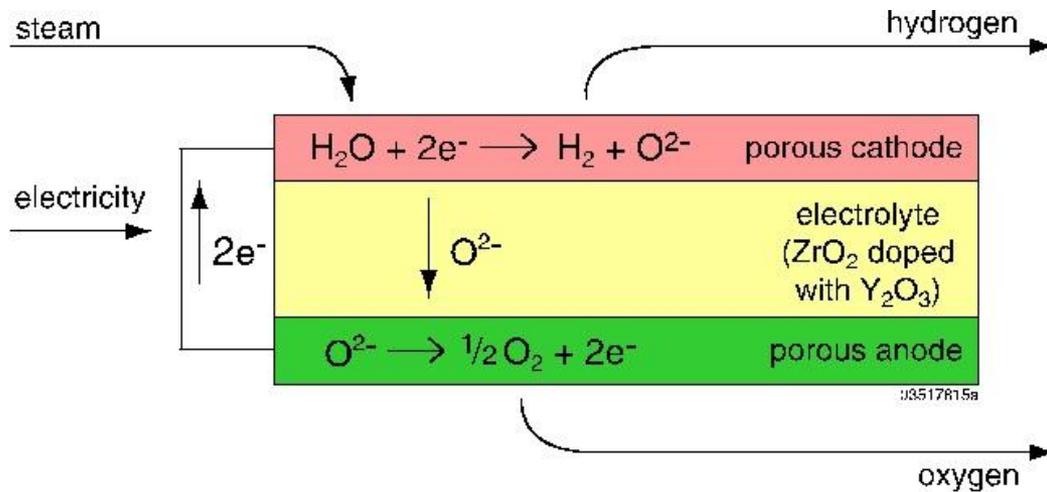
Production

- Electricity from:
  - Solar: PV electricity
  - Solar: solar thermal electricity
  - Wind
  - Hydro
  - Geothermal
  - Biomass
  - Fossil fuels

Production

- Production of hydrogen:

Electrolysis, 1%
Oil, 23%
Natural gas, 76%

Technology	Hydrogen source	Energy source
Steam reforming	Natural gas	Combustion, solar
Gasification	Coal, carbonaceous material, biomass	Combustion, solar
Thermal cracking	Natural gas, oil	Combustion, solar
Thermal dissociation	Water	Solar
Thermochemical cycles	Water	Solar, nuclear
Photoelectrochemical	Water	Solar
Electrolysis	Water	Electricity from renewable, nuclear, fossil

Production

- Prize comparison:

Technology	Primary source	Prod. cost ($/kg)	Ref.
Central steam reforming	Natural gas	1.5	[17,26]
Distrib. steam reforming	Natural gas	2.6	[26]
Gasification	Coal	1.2	[26]
Gasification with CCS	Coal	1.8	[17,26]
Distributed electrolysis	Grid electricity	6.8	[26]
Central electrolysis	Wind	3.8	[26]
Distributed electrolysis	Wind	7.3	[26]
Thermochemical cycle	Nuclear	1.4	[26]
Pyrolysis/Cracking	Natural gas + solar	3.0	[9]
Pyrolysis/Cracking	Natural gas + solar	3.6	[10]
Pyrolysis/Cracking	Natural gas + solar	4.5	[9]
Steam reforming	Natural gas + solar	2.2	[16]
FV electrolysis	Solar	9.1	[17]
Solar thermoch. S cycles	Solar	5.3	[17]
Sol. thermoch. oxide/metal	Solar	8.3	[17]

Table 2 – Cost of hydrogen production technologies.
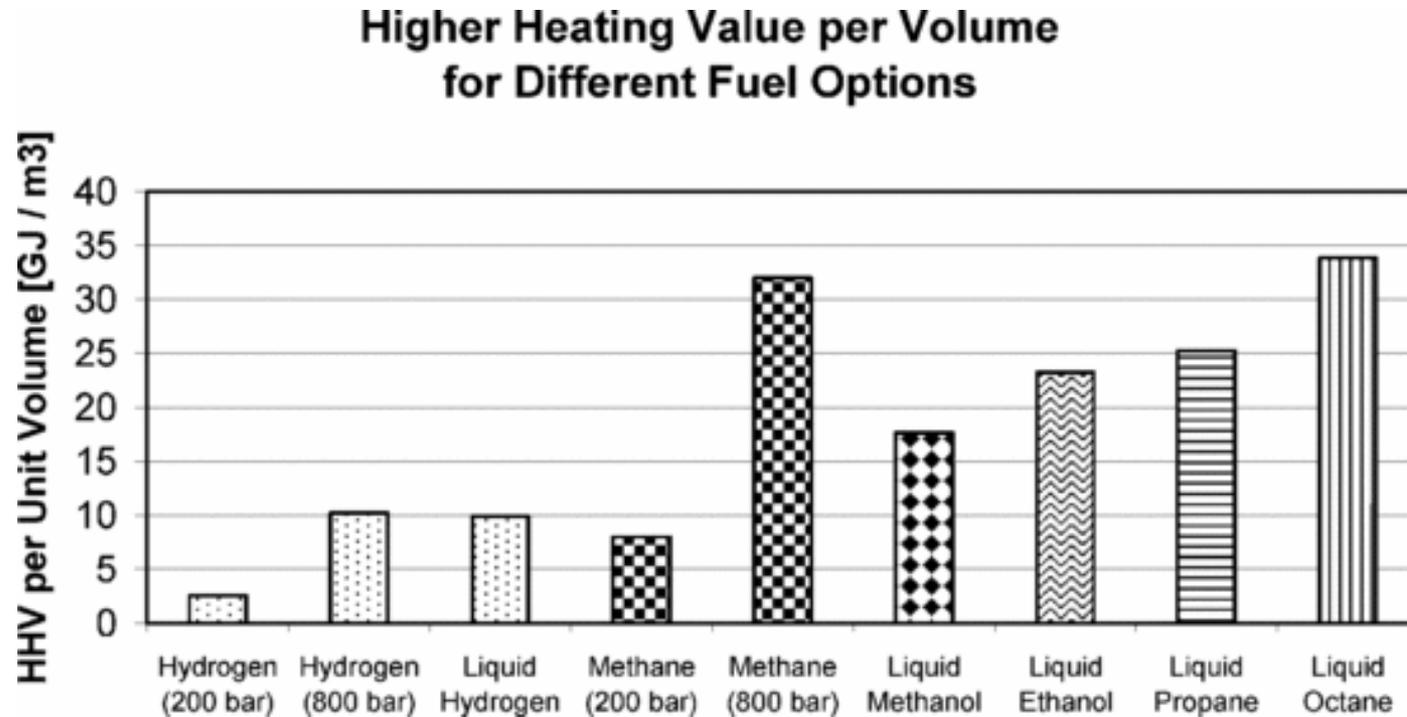
Abanades et al., IJHE, 38, 2013.

EPFL

- Outline:

  Hydrogen as an energy vector:

  1. **Motivation**
  2. **Properties**
  3. **Production**
  4. **Storage**
  5. **Distribution**
  6. **Application**

- Major drawback for hydrogen due to its extremely low density (problematic for mobility applications)

Higher Heating Value per Volume for Different Fuel Options

Storage

- Two major storage possibilities:

  - Storage that alters the state or phase:

    - Compression
    - Liquefaction

  - Processes that associate hydrogen to other substances:

    - Adsorption on substrate (e.g. activated carbon)
    - Chemical combination of hydrogen to create hydrogen-rich compound:

      - Hydrogen is tightly bound, requiring chemical process for recovery (e.g. ammonia, methanol)
      - Compounds that can be reversibly transformed into another compound with higher/lower hydrogen content
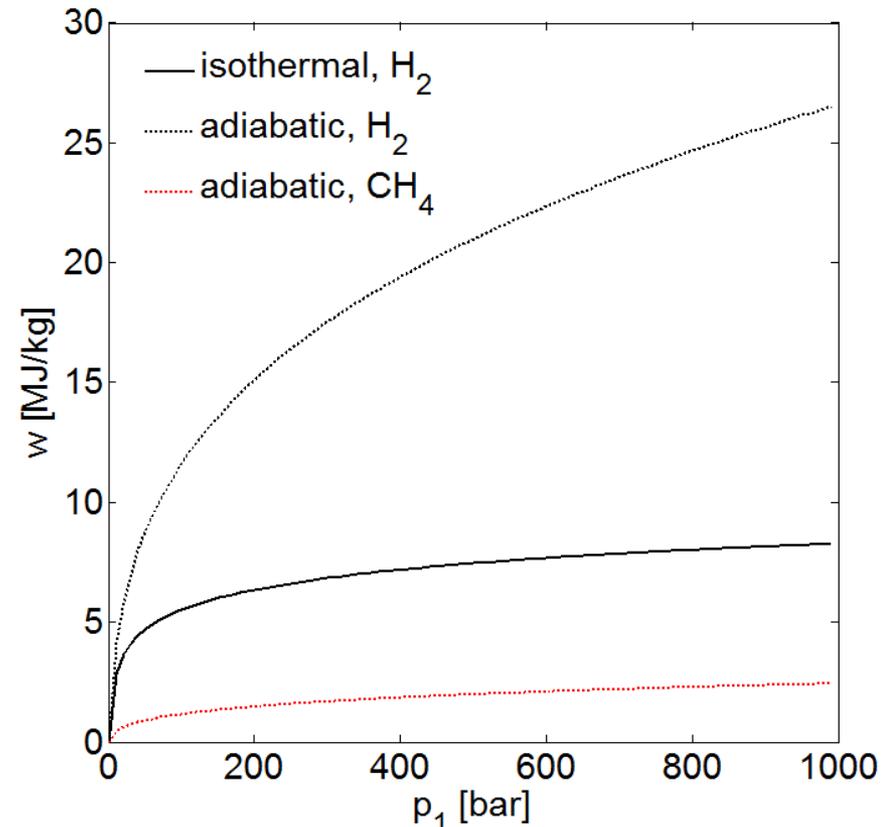   - Metal hydrides that can absorb and release hydrogen reversibly when temperature changes

- Compression:

  - Ideal isothermal compression:

  $$\frac{W}{m} = p_0 v_0 \ln\left(\frac{p_1}{p_0}\right)$$

  - Adiabatic compression:
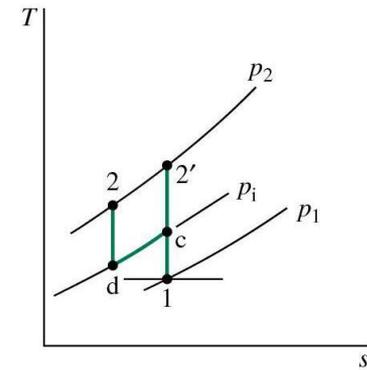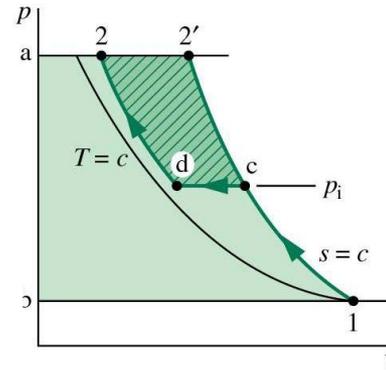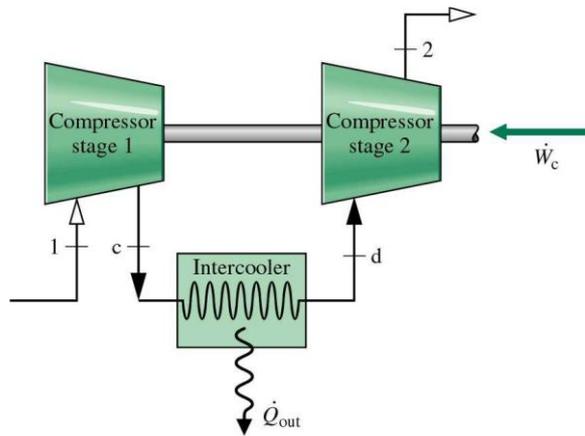
  $$\frac{W}{m} = \frac{1}{\gamma - 1} p_0 v_0 \left(\left(\frac{p_1}{p_0}\right)^{\frac{\gamma - 1}{\gamma}} - 1\right)$$

  Ratio of specific heats = c_p/c_v
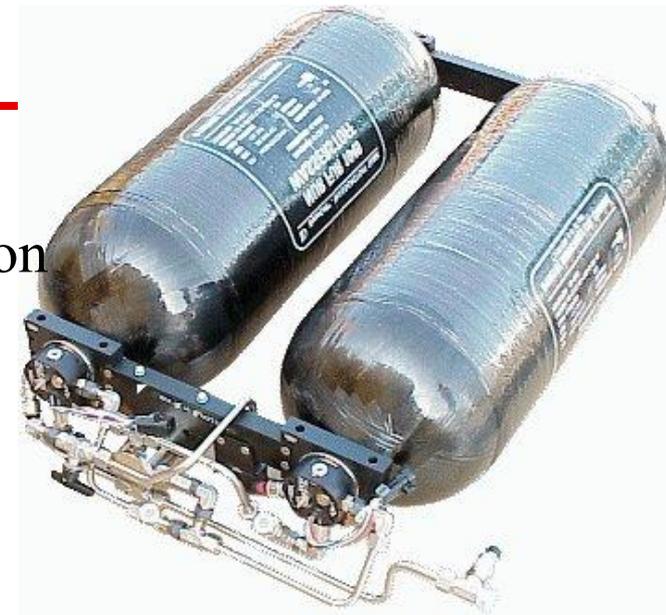 = 1.41 for hydrogen at 300 K

- Reality

  - Multi-stage compression with intercooling

Storage

- Compression:
  - Quantity of interest gravimetric concentration
  - Described by performance factor:

$$PF = \frac{p_{burst}V}{m_{container}}$$

- Mass of the container is proportional to maximum pressure (just below bursting)
- Only way to improve *PF* is finding better materials
- Currently small quantities are stored in steel pressure cylinders up to 150 bar (e.g. in laboratories), weight 90 kg, *PF* around 250'000 J/kg
- A 500 liter container at 150 bar holds ca. 6 kg of hydrogen which corresponds to 20 liters of gasoline (FC have double efficiency than IC)

Storage

- Compression:
  - For very large scale storage: underground formations (aquifers, mines, exhausted natural gas deposit, etc.)

  - Large scale storage in transport pipeline:

    1000 km long, 1.2 m diameter at 60 atm

    $\rightarrow$ 1000 TJ (~23 mio liters gasoline)

- Compression technology

- Mechanical: **volume flow** for H_2 is confined by a displacement device
  1. reciprocating piston
  2. diaphragm
  3. linear (magnetic)
  4. ionic liquid
- Non-mechanical : specifically designed for H_2 application
  1. cryogenic
  2. electrochemical (**mass flow**)
  3. adsorption (thermal)
 4. metal-hydride (thermal)

- Liquification:
  - Cooling from 293 to 20 K, and condensation at 20 K and 1 atm, requires theoretically around 14 MJ/kg $H_{2,l}$

  - But no heat sinks at 20 K exists, multi-stage process needed:

Three-stage propane refrigeration system is used for cooling hydrogen gas from ambient temperature to about 170 K, followed by multistage nitrogen expansion to obtain 77 K, and a multistage helium compression–expansion to complete the liquefaction of hydrogen at 20.3 K and atmospheric pressure
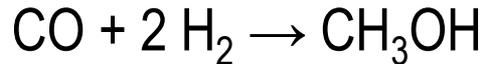
Storage

- Liquification:
  - Cooling from 293 to 20 K, and condensation at 20 K and 1 atm, requires theoretically around 14 MJ/kg $H_{2,l}$
  - Commercial production (Linde Gas AG) reports 54 MJ/kg

Bossel, 2006.
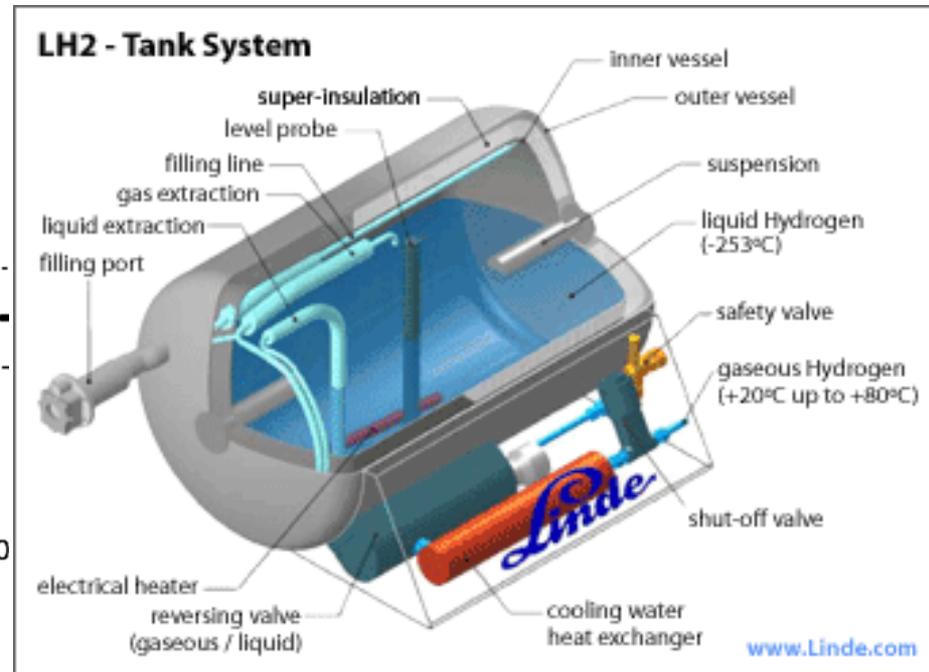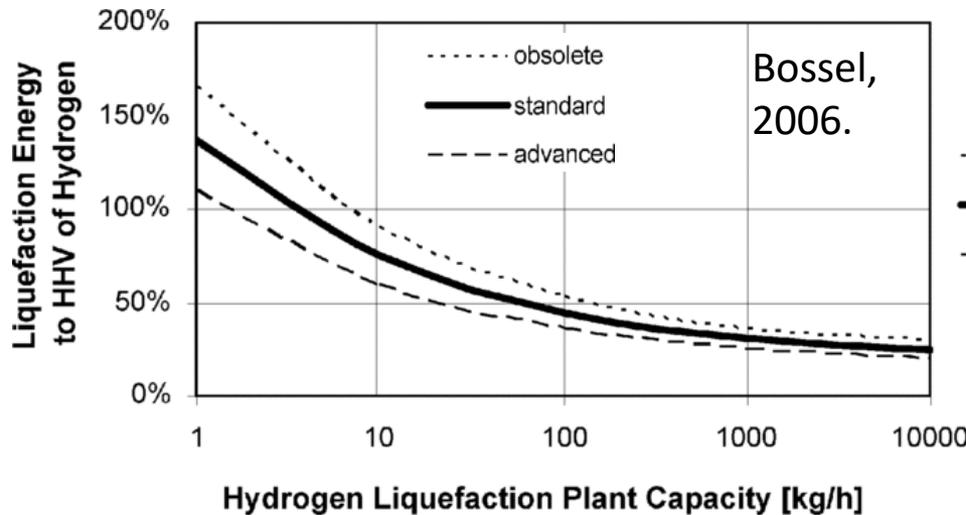
- Chemical:
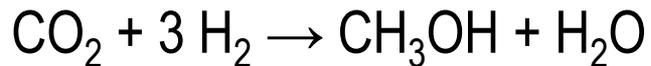 - Fischer-Tropsch synthesis: use of a catalyst to produce methanol (most widely used catalyst: mixture of Cu, ZnO, and Al_2O_3), At 50–100 bar and 250 °C

$$CO + 2\,H_2 \rightarrow CH_3OH$$

  - Methanol synthesis:

$$CO_2 + 3\,H_2 \rightarrow CH_3OH + H_2O$$

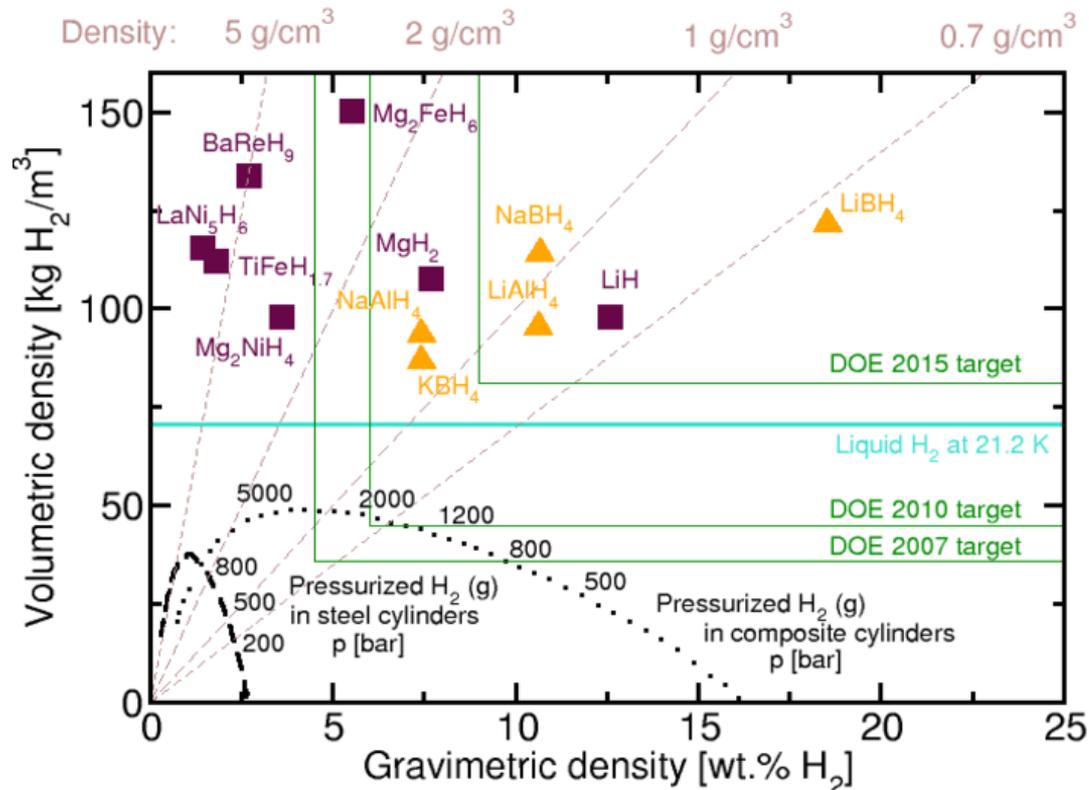 - Methanol: can be used in DMFC or ICE, already in liquid form

    Methanol as an energy vector?! But CO_2 has to come from the atmosphere

- Chemical:

  - Metal-hydrides (e.g. CaH_2, LiH): powdered metals absorb hydrogen under high pressures. With pressure release and applied heat, the process is reversed

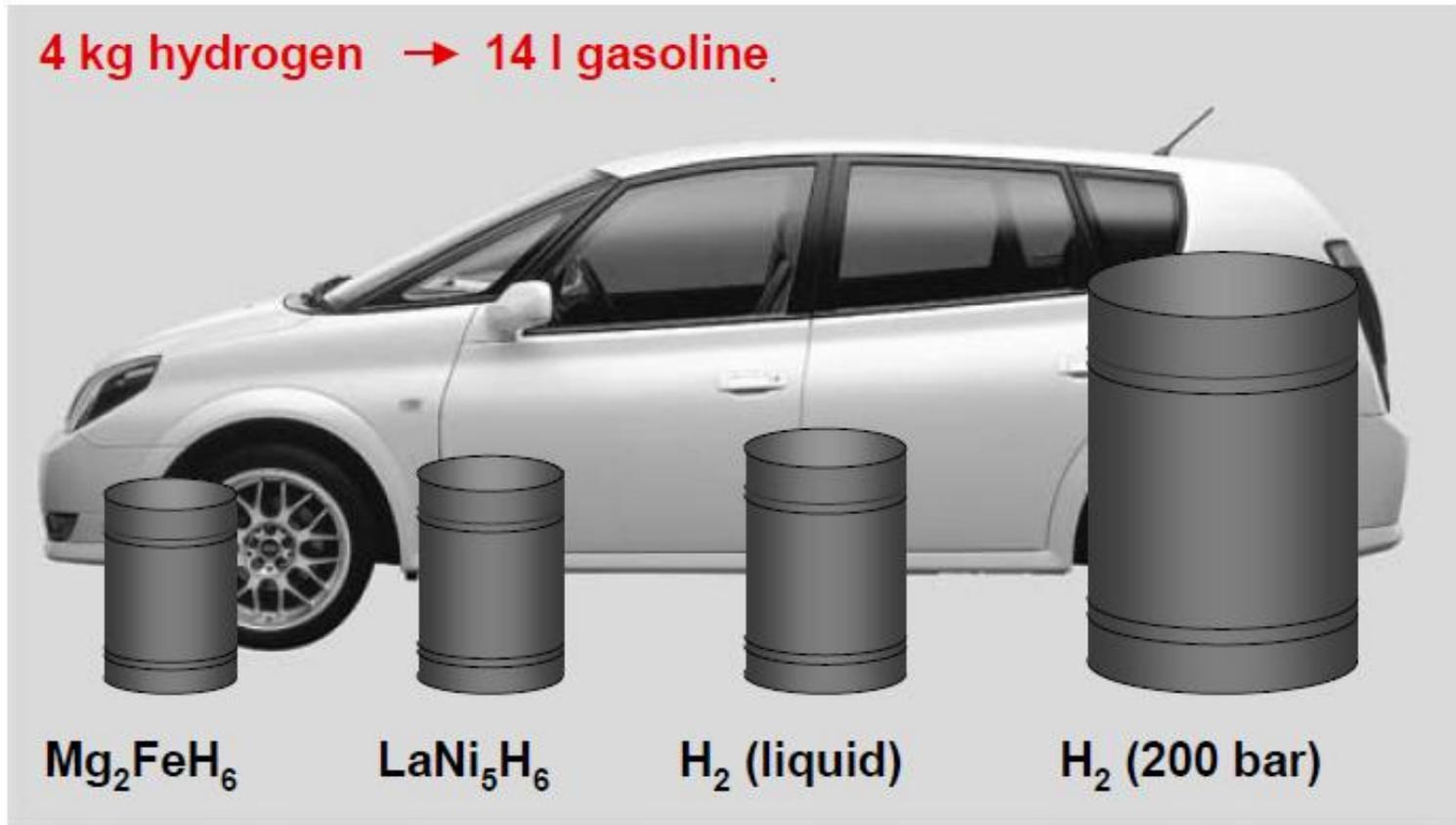 - Have a somewhat bad LCA, and energy intense for production
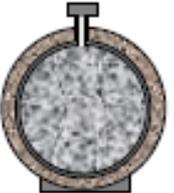

Krishna, 2012.

EPFL

- Comparison

8.6 l gasoline / 100 km = 1 kWh / km
3 l gasoline / 100 km = 0.36 kWh / km

4 kg hydrogen → 14 l gasoline

Mg_2FeH_6 $LaNi_5H_6$ H_2 (liquid) H_2 (200 bar)

Storage

- Comparison

Storage Media	Volume	Mass	Pressure	Temperature	
	max. 33 kg $H_2 \cdot m^{-3}$	13 mass%	800 bar	298 K	Composite cylind.
					established
	71 kg $H_2 \cdot m^{-3}$	100 mass%	1 bar	21 K	Liquid hydrogen
	20 kg $H_2 \cdot m^{-3}$	4 mass%	70 bar	65 K	Physisorption
	150 kg $H_2 \cdot m^{-3}$	2 mass%	1 bar	298 K	Metalhydrides
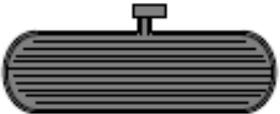
Renewable Energy

- Outline:

    Hydrogen as an energy vector:

    1. **Motivation**
    2. **Properties**
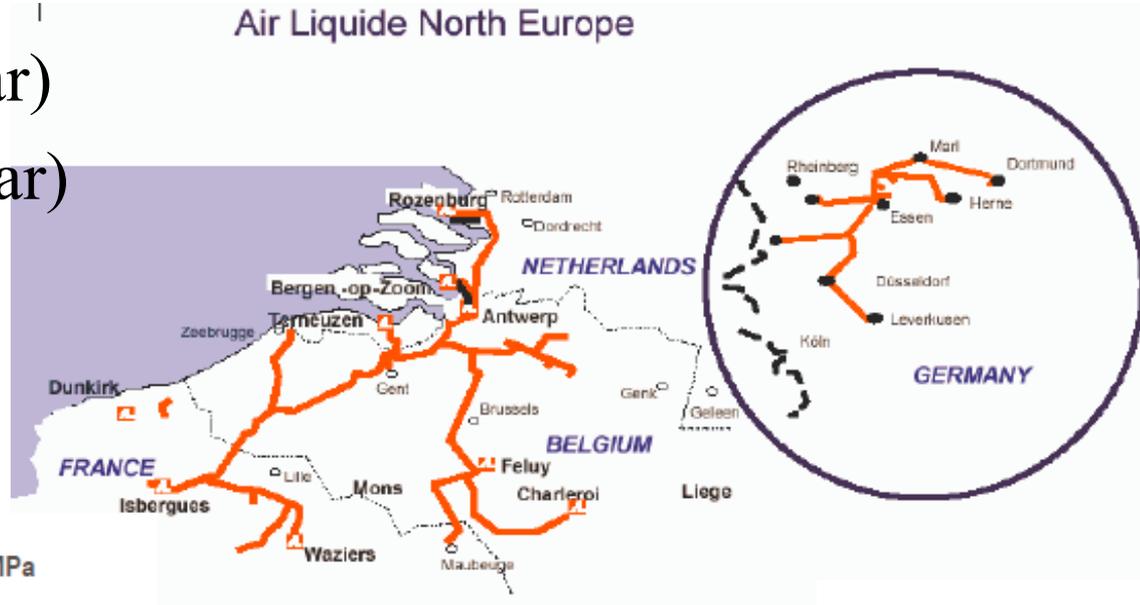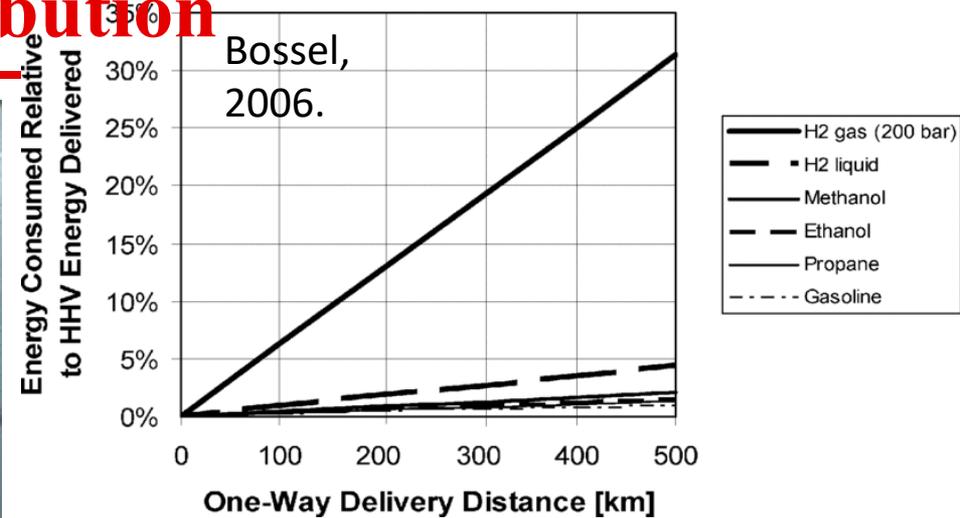   3. **Production**
    4. **Storage**
    5. **Distribution**
    6. **Application**

Distribution

- Liquid:
  - Ship
  - Truck

Bossel, 2006.

Energy Consumed Relative to HHV Energy Delivered vs. One-Way Delivery Distance [km]

- H2 gas (200 bar)
- H2 liquid
- Methanol
- Ethanol
- Propane
- Gasoline

- Gas:
  - Pipeline (0.5-300 bar)
  - Bottles (up to 200 bar)

Air Liquide North Europe

Belgium-France-NL
H_2-Pipeline, Air Liquide

Air Liquide:
Belgium, France, NL   966 km   10 MPa

Germany:
Rhein-Ruhr Pipeline   240 km   1.1/ 2.3/ 30 MPa
[operative since 1938]
Leuna-Merseburg, Linde   100 km   2-2.5 MPa

Distribution

- Concept:

Fueling station:

Trucks with compressed
or liquid hydrogen:

On site generation:
By electrolysis and renewable
By fossil fuels

Piped hydrogen

Transportation services

- What about decentralized production, even in the car?

Distribution

- Hydrogen highway

40 "H2 pumps" on the Highway about 2000 km

Distribution

- Hydrogen highway

- 3 FC- busses in each city
- Different hydrogen Productions

Emerging Renewable Power

- Outline:

Hydrogen as an energy vector:

1. **Motivation**

2. **Properties**

3. **Production**

4. **Storage**

5. **Distribution**

6. **Application**

Applications

- In transportation/mobility:
  - Internal combustion:
    - No CO_2 emissions, no smog (sulfur-based, unburned hydrocarbons, CO), no particles, reduction in NO_x
    - Improved cold starting performance
    - Efficiency similar or slightly higher (higher diffusivity, uniform fuel-air mixtures, minimal ignition energy lower, wide flammability allows to work from lean to stoichiometric mixtures, high ignition temperatures allows to use higher compression ratio)

  - Fuel cells
    - No CO_2 emissions, no smog, no particles, no NO_x
    - Improved cold starting performance
    - No noise
    - Higher efficiencies (not limited by Carnot)
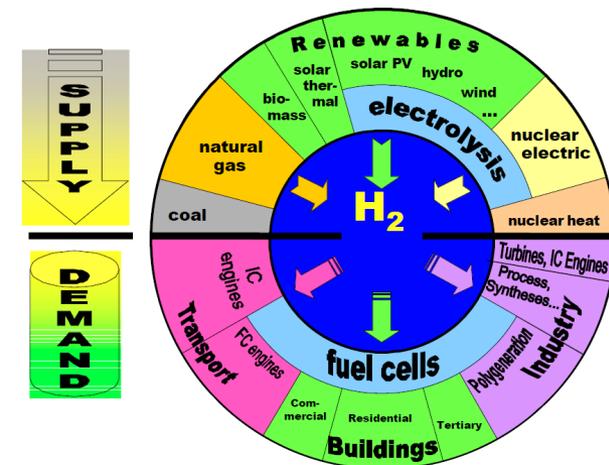
Applications

- Residential heating : natural gas network admixing, and/or hydrogen pipelines
- Industry:
  - industry heating: replacing coal, natural gas
  - industry feedstock:
    - » Refineries
    - » ammonia, methanol, other industries
    - » steel making

Learning outcomes of todays lecture

- Hydrogen as an energy vector
  - What is hydrogen and what makes it special
  - Why using hydrogen as an energy vector, alternatives
  - How can hydrogen be generated, how renewable
  - How can hydrogen be stored
  - How can hydrogen be transported/distributed
  - Where and how is hydrogen used as an end product

Additional literature

- Da Rosa: Fundamentals of Renewable Energy Processes, Elsevier, 2005.

- Grimes, Varghese, Ranjan: Light, Water, Hydrogen, Springer, 2008.