# Renewable Energy

- Outline:

**Hydrogen as an energy vector:**

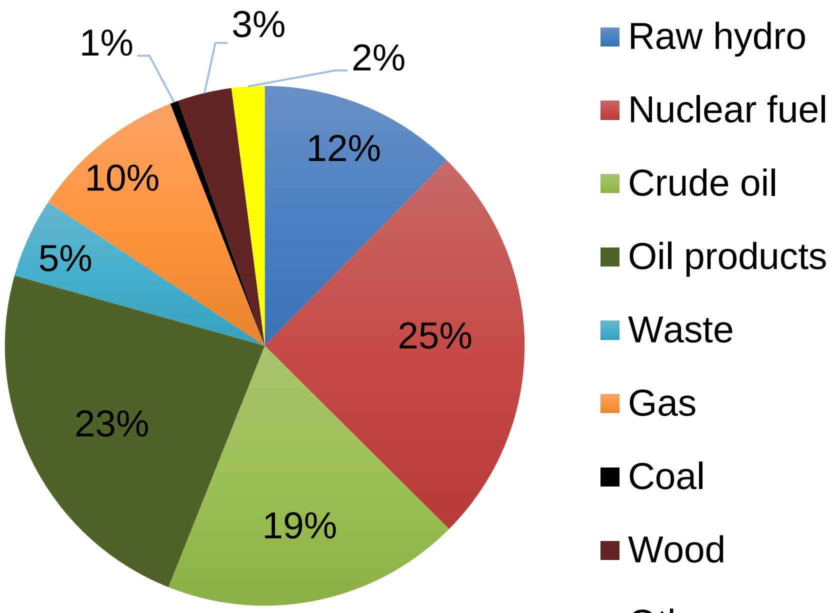
1. **Motivation**
2. **Properties**
3. **Production**
4. **Storage**
5. **Distribution**
6. **Application**

# Learning outcomes of todays lecture

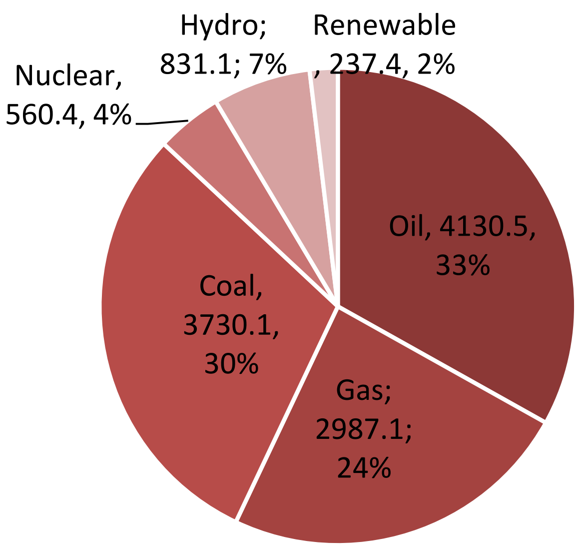
- Hydrogen as an energy vector
  - What is hydrogen and what makes it special
  - Why using hydrogen as an energy vector, alternatives
  - How can hydrogen be generated, how renewable
  - How can hydrogen be stored
  - How can hydrogen be transported/distributed
  - Where and how is hydrogen used as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

# Motivation

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

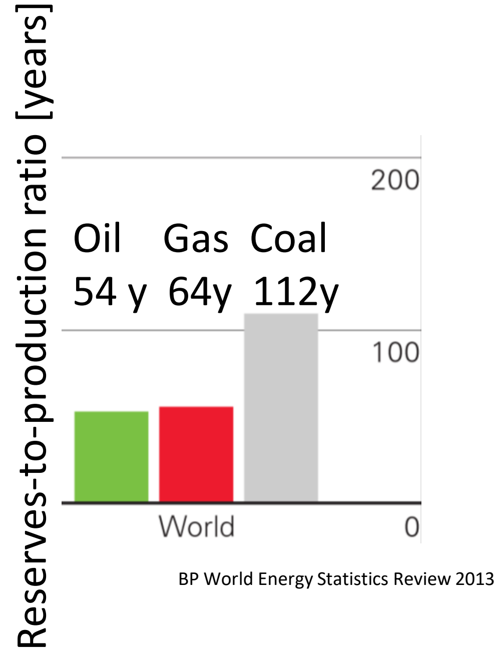



  - Global: 87% (oil, coal, gas)

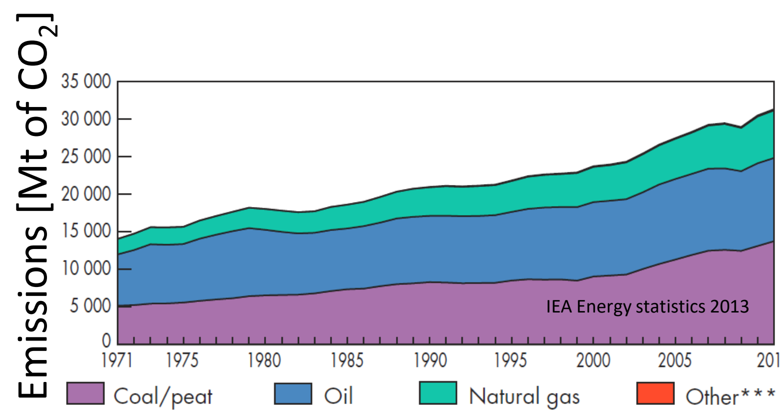


# Motivation

- 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), ozone layer depletion
    - Climate change: temperature, precipitation, snow cover, sea level, etc.*



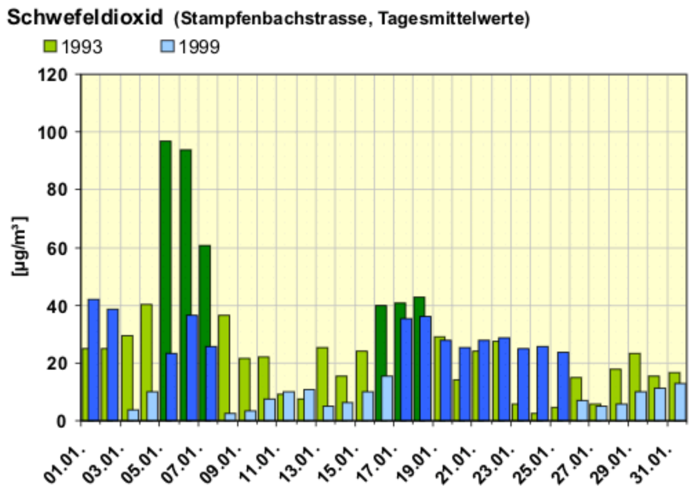

*See IPCC report: https://www.ipcc.ch/report/ar5/

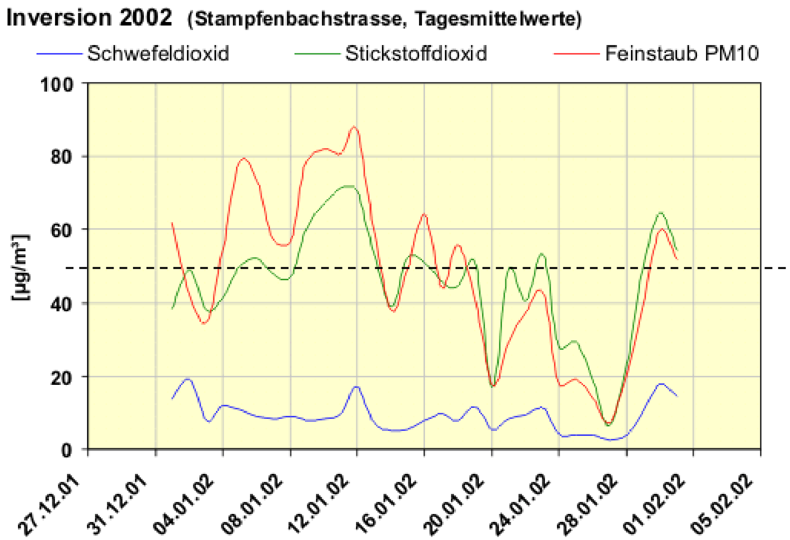



  - Geopolitical tensions over resources (security)

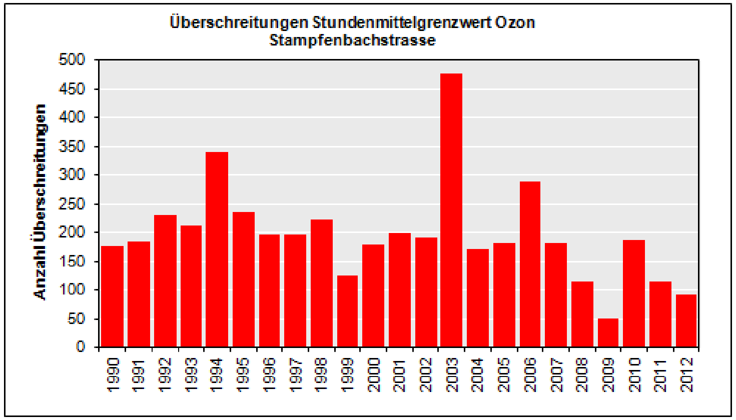
# Motivation

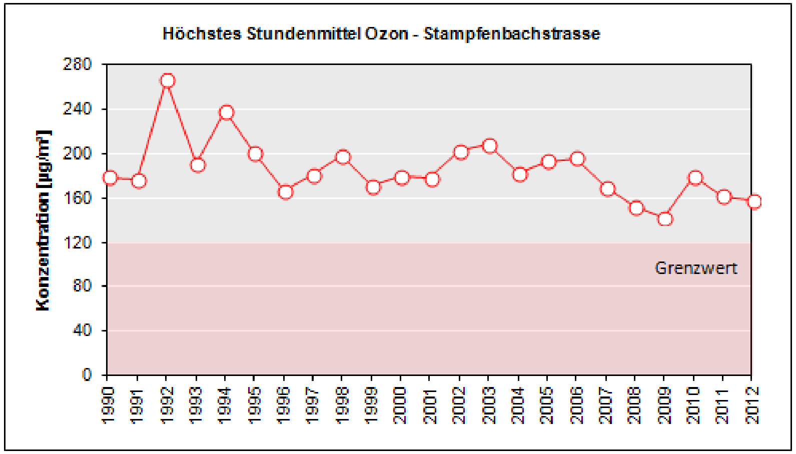
- Winter smog in Zürich:




- 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

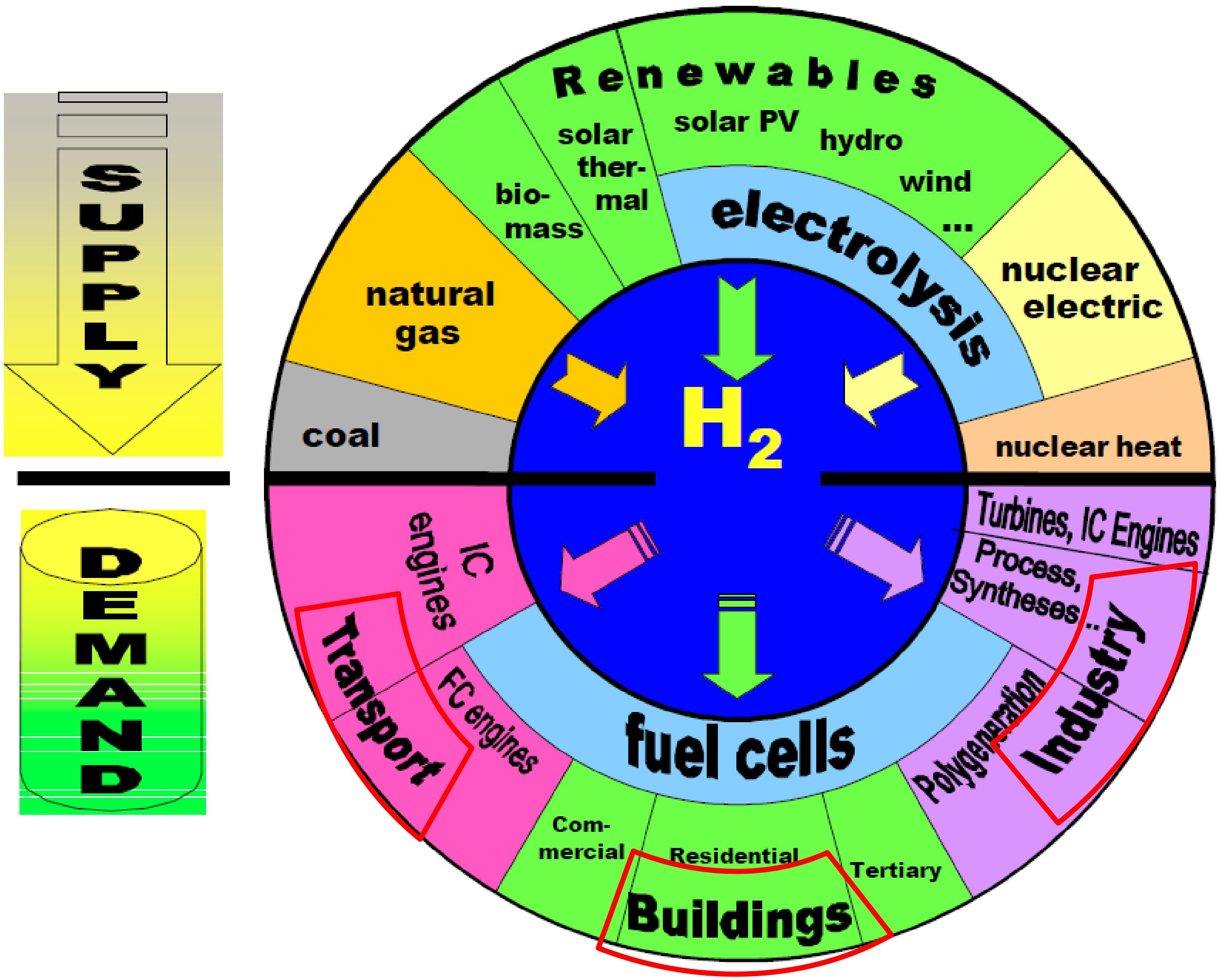
| Energy vector | Transfer attitude | Storage attitude |
|---|---|---|
| Fossil fuels | Short, medium, long range | Yes, short, medium, long term. |
| Hydrogen | Short, medium, long range | Yes, short, medium, long term. (Cryogenic exception) |
| Heat exchanging fluids | Short range | Yes, short term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

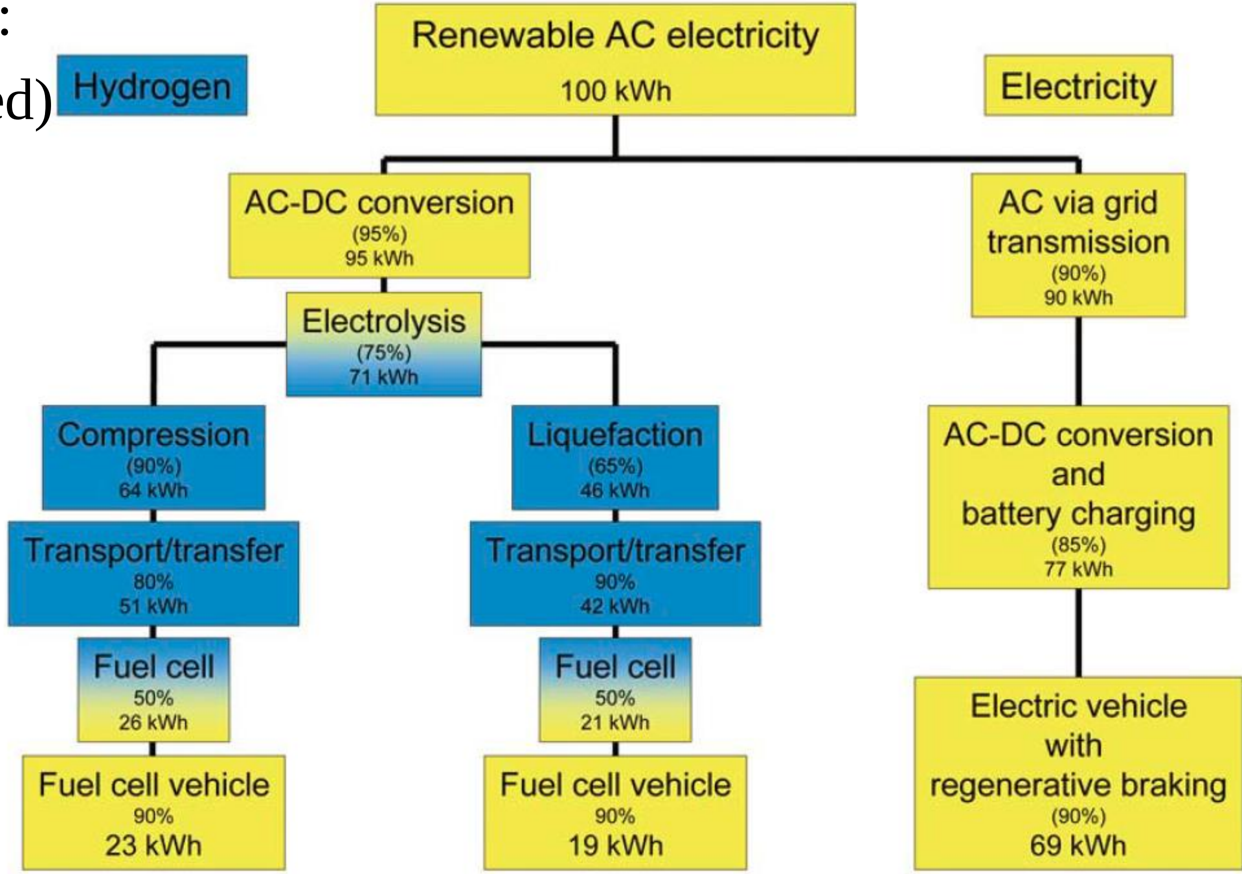
# Motivation




- 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)

- Outline:

## Hydrogen as an energy vector:

1. **Motivation**
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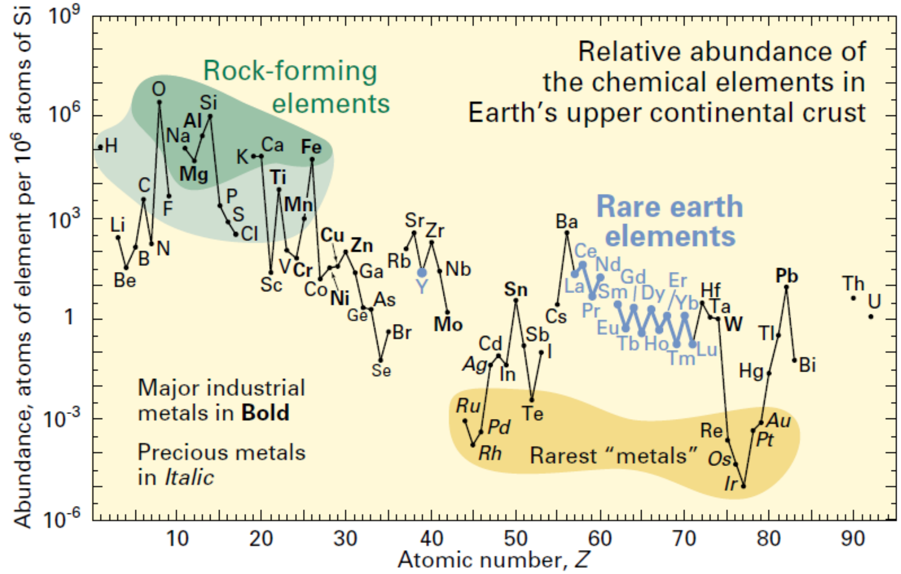
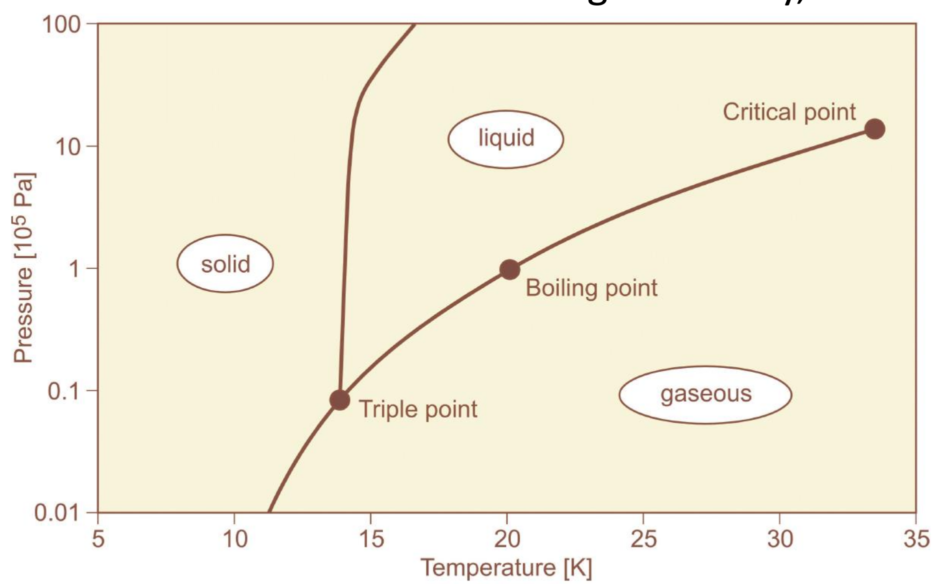
# Hydrogen properties

- 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·$10^{-5}$ 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

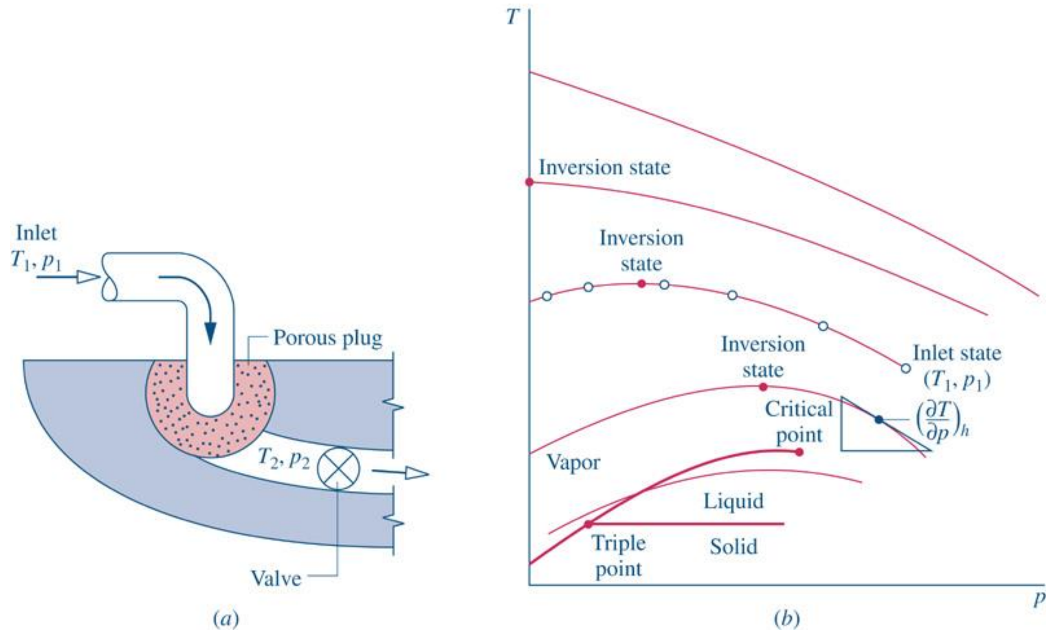


# Hydrogen properties

- 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

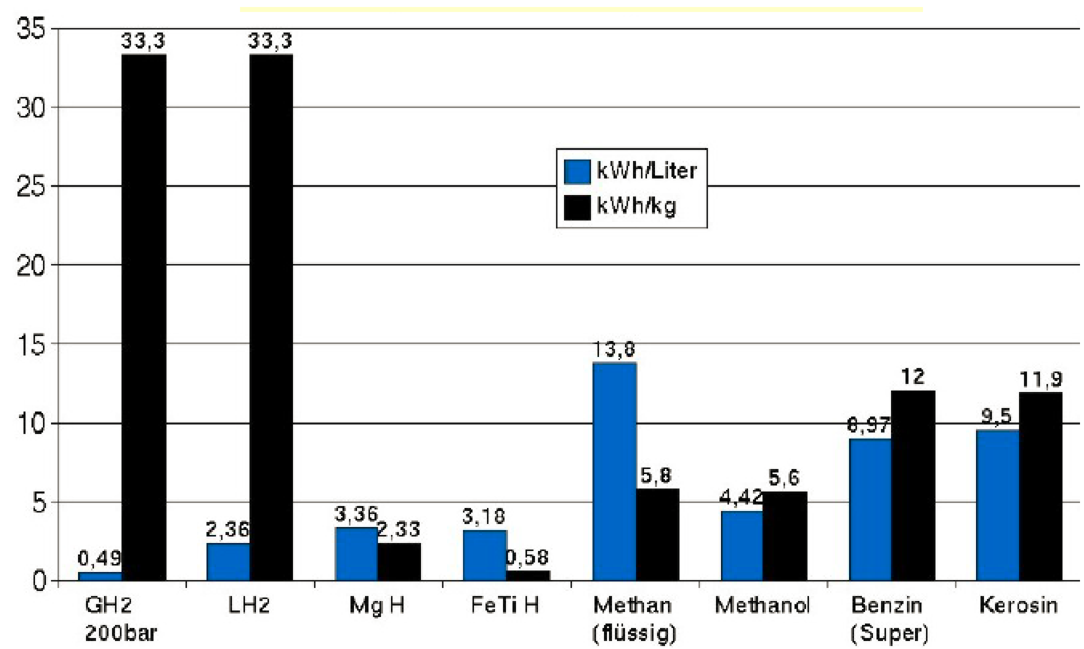



Moran and Shapiro, 2012.

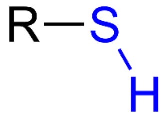
# Hydrogen properties

- 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 ( 

) can be added (already done for natural gas)

# Hydrogen properties

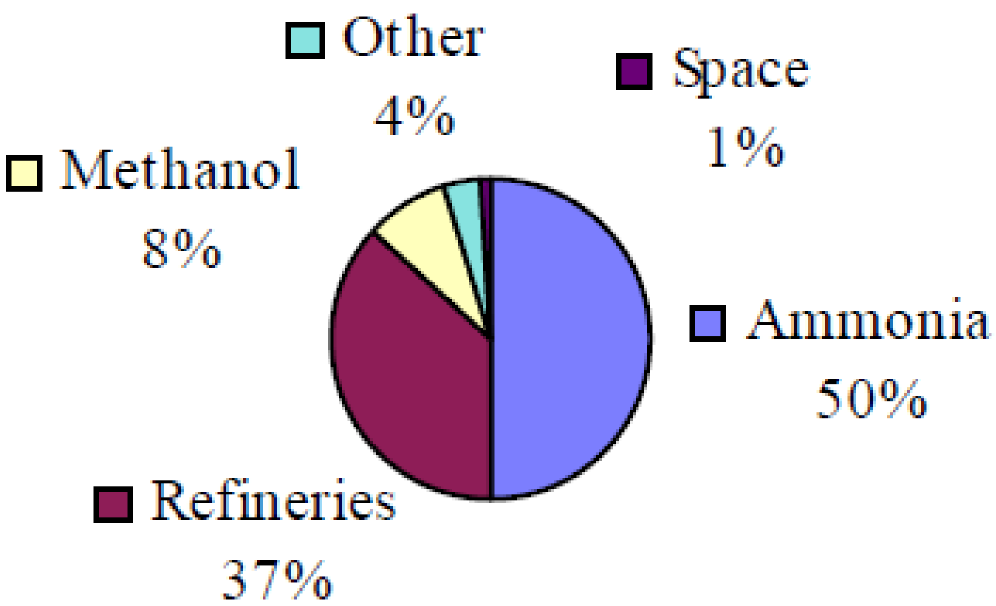
- Properties in comparison to other gases and liquids:

| 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 ~55 mio tons and used for:



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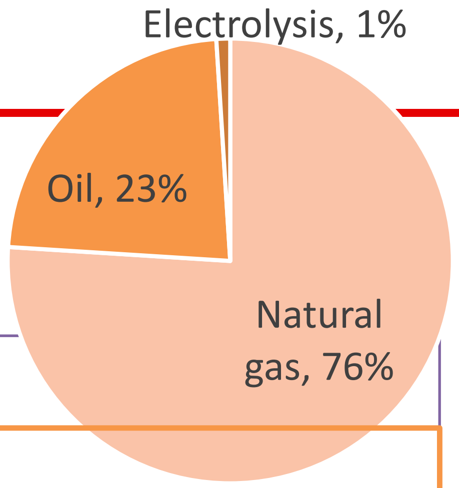
# Production



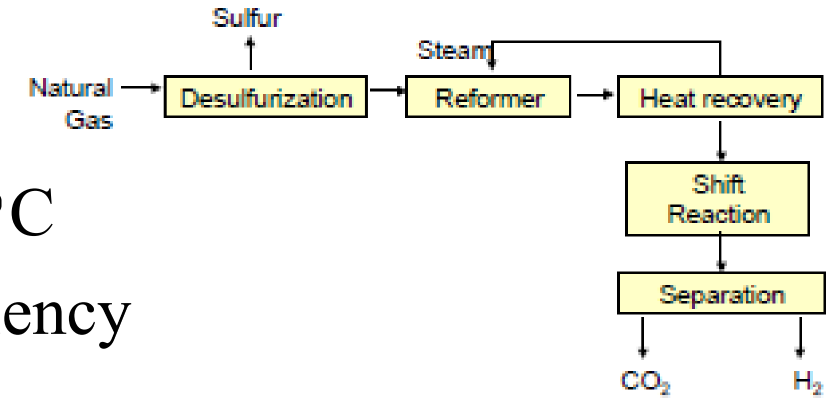

- Production of hydrogen:

| 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

$$CH_4 + H_2O \rightarrow CO + 3H_2 \quad (\Delta H = 206 \text{ kJ/mol})$$



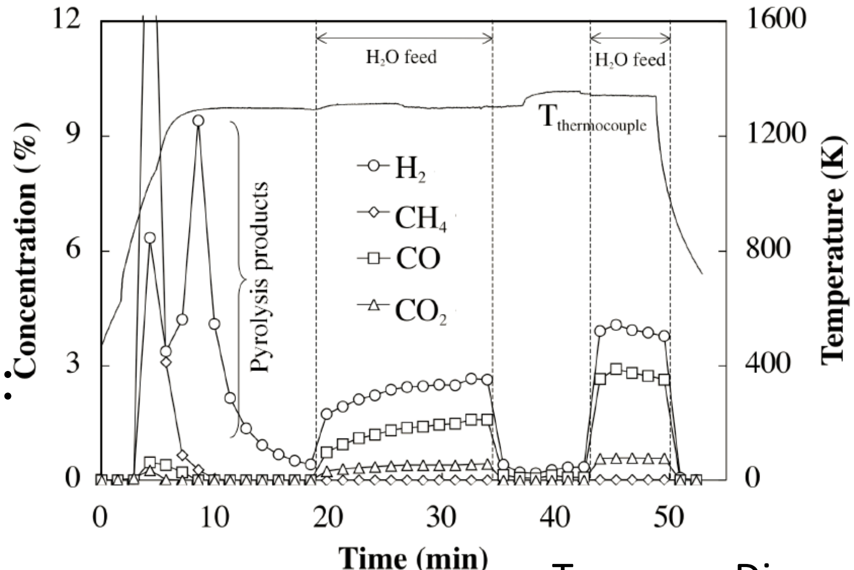

  - Operates around 700 – 925°C
  - Can achieve 65 – 75% efficiency

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

$$CH_4 \longrightarrow C + 2H_2 \ (\Delta H = 74.85 \text{ kJ/mol})$$

# Production

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

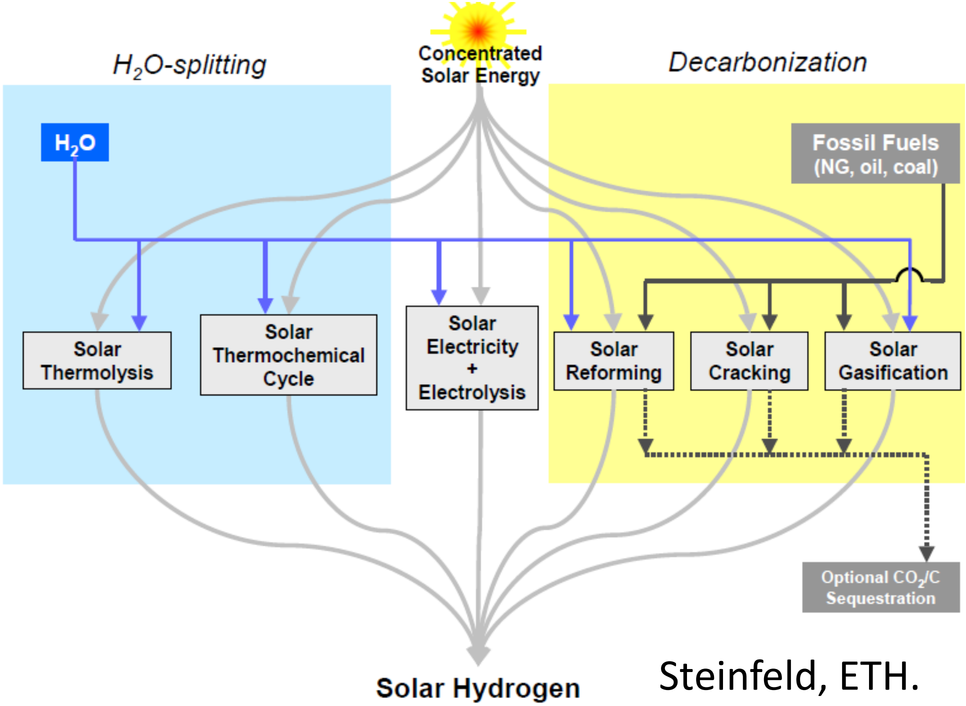
- Purification:
  - Desulfurization for gaseous feedstock: calcium-based slurries ($SO_2$ to sulfites and sulfates)
  - Desulfurization from solid/liquid feedstock: via catalysts into $H_2S$
  - $CO_2$ removal:
    - temperature swing adsorption (solubility variation of $CO_2$ with temperature)
    - 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)

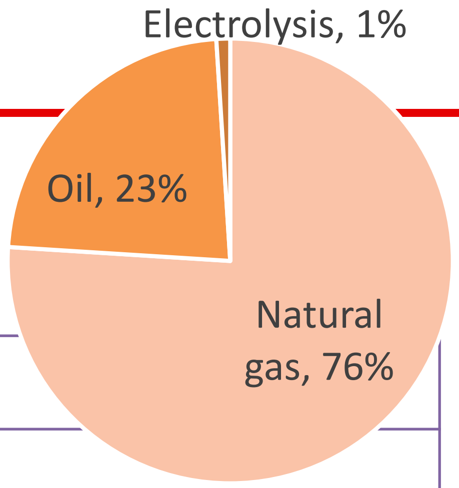
Combustion: $C_xH_y + (x+y/4)O_2 \rightarrow xCO_2 + y/2H_2O$

  - Any other heat source such as solar or nuclear:




Steinfeld, ETH.

# Production

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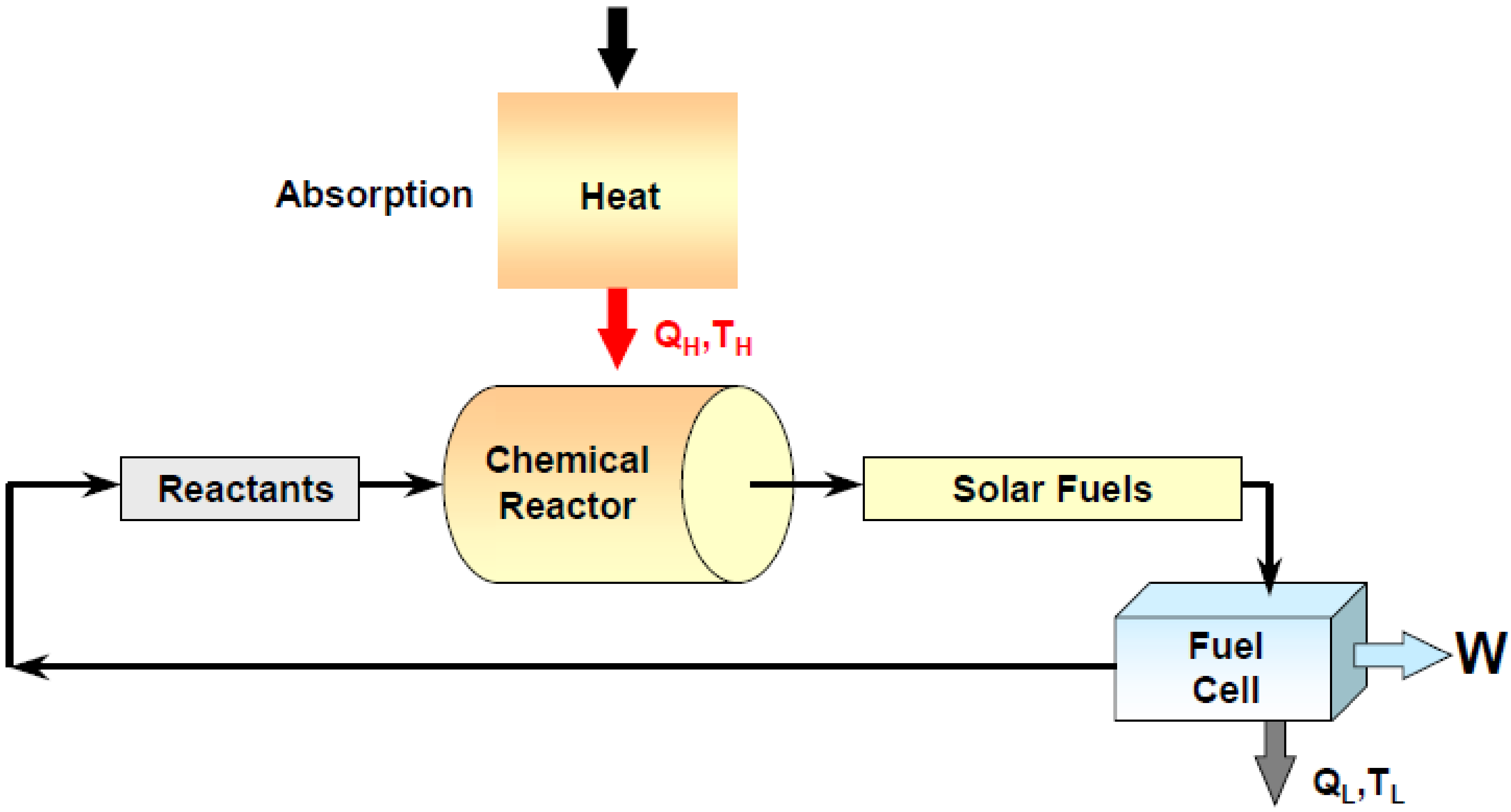
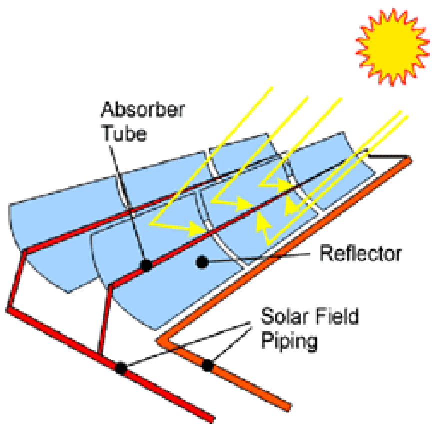
# Production

- Thermal and thermochemical approaches:

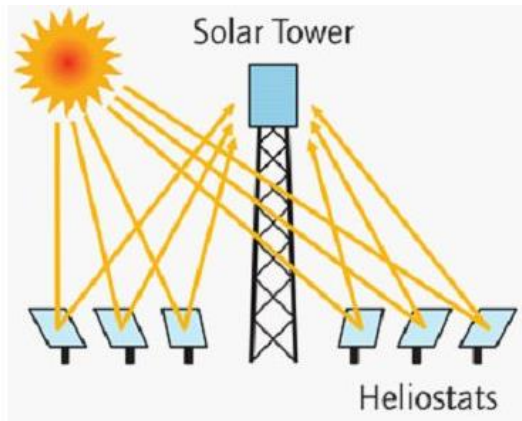


# Production

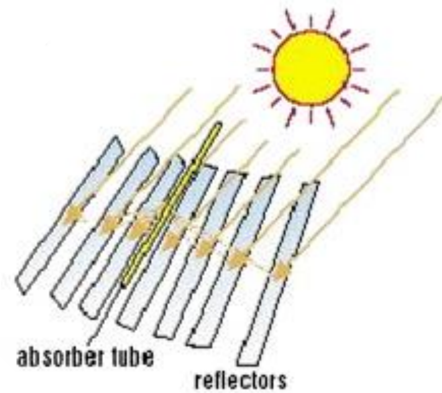
- Thermochemical cycles – solar: concentrating technologies



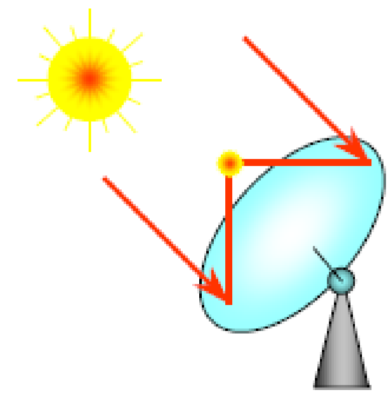

Parabolic through




Solar tower




Fresnel

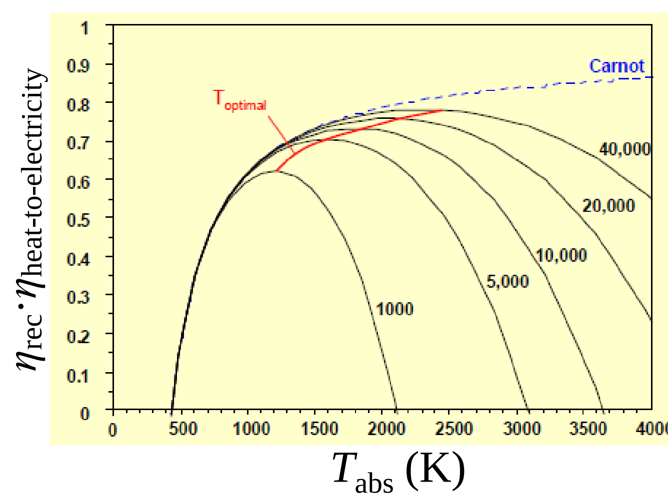


Dish

- Temperatures reachable:

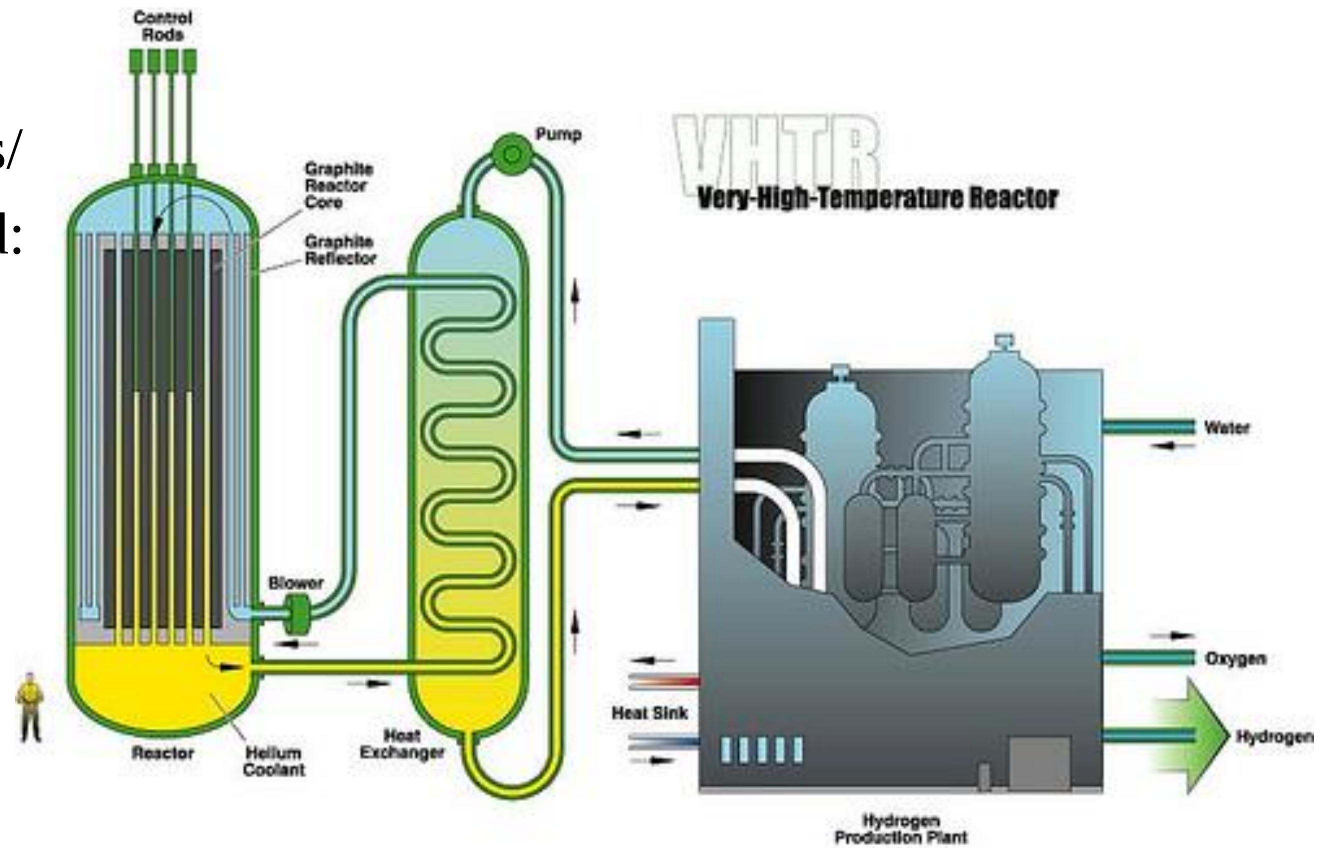
$$\eta_{\mathrm{rec}} = \frac{q_{\mathrm{use}}}{q_{\mathrm{sol,in}}} = \frac{q_{\mathrm{use}}}{CI} = \alpha - \sigma\varepsilon \frac{T_{\mathrm{abs}}^4 - T_{\mathrm{amb}}^4}{CI}$$

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



# Production

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

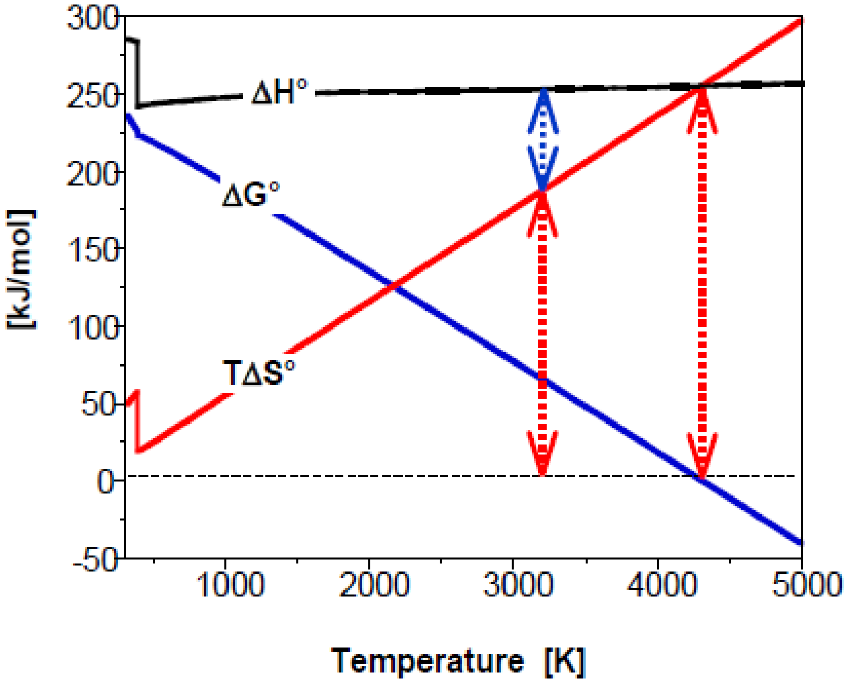


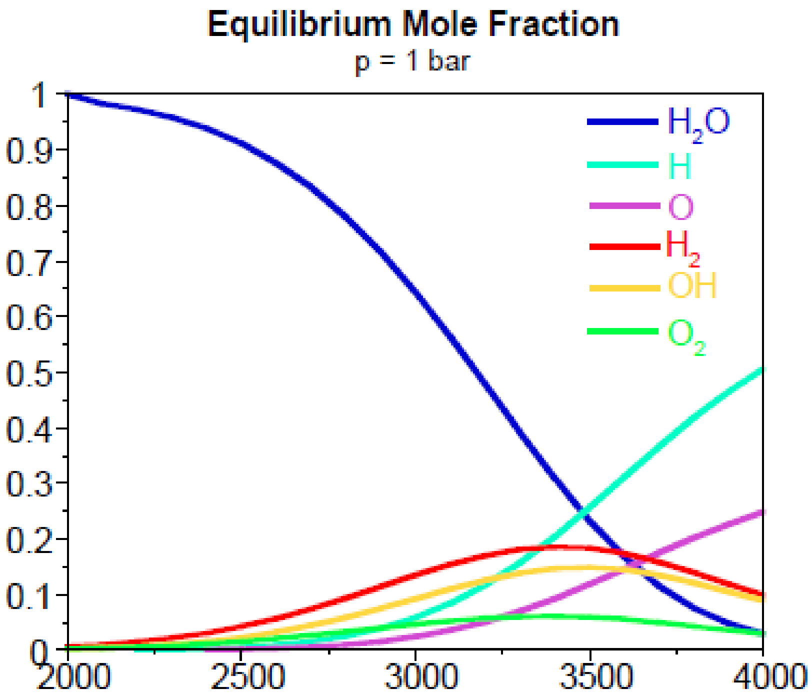

  - Compared to solar: limited in temperature (1573 K)

# Production

- Thermal dissociation:

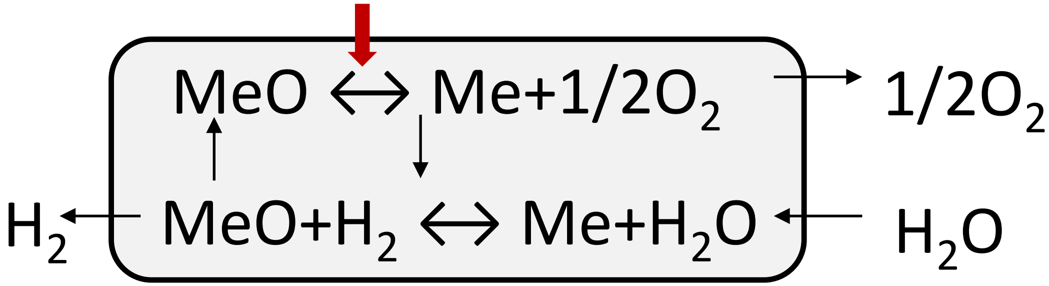
$$H_2O \rightarrow 1/2O_2 + H_2$$



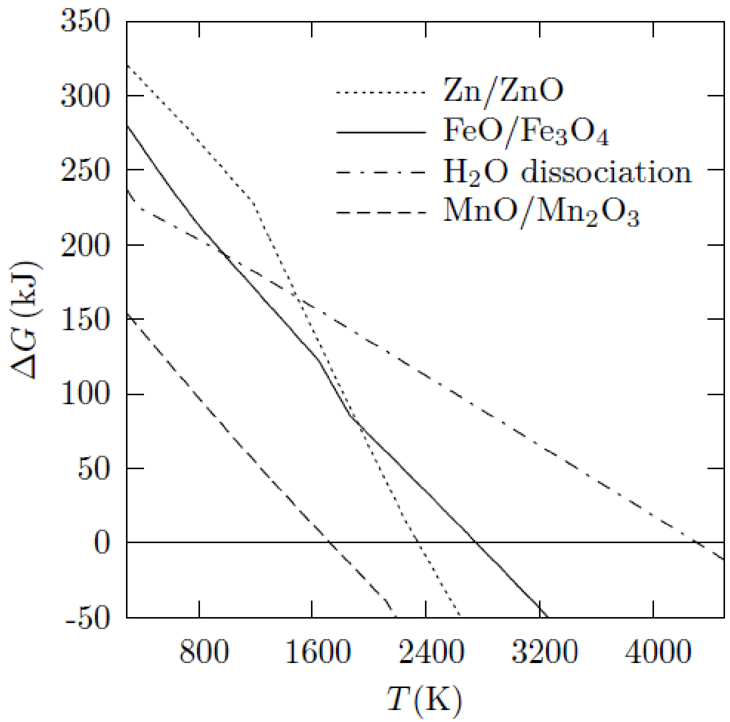



# Production

- Multi-step water-splitting cycles




- reduce required temperatures
- omit explosive $H_2/O_2$ mixture



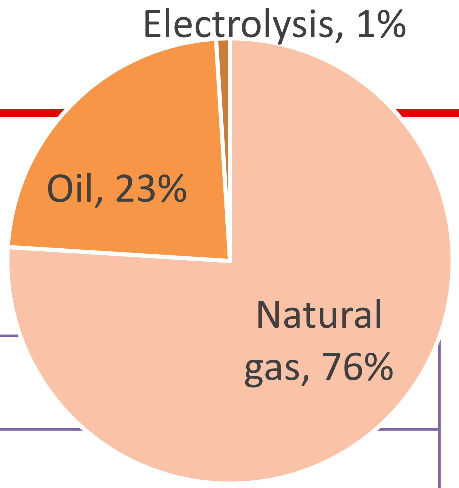
# Production

- Possible redox pairs for two-step cycles:

| Cycle | Reactions | Cycle | Reactions |
|---|---|---|---|
| Zn/ZnO | $ZnO \rightarrow Zn + O_2$ | $SoO_2/SiO$ | $SiO_2 \rightarrow SiO + 1/2\ O_2$ |
| | $Zn + H_2O \rightarrow ZnO + H_2$ | | $SiO + H_2O \rightarrow SiO_2 + H_2$ |
| $Fe_3O_4/FeO$ | $Fe_3O_4 \rightarrow 3\ FeO + ½\ O_2$ | $W/WO_3$ | $WO_3 \rightarrow W + 3/2\ O_2$ |
| | $3\ FeO + H_2O \rightarrow Fe_3O_4 + H_2$ | | $W + 3H_2O \rightarrow WO_3 + 3H_2$ |
| $In_2O_3/In_2O$ | $In_2O_3 \rightarrow In_2O + 1/2\ O_2$ | Hg/HgO | $Hg + H_2O \rightarrow HgO + H_2$ |
| | $In_2O + 2H_2O \rightarrow In_2O_3 + 2H_2$ | | $HgO \rightarrow Hg + 1/2O_2$ |
| $SnO_2/Sn$ | $SnO_2 \rightarrow Sn + O_2$ | Cd/CdO | $Cd + H_2O \rightarrow CdO + H_2$ |
| | $Sn + 2H_2O \rightarrow SnO2 + 2H_2$ | | $CdO \rightarrow Cd + 1/2O_2$ |
| $MnO/MnSO_4$ | $MnSO_4 \rightarrow MnO + SO_2 + 1/2O_2$ | $CO/CO_2$ | $CO + H_2O \rightarrow CO_2 + H_2$ |
| | $MnO + H_2O + SO_2 \rightarrow MnSO_4 + H_2$ | | $CO_2 \rightarrow CO + 1/2O_2$ |
| $FeO/FeSo_4$ | $FeSO_4 \rightarrow FeO + SO_2 + 1/2O_2$ | $Ce_2O_3/CeO_2$ | $CeO_2 \rightarrow Ce_2O_3$ |
| | $FeO + H_2O + SO_2 \rightarrow FeSO_4 + H_2$ | | $Ce_2O_3 + H_2O \rightarrow 2CeO_2 + H_2$ |
| $CoO/CoSO_4$ | $CoSO_4 \rightarrow CoO + SO_2 + 1/2O_2$ | Mg/MgO | $MgO \rightarrow Mg + 1/2O_2$ |
| | $CoO + H_2O + SO_2 \rightarrow CoSO_4 + H_2$ | | $Mg + H_2O \rightarrow MgO + H_2$ |
| $Fe_3O_4/FeCl_2$ | $Fe_3O_4 + 6HCl \rightarrow 3FeCl_2 + 3H_2O + 1/2O_2$ | SnO/SnO2 | $SnO_2 \rightarrow SnO + 1/2O_2$ |
| | $3FeCl_2 + 4H_2O \rightarrow Fe_3O_4 + 6HCl + H_2$ | | $SnO + H_2O \rightarrow SnO_2 + H_2$ |
| $Mo/Mo_2$ | $MoO_2 \rightarrow Mo + O_2$ | | |
| | $Mo + 2H_2O \rightarrow MoO_2 + 2H_2$ | | |

# Production

- Production of hydrogen:

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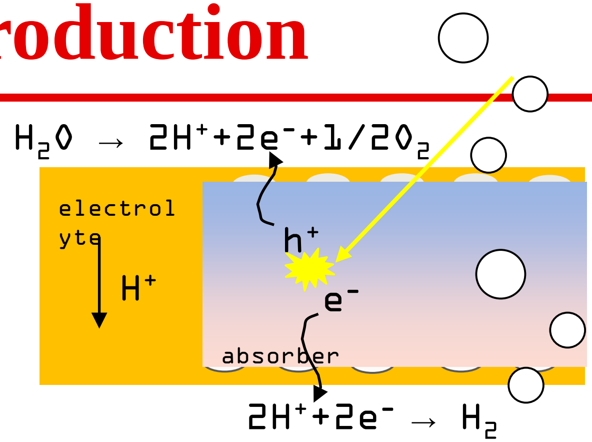
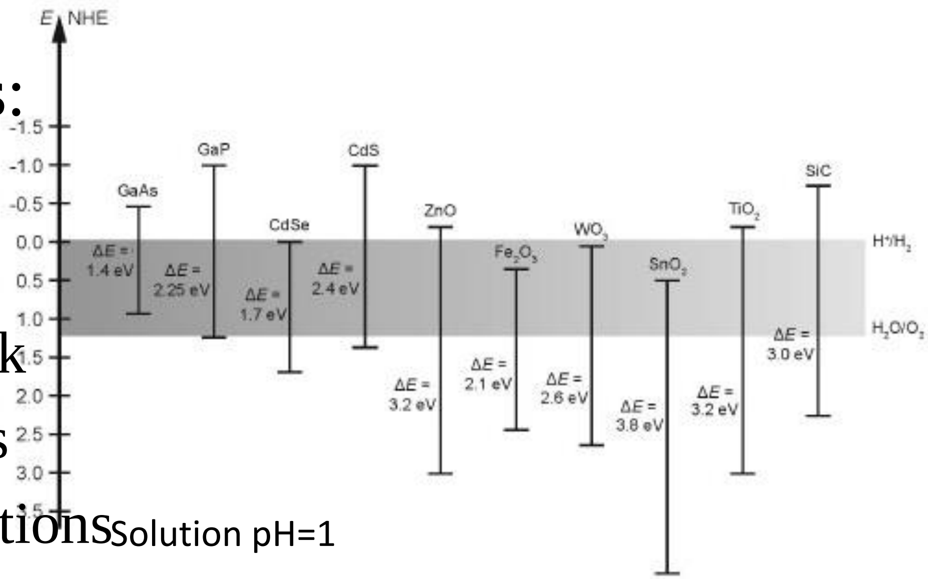
# Production

- Photoelectrochemical:

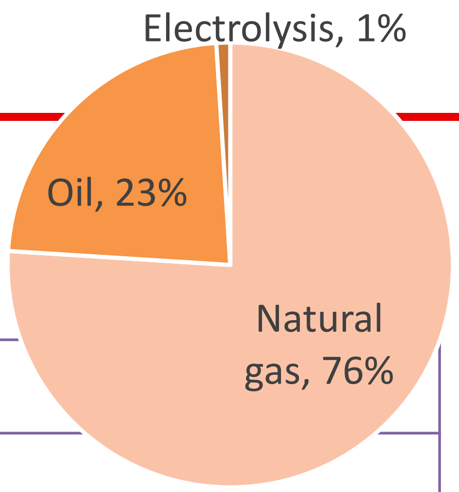



- Stringent material requirements:
  - band gap size
  - suitable band edge position
  - high chemical stability in the dark and under illumination, as well as under highly acidic or base conditions
  - efficient charge transport in the semiconductor
  - selective and efficient electrochemical reactions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




Solution pH=1

# Production



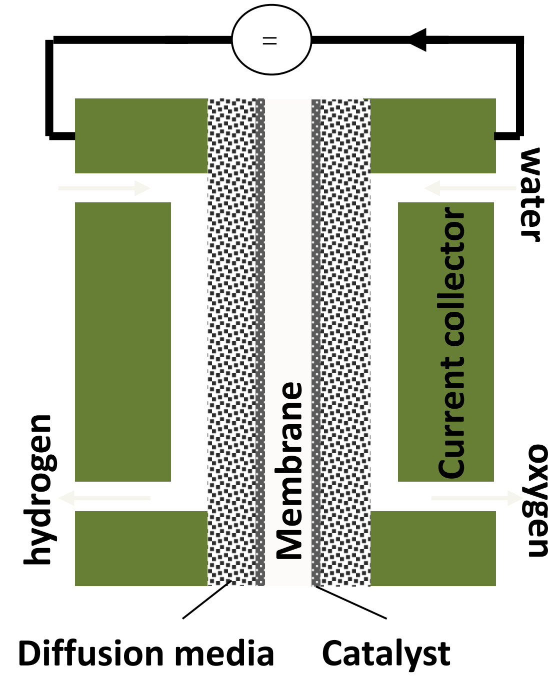

- Production of hydrogen:

| 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

- Electrolysis, e.g. SPE

$$H_2O \rightarrow 1/2O_2 + H_2 \ \ (\Delta G = 237 \text{ kJ/mol})$$




- At standard conditions (25 °C and 1bar)

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

- Practical:

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

Overpotential due to electrochemical reactions and ohmic losses

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

# 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

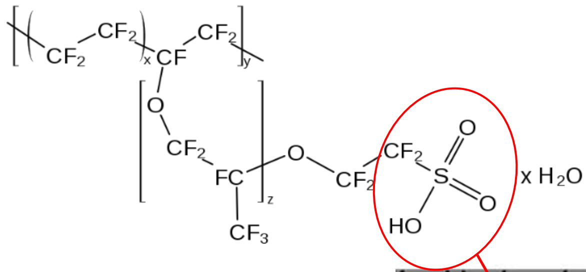
# Production

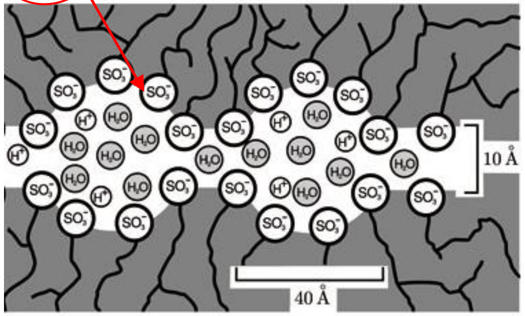
- Solid polymer electrolyzer: polymeric electrolyte

  PEM fuel cell:

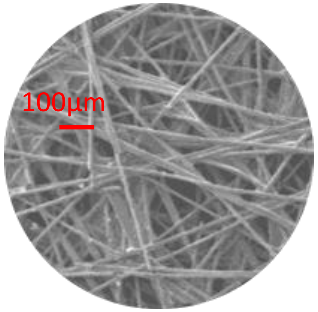
  Anode: $H_2O \rightarrow \frac{1}{2}O_2 + 2H^+ + 2e^-$ Cathode: $2H^+ + 2e^- \rightarrow H_2$

- 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



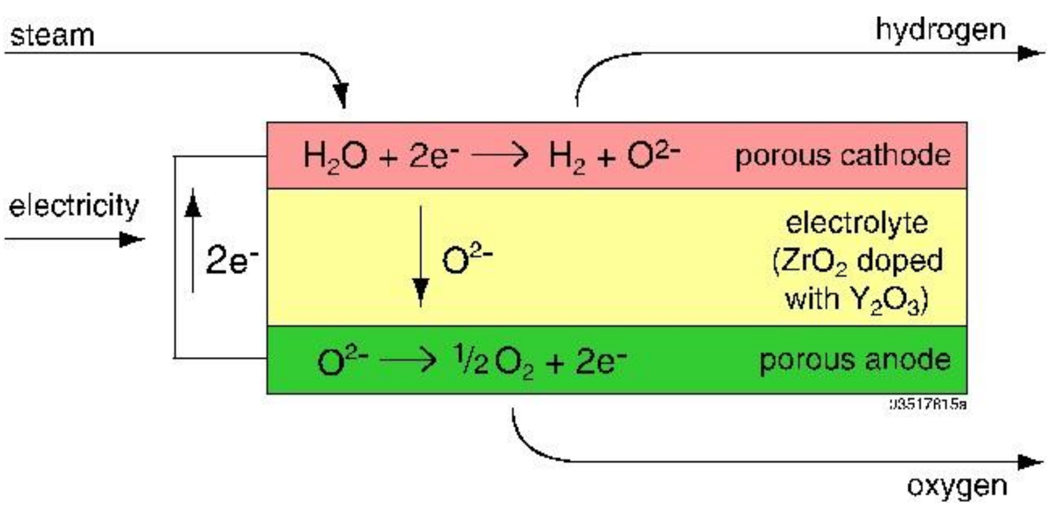

EPFL

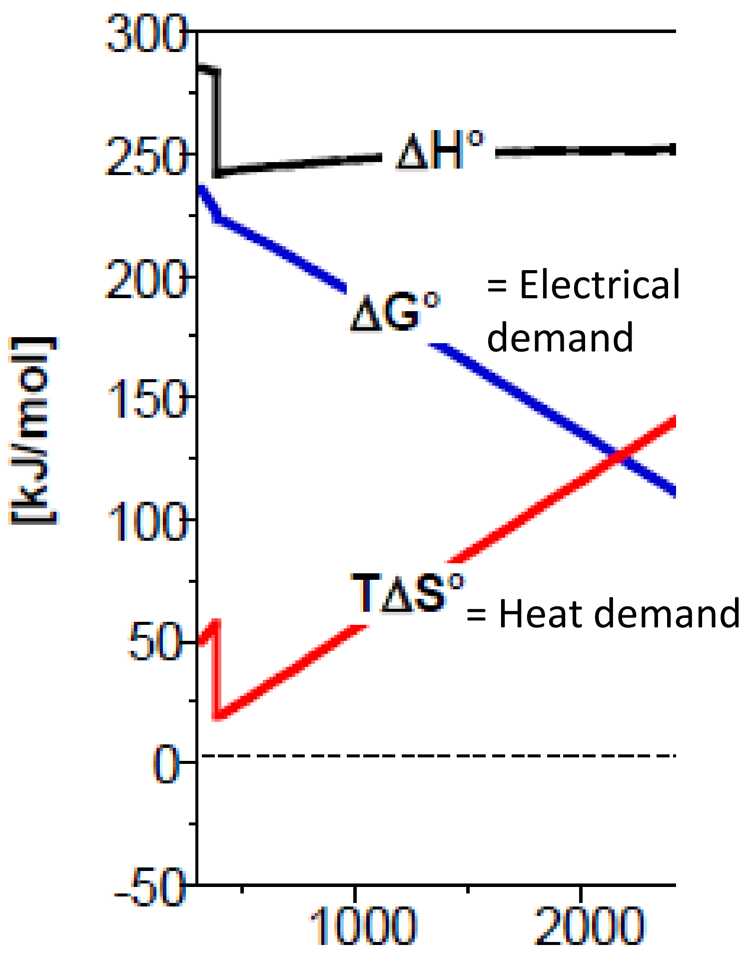
# Production

- Solid oxide electrolyzers: operate at very high temperatures (~700-1000°C)

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

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



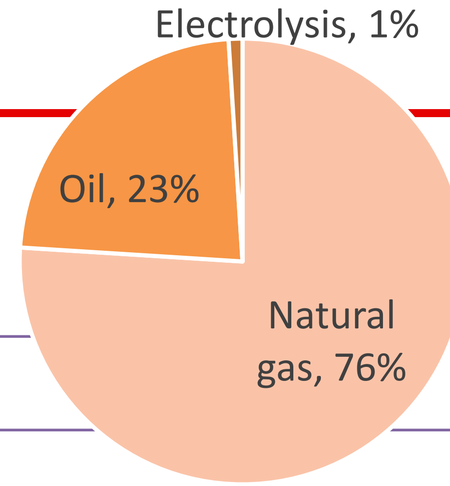



# Production

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

# Production

- Production of hydrogen:




| **Technology** | **Hydrogen source** | **Energy source** |
|---|---|---|
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| Photoelectrochemical | Water | Solar |
| Electrolysis | Water | Electricity from renewable, nuclear, fossil |

# Production

- Prize comparison:

**Table 2 – Cost of hydrogen production technologies.**

| 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] |

Abanades et al., IJHE, 38, 2013.

# Renewable Energy

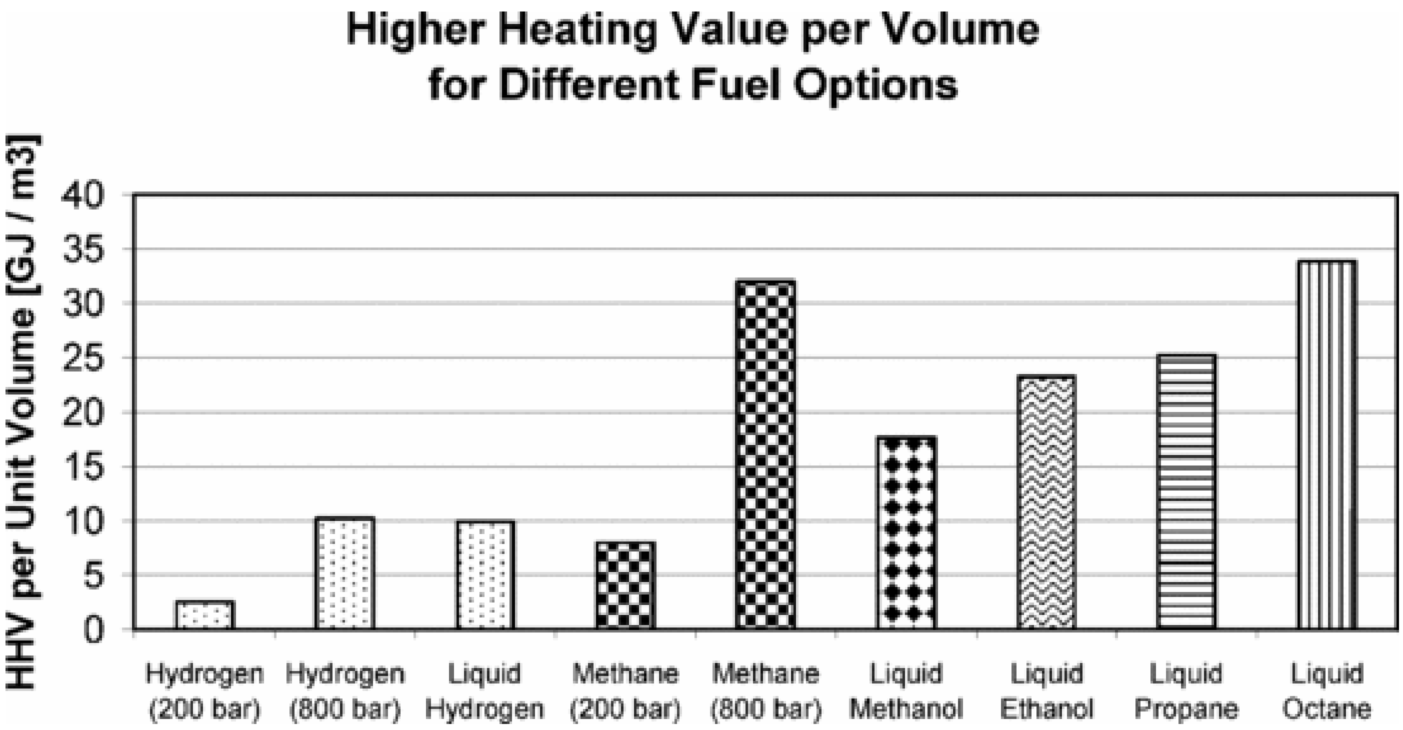
- Outline:

**Hydrogen as an energy vector:**

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

# Storage

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



# 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

# Storage

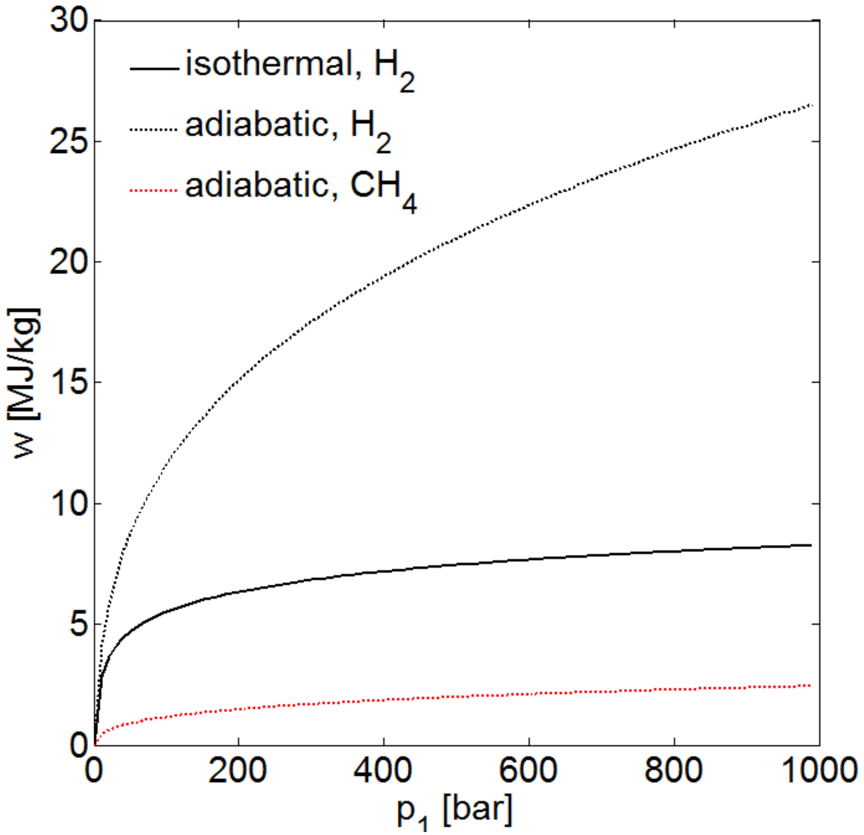
- Compression:
  - Ideal isothermal compression:

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

  - Adiabatic compression:

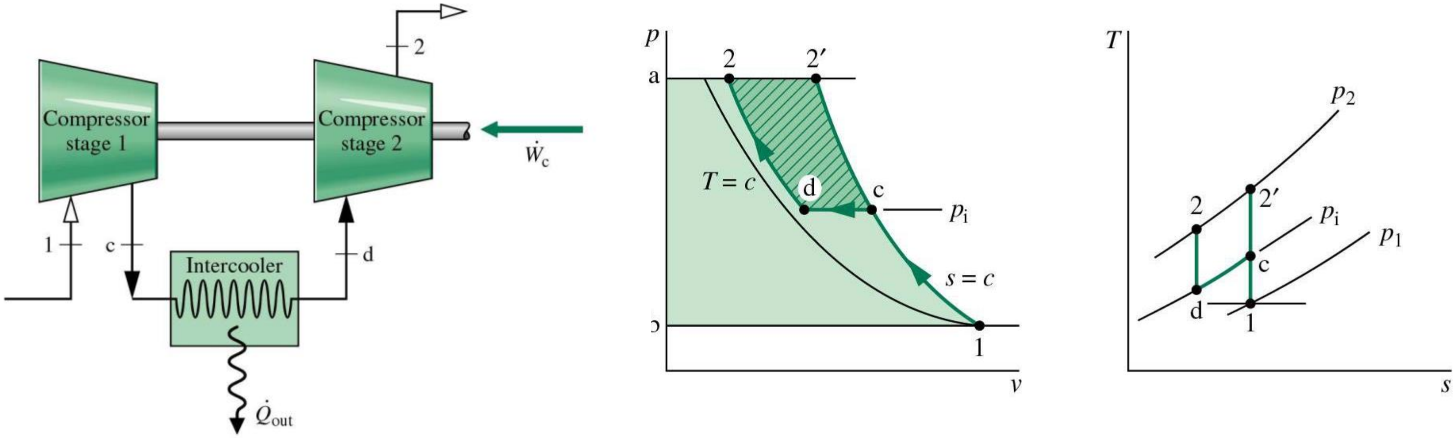
$$\frac{W}{m} = \frac{1}{\gamma - 1} p_0 v_0 \left(\left(\frac{p_1}{p_0}\right)^{\frac{\gamma-1}{\gamma}} - 1\right)$$

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



# Storage

- 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

    → 1000 TJ (~23 mio liters gasoline)

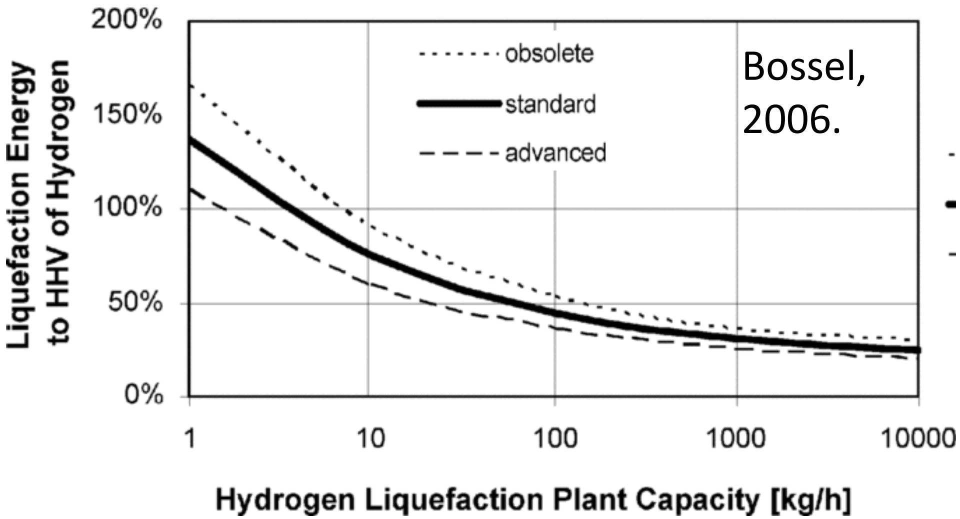
# Storage

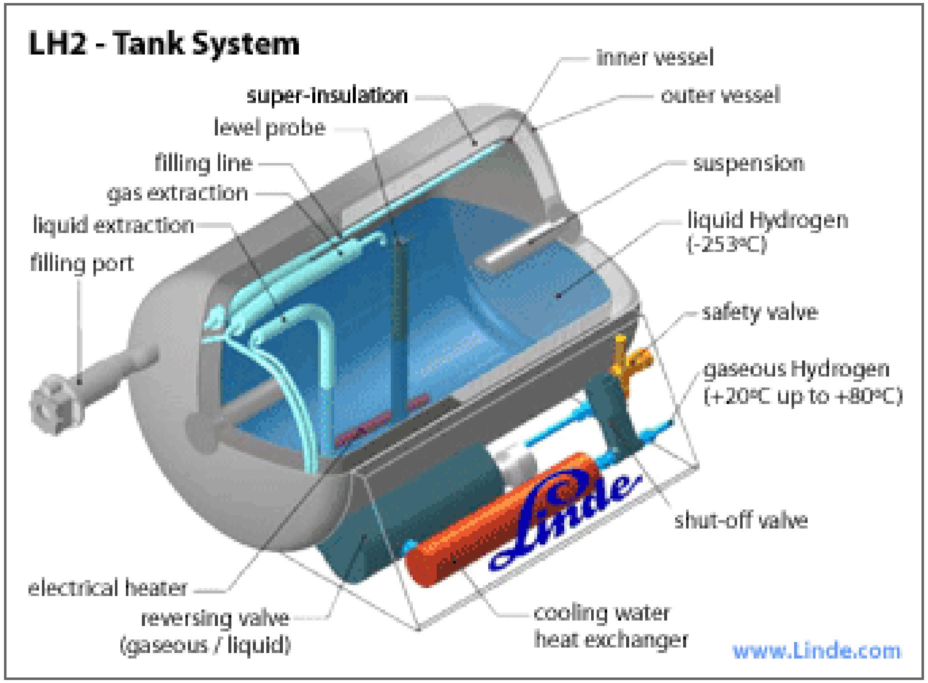
- Liquification:
  - Cooling from 293 to 20 K, and condensation at 20 K and 1 atm, requires theoretically around 14 MJ/kg $H_{2,l}$
  - But no heat sinks at 20 K exists, multi-stage process needed:

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



# Storage

- 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

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

  - Methanol synthesis:

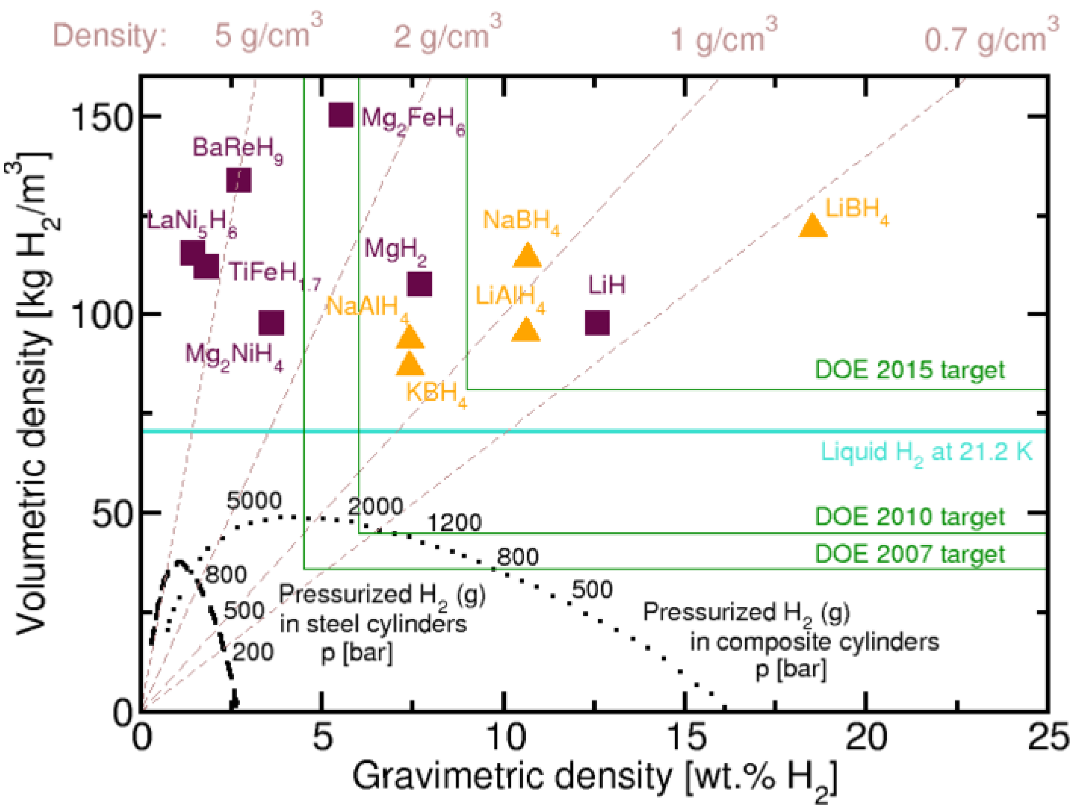
$$CO_2 + 3\,H_2 \longrightarrow CH_3OH + H_2O$$

  - 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

# Storage

- 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

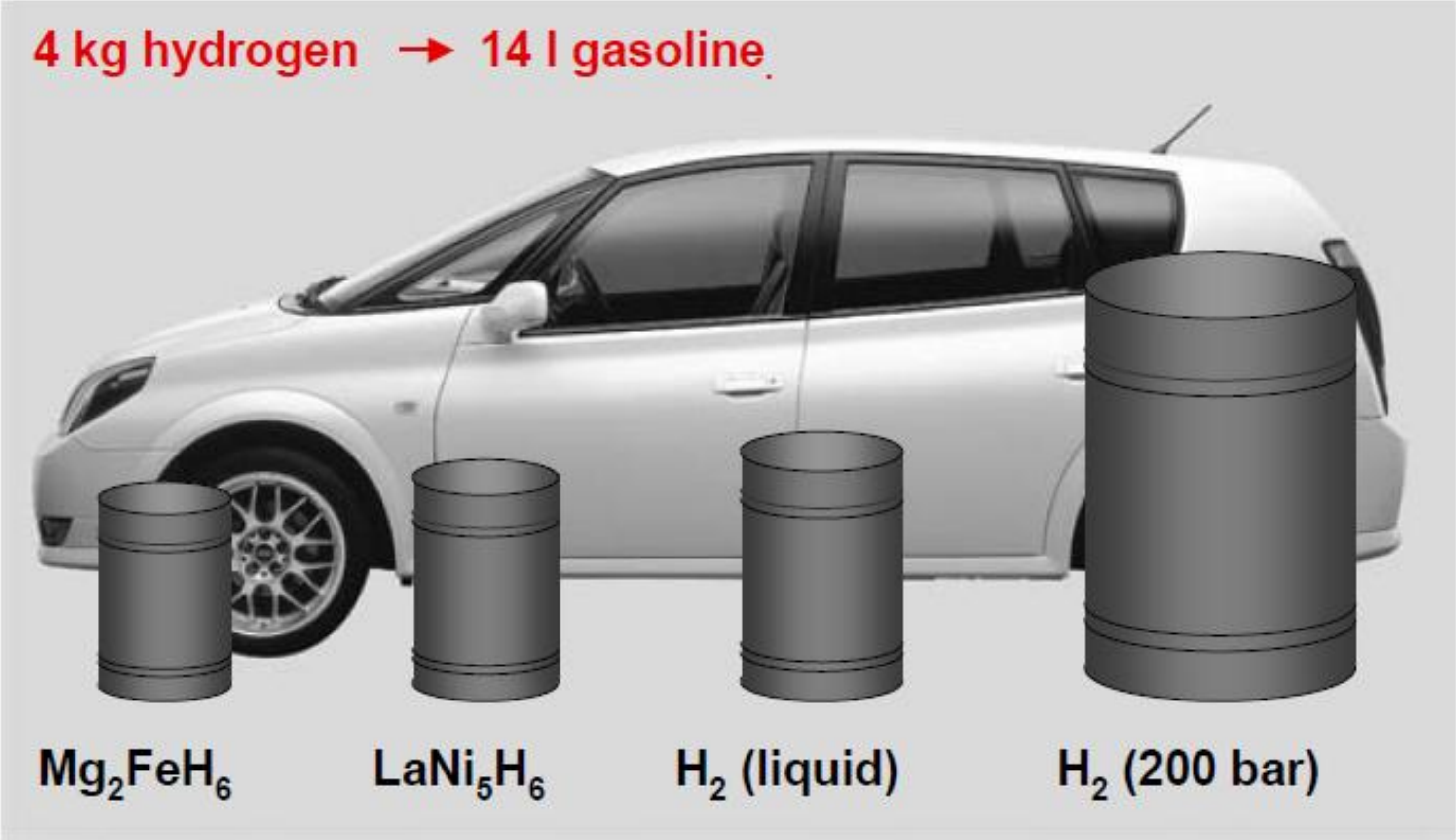



Krishna, 2012.

# Storage

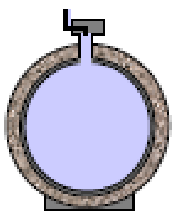
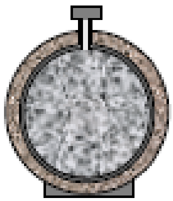
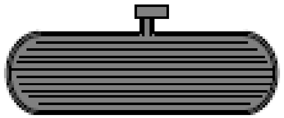
- Comparison

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



# 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

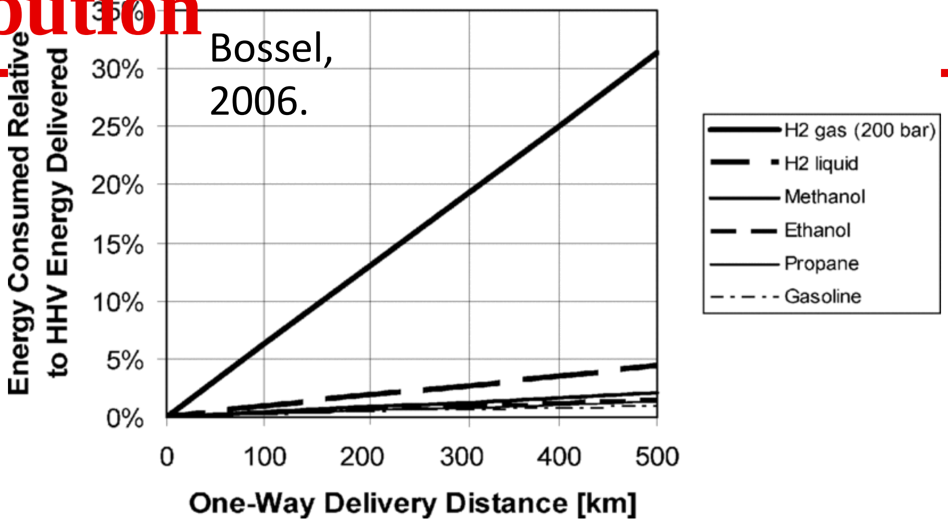
- Outline:

**Hydrogen as an energy vector:**

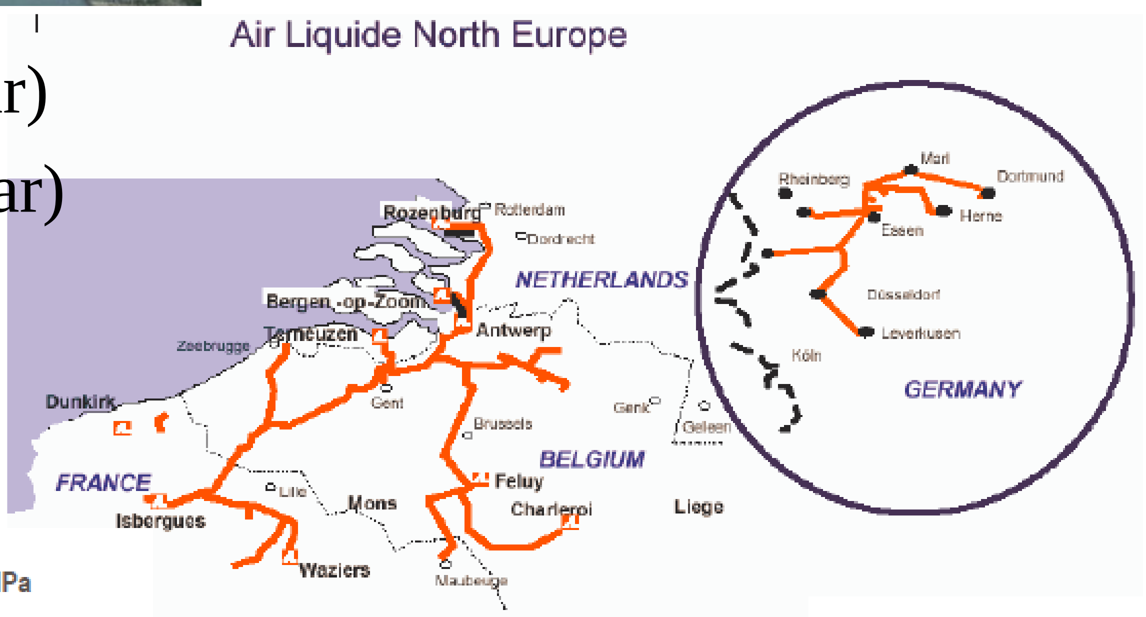
1. **Motivation**
2. **Properties**
3. **Production**
4. **Storage**
5. **Distribution**
6. **Application**

# Distribution

- Liquid:
  - Ship
  - Truck




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




Belgium-France-NL
$H_2$-Pipeline, Air Liquide

| | | |
|---|---|---|
| Air Liquide: | | |
| Belgium, France, NL | 966 km | 10 MPa |
| Germany: | | |
| Rhein-Ruhr Pipeline [operative since 1938] | 240 km | 1.1/ 2.3/ 30 MPa |
| Leuna-Merseburg, Linde | 100 km | 2-2.5 MPa |

# Distribution

- Concept:

Trucks with compressed or liquid hydrogen:

Fueling station:


Transportation services

On site generation:
By electrolysis and renewable
By fossil fuels

Piped hydrogen

- What about decentralized production, even in the car?

# Distribution

- Hydrogen highway

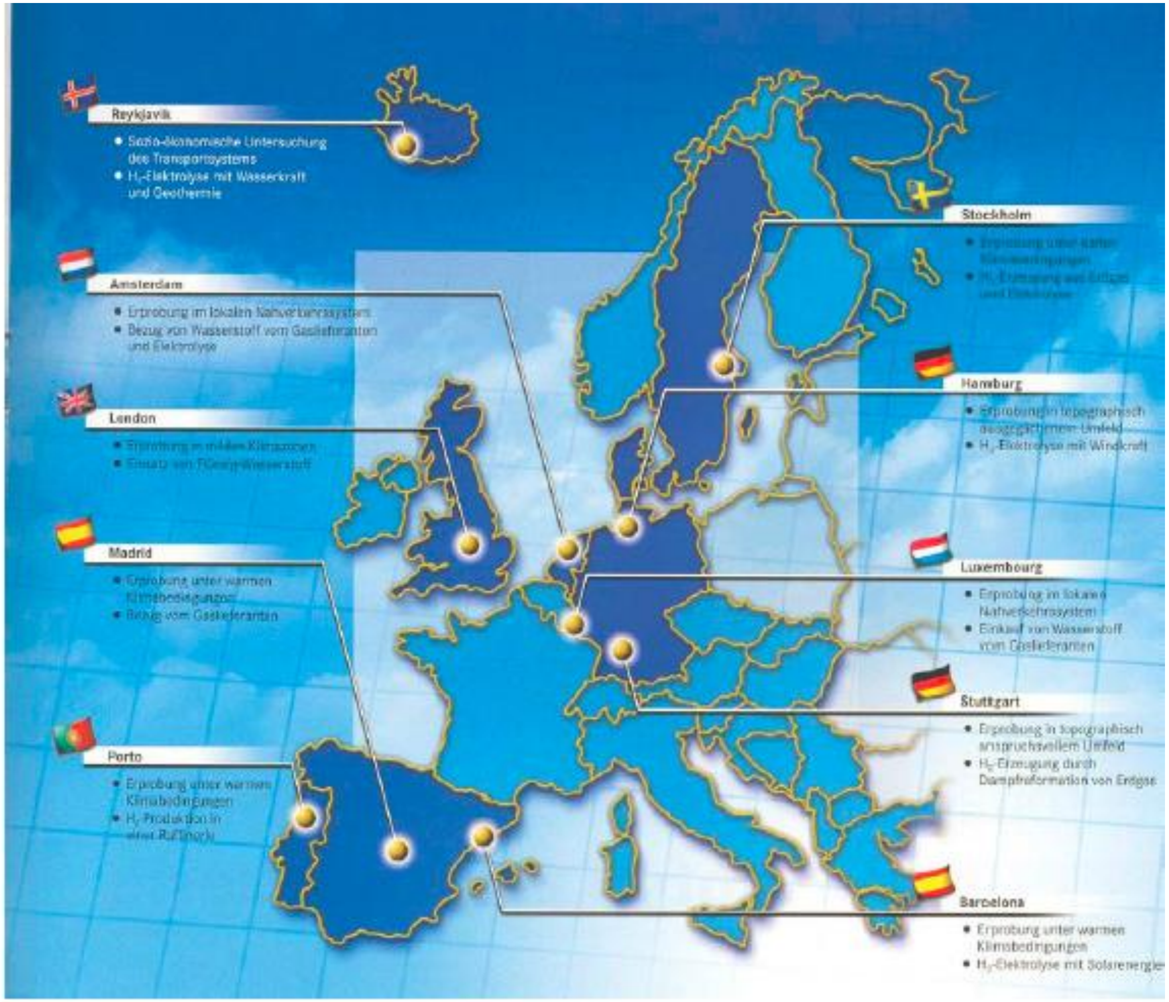
Berlin
Wolfsburg
Hannover
Bochum
Düsseldorf
Köln
Wiesbaden
Frankfurt
Rüsselsheim
Mannheim
Stuttgart
Augsburg
München
Ingolstadt
Leuna
Leipzig


**40 “H2 pumps” on the Highway about 2000 km**

# Distribution

- Hydrogen highway

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



# Emerging Renewable Power

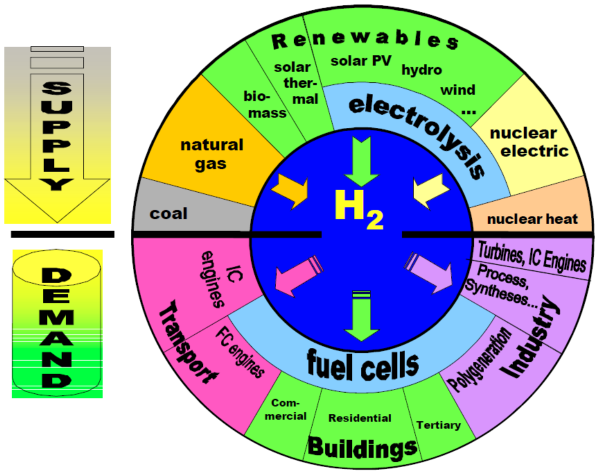
- Outline:

**Hydrogen as an energy vector:**

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

# Application

- In transportation:
  - 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)



# 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.