Hochschule Kempten
University of Applied Sciences

Fakultät Maschinenbau

Hydrogen Technologies

Lecture 2: Production of Hydrogen (Overview, SMR, Gasification, Kaverner)

Prof. Matthias Klingele

Repetition

- Hydrogen will play a role in reaching climate neutrality.
- We will need a lot of Hydrogen.

Lecture Outline

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1	07.10.2025	S0.13b	HYTECH 1	Hydrogen and Energy transition
1	07.10.2025	S0.13b	HYTECH 2	Hydrogen Production Overview
2	14.10.2025	S0.13b	HYTECH 3	Electrolysis - Electrochemistry and Thermodynamics
2	14.10.2025	S0.13b	HYTECH 4	Electrolysis - Kinetics, U-I-Curve
3	21.10.2025	S0.13b	HYTECH 5	Tutorial Hydrogen Production
3	21.10.2025	S0.13b	HYTECH 6	Tutorial Hydrogen Production
4	28.10.2025	S0.13b	HYTECH 7	Electrolysis - Membrane Materials
4	28.10.2025	S0.13b	HYTECH 8	Electrolysis - Catalysis, Electrodes
5	04.11.2025	S0.13b	HYTECH 9	Hydrogen Storage - Compression, Liquefication
5	04.11.2025	S0.13b	HYTECH 10	Hydrogen Storage - Metal Hydrides, LOHCs, Ammonia
6	11.11.2025	S0.13b	HYTECH 11	Fuel Cells - Introduction
6	11.11.2025	S0.13b	HYTECH 12	Fuel Cells - Thermodynamics and Polarization
7	18.11.2025	S0.13b	HYTECH 13	Fuel Cells - Systems
7	18.11.2025	S0.13b	HYTECH 14	Fuel Cells - Materials
8	25.11.2025	S0.13b	HYTECH 15	Characterization Methods
8	25.11.2025	S0.13b	HYTECH 16	Characterization Methods
9	02.12.2025	S0.13b	HYTECH 17	Tutorial Fuel Cells
9	02.12.2025	S0.13b	HYTECH 18	Tutorial Fuel Cells
10	09.12.2025	S0.13b	HYTECH 19	Electrolysis and Fuel Cells: Material Level Degradation
10	09.12.2025	S0.13b	HYTECH 20	Electrolysis and Fuel Cells: System Level Degradatiion
11	16.12.2025	S0.13b	HYTECH 21	Power to Liquid
11	16.12.2025	S0.13b	HYTECH 22	Power to Liquid
12	23.12.2025	S0.13b	HYTECH 23	Lab-Tour
12	23.12.2025	S0.13b	HYTECH 24	Lab-Tour
12	13.01.2026	S0.13b	HYTECH 25	?
12	13.01.2026	S0.13b	HYTECH 26	?
13	20.01.2026	S0.13b	HYTECH 27	Repetition und exam preparation
13	20.01.2026	S0.13b	HYTECH 28	Repetition und exam preparation

Introduction

H_2 production

H_2 storage and logistics

H_2 Utilization

TBA

The Colours of Hydrogen

NDR

[Grüner Wasserstoff: Salzgitter AG investiert 100 Millionen Euro]

Der Konzern hat eine Großanlage bestellt, die ab 2026 rund 9.000 Tonnen grünen Wasserstoff pro Jahr produzieren soll.

vor 3 Tagen

Utopia

Blauer Wasserstoff: Wie umweltfreundlich ist er?

Mit Wasserstoff soll die Energiewende gelingen. Doch ob blauer Wasserstoff wirklich zum Klimaschutz beitragen kann, ist umstritten.

07.05.2023

Cleanthinking

Oranger Wasserstoff aus Abfällen: Green Hydrogen Technology setzt neue Maßstäbe

Oranger Wasserstoff aus Abfällen: Green Hydrogen Technology setzt Maßstäbe, wandelt Klärschlamm und Plastik in H2 für Industrie und Verkehr.

vor 1 Monat

Goals for Lecture 2

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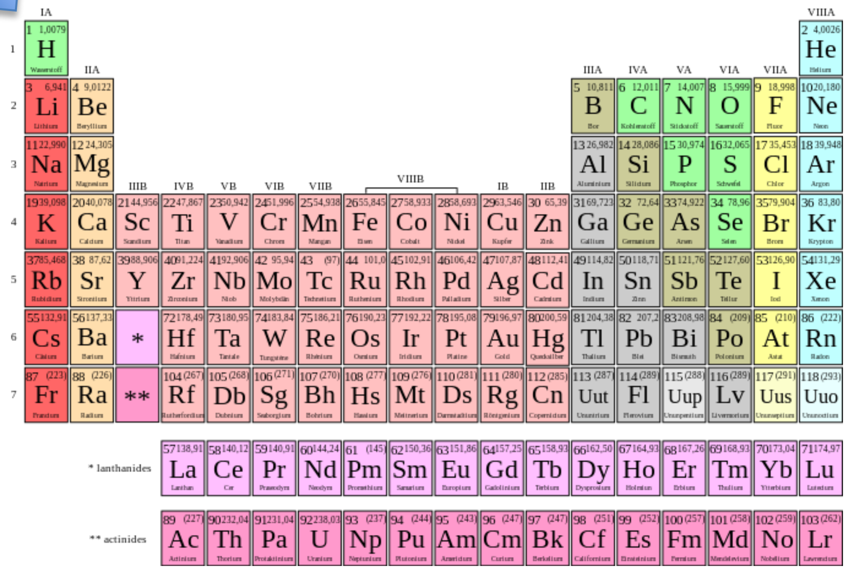
Knowledge of:

- **Key facts about Hydrogen**
- **Overview: Hydrogen production methods (the colours of hydrogen)**

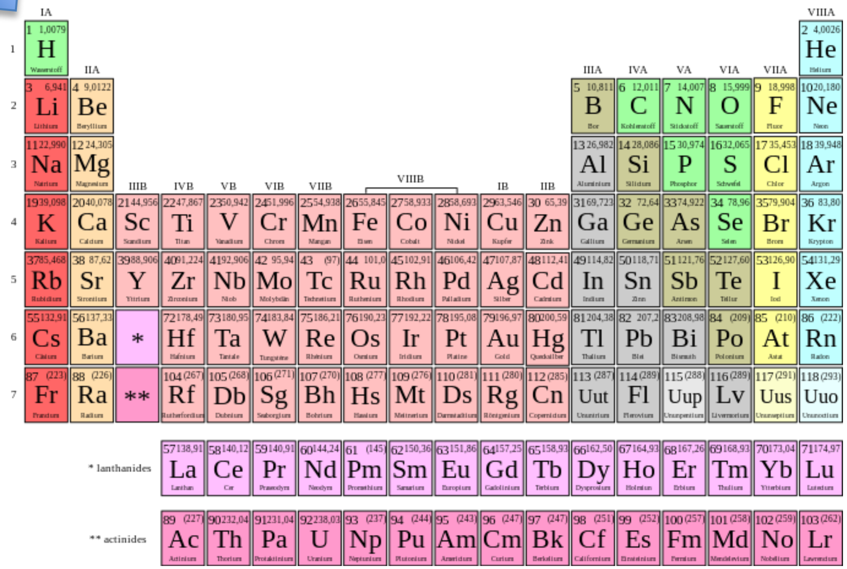
What is Hydrogen?

- 1 proton, 1 electron
- Makes up 70 wt% of the universe



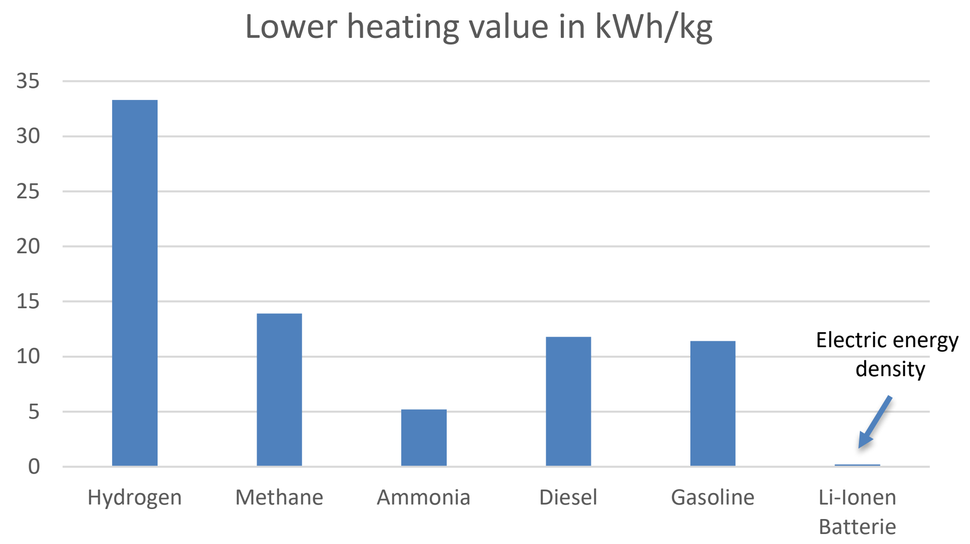
What is Hydrogen?

- 1 proton, 1 electron
- Makes up 70 wt% of the universe
- Earth: 0.87 wt%



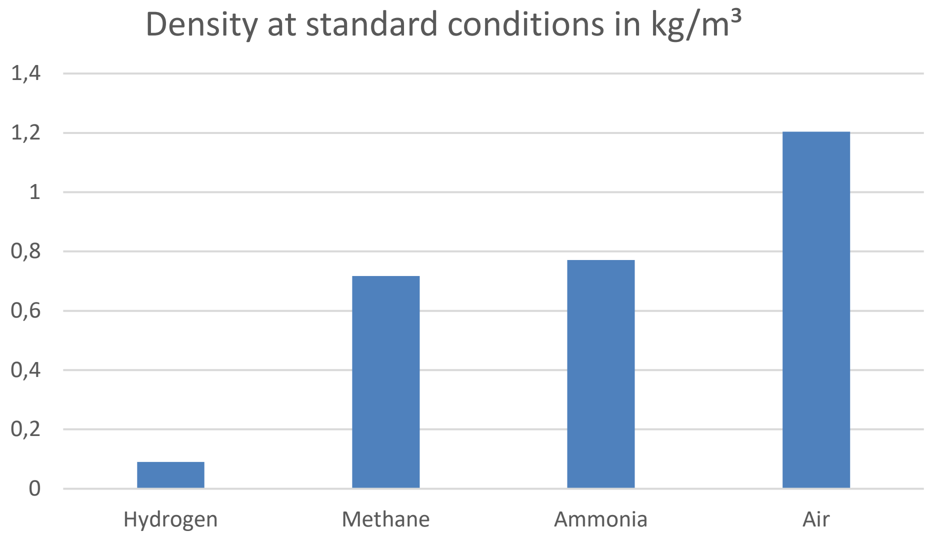
What is Hydrogen?

- High gravimetric energy density: 33.3 kWh/kg



What is Hydrogen?

- High gravimetric energy density: 33.3 kWh/kg
- Low density at standard conditions: 0.09 kg/m²



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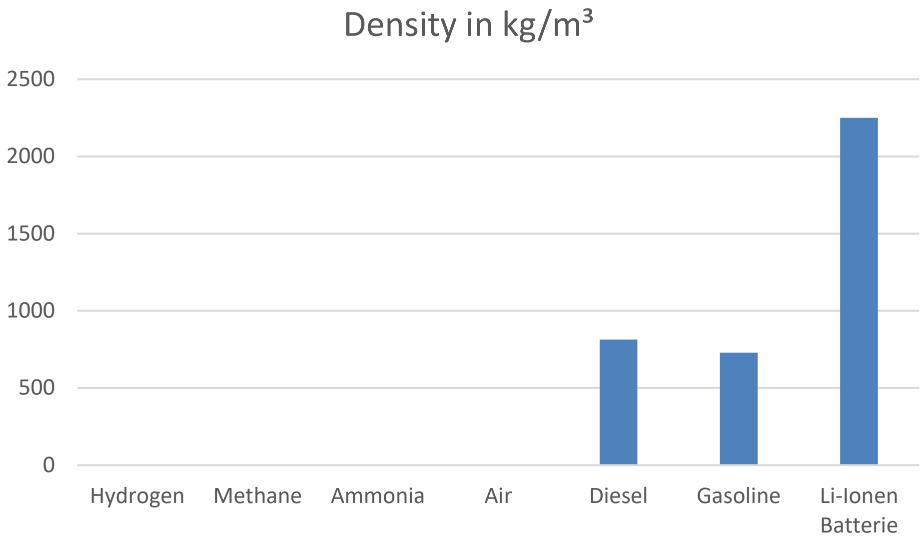
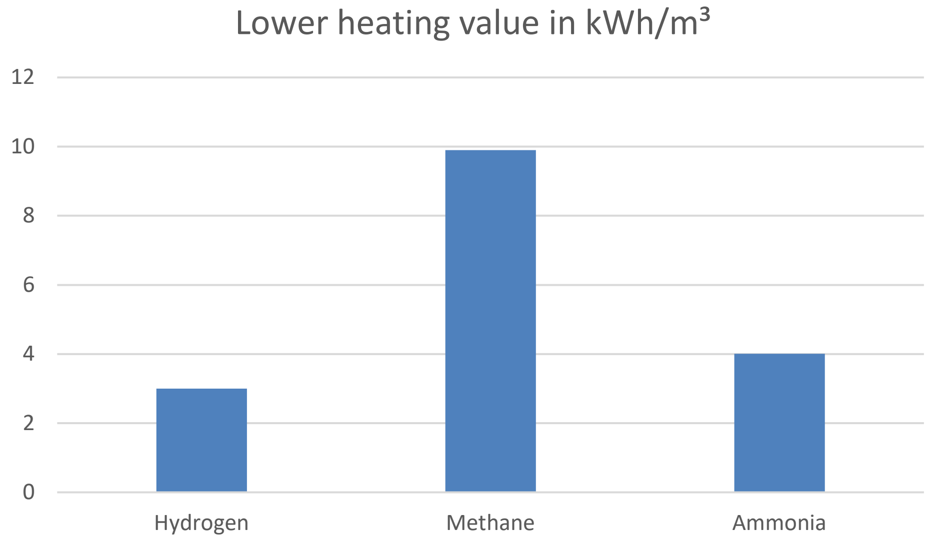


What is Hydrogen?

- High gravimetric energy density: 33.3 kWh/kg
- Low density at standard conditions: 0.09 kg/m²
- Low volumetric energy density: 3 kWh/m³



What is Hydrogen?

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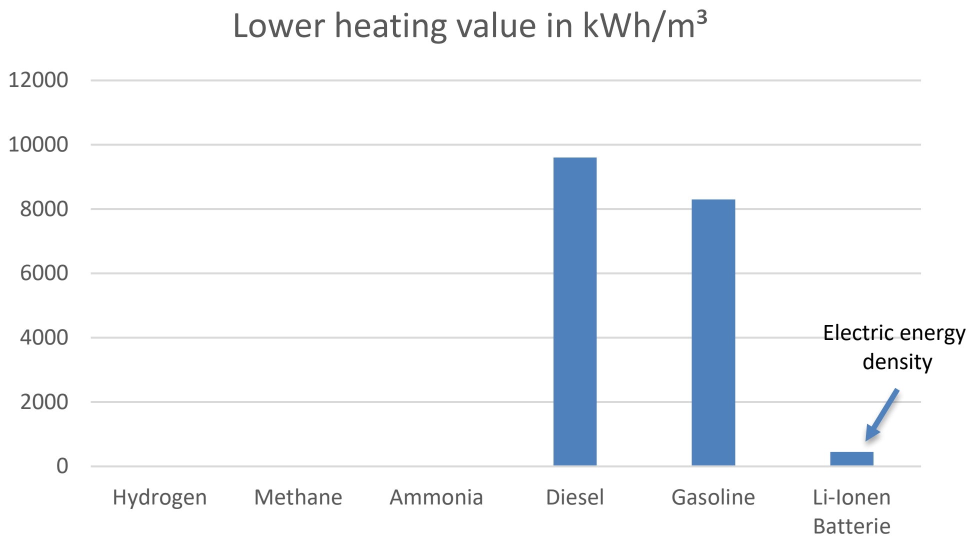
- High gravimetric energy density: 33.3 kWh/kg
- Low density at standard conditions: 0.09 kg/m²
- Low volumetric energy density: 3 kWh/m³

Compression/densification needed!



Production of Hydrogen (H_2)

- **Resources**
  - Water
  - Hydrocarbon
  - Both
- **Energy source for splitting up the Ressources**
  - Heat
  - Electricity
  - Both
- **Hydrogen production methods are different combinations of the above…**

Production of Hydrogen („Farbenlehre“)

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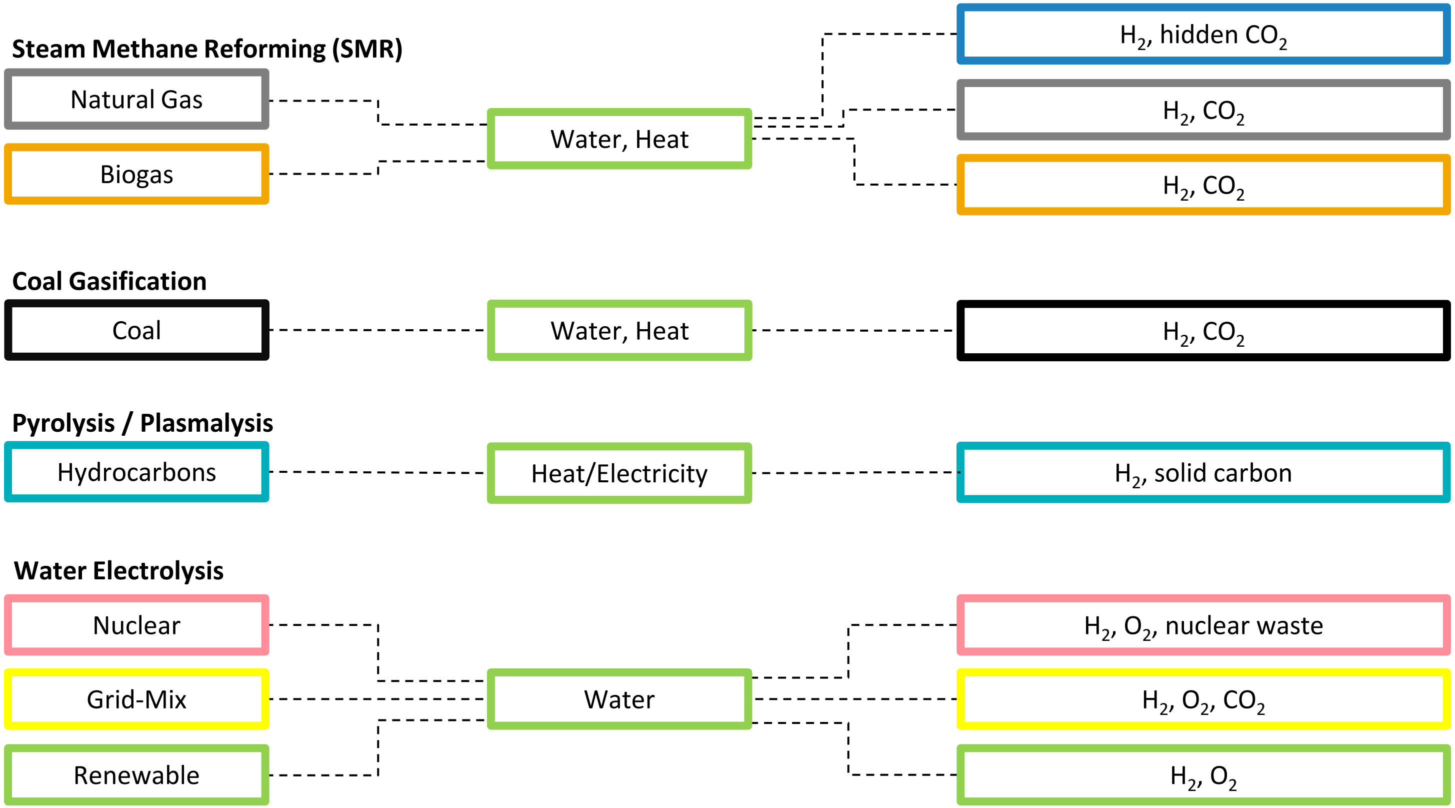
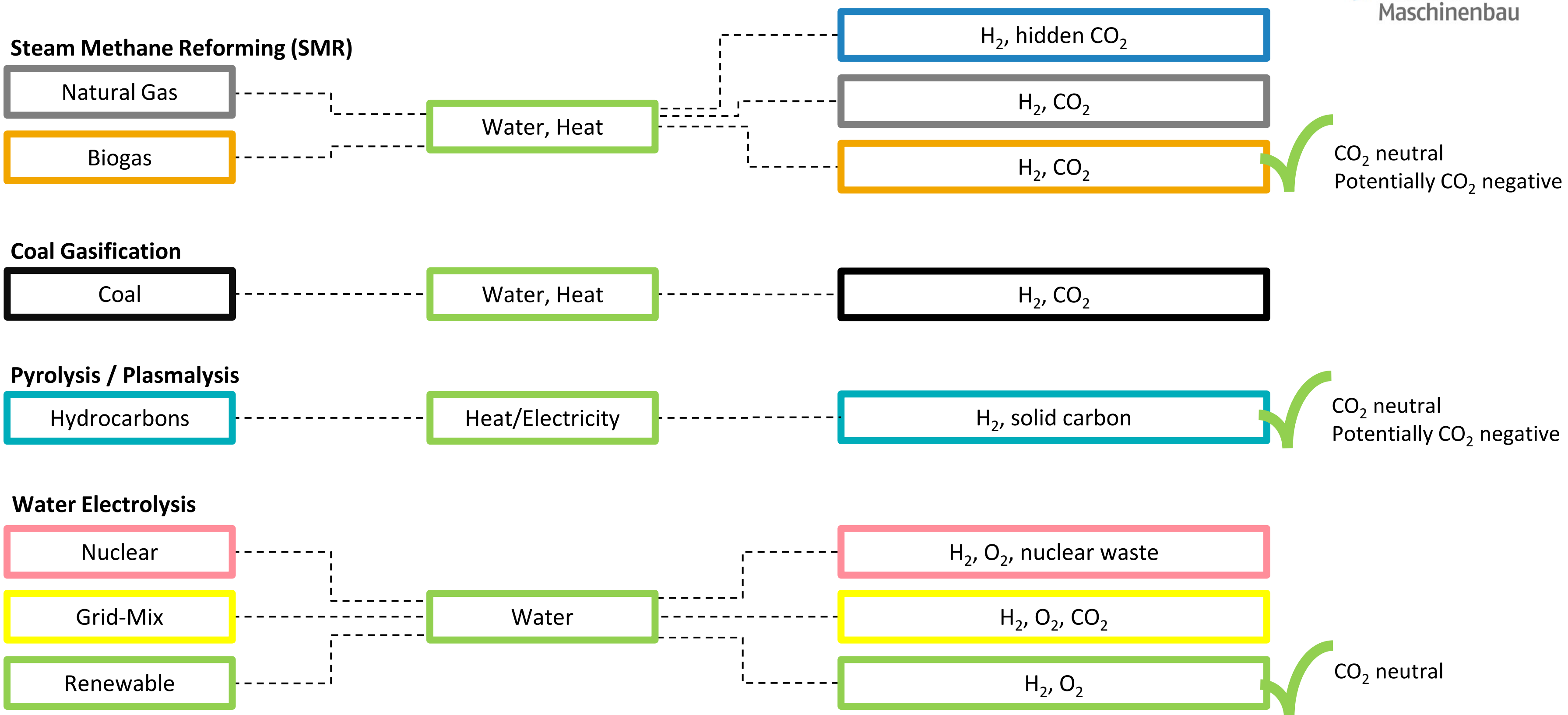
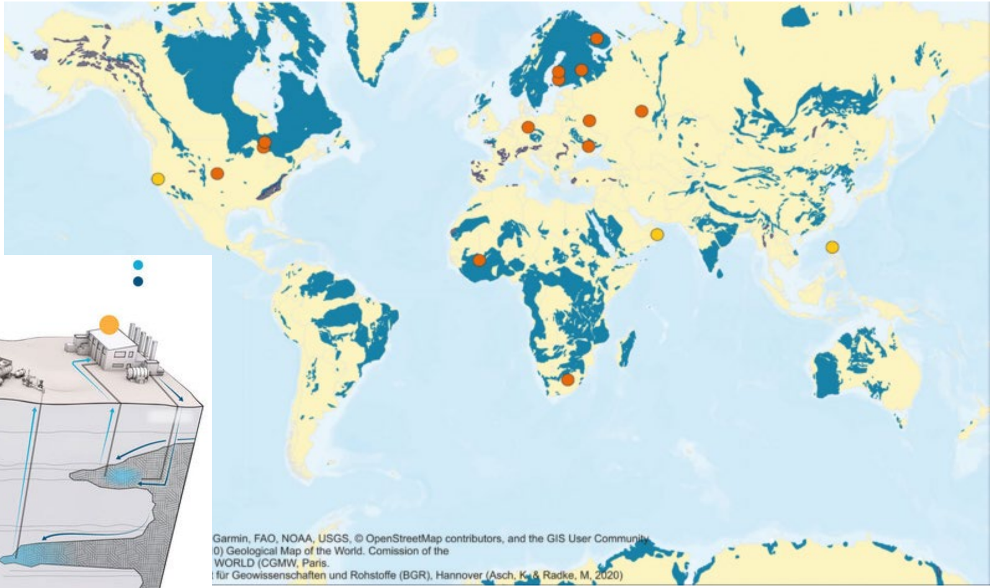


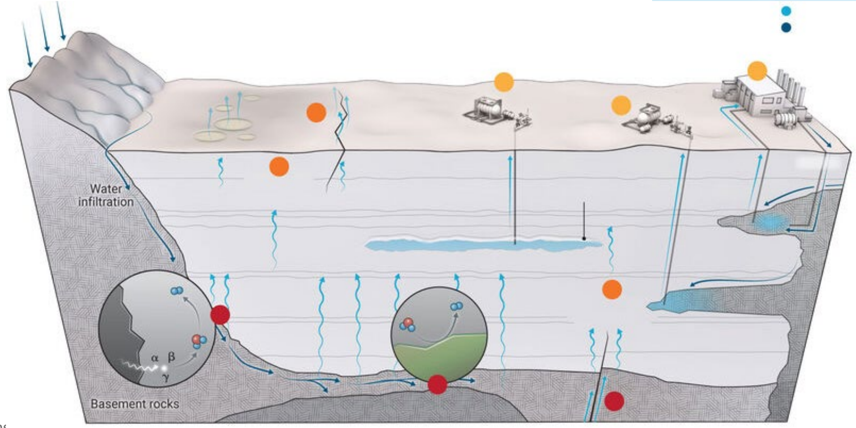
Production of Hydrogen („Farbenlehre“)



White Hydrogen

- **„Natural“ Hydrogen**
  - Due to high energy radiation
  - Due to chemical reactions
  - From „deep inside“





Steam Methane Reforming (SMR)

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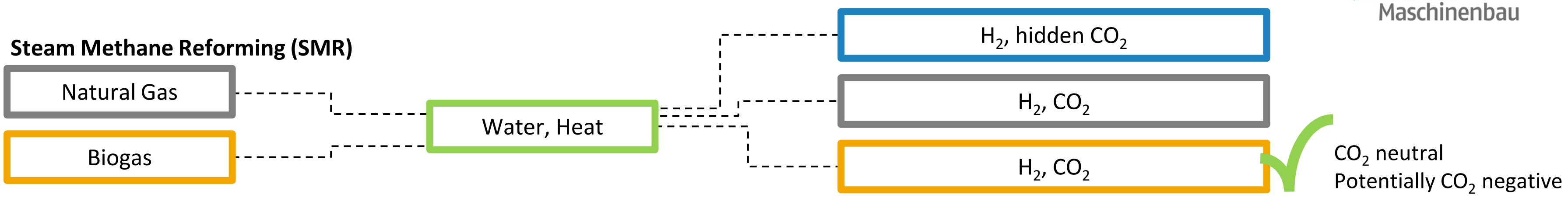
Steam Methane Reforming (SMR)

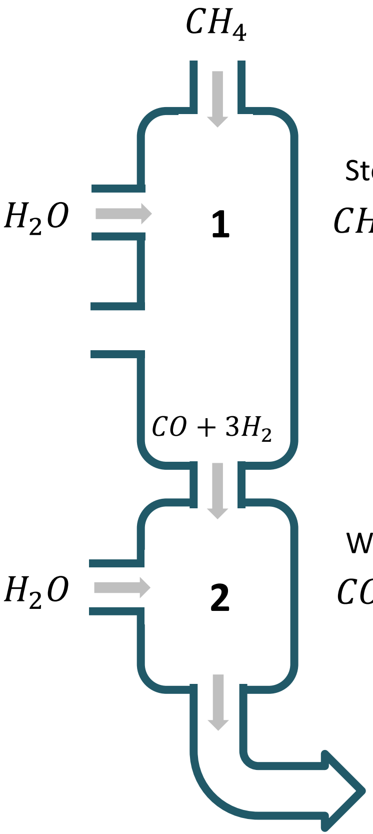


Steam-Methane-Reforming (SMR)

- **Thermochemical reaction at an heterogeneous catalyst (Nickel)**

- **1: Steam-Methane-Reforming**
  Endotherm (ca. 800 ° C heat needed)

- **2: Water-Gas-Shift-Reaction (WGS)**
  Increases H_2 yield
  Exotherm!



Steam-Methane-Reforming

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

$$\Delta H = +206{,}2 \mathrm{kJ/mol}$$

Water-Gas-Shift-Reaction

$$CO + H_2O \rightarrow CO_2 + H_2$$

$$\Delta H_R = -42{,}3\ \mathrm{kJ/mol}$$

Autothermal SMR

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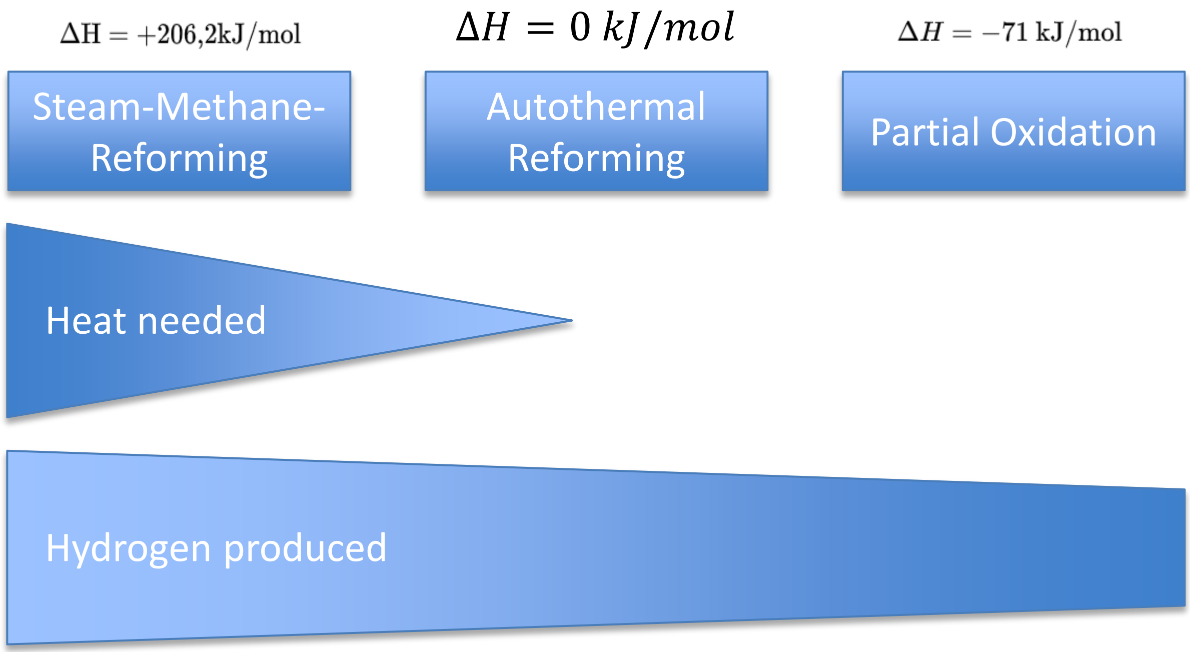


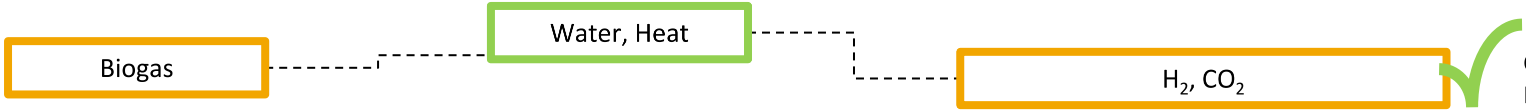
Real World

- High TRL technology
- Capacity of up to 18 tons H_2/h

https://www.engineering-airliquide.com/de/methan-dampfreformierung-wasserstofferzeugung (letzter Zugriff: 10.03.22)

SMR-Hydrogen based on Biogas

Steam Methane Reforming (SMR)



CO_2 neutral
Potentially CO_2 negative

SMR-Hydrogen based on Biogas

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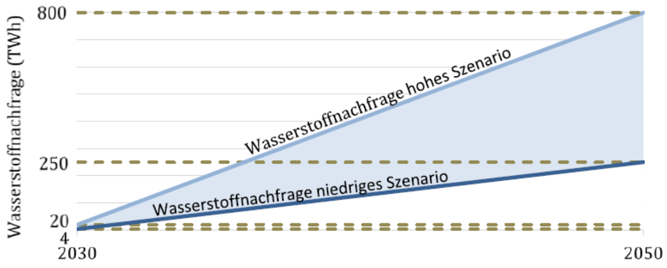
- **Technology is the same as for natural gas (except for additional purification steps)**
  - Methane content natural gas: ~ 85 %
  - Methane content Biogas: ~ 50 – 75 %

- **Volumetric efficiency is dependent from methane content and reactor technology**
  - From experience: 1 kg H_2 needs ~ 13 kg Biogas
  - H_2-potential in Germany 2019: 1,7 Billion kg (58 TWh)

Green Hydrogen demand in Germany per year



Fraunhofer, „Eine Wasserstoff-Roadmap für Deutschland“, 2019

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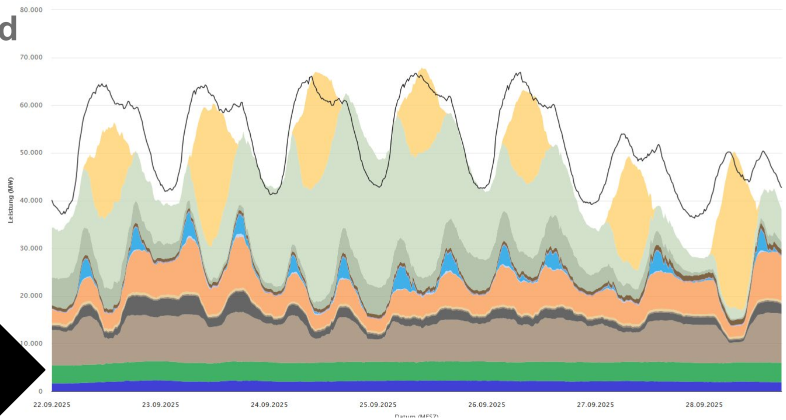
- **Biogas is needed for the decarbonization of the electric grid**



SMR-Hydrogen based on Biogas

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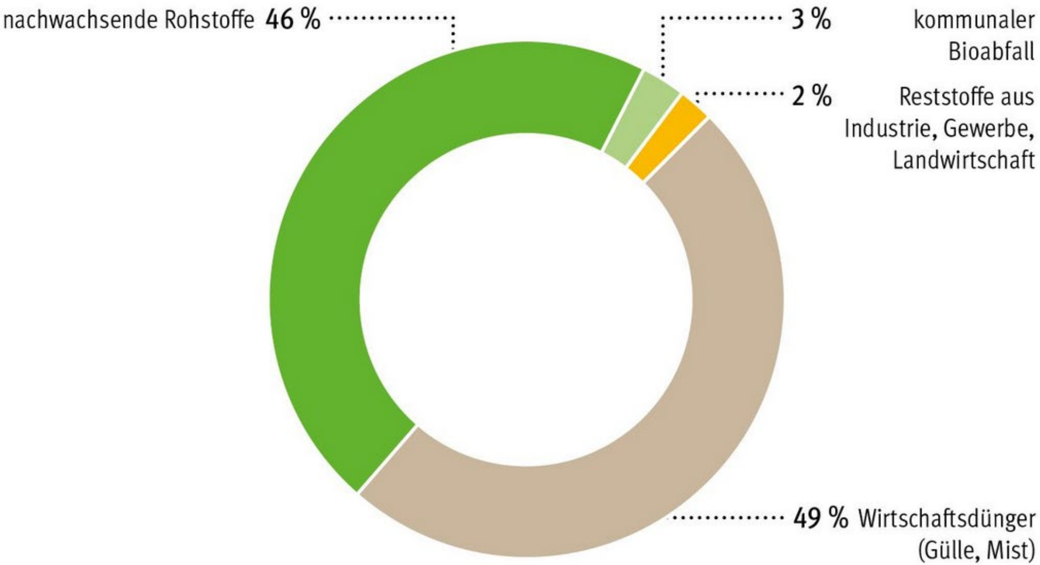
- **Biogas is needed for the decarbonization of the electric grid**

- **Regarding energy efficiency, Biogas-Hydrogen would still make sense**
  - Only ~ 55 % of produced heat of Biogas-KWK is utilized!

(Rensberg et al., DBFZ REPORT NR. 32, Wärmenutzung von Biogasanlagen)

Why not just produce more Biogas?

- **46% of the Biogas ressources are planted on purpose!**
- **More Biogas means more land use**
- **Example:**
  - 1kg H_2 needs ~ 25 m² Corn
  - Commute KE – ME: 16.000 km
  - Hydrogen Car: 160 kg H_2
  - 160 * 25 m² = **4000 m²**
- **For this reason, government does NOT see H_2 from Biogas as „green“**



Fachagentur Nachwachsende Rohstoffe e. V. , 2021

Real world…

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First start-ups are developing, showing demo facilities…

Steam Methane Reforming (SMR) with CCS

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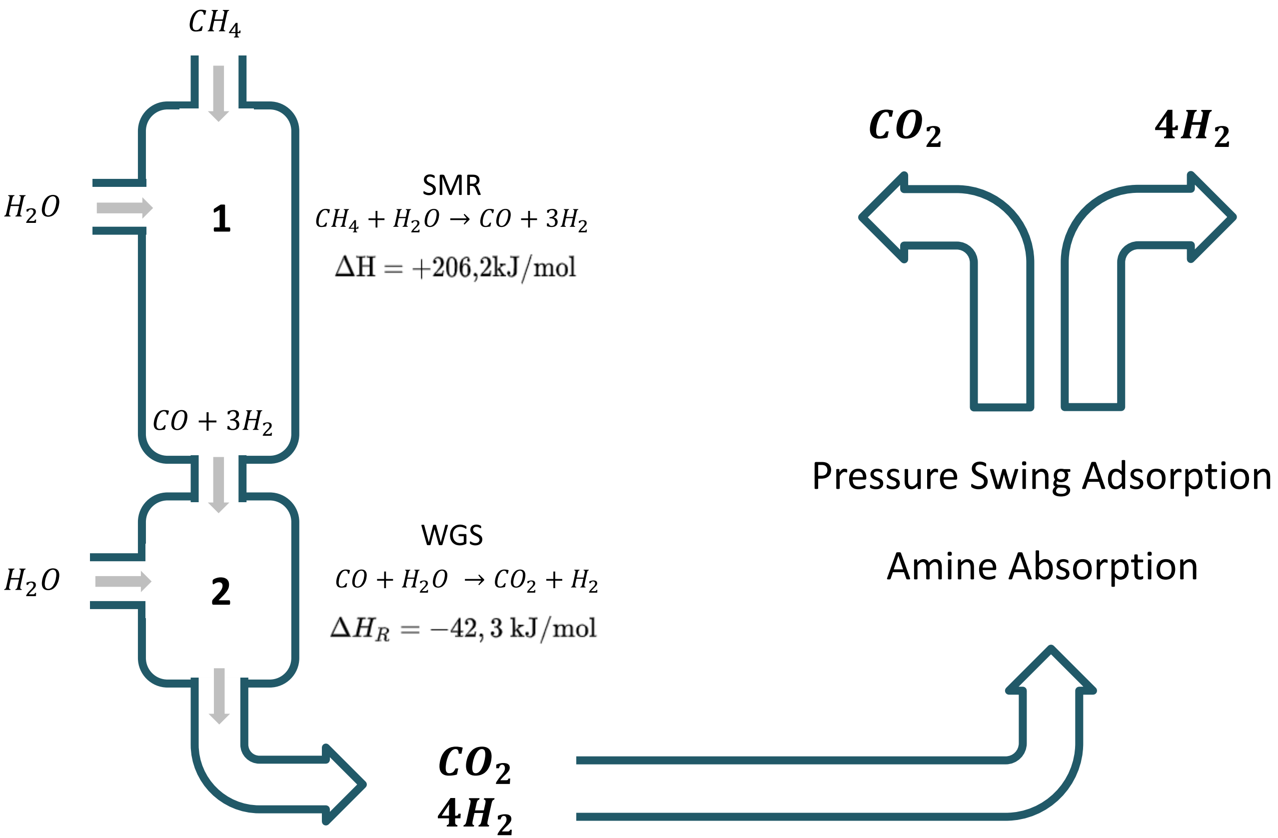
Steam Methane Reforming (SMR)

Natural Gas

Water, Heat

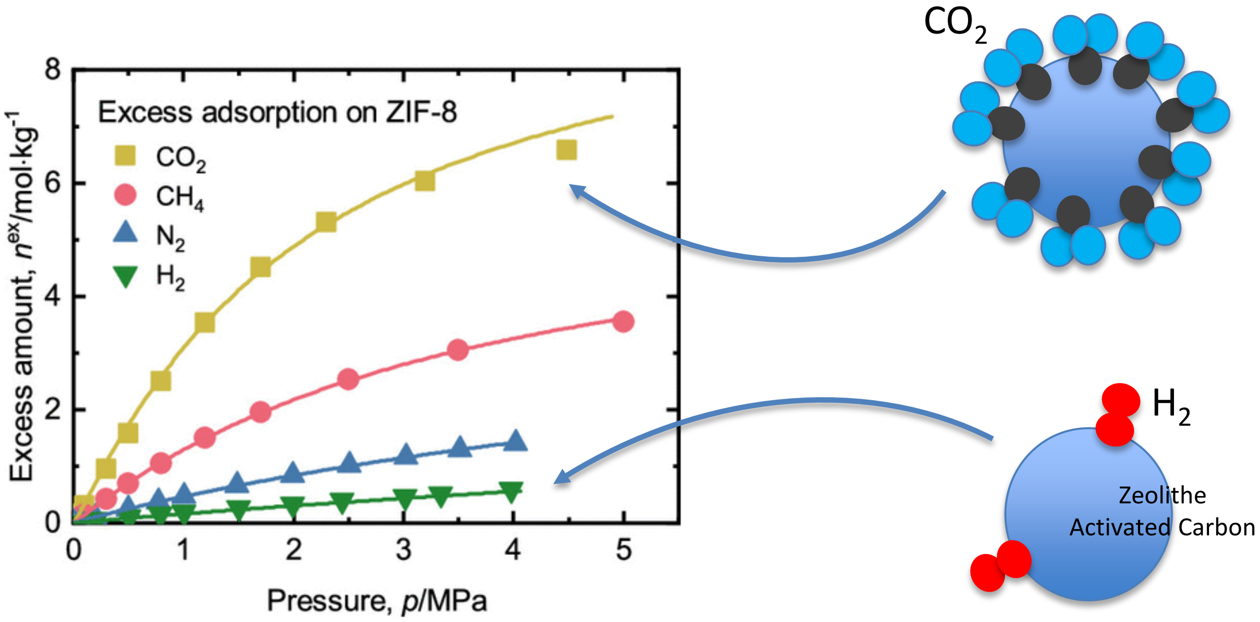
H_2, hidden CO_2

Steam Methane Reforming (SMR) with CCS



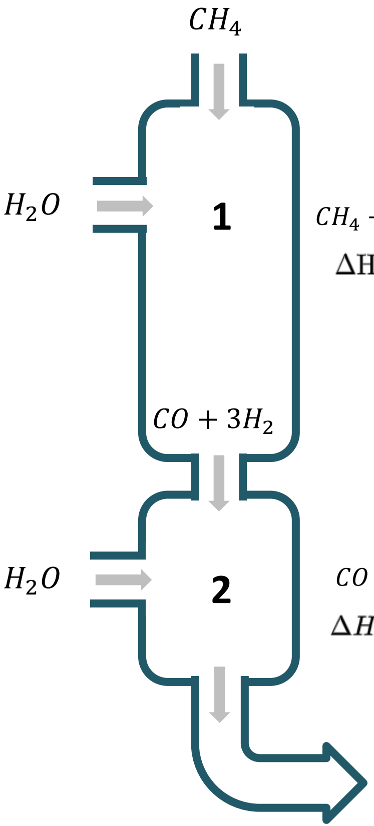
Pressure Swing Adsorption

- **Relies on the different Langmuir Adsorption Isotherms of CO_2 and H_2**
  - Quantifies how much adsorbate can fit on a surface at a given pressure



https://doi.org/10.1021/acs.jced.1c00900

Pressure Swing Adsorption



SMR

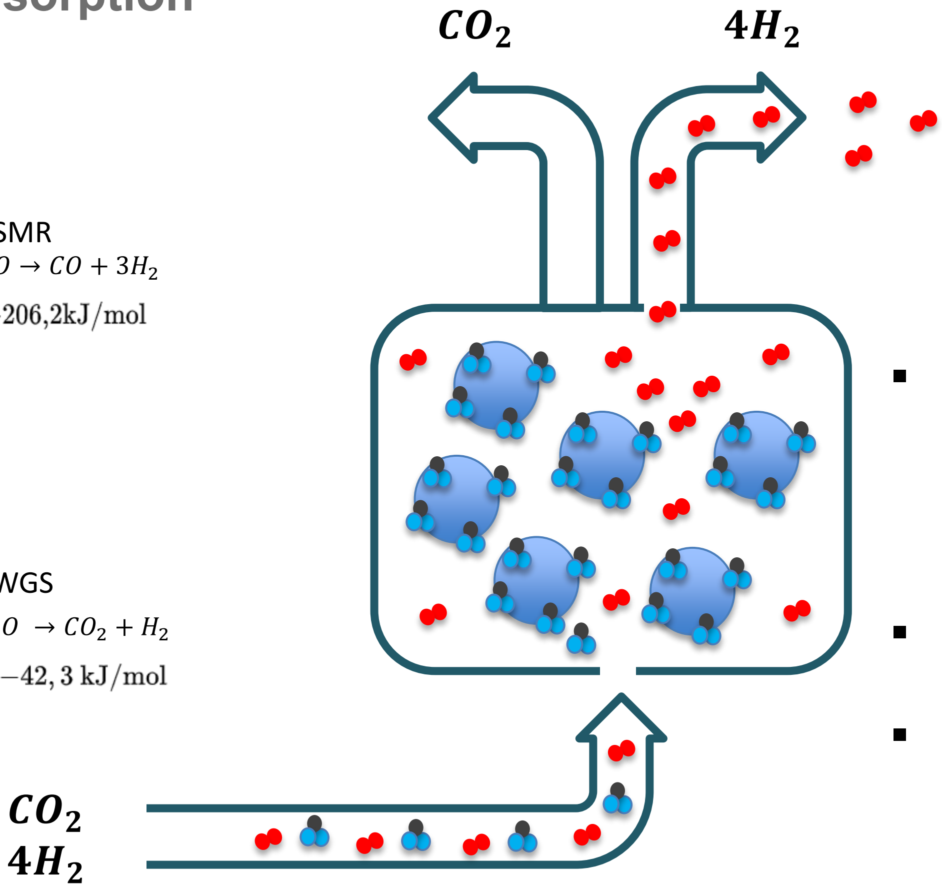
$$CH_4 + H_2O \rightarrow CO + 3H_2$$

$$\Delta H = +206{,}2 \mathrm{kJ/mol}$$

WGS

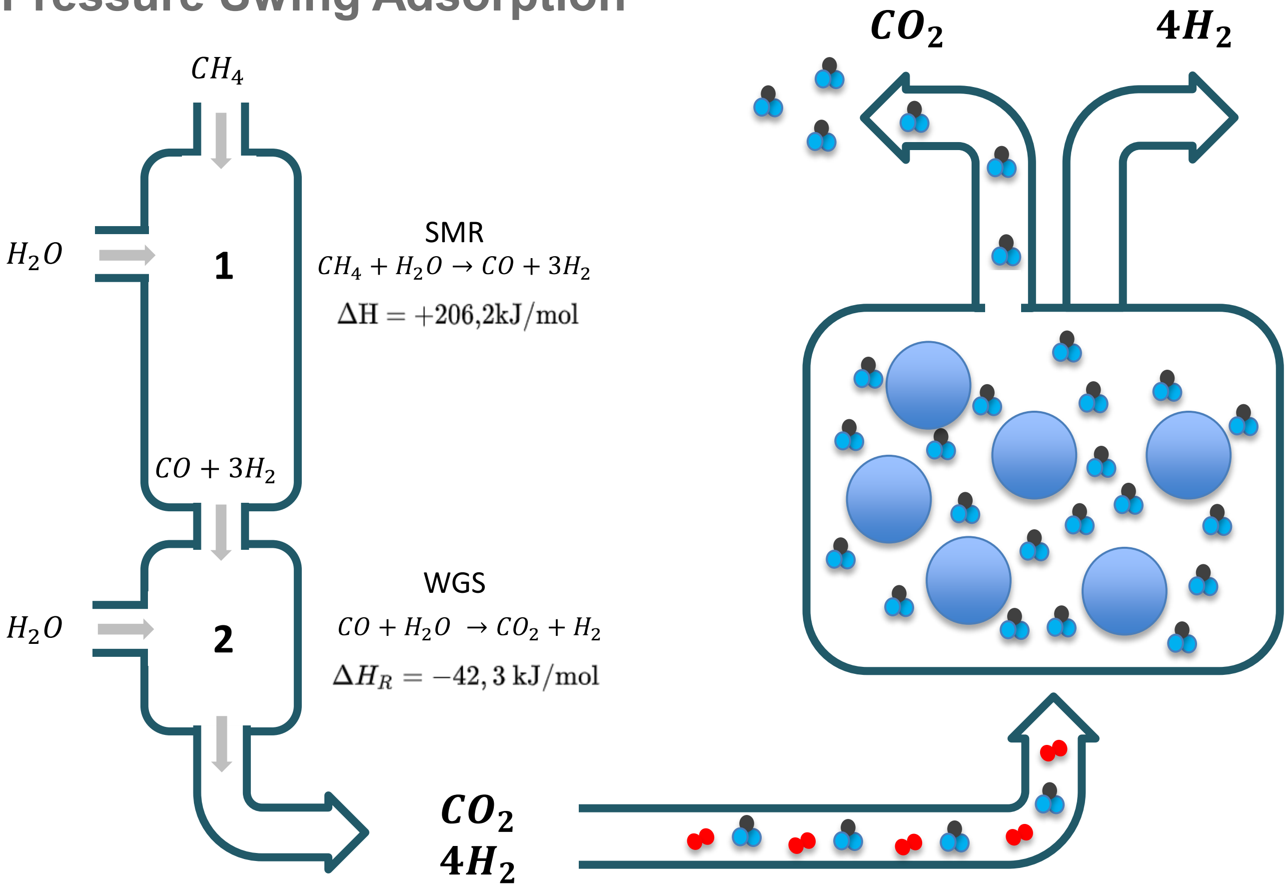
$$CO + H_2O \rightarrow CO_2 + H_2$$

$$\Delta H_R = -42{,}3 \mathrm{~kJ/mol}$$



- Step 1: High pressure
  - Inlet open
  - H_2 outlet open
  - CO_2 outlet closed
- CO_2 adsorbes
- Pure H_2 is collected

Pressure Swing Adsorption



- Step 2: Low pressure
  - Inlet closed
  - H_2 outlet closed
  - CO_2 outlet open
- CO_2 desorbes
- CO_2 is collected

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Amine Absorption

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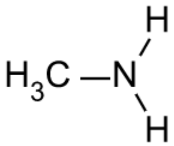
- **Relies on chemical reaction (chemisorption, absorption) of CO_2 with Amines**
  - Amonia, which has 1, 2 or 3 Hydrogen atoms replaced with arylic or alcylic groups

Example: Methylamin 

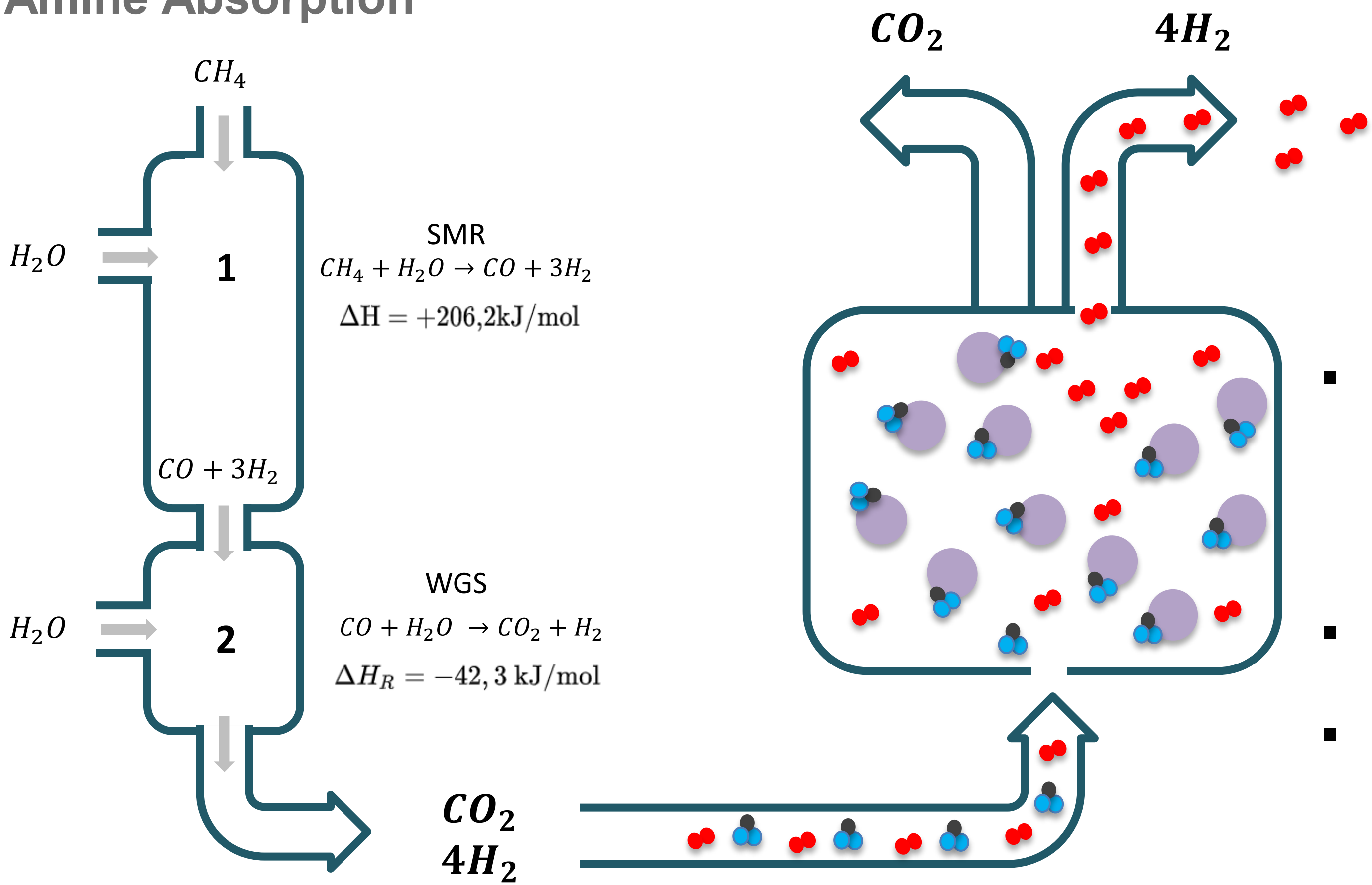
- **Reaction:** $$\mathrm{R{-}NH_2} + \mathrm{CO_2} \rightleftharpoons \mathrm{R{-}NHCOO^-} + \mathrm{H^+} \qquad \Delta H = -85 kJ/mol$$

Amine

Amine and reversibly bound CO_2

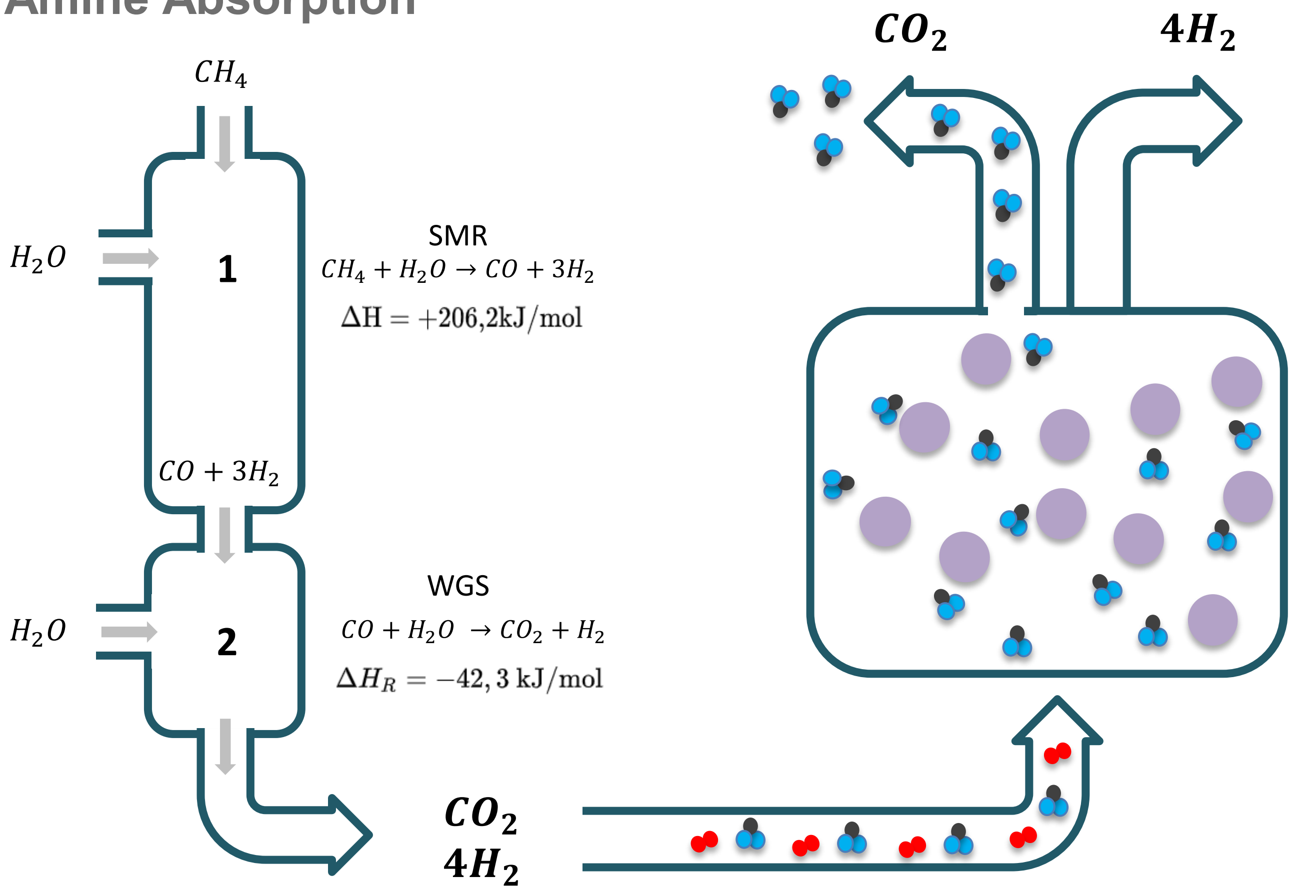
- **CO_2 fixation is exothermal, CO_2 release is endothermal (needs heat!)**

Amine Absorption



- Step 1: Low Temp
  - Inlet open
  - H_2 outlet open
  - CO_2 outlet closed
- CO_2 reacts with amine
- Pure H_2 is collected

Amine Absorption



- Step 2: High Temp
  - Inlet closed
  - H_2 outlet closed
  - CO_2 outlet open
- CO_2 desorbes
- Pure CO_2 is collected

Carbon Capture and Storage (Blue Hydrogen)

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- Self explanatory: Capture CO_2, store it somewhere (underground)
- Would largely solve the energy crisis if it worked

- Is almost exclusively promoted by the natural oil and gas industry

Carbon Capture and Storage (Blue Hydrogen)

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- **Extremely difficult to assess (you can‘t see slipping gases)**
  - Makes it hard to argue against!

- **Fact: Geological consequences happen (cracks in the rock formations)**

- **Fact: Ecological Impact is small if leakage happens**

- **Fact: Methane is slipping along the production chain with massive climate impact!**
  - „Mining“ of natural gas
  - Incomplete conversion to hydrogen

- **Fact: Carbon capture rates are limited to ~ 90 % (cost reasons)**

Coal Gasification

Coal Gasification

Coal - - - Water, Heat - - - H_2, CO_2

$$\mathrm{C} + \mathrm{H_2O} \longrightarrow \mathrm{CO} + \mathrm{H_2} \qquad \Delta H_R = +131\ \mathrm{kJ/mol}$$

Production of Hydrogen („Farbenlehre“)

Pyrolysis / Plasmalysis

Hydrocarbons - - - - Heat/Electricity - - - - H_2, solid carbon

CO_2 neutral
Potentially CO_2 negative

Pyrolysis / Plasmalysis of Hydrocarbons

- Kvaerner-Process: Splitting of Hydrocarbons into Hydrogen and Carbon using energy

$$C_nH_m \longrightarrow nC + \frac{m}{2}H_2$$

- No oxygen is involved: No CO_2 emissions! (In contrast to SMR or Coal gasification)
- Carbon „emissions“ are solid, and can be stored or recycled
- Potentially CO_2 negative, if biogenic Hydrocarbons are used

Efficiency of Kvaerner Process

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Example Methane:

- **Kvaerner:** $CH_4 \rightarrow C + 2\,H_2$ $\Delta H = +74{,}6\ kJ/mol$
- **SMR:** $CH_4 + H_2O \rightarrow CO + 3H_2$ $\Delta H = +206{,}2\ kJ/mol$
- **Electrolysis** $2H_2O \rightarrow 2H_2 + O_2$ $\Delta H = +571{,}7\ kJ/mol$

Kvaerner Process can be very efficient!

How can Energy be provided?

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- **Heat**
  - Example: Molten Zinn Reactor
  - Heat can be provided by combustion or electricity
- **Plasma**
  - Example: AC Plasma reactor
  - Plasma can be provided by heat or electricity

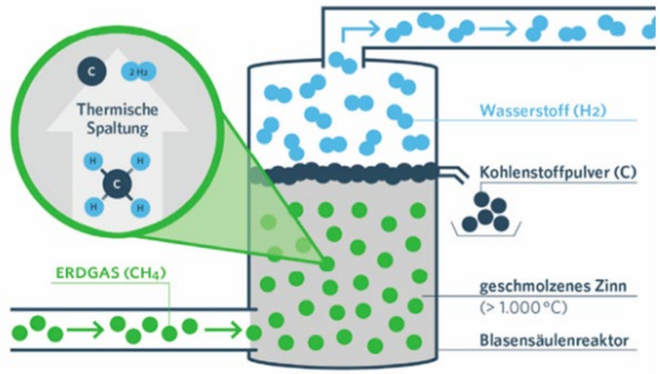

Figure: Gazprom

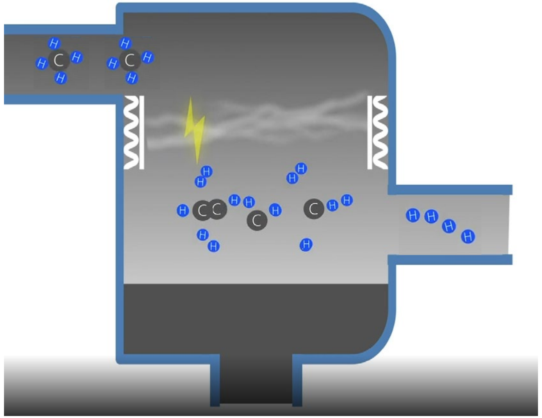

Figure: Graforce

Next time:

Water Electrolysis