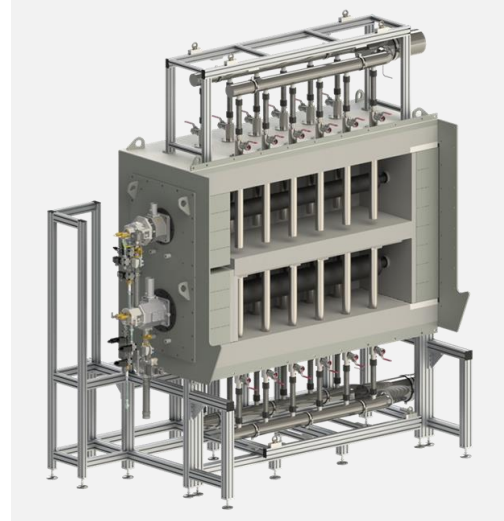




Potentiale der Elektrowärme und CO₂-neutraler Brennstoffe für die Thermoprozesstechnik

Potentials of electric heat and CO₂-neutral fuels for thermoprocessing technologies

Herbert Pfeifer

Institute for Industrial Furnaces and Heat Engineering
RWTH Aachen University



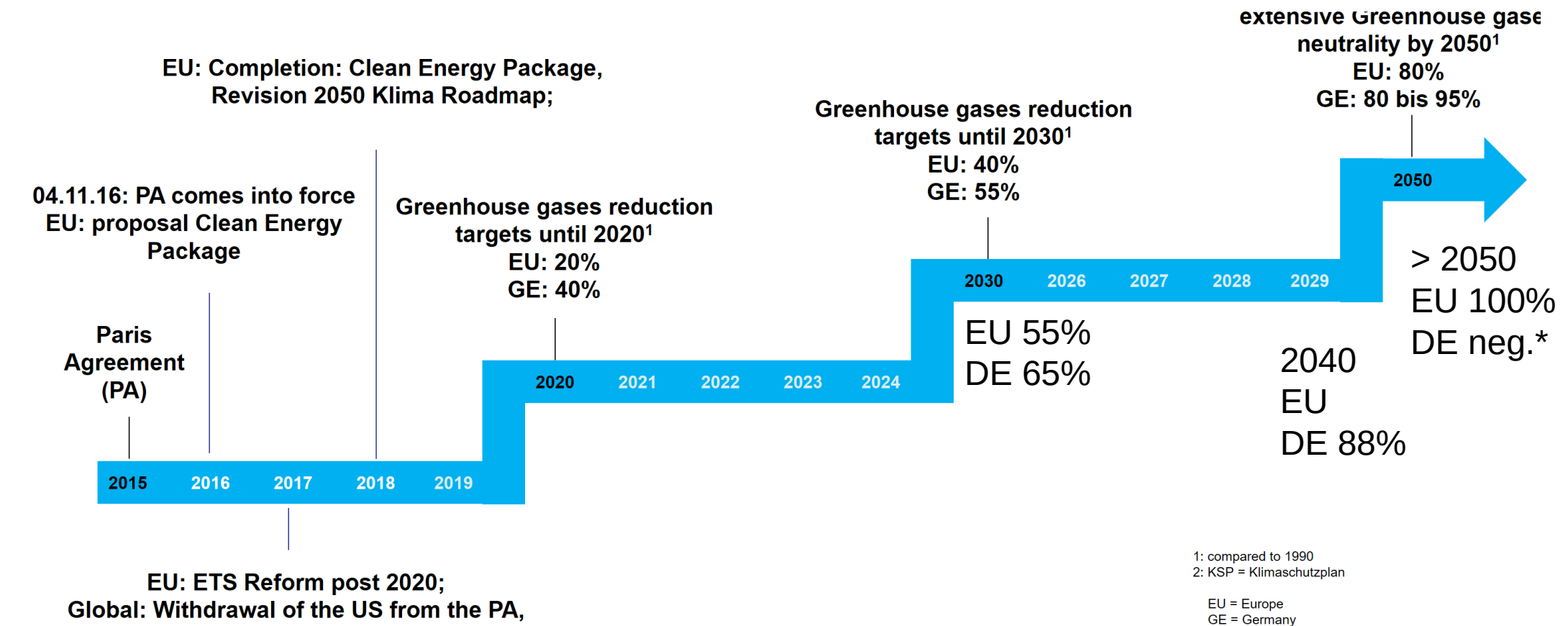
„Process and plant technology for the thermochemical and thermo-physical treatment of **materials and substances** in such a way that the **optimum product properties** are set **economically/ecologically** by the specific adjustment and control of the **material temperature** and the **process atmosphere**”.

All materials, **all** thermal processes in furnaces (metals, glass, ceramics, raw materials, electrical engineering and electronics, food, ...)

➡ **Industrial furnaces (thermoprocessing equipment) are important elements of the **process and manufacturing chain** from steelmaking to product**



Roadmap: Climate policy



CECOF Dr. Franz Beneke 70 years of Ebner in motion

* negative Greenhouse Gas-Emissions



So far

- Technical feasibility for given process
- Availability of energy sources
(electricity, grid gases, non-grid gases)
- Cost (economy)
Energy efficiency
Price ratio electricity/fuel gas
- Pollutants (NO_x , CO, ...)

Future

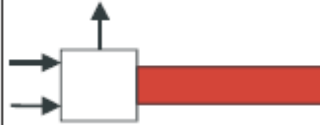
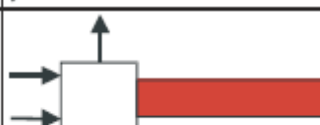
- CO₂ minimization **to zero**
Scope 1 (*direct*), Scope 2 (*including electricity*), Scope 3 (*including production, materials etc.*)
- Electrification/Hybrid Heating
- CO₂-neutral fuels
Hydrogen (material and energy use)
Synthetic fuels (eFuels)
C-free energy sources/fuels such as ammonia, dimethyl ether, bio gas
- Carbon footprint



Classification of industrial furnaces according to the heating method

(a) Fuels and other

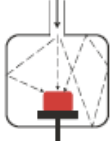
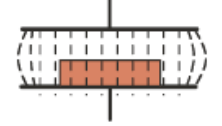
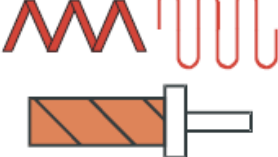
(b) Selection of electric heating processes

Heating			Principle
Fuels	gaseous	direct	Burner 
		indirect	Radiant tube Radiating surface Muffle 
	liquid	direct	Burner 
		indirect	Radiant tube Radiating surface Muffle 
	combined gas / liquid		Burner 
Combined (Hybrid)			Fuel / electric Hybrid Heating
Others			Gas
			Thermo-oil
			Hot water
			Steam

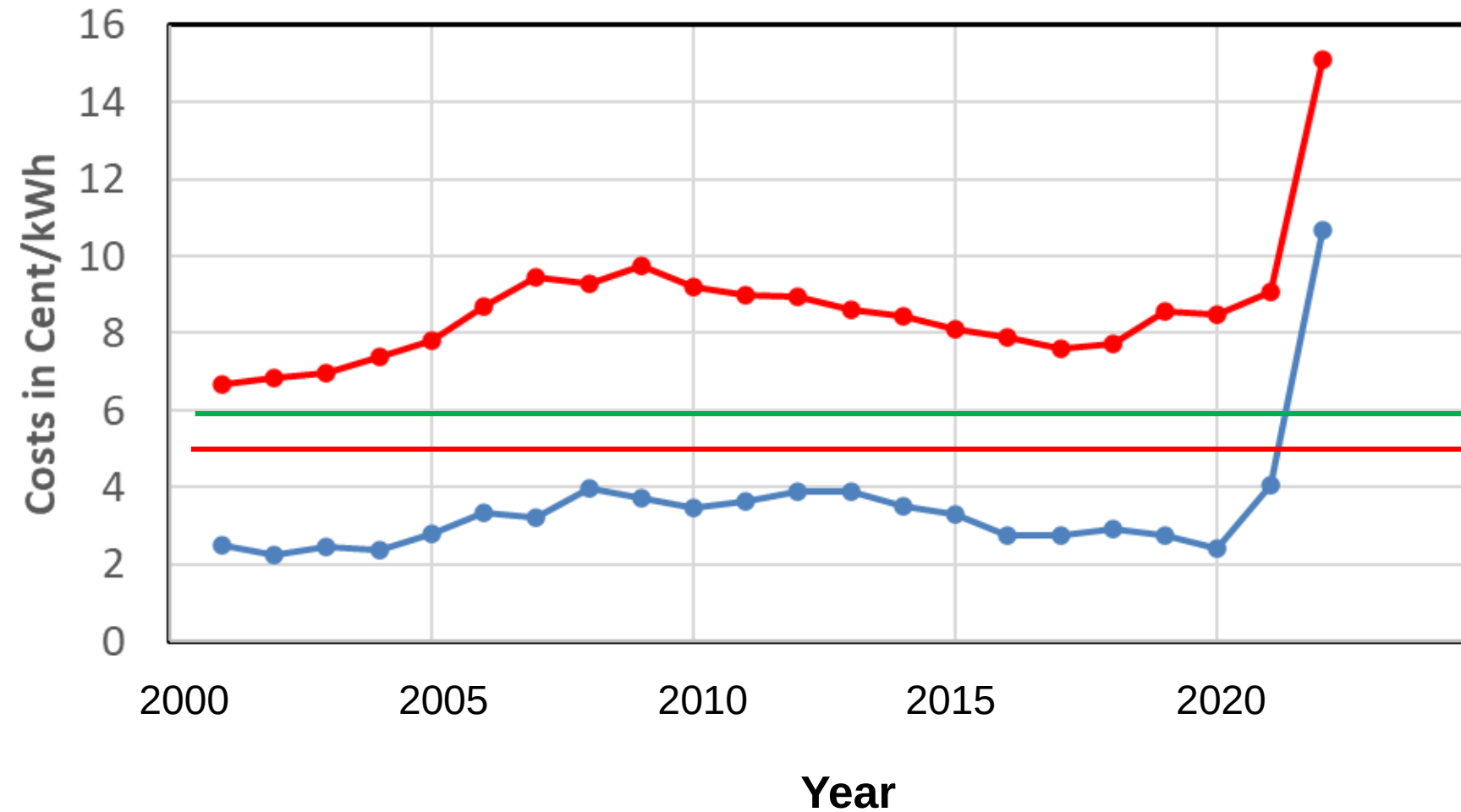
H₂

→ CO₂-free



Heating		Principle	Example
electric	direct principles	Closed iron core	 Induction channel furnace
		Iron core partially closed	 Inductive coil reheating
		without flux guide	 Induction crucible furnace
		conductive	 Wire reheating
		dielectric	Microwave  Dryers for foundry cores
	indirect principles	EH HF	 Paper drying
		Resistance heating	Metallic resistance heaters (spiral, strips, cartridge, salt bath)  Case hardening
		Electric arc	 EAF-furnace
		Plasma	 Plasma cutting

Prices for electricity and natural gas for industry (Germany) (Source: STATISTA)



Suggested

SPD party
5 Cent/kWh

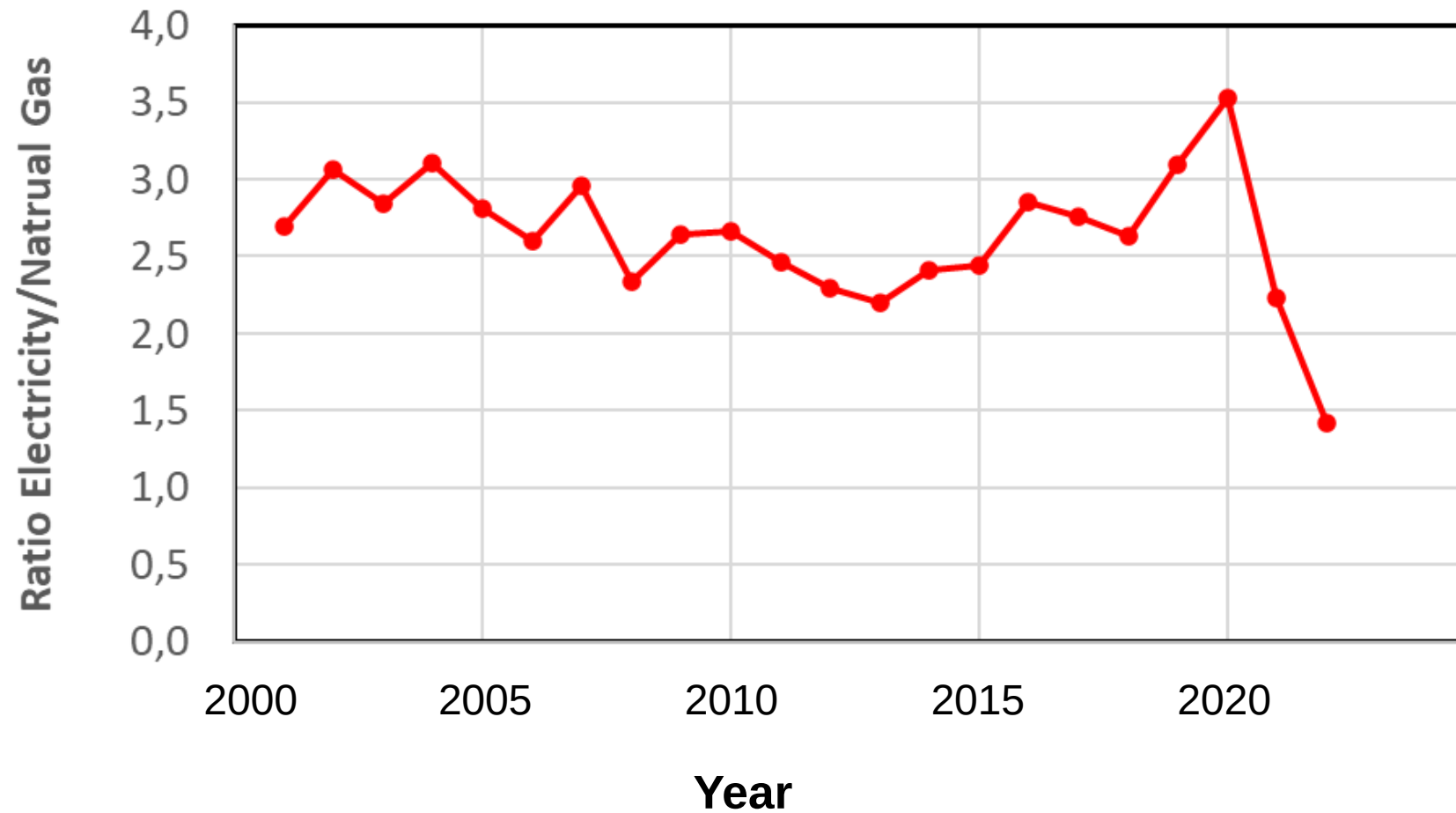
Green party
6 Cent/kWh

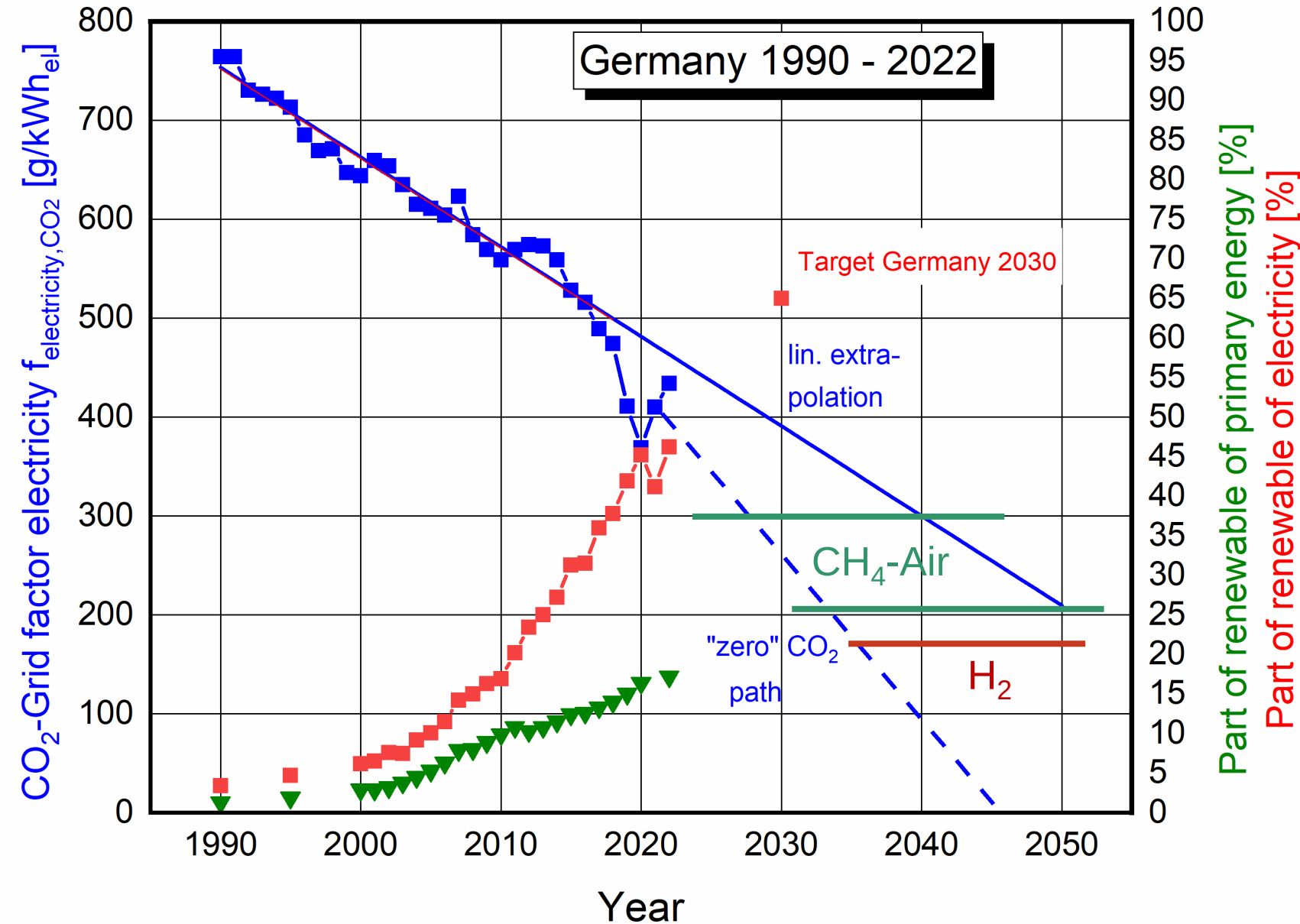
Who is eligible?

How long?



Cost Ratio of Electricity/Natural Gas for Industry in Germany (Source: STATISTA)





Needed activities of thermoprocessing industry for further customers

Whats to do?

Power-to-X (X: fuels) - (or) ready for use

E-ready

Electrification (energy density limited for resistance heating)

H₂-ready

„Hydrification“ (Hydrogen from renewable energies, infrastrukt, import, storage)

A-ready Ammonia (NH₃)

„Ammonisation“ (transport, production, storage)

eFuel-ready

Synthetic Natural gas

B-ready (Bio-gas)

Bio gas to NG or H₂

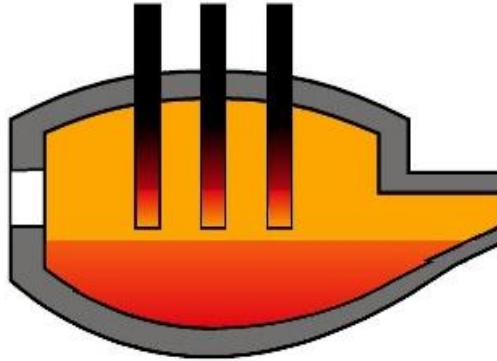
D-ready

Dimethylether

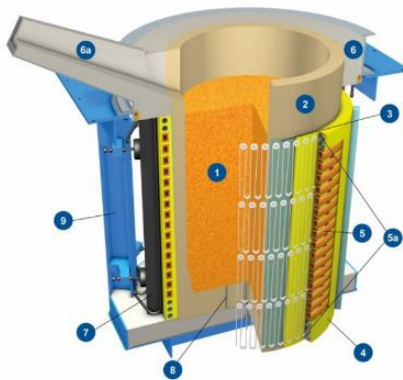
X-ready

„Ready for everything“





EAF



Inductive melting



Hydrogen



Resistance heating



Inductive heating



Classification of industrial furnaces according to the heating method

(a) Fuels and other

(b) Selection of electric heating processes

Heating			Principle
Fuels H_2	gaseous	direct	Burner
		indirect	Radiant tube Radiating surface Muffle
	liquid	direct	Burner
		indirect	Radiant tube Radiating surface Muffle
	combined gas / liquid		Burner
	Combined (Hybrid)		Fuel / electric
	Others		Gas Thermo-oil Hot water Steam

Hybrid Heating

→ CO_2 -free

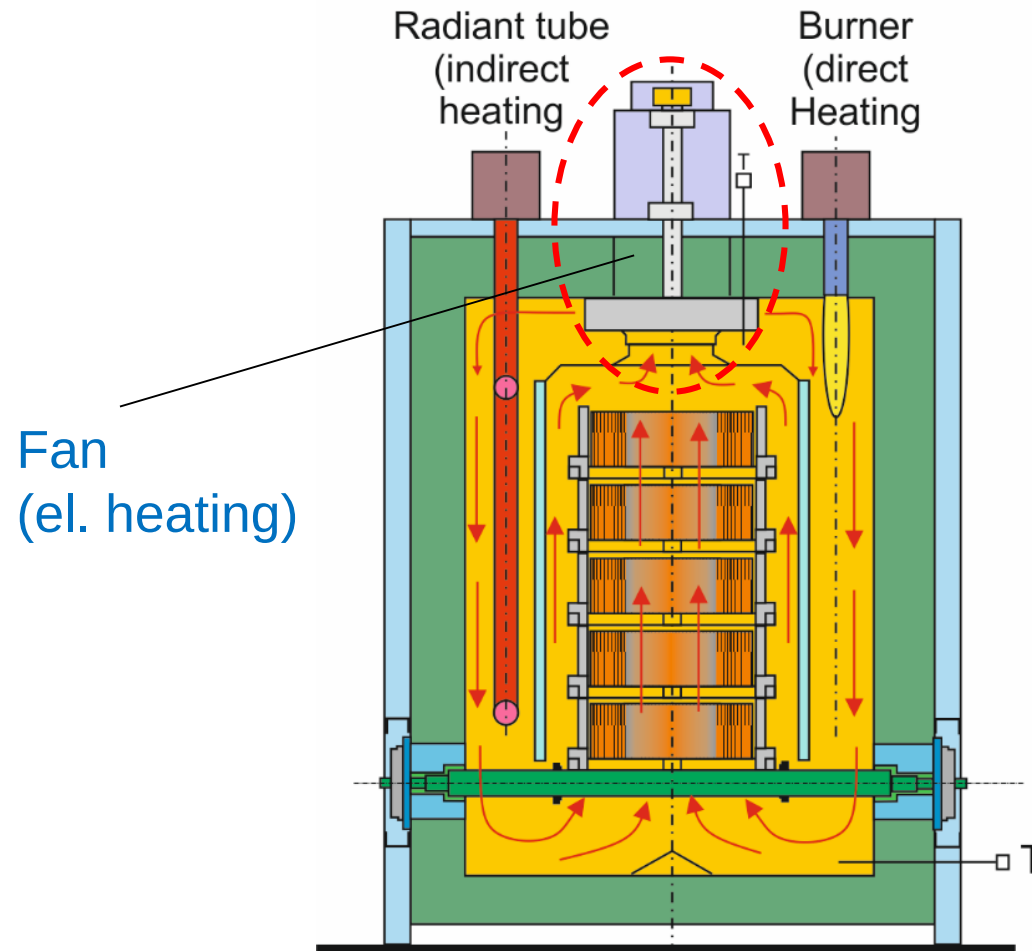


Heating		Principle	Example
electric	direct principles	Closed iron core	Induction channel furnace
		Iron core partially closed	Inductive coil reheating
		without flux guide	Induction crucible furnace
		conductive	Wire reheating
		dielectric	Microwave
	indirect principles	EH HF	Paper drying
		Resistance heating	Case hardening
		Electric arc	EAF-furnace
		Plasma	Plasma cutting

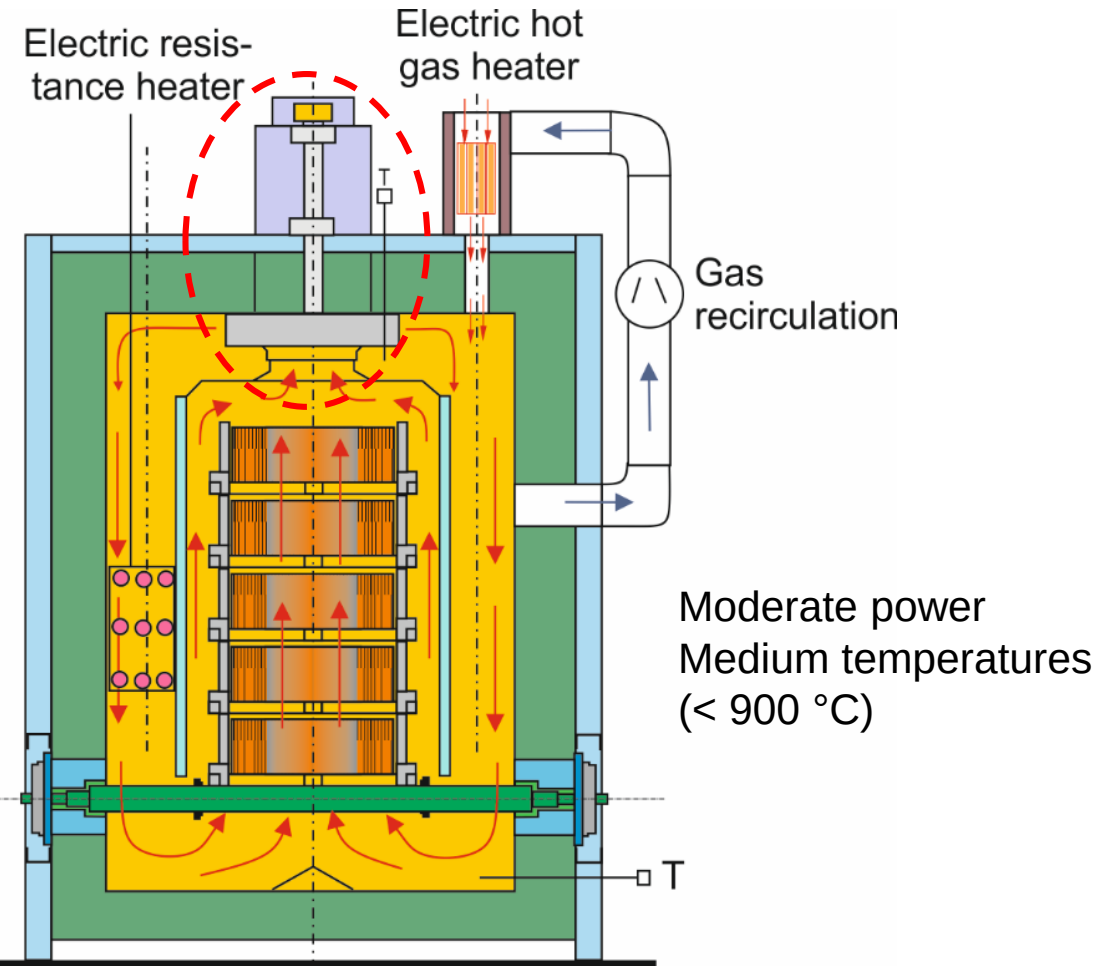


Scenario for the electrification of a coil annealing (non ferrous) system with **forced convection**

State of the art – direct or indirect
fossil heated

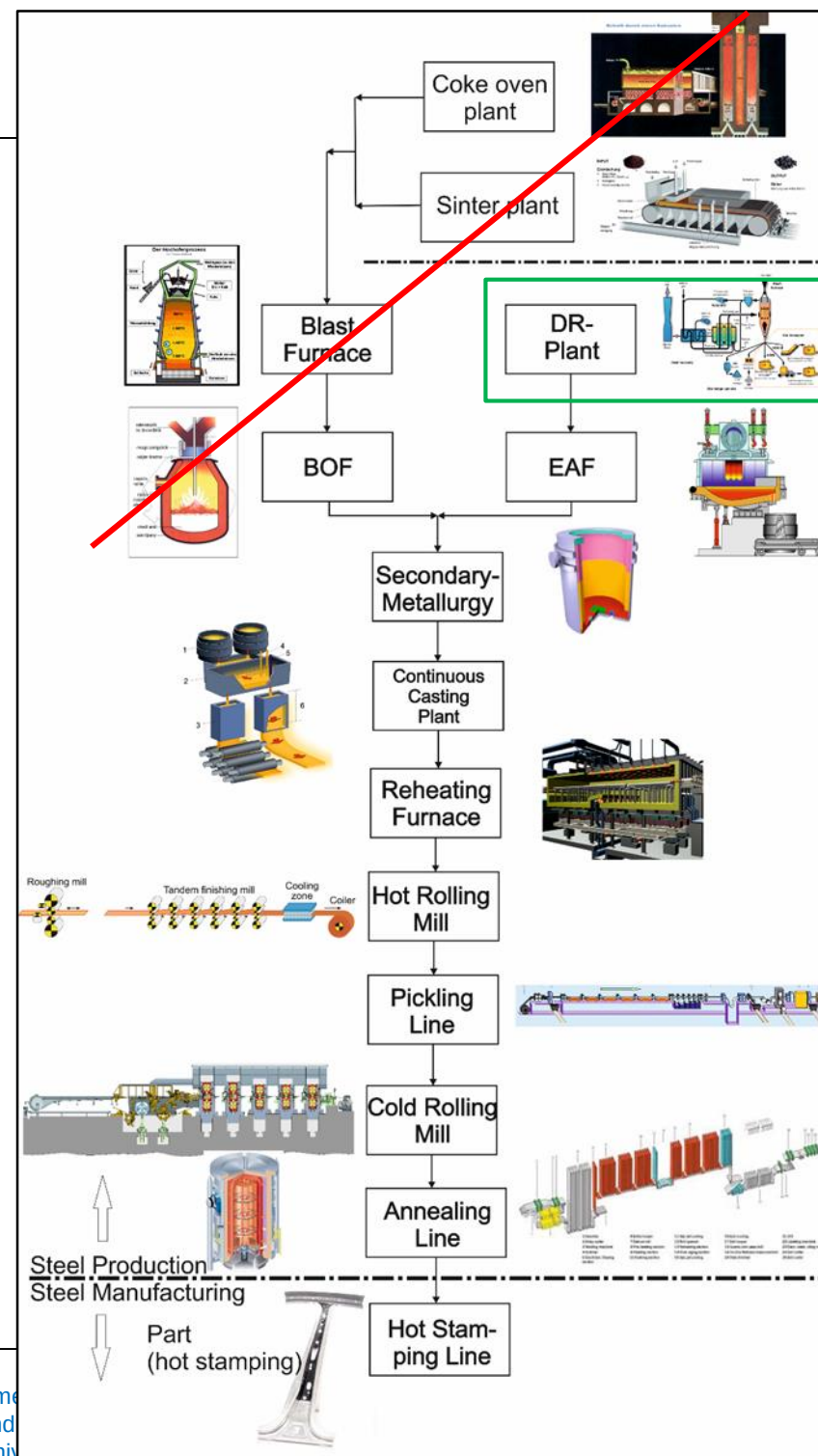


Electric heated – Resistance heating elements
or electric hot gas heater



Consequences for design and use: New concepts, fan is heat input by electricity, hybrid, retrofittable,





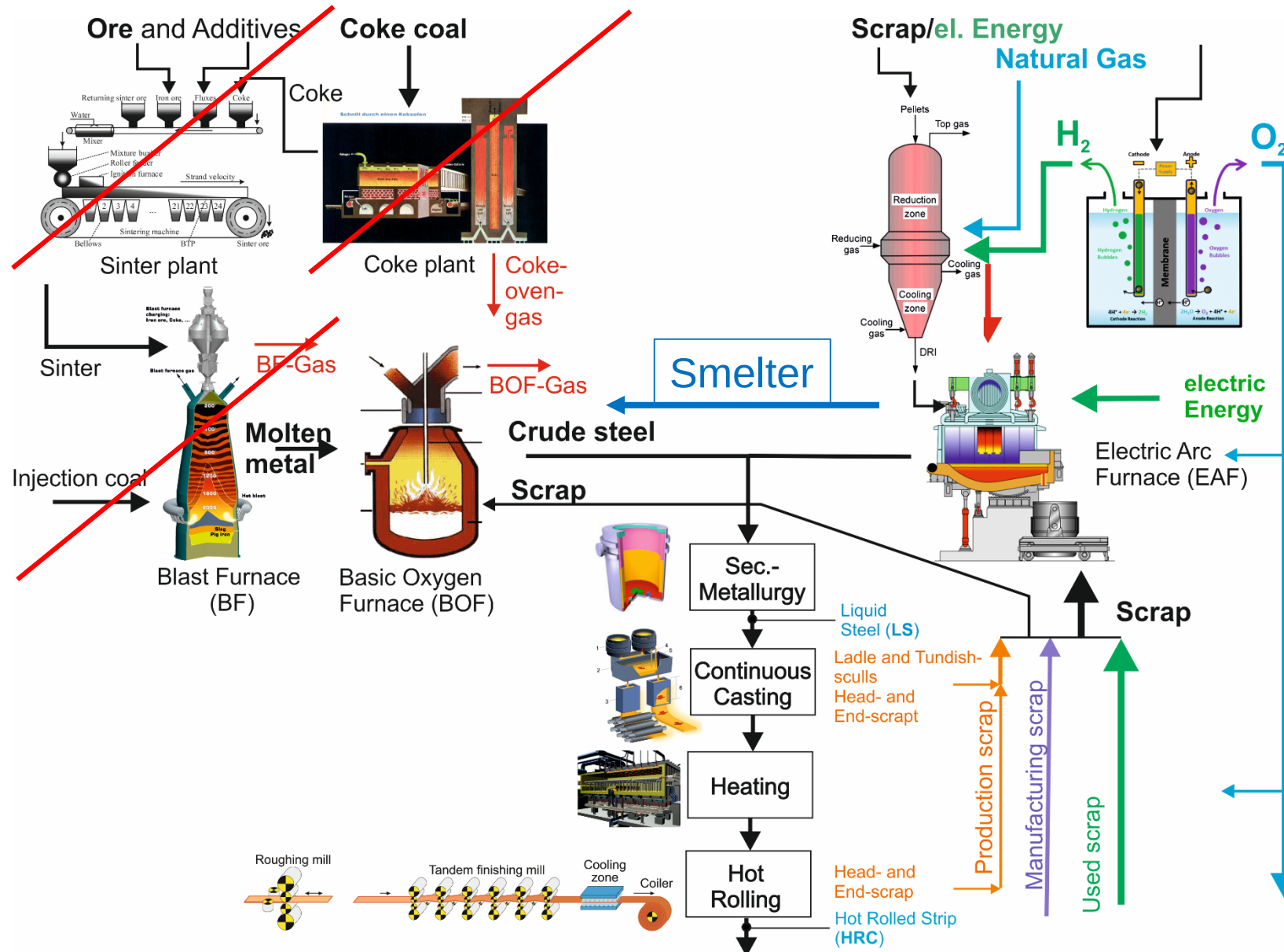
Consequences

- Changes of Process route from COP, SP, BF and BOF to DR-Plant and EAF (OBSF)
- Influence on Carbon Foot-Print
- Hydrogen for Reheating Furnaces and Continuous Annealing Lines



Option for action: Increased use of natural gas and hydrogen for iron production

From ore to steel - perspective process mix in Germany - direct reduction



Direct-Reduction
(NG → H₂)

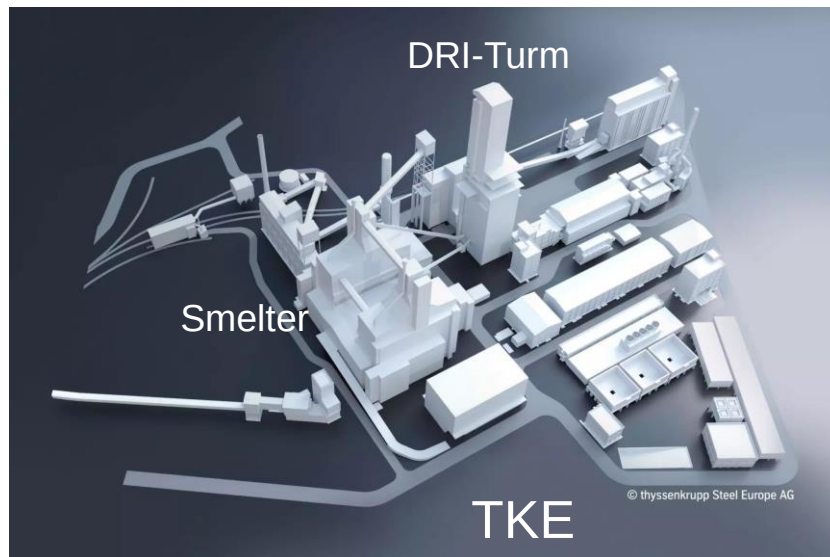
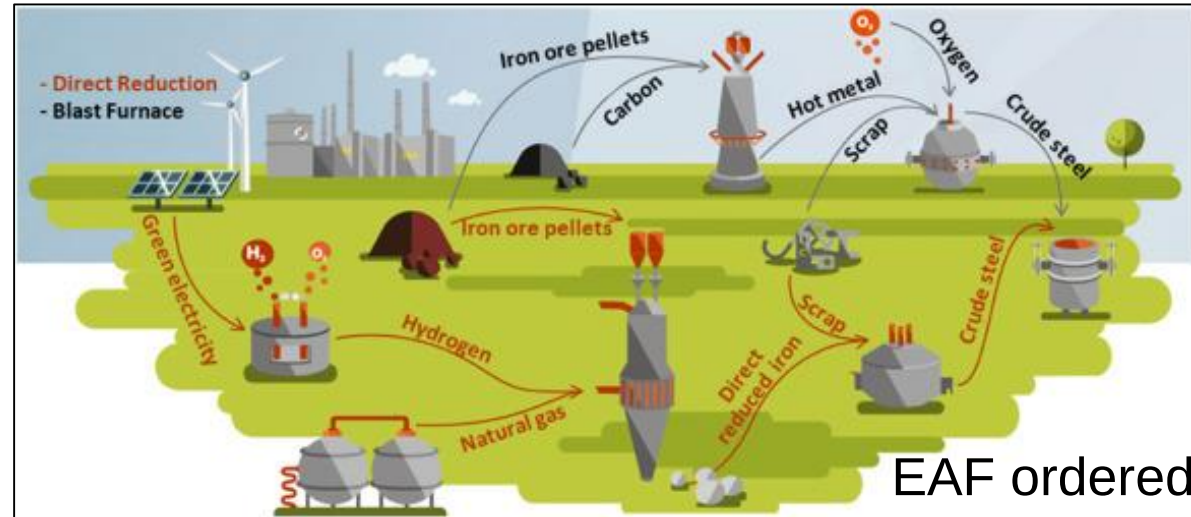
+

Electric Arc Furnace and/or OSBF (SAF)
(Electric Energy)



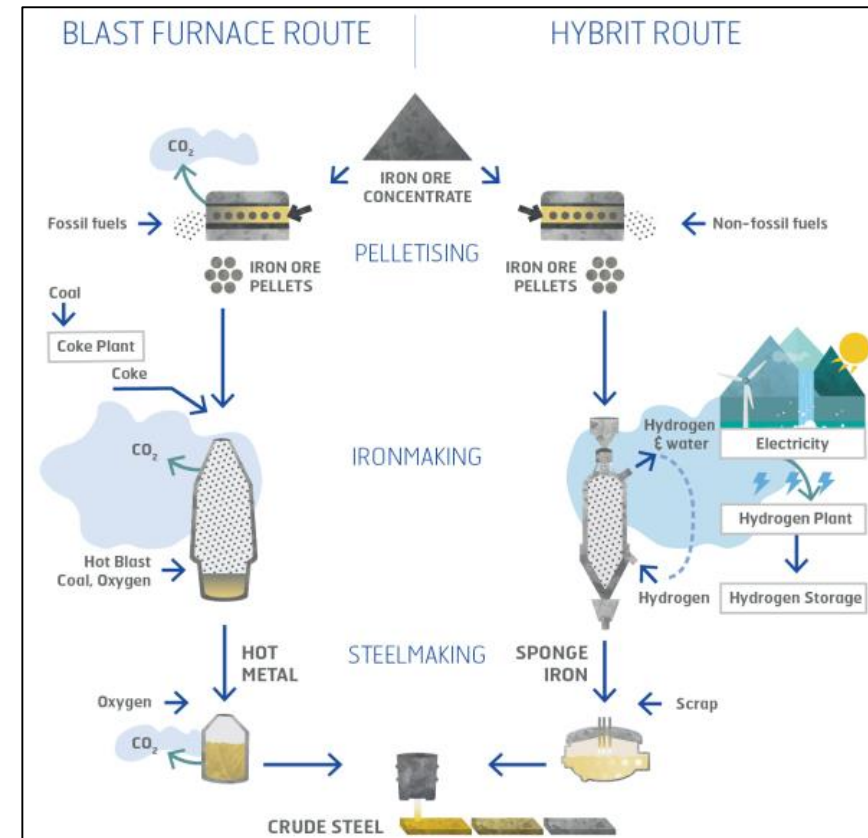
Initiatives for CO₂-free or low-CO₂ steel production (examples)

Salcos (Salzgitter, D) Salzgitter Low CO₂ Steelmaking

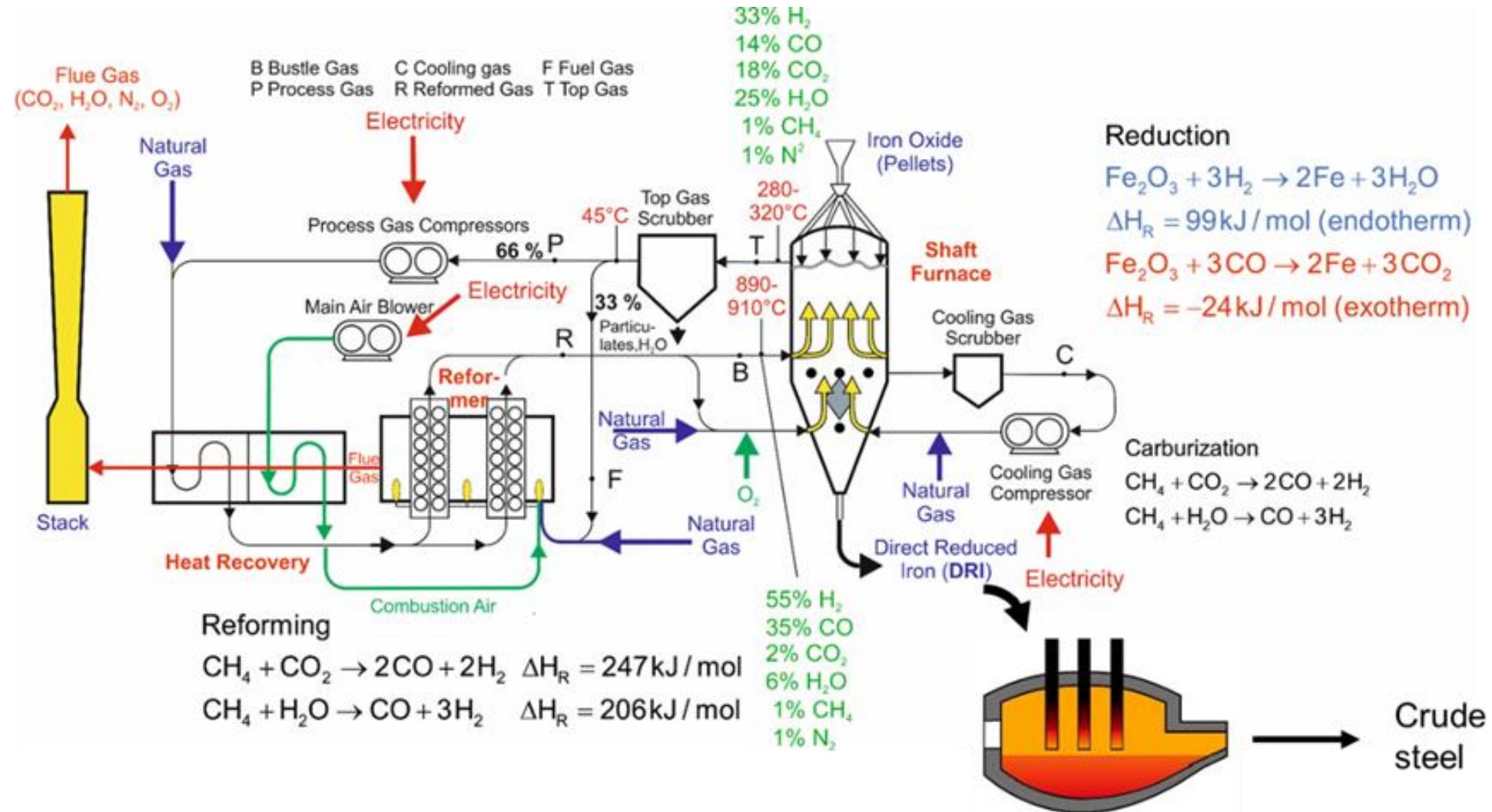


DRI-plant
and two
smelters
ordered

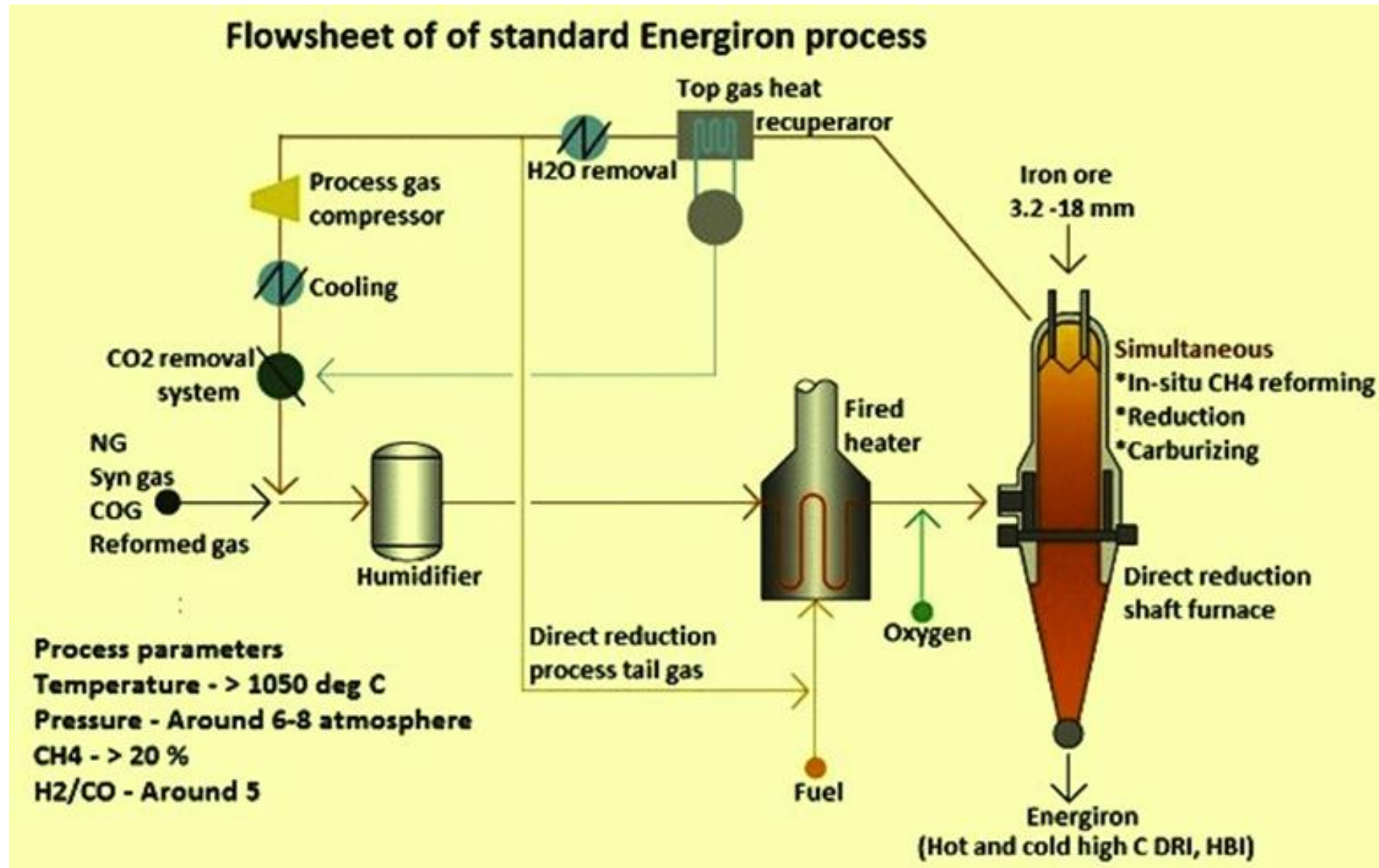
HYBRIT(LKAB, SSAB, Vattenfall, S) Hydrogen Breakthrough Ironmaking Technology



Direct reduction process (MIDREX)



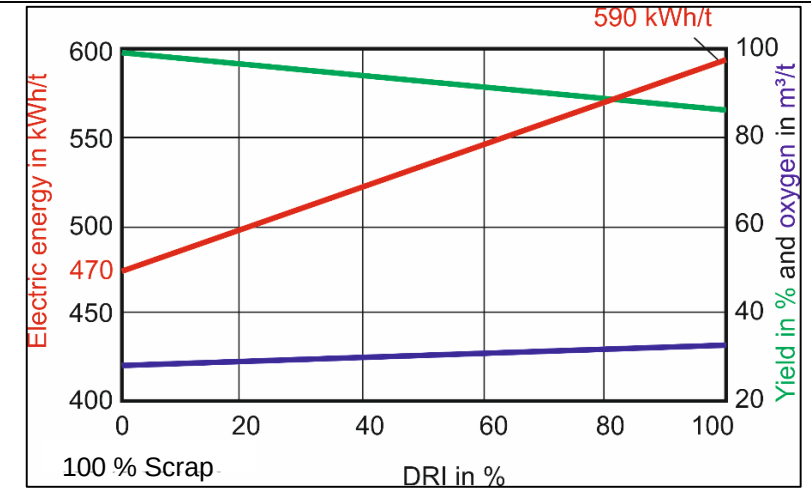
Direct reduction process (Energiron ZR)



CO₂-Emissions (80% DRI + 20% Scrap)

Typical production		CO ₂
Production	175-320 t/h	
Typical annual production	1.5 – 2.5 Mt/y	
Commodities and Energy		
Iron ore pellets	1380 – 1450 kg/t DRI	
Coating of pellets	1 – 4 kg/t DRI	
Natural gas	9,6 – 11,3 GJ/t DRI 265 – 315 m ³ NG/t DRI 2650 – 3150 kWh/t DRI	530 – 630 kg CO ₂ /t DRI
Oxygen	20 – 50 m ³ /t DRI	6 – 15 kg CO ₂ /t DRI
Nitrogen	10 – 30 m ³ /t DRI	
Electricity	80 – 150 kWh/t DRI	28 – 53 kg CO ₂ /t DRI ¹⁾
Product		(-36) – (-144) CO ₂ /t DRI
DRI	1000 kg (90-94% Fe, 1-4% C, 3-6% other oxides)	Summe 528 – 544 kg CO₂/t DRI

¹⁾ 0,35 kg CO₂/kWh_{el}



80% DRI (2% C) / 20% Scrap

DRI-Production
DRI-Melting
Scrap Melting
Σ Liquid Steel
Yield Hot Rolled Strip
Reheating

470 kg CO₂/t_{St}
410 kg CO₂/t_{St}
80 kg CO₂/t_{St}
960 kg CO₂/t_{liquid st}
95%
70 kg CO₂/t_{St}
1080 kg CO₂/t_{HRSt}



Process flow for Direct Reduction Process – 100 % H₂

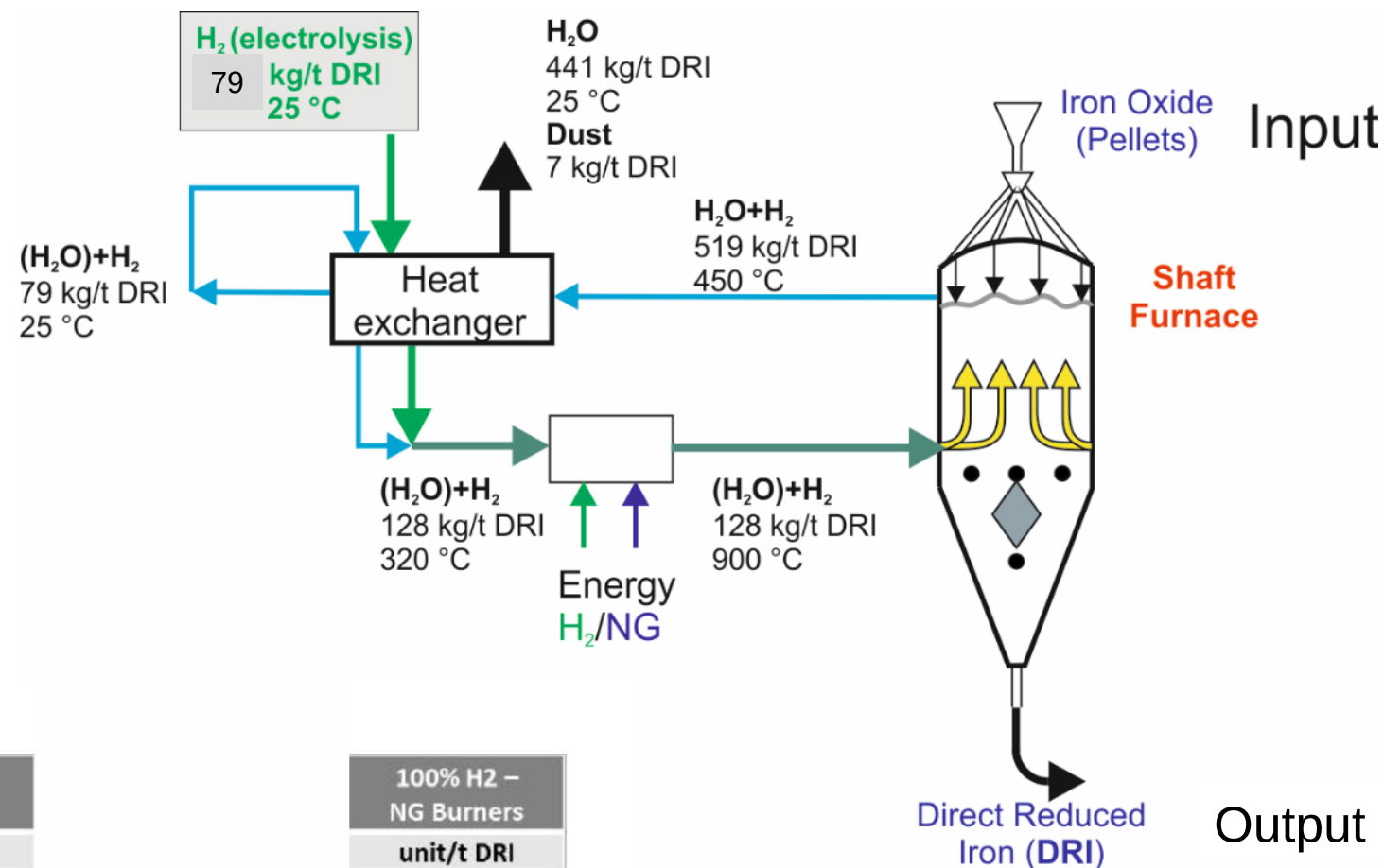


Table: Main inputs an

	Unit	100% H2
Item		unit/t DRI
Natural Gas	GJ	0
	Nm3	0
Hydrogen	GJ	9,4
	Nm3	870
Overall Gas	GJ	9,4
Max C in DRI	%	0
CO ₂	kg	0,0

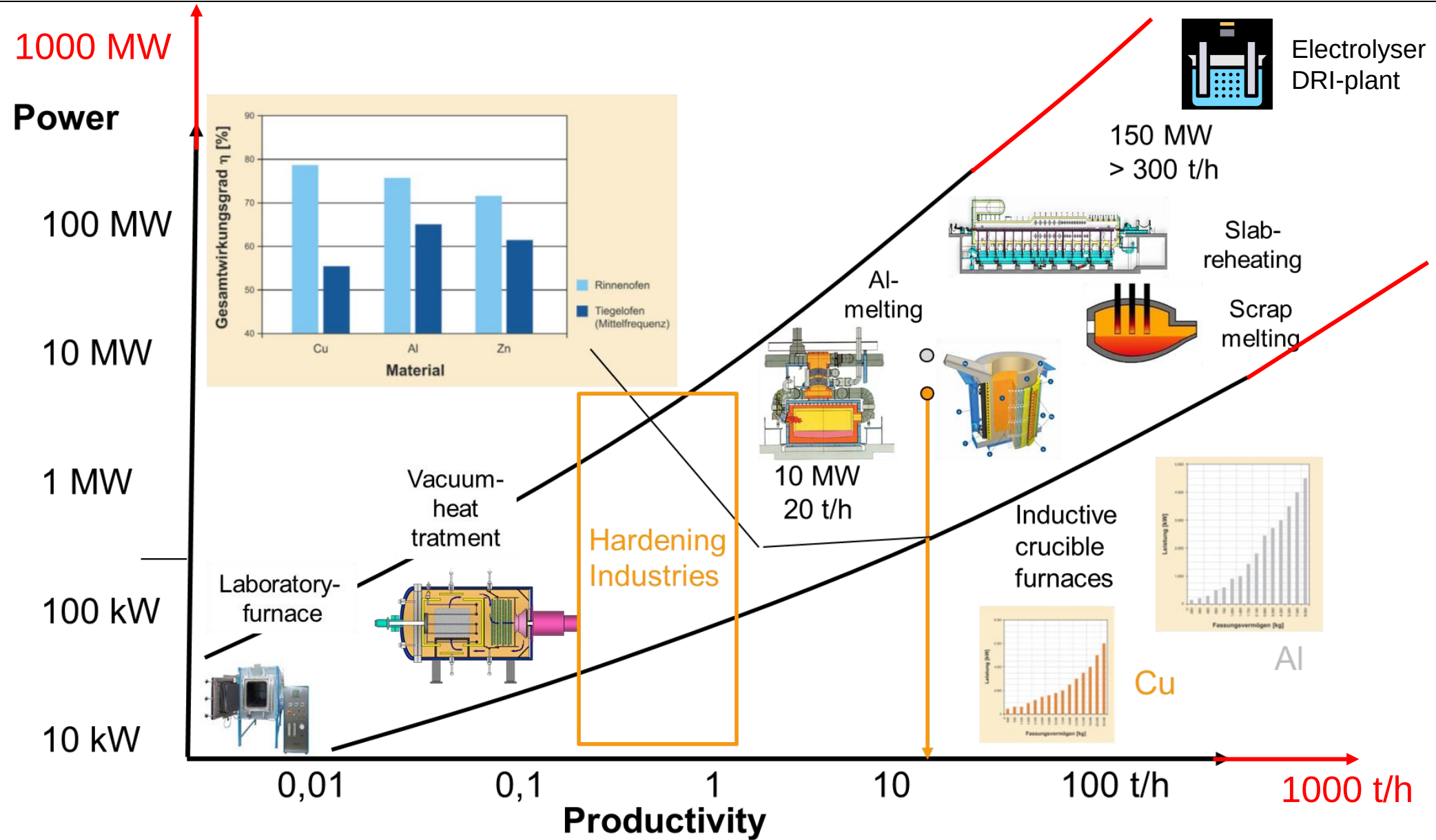
78 kg H₂/t DRI

100% H2 – NG Burners
unit/t DRI
2,7
84
6,7
620
9,4
0
150

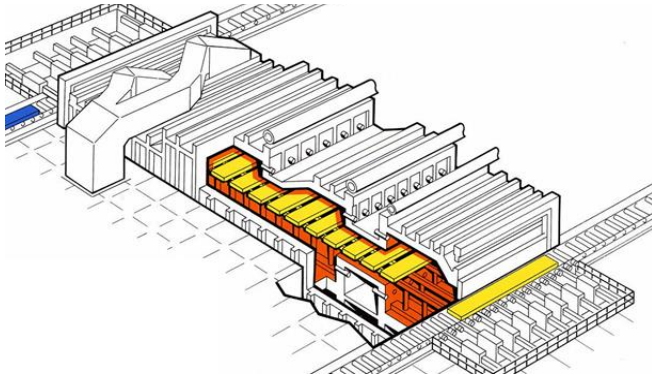
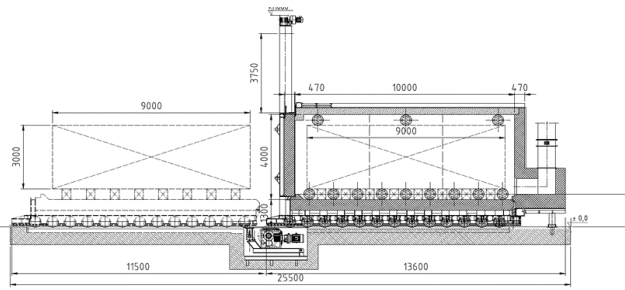
56 kg H₂/t DRI



Power and productivity range of industrial furnaces - Electrical energy vs. fuels



Limits of electric-resistance heated industrial furnaces for heating of metals

Ofentyp	Furnace type	Max. Temperatur	Characteristic data
	Walking beam furnace, pusher type furnace 	1250 °C	A: 100 bis 150 MV B: 400 m² C: 30 kW/m² D: 12 MW
	Chamber furnace - Forging 	1350 °C	A: 8 MW B: 60 m² C: 20 kW/m² D: 1,2 MW

Ofentyp	Furnace type	Max. Temperatur	Characteristic data
	Chamber furnace – heat treatment 	750 °C	A: 1,5 MW B: 60 m² C: 50 kW/m² D: 3 MW

A: Installierte Leistung **B:** Vorhandene Fläche **C:** Spez. max. Leistung Heizleiter **D:** el. installierbare Leistung

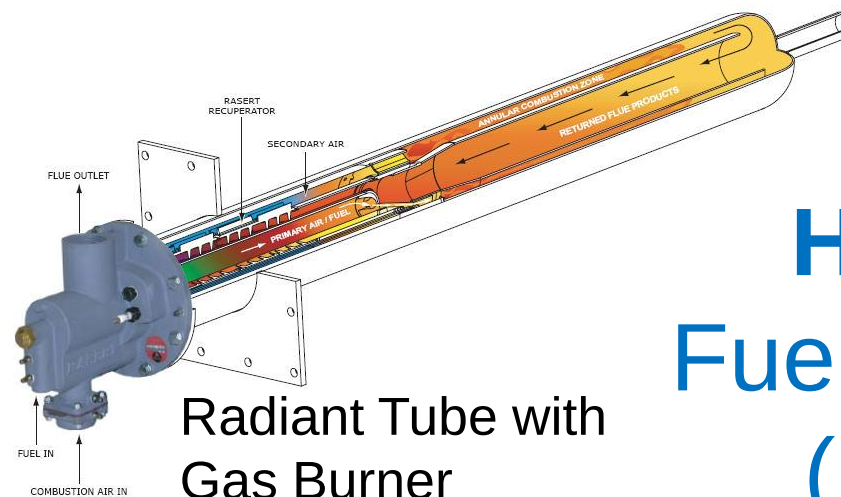
A: Installed power B: Available surface C: Spec. permissible power D: Installed power





Electric Radiant Tube

Hybrid Radiant Tube



Radiant Tube with Gas Burner

Hybrid Heating Fuel and/or Electricity (Power to heat)



0. Step: State of the art

1st Step: Hybrid Heating

2nd Step: Electric Heated Furnace

3rd Step: Hydrogen

4th Step: Synthetic Methane

„Hybrid Heating“: Flexible heating technologies for industrial furnaces
(by adapting to volatile renewable energy sources)



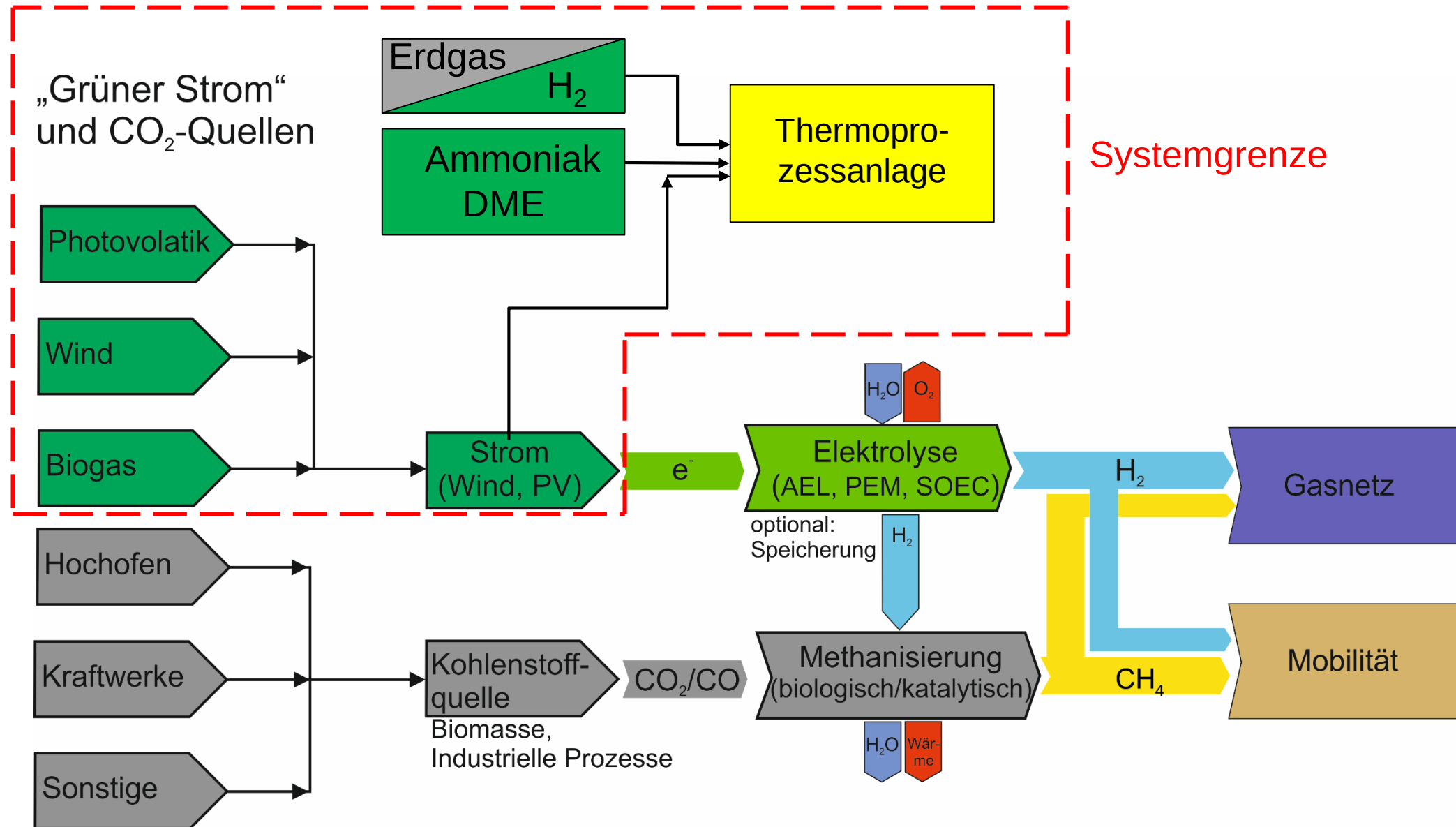
Hybrid heating describes the **flexible use of energy** in the future, but also the resulting uncertainties. The needed decarbonization of Thermoprocess industry and the associated use of renewable energies in place of the fossil fuels used to date, such as oil or gas, pose a wide range of **risks and challenges**, particularly for energy-intensive sectors such as industrial furnace technology. In order to be able to master these safely, economic business models are essential in addition to innovative thinking and action, for which new, strategic cooperations are often required.

In general, **in technology, hybrid means a system in which two technologies are combined**. The preceding designation hybrid emphasizes a whole composed of different types or processes. **The special feature is that the elements brought together already represent solutions in themselves, but by bringing them together new desired properties can arise.**

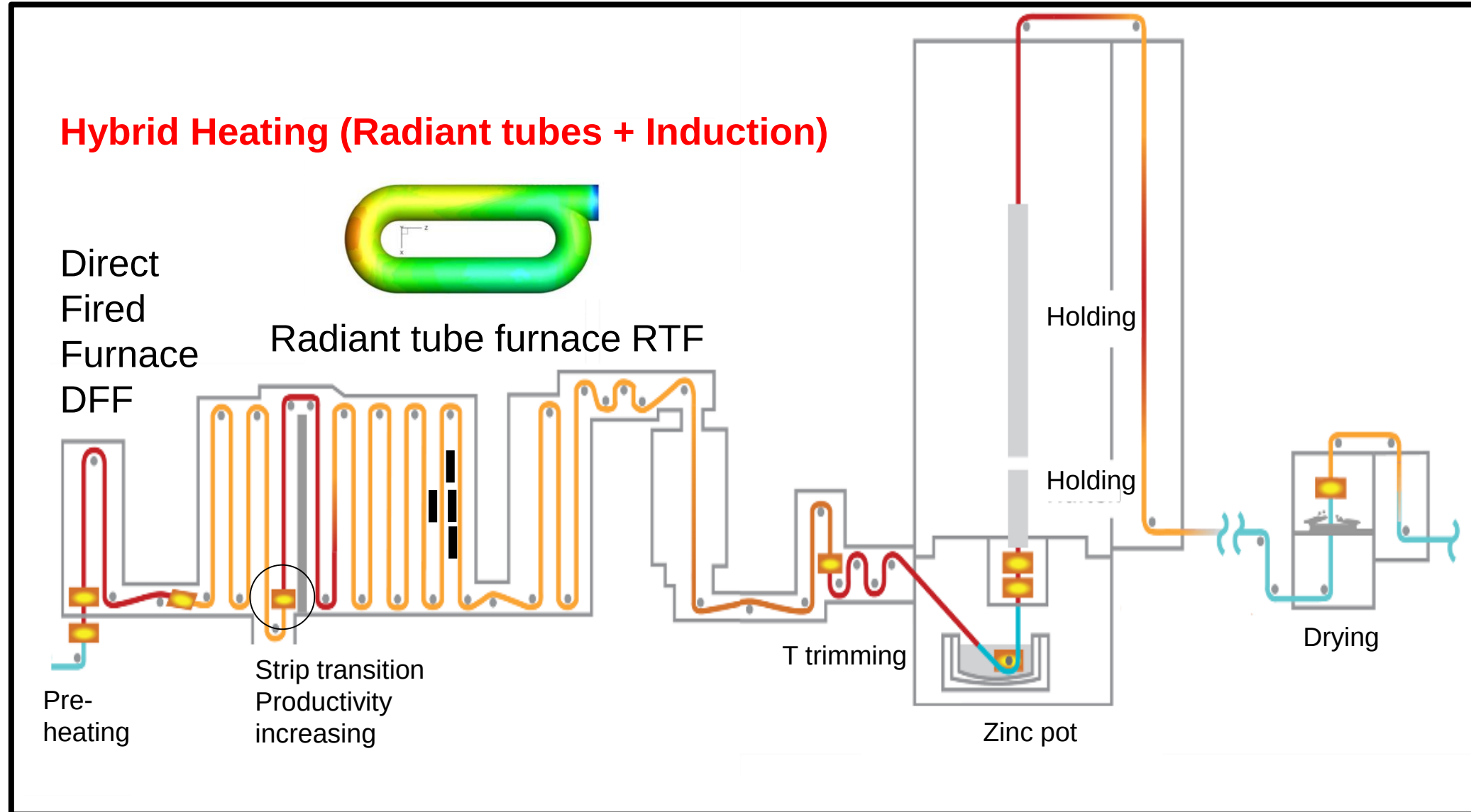
→ Flexibility concerning mix of electricity and fuel, minimization of operating costs, prepared for the future, ...



Sustainable energy supply: Power-to-G - Routes (X: fuels)



Selection options for the use of inductive cross-field heating systems in continuous plants for annealing steel strip – Hybrid Heating



Full hybrid (Attempt of definition)

Plant can be operated

- completely with fuel
- completely with electricity

Fast change between the energy sources (electricity, natural gas, others)

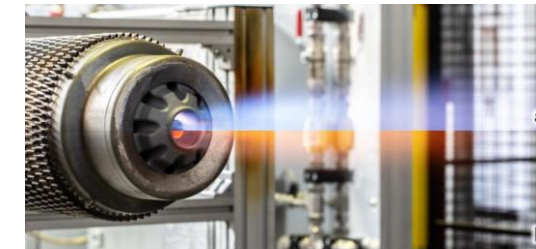
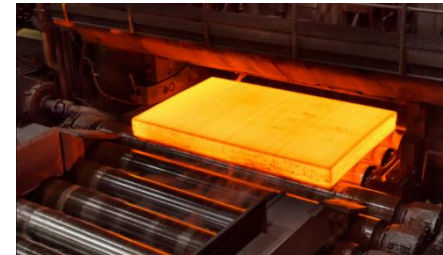
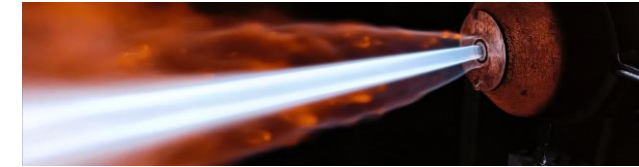
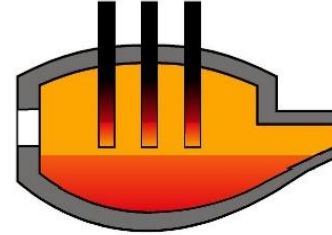
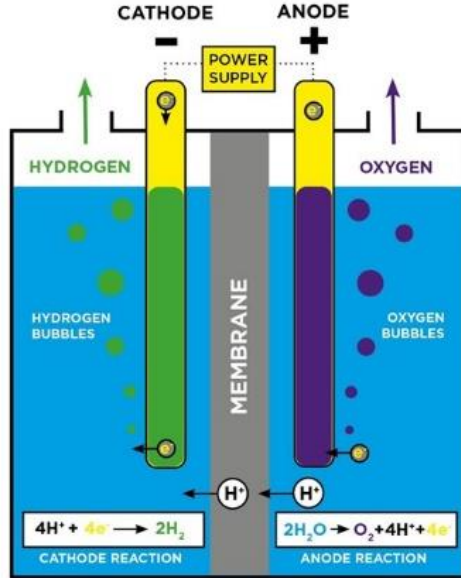
Data transfer of energy prices

Monitoring of CO₂-footprint

.....

Energy supply contract



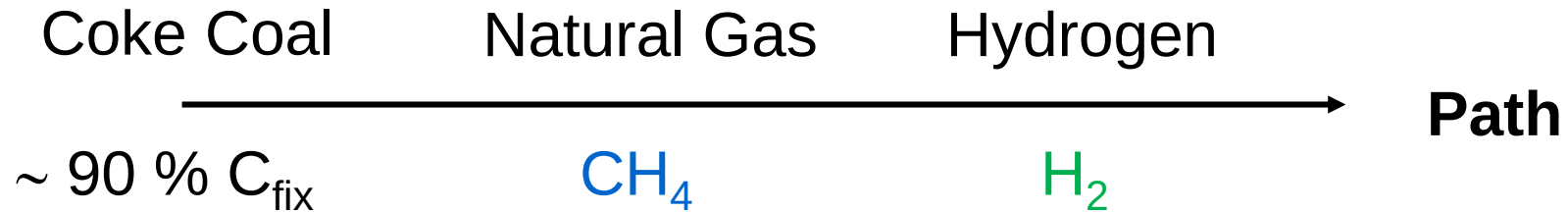


Energetic use of alternative (renewable) fuels (Fuels to Heat)

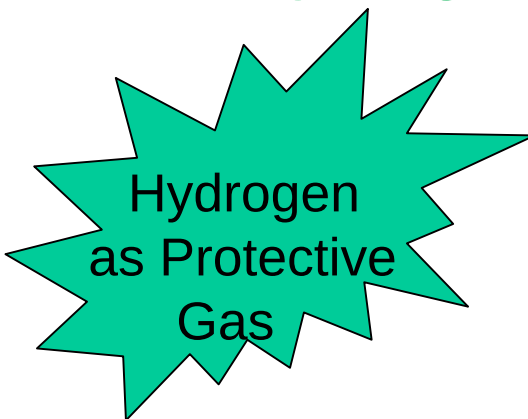
Hydrogen (mixtures) - H₂ ready burners
Ammonia



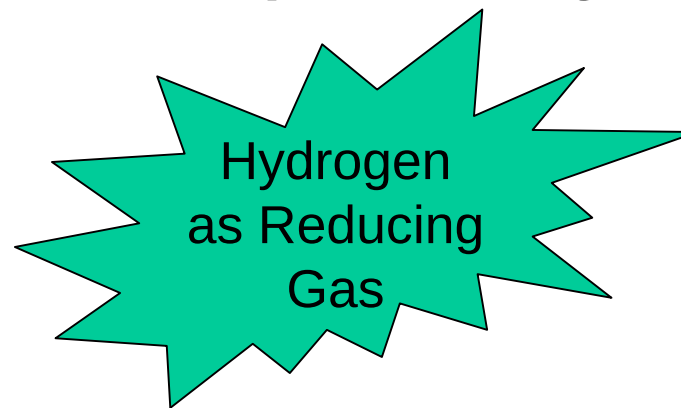
Carbon - **Hydrogen** - Ratio



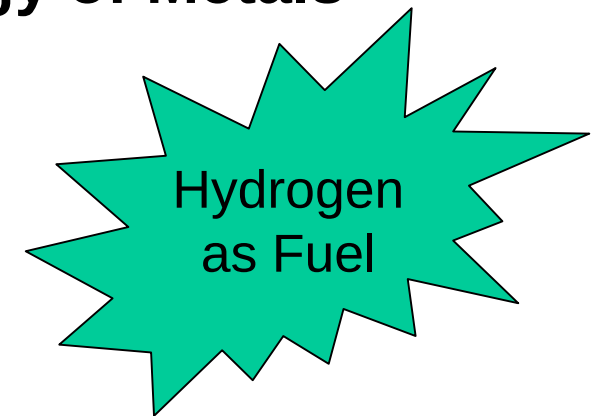
Hydrogen and Thermoprocessing Technology of Metals



5 to 100% H₂ ✓



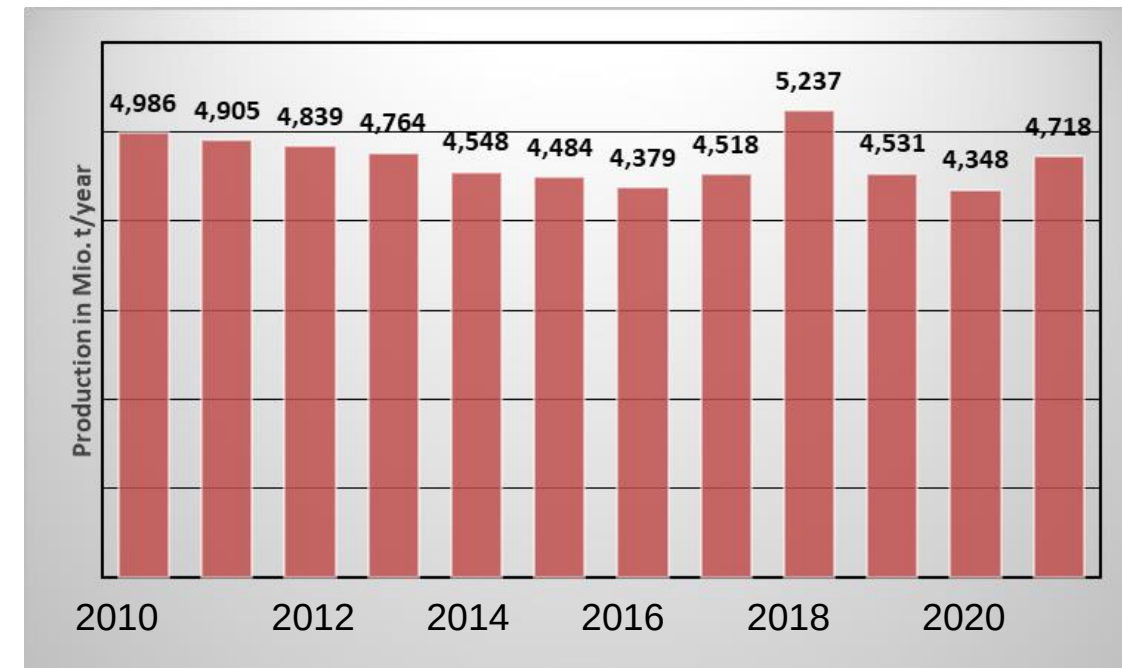
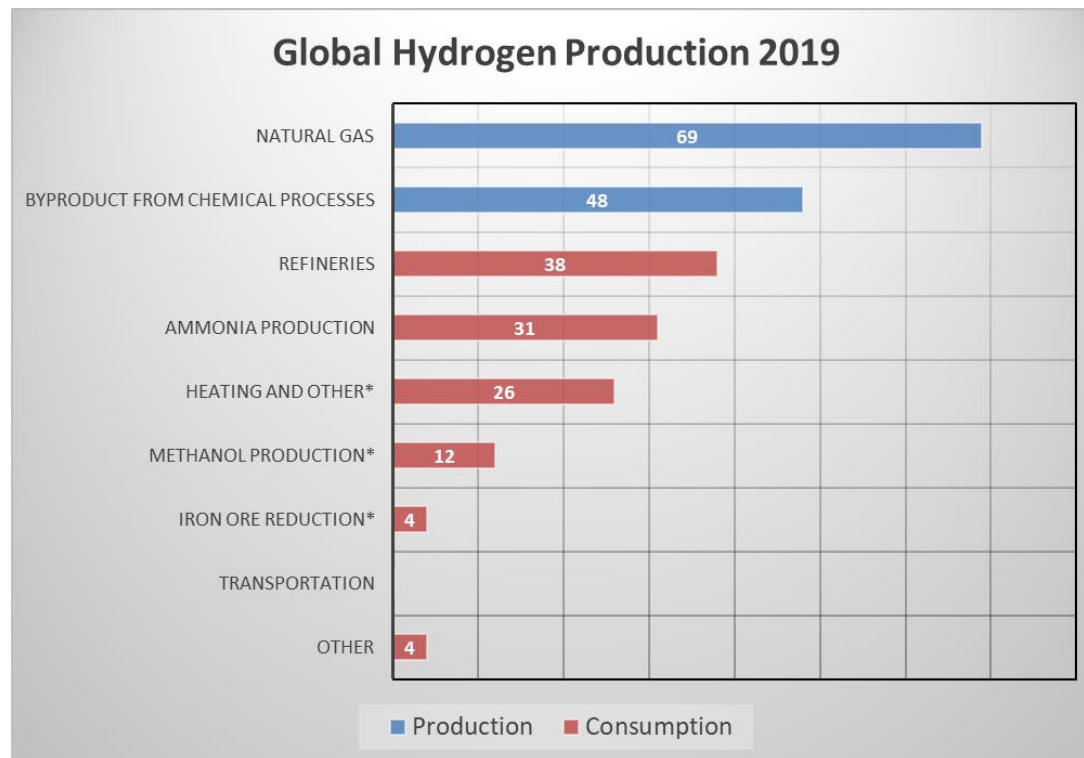
0% H₂ (100% CH₄) → 100% H₂ (0% CH₄)



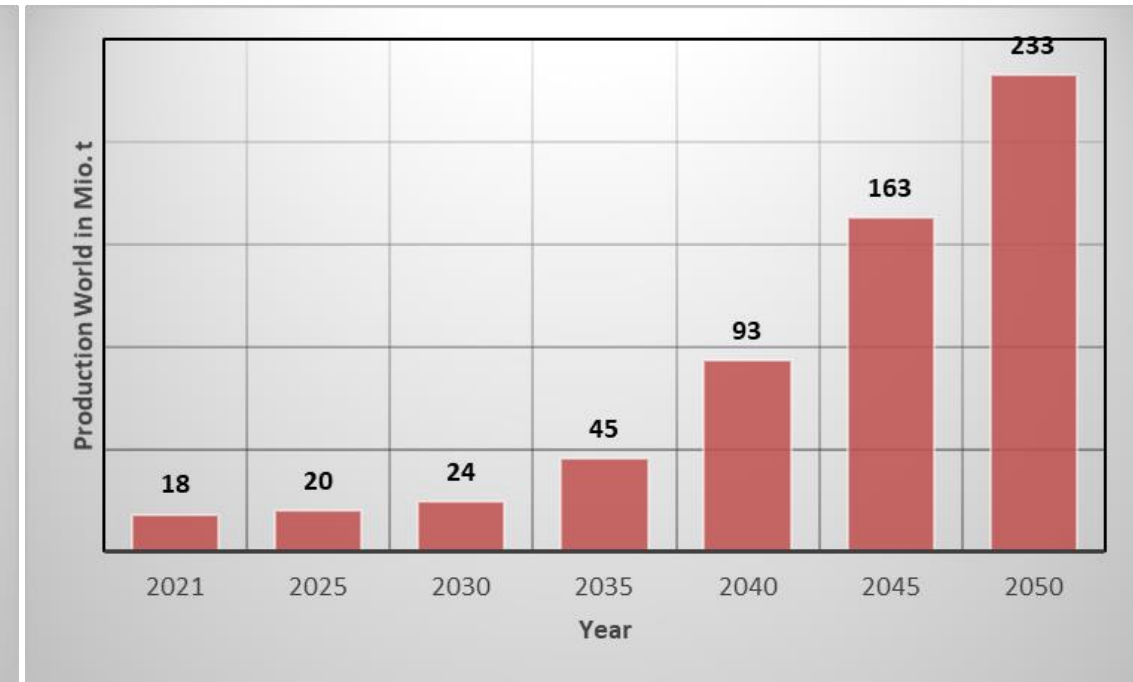
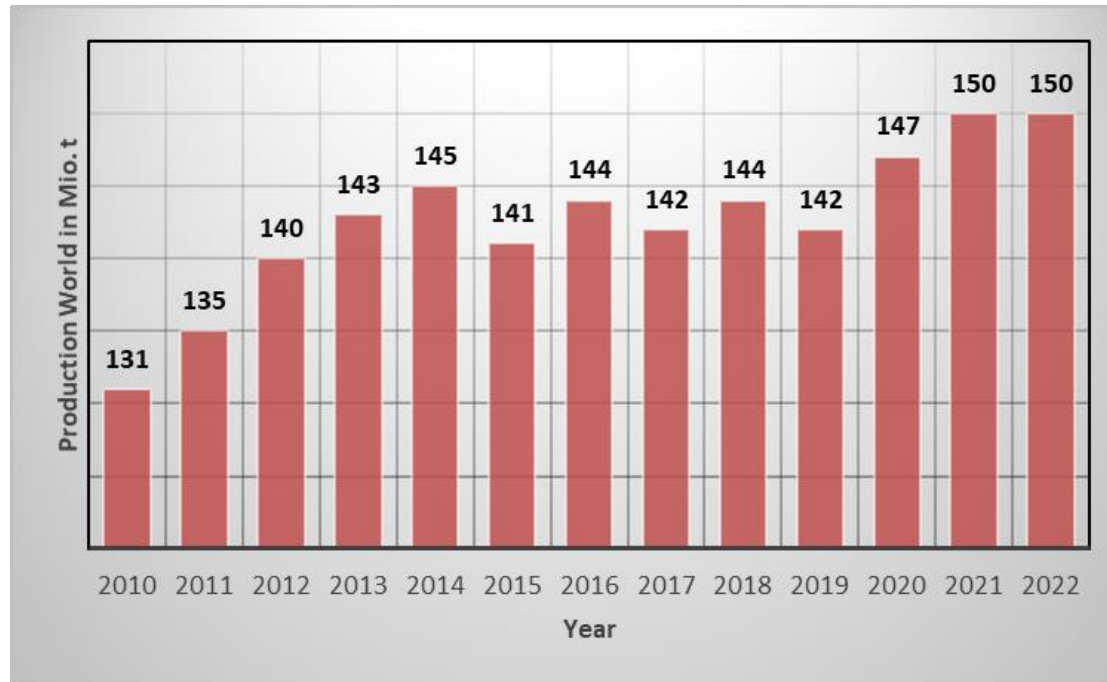
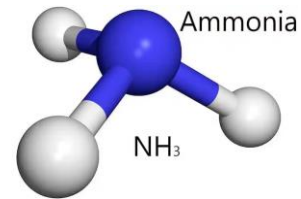
Substitution Natural Gas/
Co-Gases → H₂



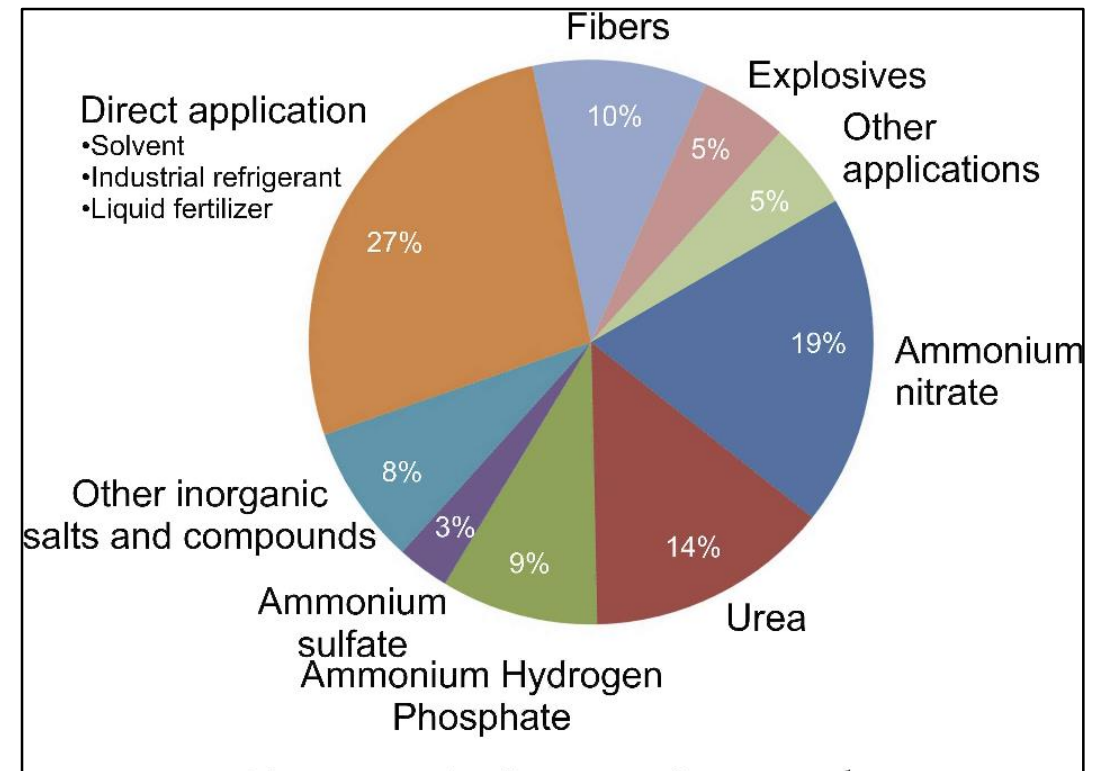
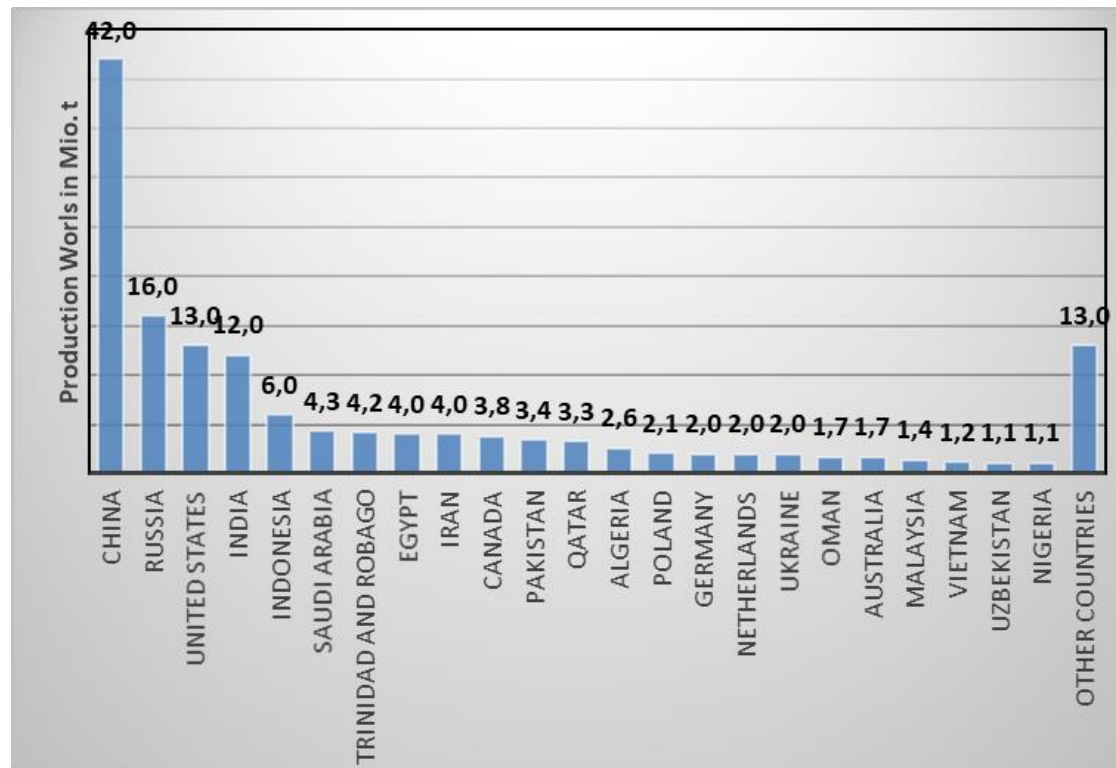
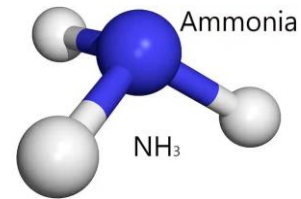
Global Hydrogen Production 2019 and Production in Germany 2010 to 2021



Global Ammonia Production 2010 - 2022 and expected traded ammonia till 2050



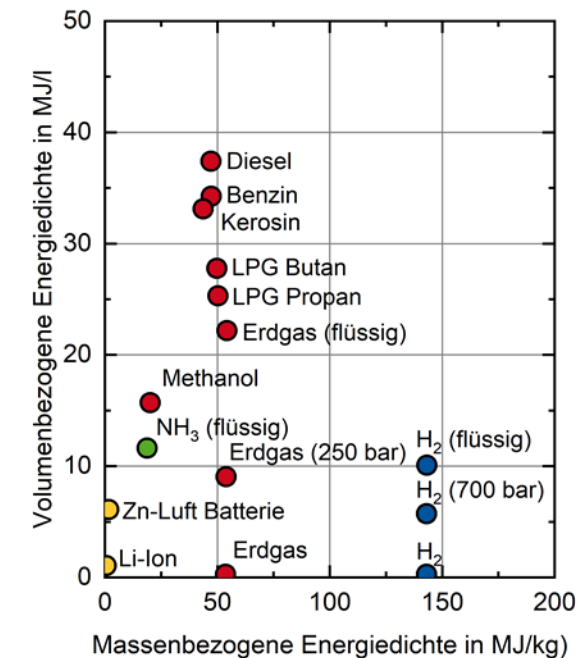
Ammonia Production for countries and Use of Ammonia



„Green“ Hydrogen and Ammonia as Fuel

- Pressure-liquefied ammonia is also being discussed as a fuel of the future due to its transport suitability and energy density compared to hydrogen.
- Easy storage compared to hydrogen

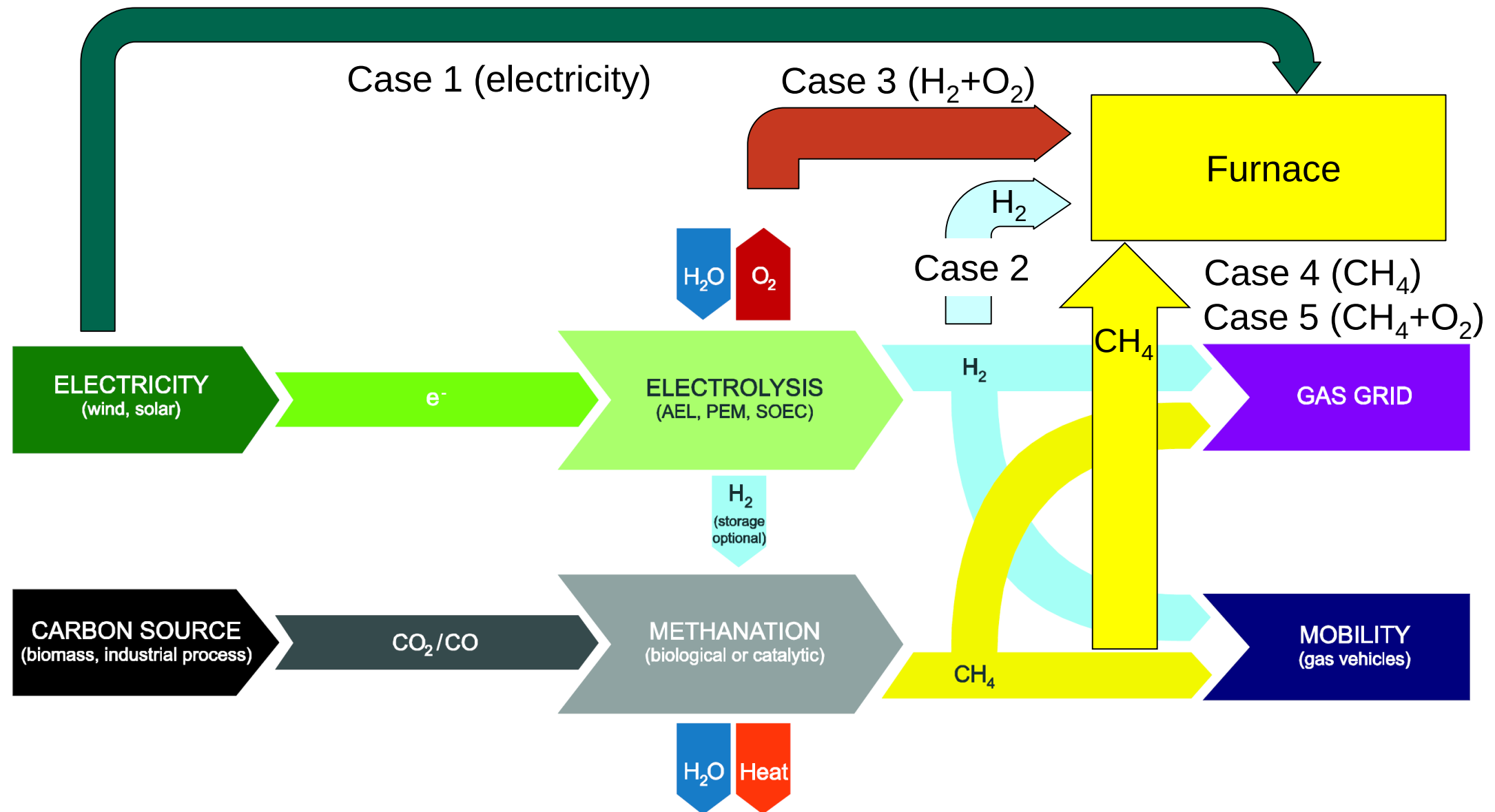
Property	NH ₃	H ₂	CH ₄	C ₃ H ₈
Boiling temperature in °C (bei 1 bar)	-33.4	-253	-161	-42.1
Condensation pressure in bar (bei 25 °C)	9.90	N/A	N/A	9.40
Net calorific value in MJ/kg	18.6	120.0	50.0	46.4
Ignition range (air ratio)	0.71-1.59	0.14-10.00	0.59-2.00	0.40-1.96
Adiabatic flame temperature in °C	1800	2110	1950	2000
Laminar flame velocity un in m/s	0.07	2.91	0.37	0.43
Ignition temperature in °C	650	520	630	450



Quellen: N. Olson, The 11th Annual NH₃ fuel conference, Des Moines (2014), <https://nh3fuelassociation.org/events-conferences/2014-nh3-fuel-conference/>
H. Kobayashi et al., Proceedings of the Combustion Institute 37 (2019) 109-133



Exemplary power-to-gas-to heat process chain (for hydrogen)



Source: Götz, M. et al.: Renewable Power-to-Gas: A technological and economic review, Renewable energy 85 (2016), p. 1371/90



Continuous replacement of Natural Gas (CH_4) → Hydrogen (H_2)

→ Hydrogen ready

Direct variations to be considered

- Energy density in the flame
 - Heat transfer at burner nozzle
 - Nitrogen oxides NO_x

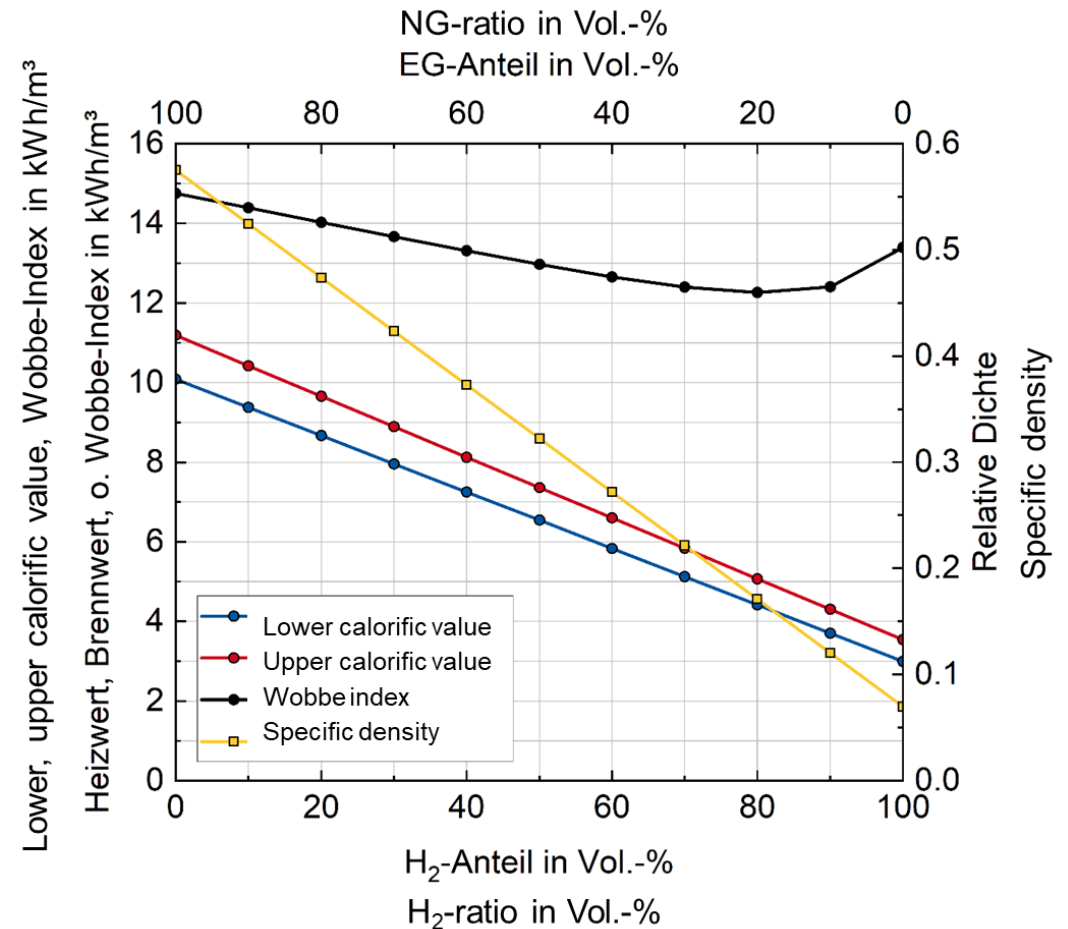
Indirect effects of the H_2O -rich off-gases with

- Refractories
- Product



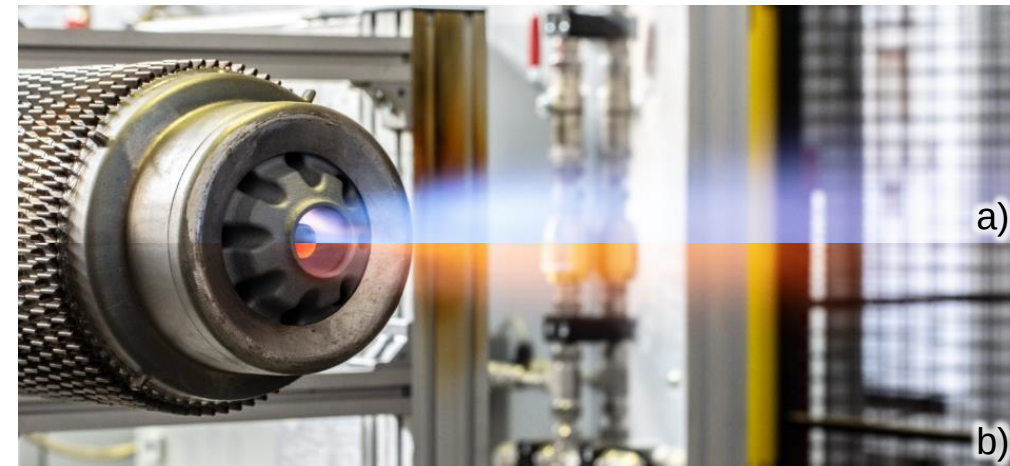
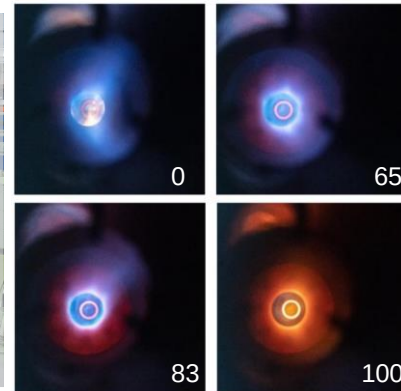
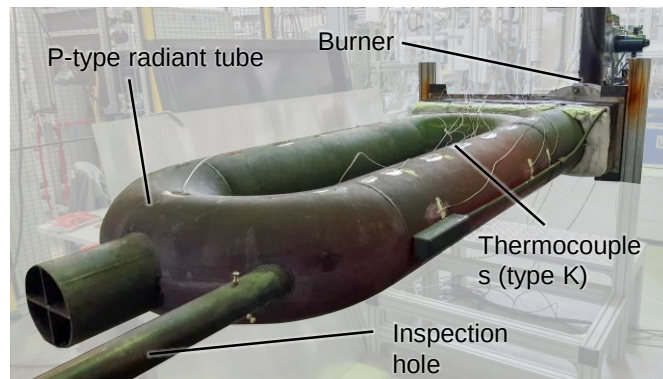
Properties of Hydrogen and Hydrogen-Natural Gas-Mixtures

Properties	H ₂	Russian NG
Lower calorific value in kWh/m ³	3,00	10,09
Upper calorific value in kWh/m ³	3,54	11,19
Density in kg/m ³	0,09	0,74
Density related to air	0,58	0,07
Upper Wobbe-Index in kWh/m ³	14,76	13,39
Adiabatic flame temperature in °C	2247	2039
Specific air in m ³ _{Air} /m ³ _{Fuel} (air ratio 1)	2,38	9,63
Specific air in m ³ /kWh (air ratio 1)	0,95	0,79
Specific off-gas (moist) in m ³ /m ³ (air ratio 1)	2,88	10,64
Specific off-gas (moist) in m ³ /kWh (air ratio 1)	1,05	0,96
Lam. flame velocity in m/s	2,91	0,37
Ignition energy in mJ	0,02	0,29
Ignition temperature in °C	580	630

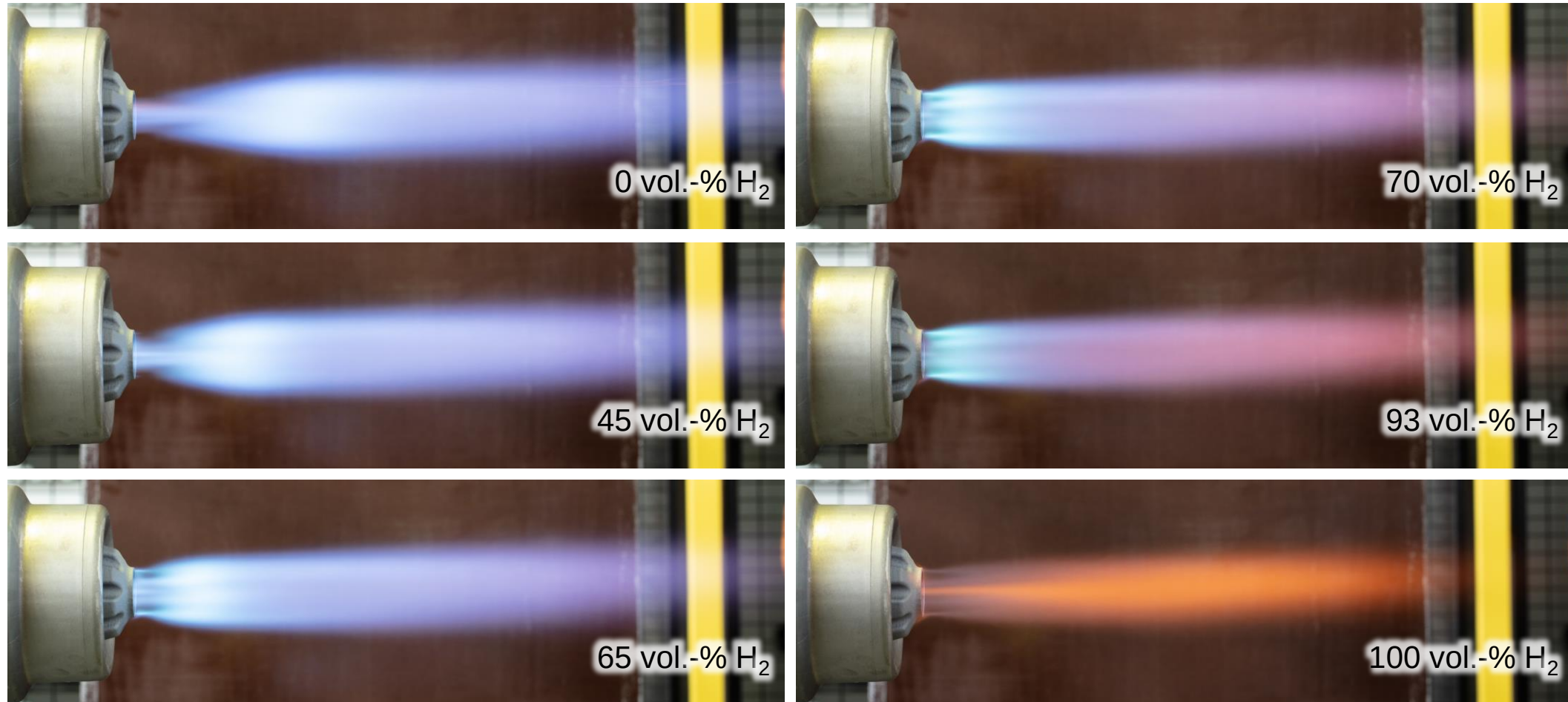


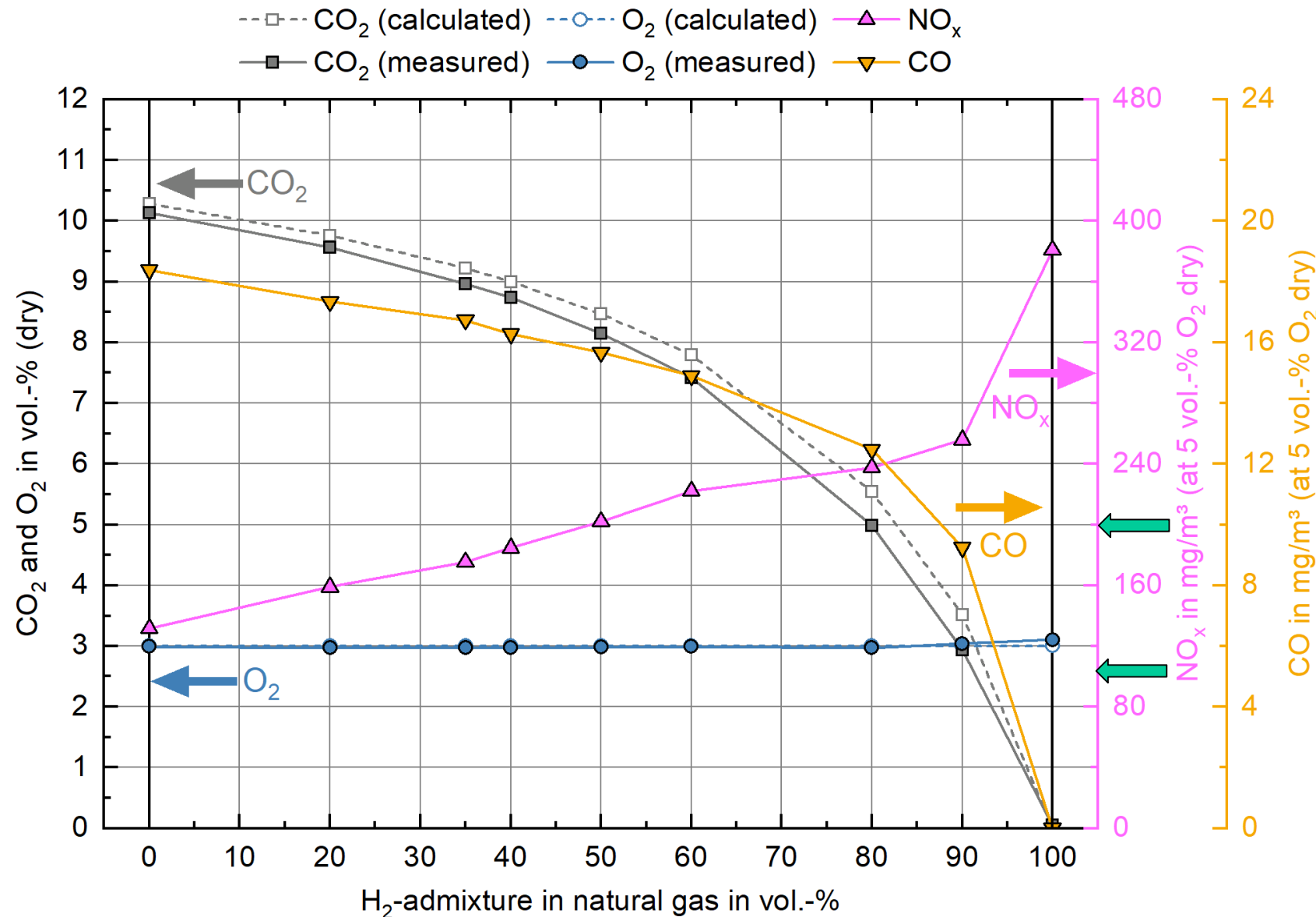
Burner tests at IOB – Rekuperative burner 120 kW

- Rekuperative burner at 120 kW in a P-type radiant tube
- Operation with 100 Vol.-% Natural gas (a) to 100 Vol.-% H₂ (b)
- Focussing of flame pattern, temperature distribution and emissions



Burner tests at IOB – Flame visualisation





TA-Luft

5.2.4 Gaseous anorganic species

Limit value:

CO < 100 mg/m³

Nitrogen oxides

< 350 mg/m³ (200 ppm) or 1.8 kg/h

→ approx. **up to 5 MW**

5.4.1.2.3 Plants for the generation of electricity, steam, hot water, process heat or heated exhaust gas in combustion plants by the use of ... methyl esters of vegetable oils, **natural gas** ... gases of the public gas supply or **hydrogen** with a rated thermal input of **less than 50 MW** → cc) a temperature of more than 210 °C or an overpressure of more than 1.8 MPa → 150 mg/m³ (88 ppm)



Flames of a pre-conventional High Speed Burner (staged air)

$P_{\text{Burner}} = 25 \text{ kW}$ | $\lambda_{\text{primary}} = 0,60$ | $\lambda_{\text{total}} = 1,15$ | $T_{\text{furnace}} = 500 \text{ °C}$ | $T_{\text{Air}} = 20 \text{ °C}$

0% H₂

10% H₂

20% H₂

35% H₂

50% H₂

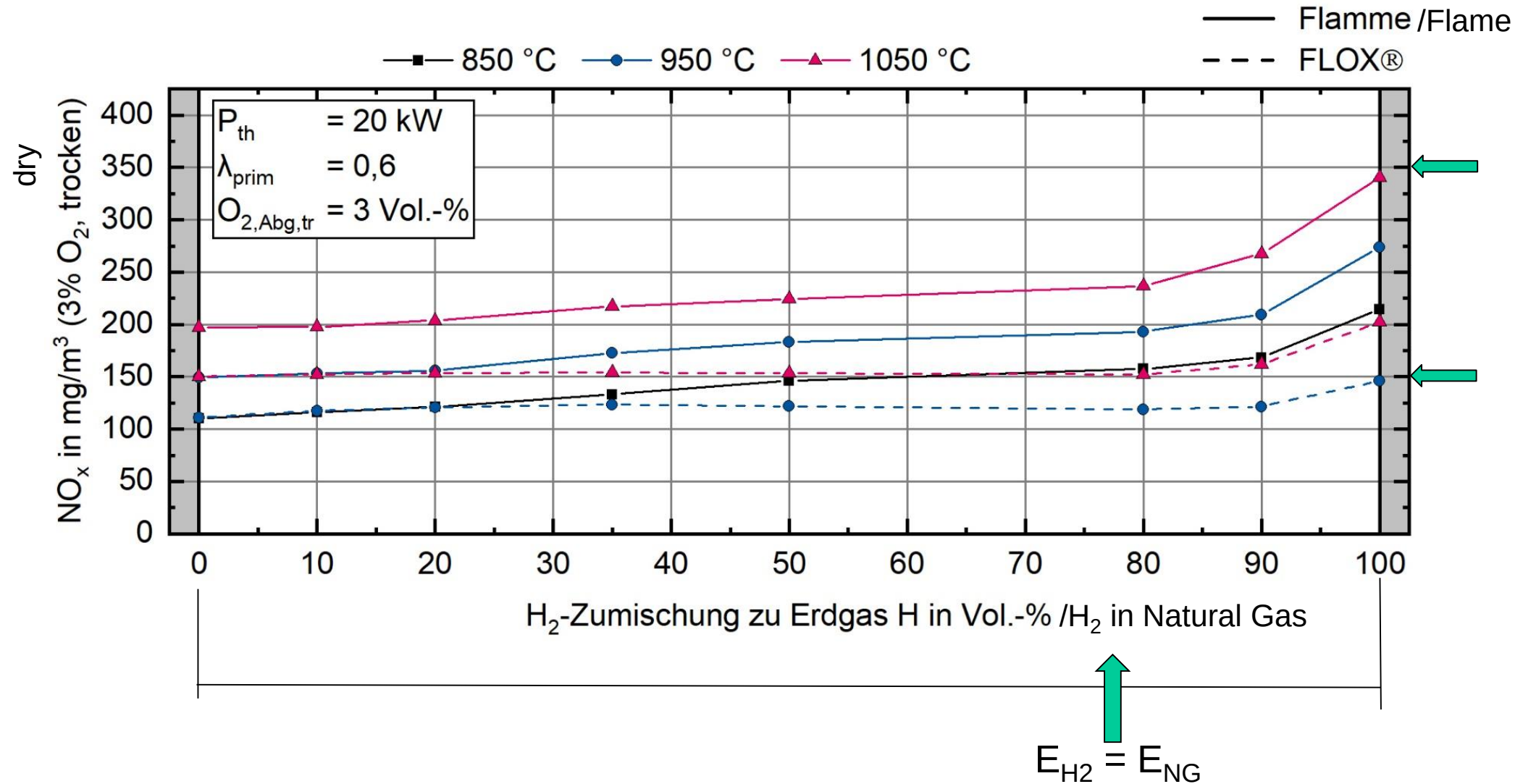
80% H₂

90% H₂

100% H₂

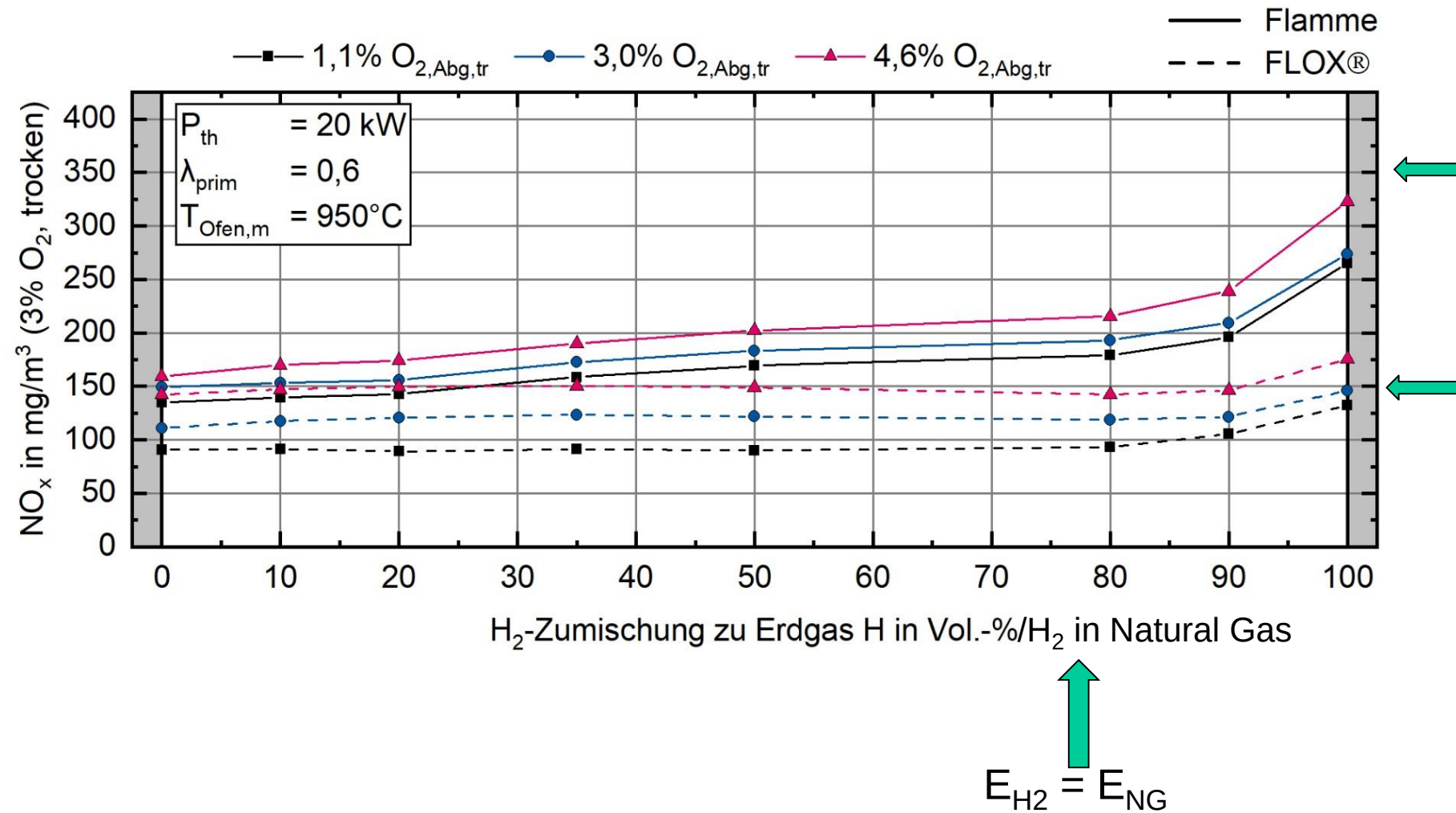
Results (staged air)

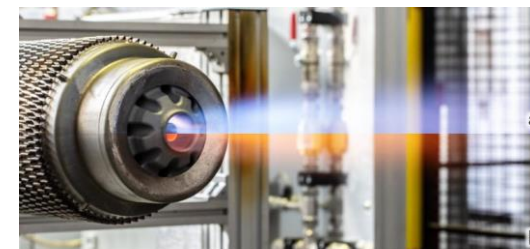
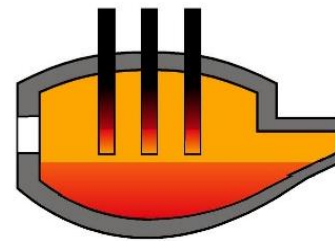
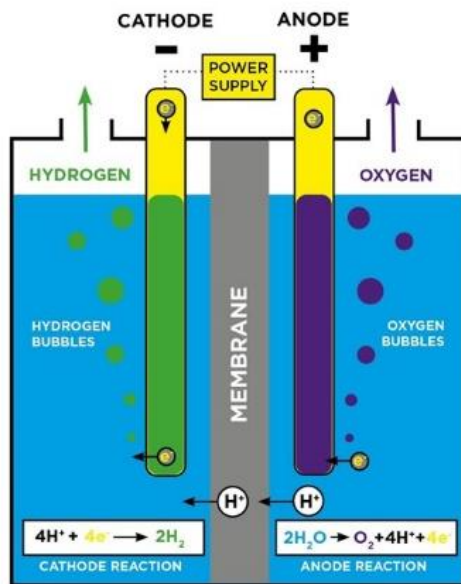
Steady state experiments – variable furnace temperature



Results

Steady state experiments – variable oxygen in off-gas (air ratio)



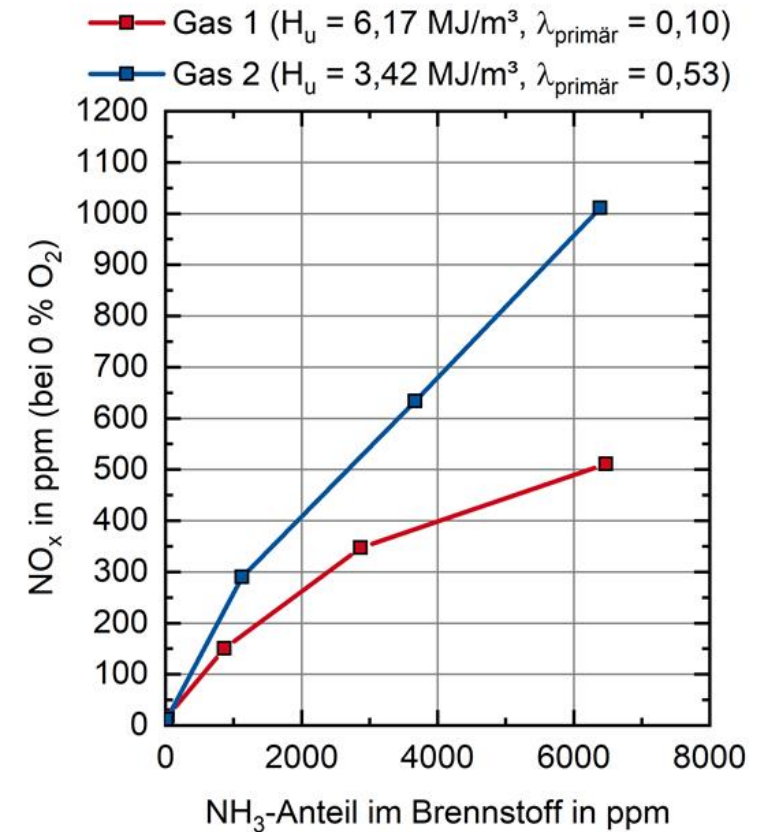
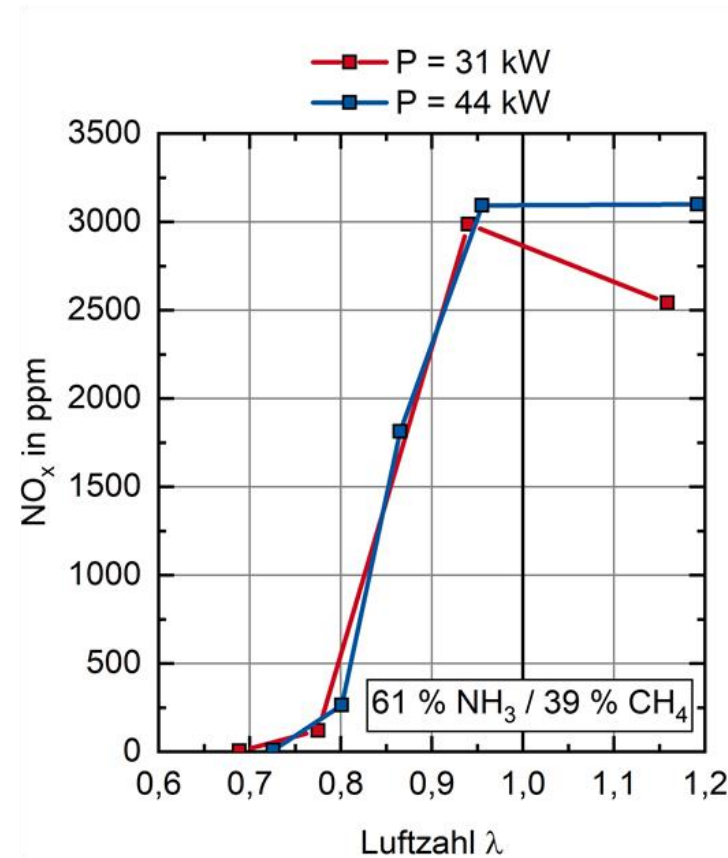
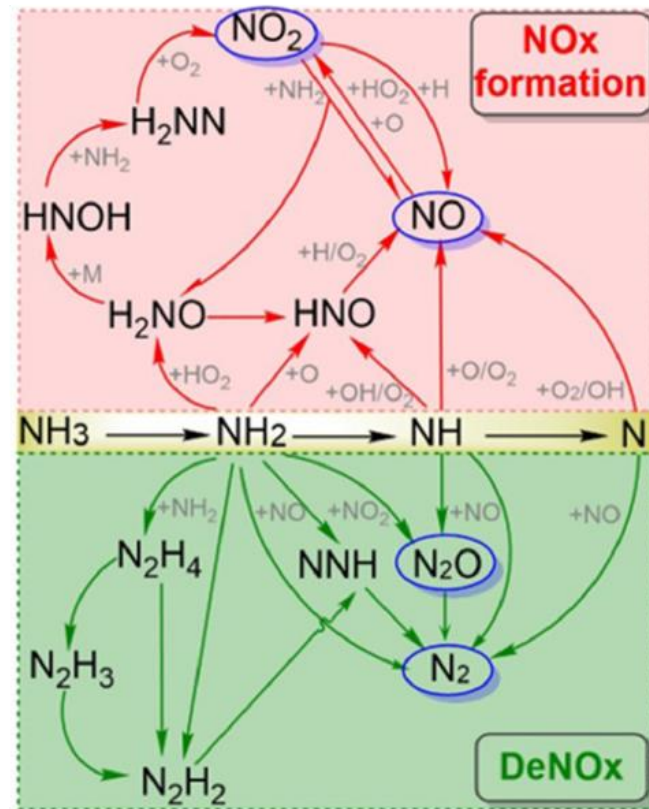


Energetic use of Ammonia NH_3



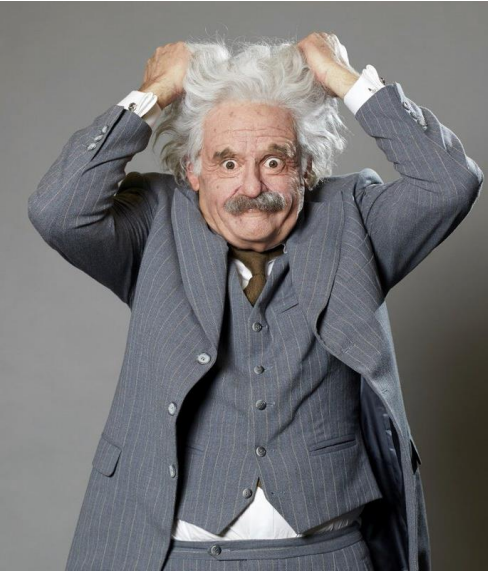
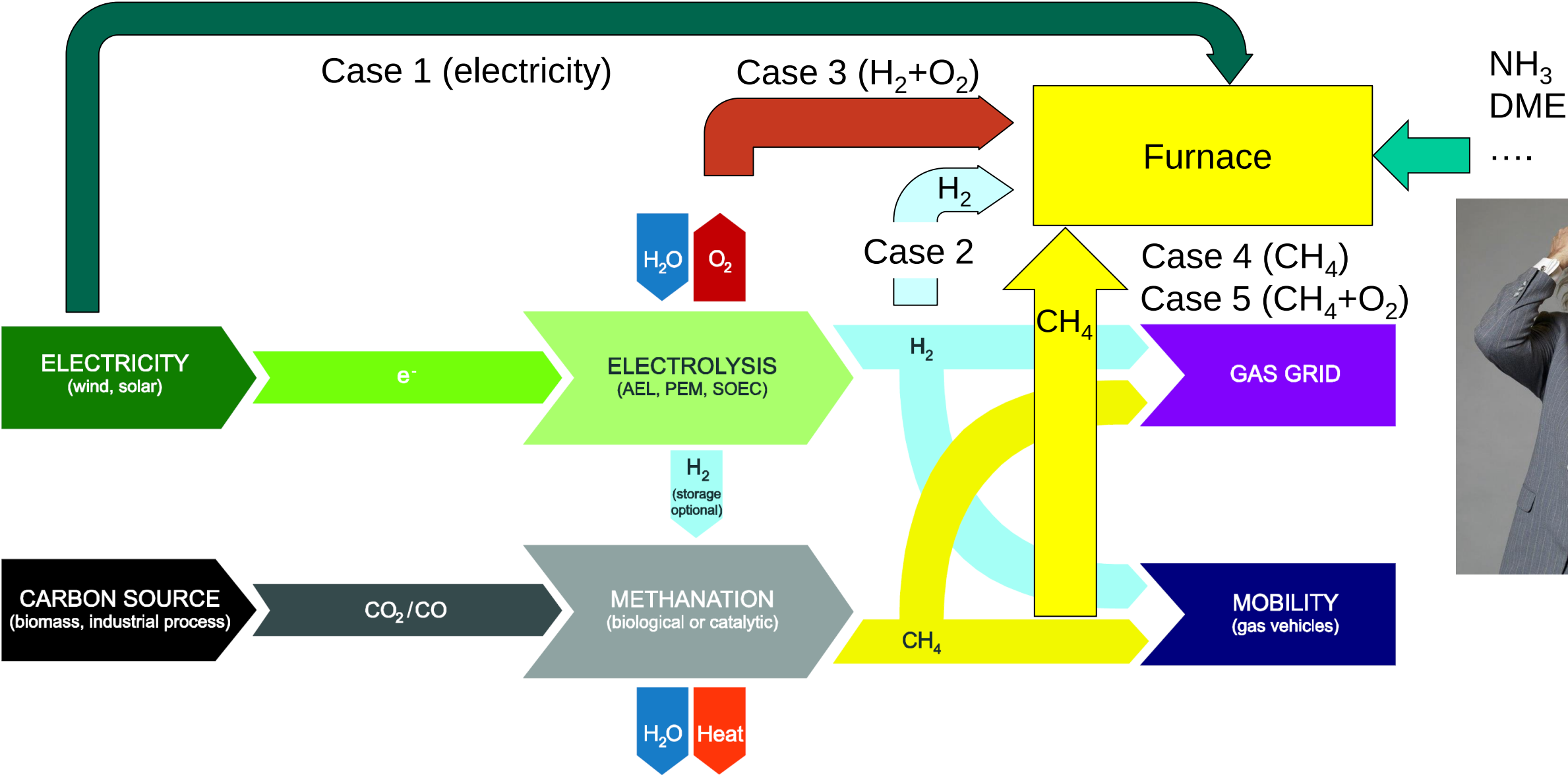
State of the art - combustion of ammonia

- Very high fuel NO emissions usually occur during ammonia combustion via the NNH formation pathway.



Quellen:
 Z. Xiaoyuan et al., Combust. and Flame 234 (2021), 111653
 J.A. Miller, M.D. Smooke, R.M. Green, R.J. Kee Combust. Sci. Technol., 34 (1983), pp. 149-176
 A. Valera-Medina et al., Applied Energy 185 (2017) 1362–1371

Exemplary power-to-gas-to heat process chains



Source: Götz, M. et al.: Renewable Power-to-Gas: A technological and economic review, Renewable energy 85 (2016), p. 1371/90



Thank you for your attention

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