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The role of combustion (and fuels) in a decarbonizing world

Opening Keynote

IFRF Conference 2025

“Sustainable and Safe Industrial Combustion"

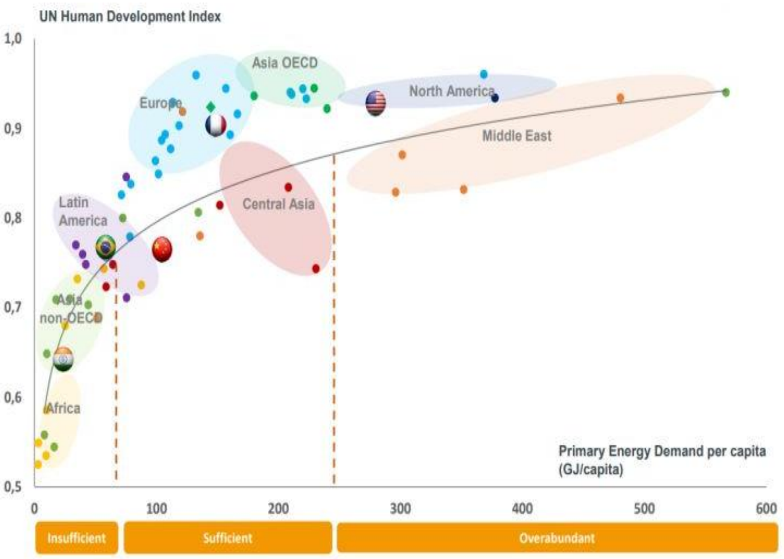
Jörg Leicher, Christoph Wieland, June 17, 2025

Sheffield, UK

Energy is at the heart of (almost) everything

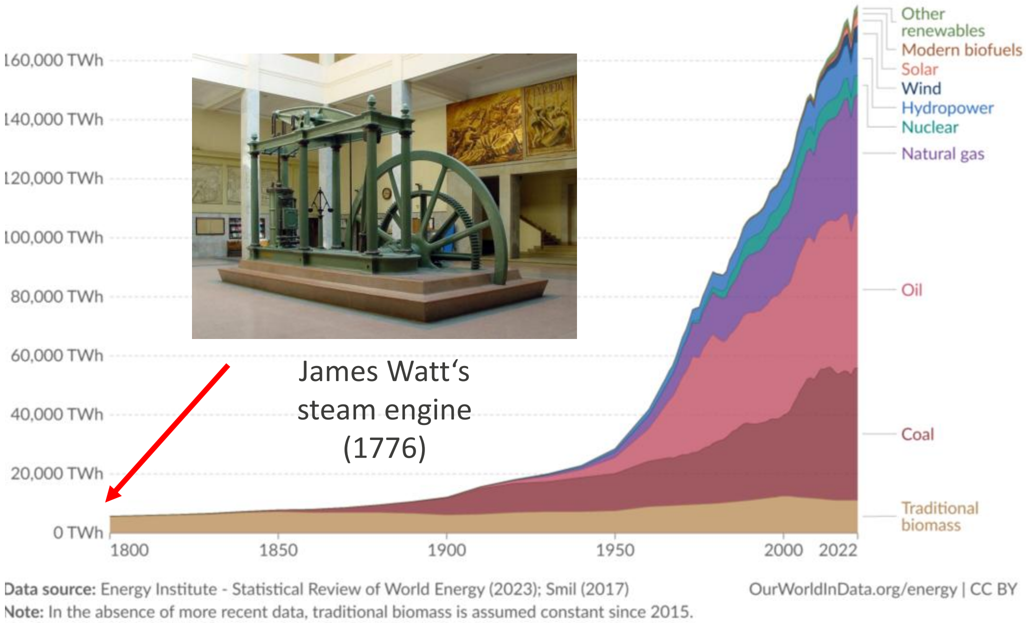
Energy (& combustion) are essential

Access to energy is essential to human development



Source: TotalEnergies Energy Outlook 2024

Global primary energy demand in TWh



Energy (& combustion) took us from here…

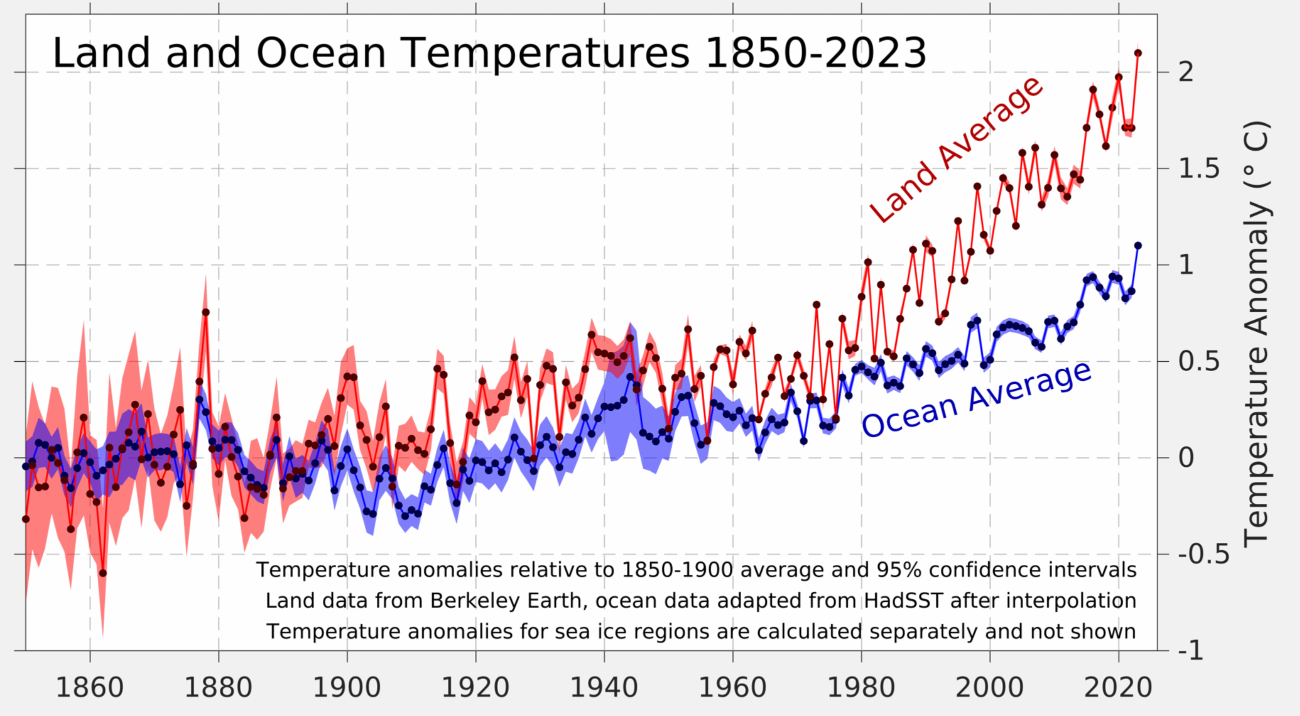
Cosmeton Medieval Village, Wales

… to where we are today!

Cosmeton Medieval Village, Wales

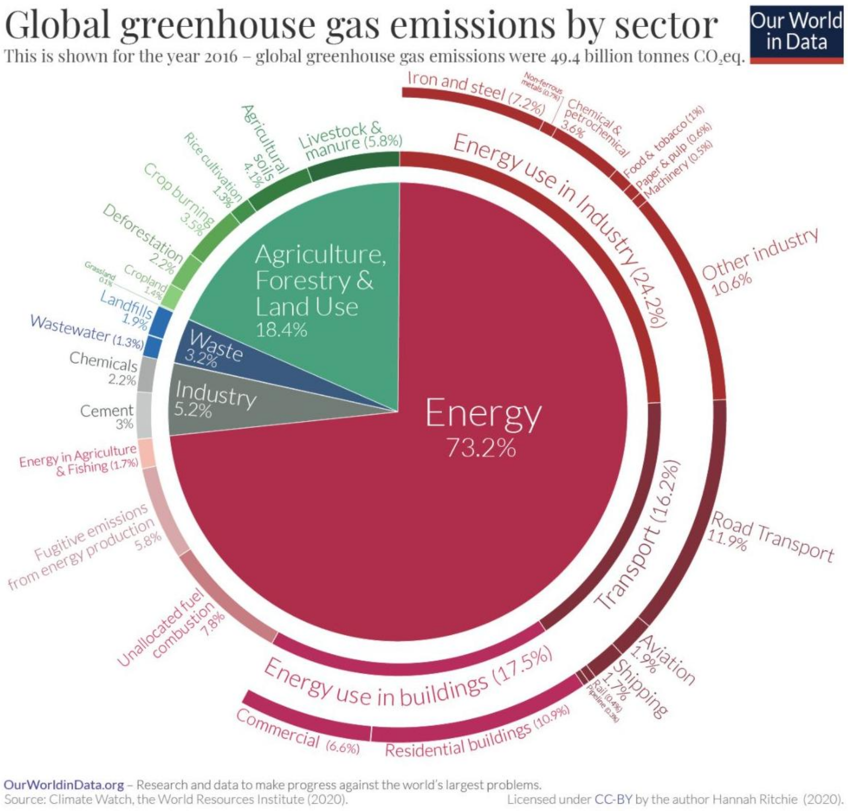
Tokyo, Japan

But there is a price, …

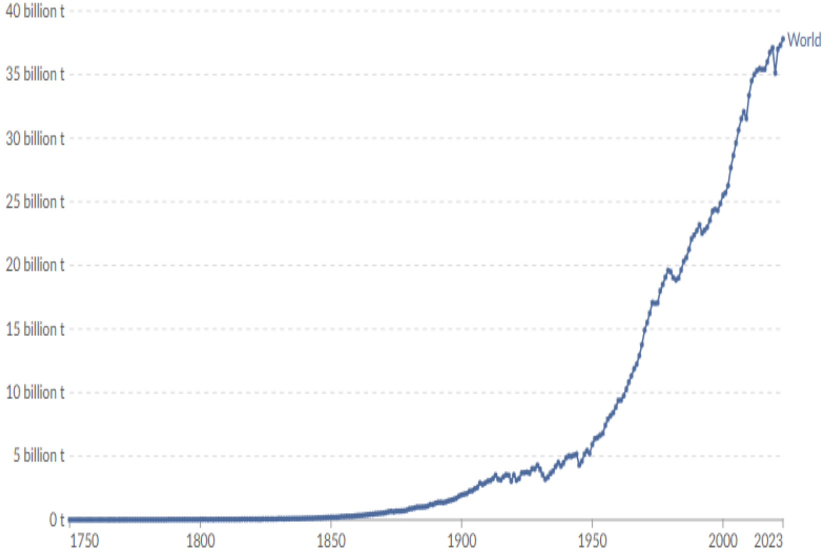


Source: Berkeley Earth

… and it‘s being paid in greenhouse gas emissions



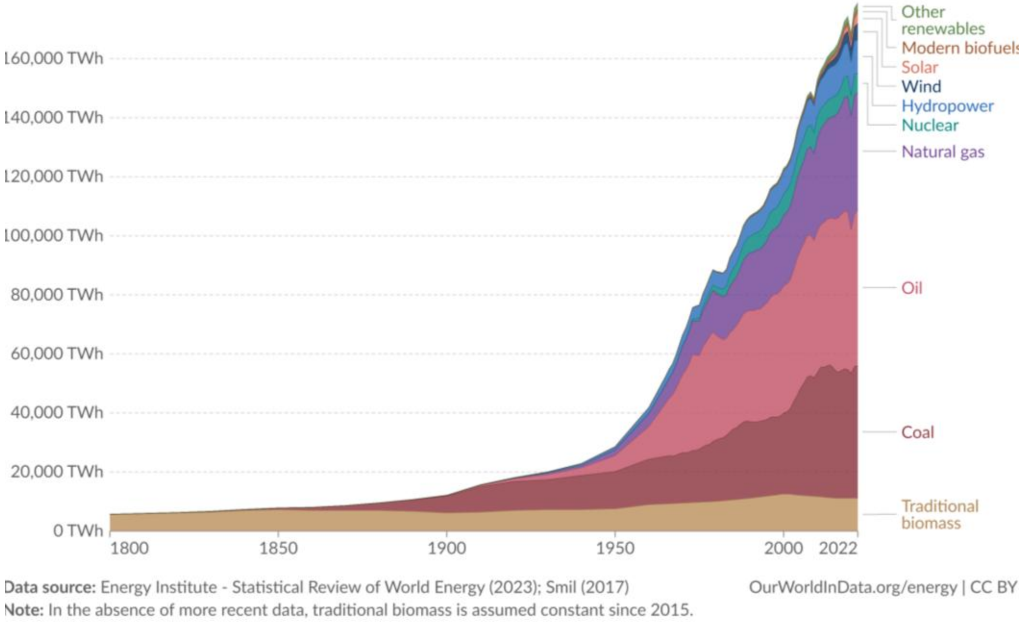
Global annual CO_2 emissions in 10^9 t/a



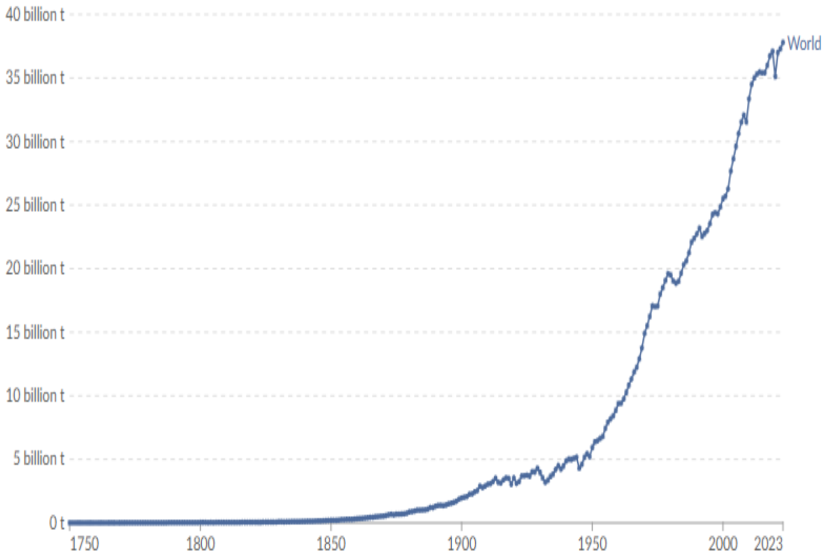
Source: Global Carbon Project / Our World in Data

… and it's being paid in greenhouse gas emissions

Primary energy demand in in TWh/a



Global annual CO_2 emissions in 10^9 t/a



Source: Global Carbon Project / Our World in Data

How to fix this?

- Energy needs to be decoupled from GHG emissions.

- **Electricity** will play a much bigger role in a future decarbonized energy system than ever before:
  It is relatively **easy to generate** without GHG emissions (renewables, nuclear) **and** electricity **can be efficiently transformed** into other forms of energy when needed (e.g. EV, heat pumps, …).

- **But:** renewables like wind and solar are **intermittent**, yet **security of energy supply** is essential for a modern society.
  Batteries and **end-use flexibility** alone will **not be enough**.

A night-time view of the Korean peninsula

Image: NASA

How to fix this?

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A few figures for Germany, to put matters into perspective:

- about 20 % of the energy demand today is needed as electricity (about 500 TWh/a). Roughly the same amount of energy is needed for industrial process heating alone!
- The share of renewable energies in power generation was about 59 % in Germany in 2024, but „only“ 22 % in end energy demand.
- The natural gas grid transports about twice the amount of energy as the power grid per year in the country.
- Storage capacity for natural gas: ~260 TWh
  Pumped hydro capacity: ~ 0.037 TWh
  Total battery storage installed today: ~ 0.019 TWh

nage: NASA

The ongoing need for fuels

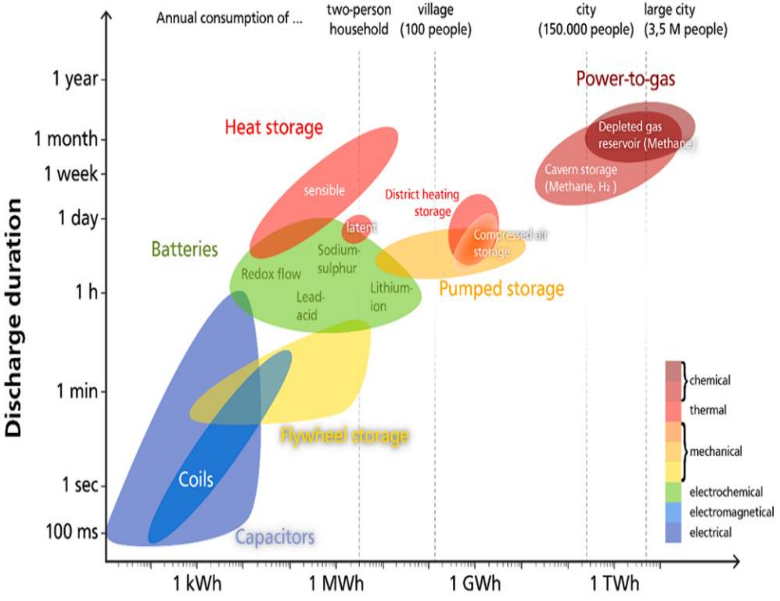
- Electricity as an energy carrier has drawbacks when **high energy densities**, **large-scale energy storage** and/or **transport** are required.
  Today, many of these functions are covered „en passant“ by fossil fuels.

- **Synthetic fuels** can serve to fulfill specific roles in a future decarbonized energy system.
  Biogenic fuels are another option, but **biomass potential is limited**.
  There can also be ethical concerns („fuel vs. food“?) and we need carbon feedstock for the chemical industry.
  What about **metal fuels**? => Keynote P. de Goey (Wednesday, 1.15 pm)!

- The **added value** of using a fuel instead of direct electrification has to be weighed up against the **efficiency losses** that come with the **production and combustion of a fuel**.

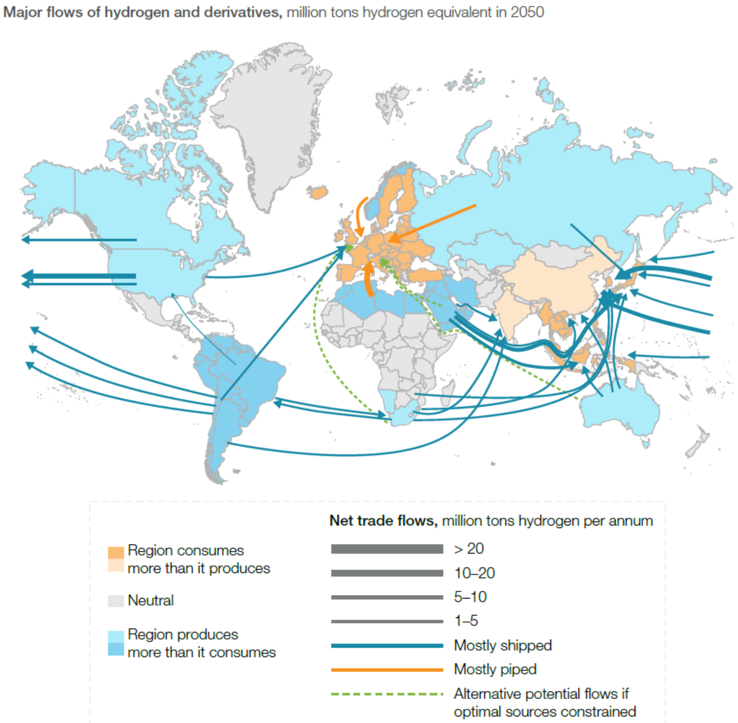
Systemic tasks for alternative fuels

Long-term energy storage at utility scale



Source: Dreizler, A., et al. :The role of combustion science and technology in low and zero impact energy transformation processes, Applications in Energy and Combustion Science, 2021. doi: 10.1016/j.jaecs.2021.100040

Global distribution of decarbonized energy



Source: Hydrogen Council / McKinsey & Company 2022

Decarbonization of hard-to electrify end-use applications

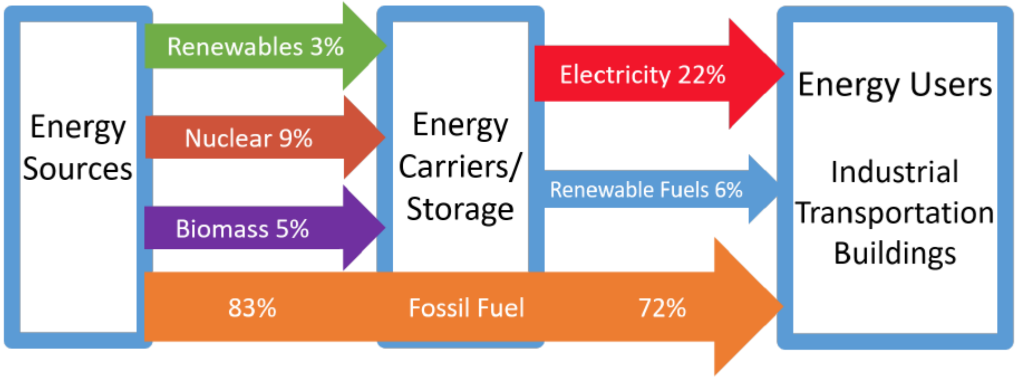
Aviation

Shipping

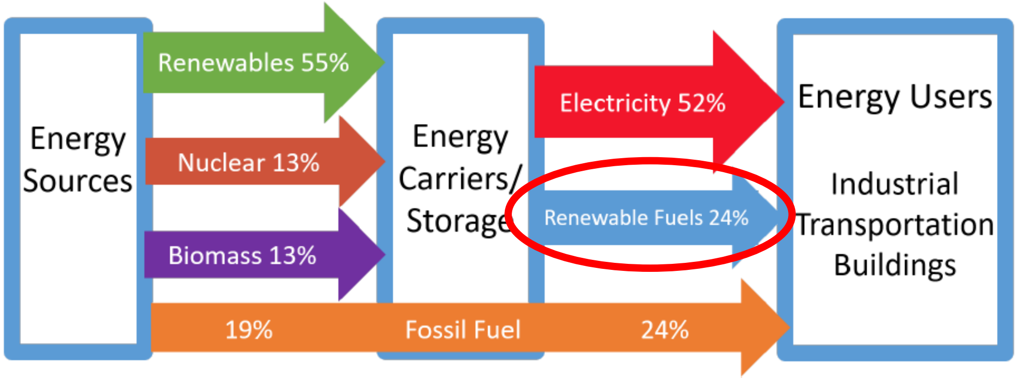
HT process heating

Dispatchable power generation

A future net-zero cost-optimized energy system for the U.S.



(a) Current US Energy System

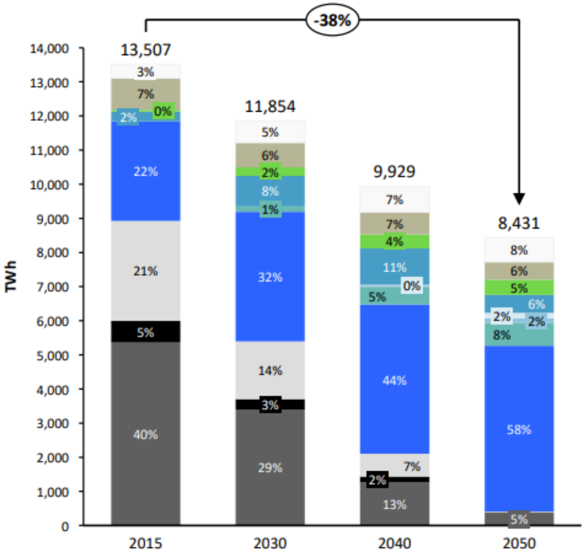


(b) Least Cost Net-Zero US Energy System

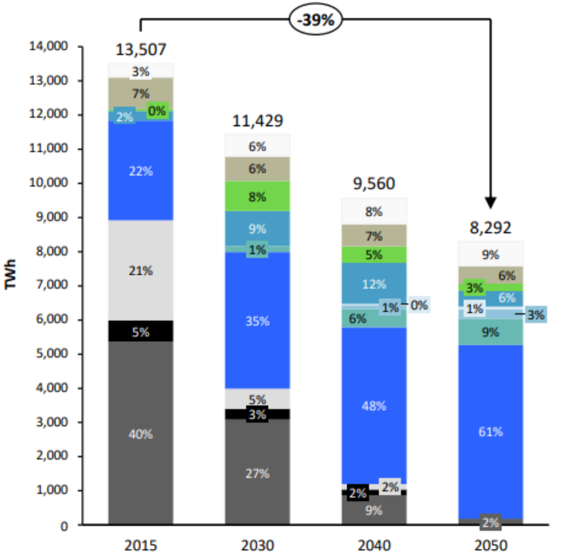
Source: Lieuwen. T., Roles for Combustion in a Net-Zero CO2 Society, Keynote Lecture, 40th International Symposium: Emphasizing Energy Transition. Milan, Italy, 2024

Final energy demand (EU27+UK) by energy carrier and policy scenario

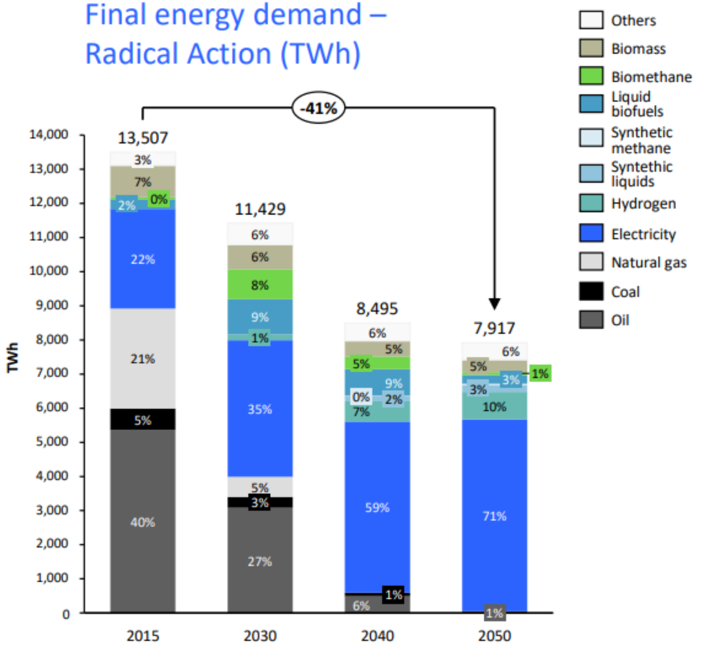
Final energy demand – FF55-inspired (TWh)



Final energy demand – REPowerEU-inspired (TWh)



Final energy demand – Radical Action (TWh)



1. Agriculture and other sectors are included in the scenarios but not extensively researched and modified
2. Does not include feedstock and non-energy use. Includes domestic and international transport.
3. Others include heat for example solar thermal energy
4. Assumption: 2% of methane is biomethane in 2015 (excl. electricity generation) calculated via: Scarlat et al (2018)
5. Assumption: 5% of liquids are biofuels in 2015: Transport and environment (2021)

Source: Decarbonisation Speedways, Eurelectric, 2023

Final energy demand (EU27+UK) by energy carrier and policy scenario

Depending on the policy scenario, **between 30 – 40 % of the EU‘s final energy demand** will still be provided by some kind of fuel in 2050, according to EURELECTRIC.
Forecasts for other parts of the world come to similar conclusions.

In a similar vein, forecasts predict a significant role for **hydrogen** and other fuels for **high-temperature process heating**, alongside electric heating technologies.

The role of fuels will change: they will no longer serve mostly to provide primary energy, but **to complement renewables** and other sources **when and where needed**.

Source: Decarbonisation Speedways, Eurelectric, 2023

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New challenges for combustion science and engineering

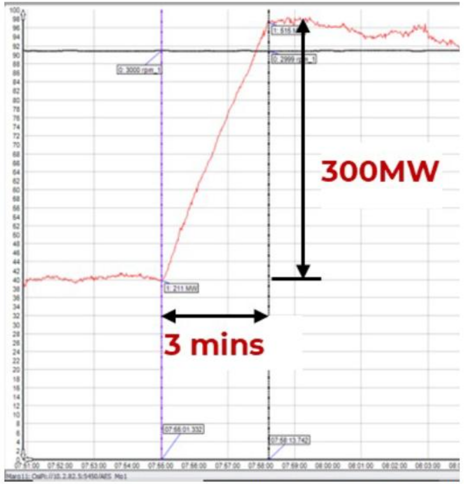
Combustion and fuels in a new energy landscape

- The need to **decarbonize energy** while ensuring **security of supply** at **acceptable cost** changes many things. More system-level integration and communication is needed than ever before, not only between different energy infrastructures, but also between energy providers, infrastructure operators (grid, storage, …) and end users.

- **Flexibility is key**, and can come in many forms:
  – **Load** flexibility: dynamic operation,
  demand side management, …
  – **Energy** flexibility: hybrid operation, …
  – **Fuel** flexibility: alternative fuels, multi-fuel systems, …

- Many of these concepts are not new per se, but their application so far was rather limited.

Dynamic behavior of a power plant gas turbine



Field measurement ramp rate (H-class GT): 100 MW/min

Image: Ansaldo

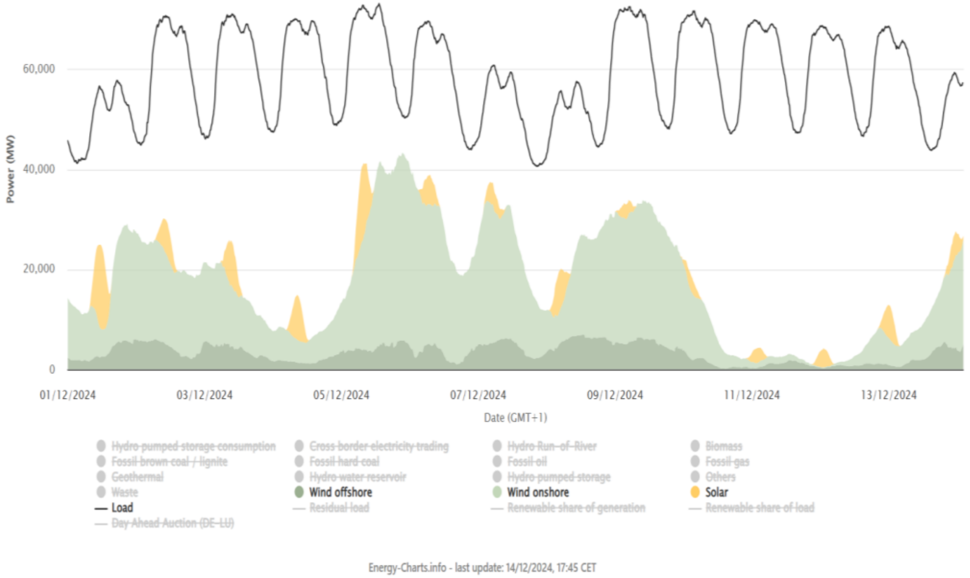
Flexibility can come in many forms: Dynamic behavior

- Efficiency may become less important than **dynamic flexibility** and **response times** for some applications, e. g. thermal power plants.

- Thermal power plants compete with utility-scale batteries for grid balancing on short time scales, yet they are still required for longer durations.

- What about the dreaded „Dunkelflaute“?
  What about a „Hellbrise“,
  i.e. a sudden oversupply of renewables?

Renewable power generation and demand in Germany, Dec. 1-14, 2024



Flexibility can come in many forms: hybrid heating

Gas-assisted electric arc furnace

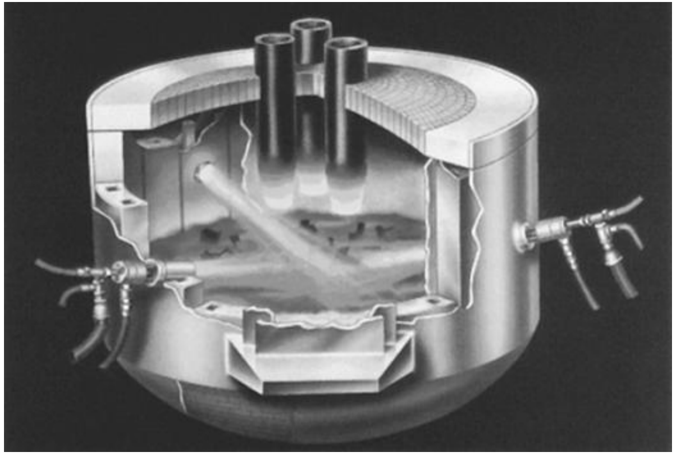


Image: Baukal, C.E., Jr. Heat Transfer in Industrial Combustion, CRC Press, USA, 2000

Example of a planned oxy-fuel/electric hybrid glass melting furnace (up to 50 % electric)

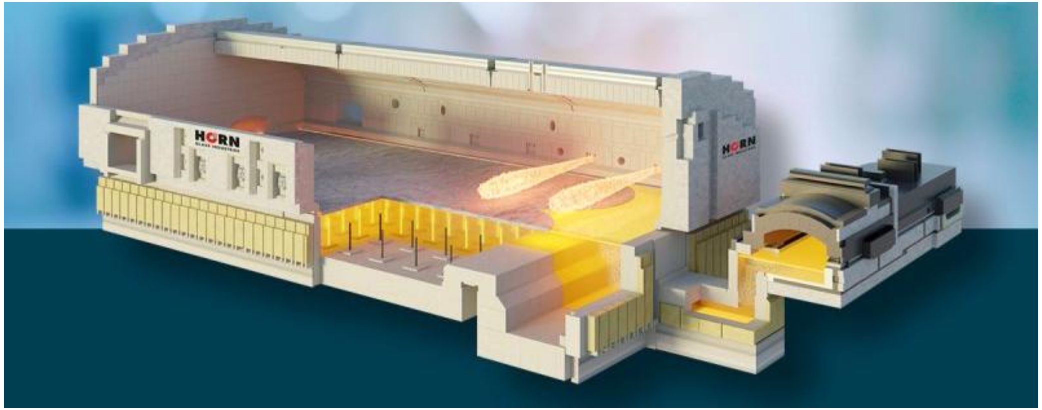


Image: Gerresheimer/Horn

Hybrid heating **today** mostly serves to **improve the process** or the **product**.
But it can also be used to for **demand-side management** and **grid-level services**.

Fuel flexibility: some new fuels can be challenging

	unit	CH_4	H_2	NH_3		Methanol (CH_3OH)
$H_{i,vol}$	MJ/m^3	35.83	10.80	14.14		15,700 (l) / 28.46 (g)*
$H_{i,m}$	MJ/kg	50.03	120.0	18.60		19.9
$H_{S,vol}$	MJ/m^3	39.75	12.75	17.09		17,900 (l) / 32.46 (g)*
$H_{S,m}$	MJ/kg	55.51	141.78	22.48		22.7
ρ	kg/m^3	0.716	0.09	0.76		790 (l) / 1.43 (g)*
W_S	MJ/m^3	53.28	48.24	22.0		-
O_{2min}	m^3/m^3	2	0.5	0.75		1.5
Air_{min}	m^3/m^3	9.524	2.381	3.571		7.143
T_{ad} ($\lambda = 1$)	°C	1,951	2,106	1,798		1,947
s_L ($\lambda = 1$)	cm/s	38.57	209	6.8		40.9
MIE	mJ	0.28	0.016	14		0.2

All values given in (25 °C / 0 °C, 1.01325 bar)

*: Theoretical values of the gas phase at 0°C.
The boiling temperature of methanol is 65 °C (1 atm).

There are good technical reasons why nobody seriously considered burning hydrogen or ammonia before… **but things change**.

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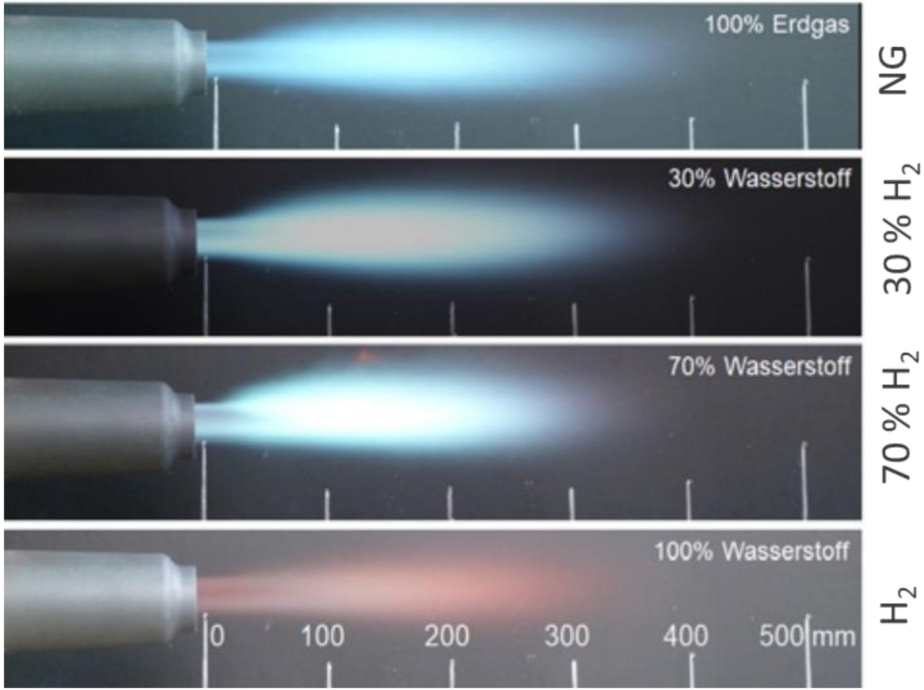
Hydrogen

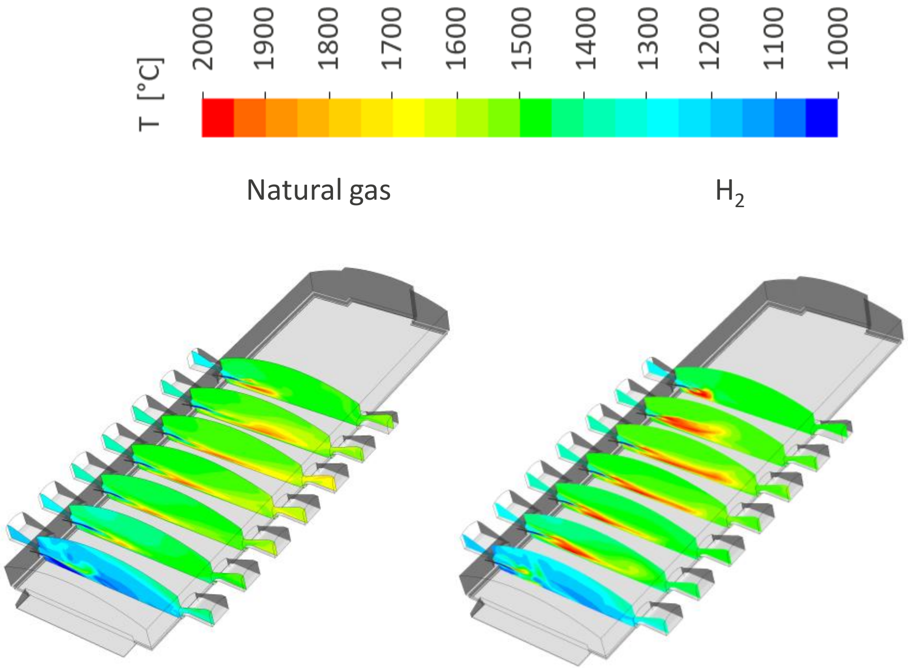
- Many energy-intensive industries look to **hydrogen** as one promising option for de-carbonization, especially those who use natural gas in HT applications today.
- The **non-premixed combustion processes** in process heating tend to be more robust when switching to H_2 than the lean premixed combustion found in power plant gas turbines.
- Some open questions remain, e. g.:
  - product quality and refractory issues
  - NO_X emissions (and how to compare them fairly)
  - **availability** and **price**



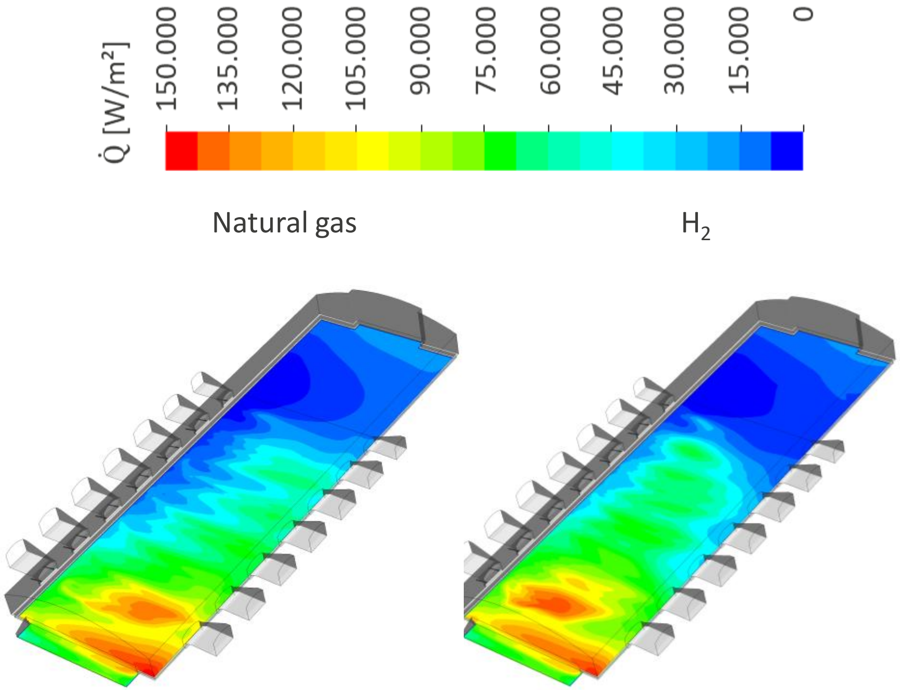
Source: Gitzinger, H.-J.,Rieken, M., Schröder, L., Veränderungen durch Wasserstoff beim Betrieb von Rekuperator- und Impulsbrennern, Prozesswärme, pp. 40-45, 01/2022

Natural gas combustion vs. hydrogen combustion in a regenerative glass melting furnace

Temperature



Heat flux density



P: 30 MW; λ: 1.1; T_{air}: 1,300 °C

$\dot{Q} = 19.5\ \mathrm{MW}$

$\dot{Q} = 20.1\ \mathrm{MW}$

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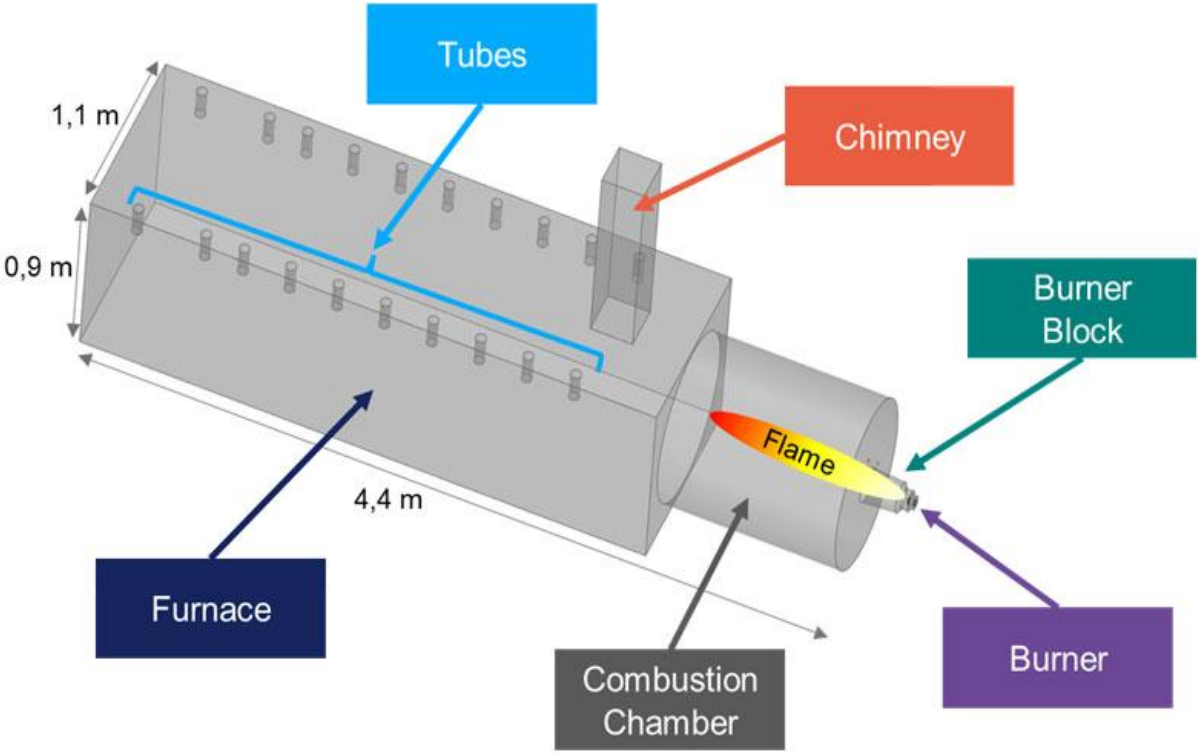
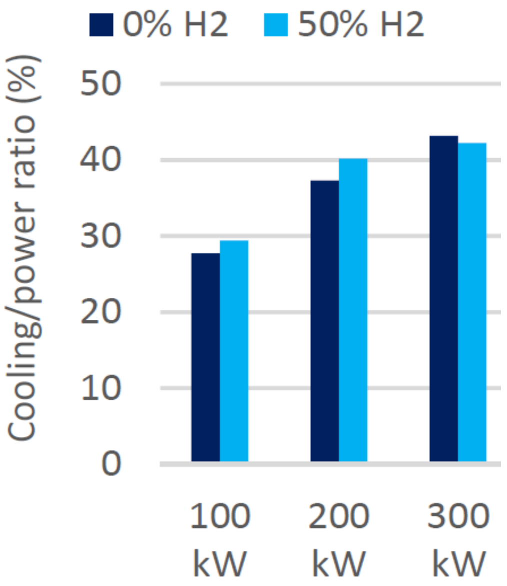
Experimental investigations (P = 100 – 300 kW, λ = 1.1)

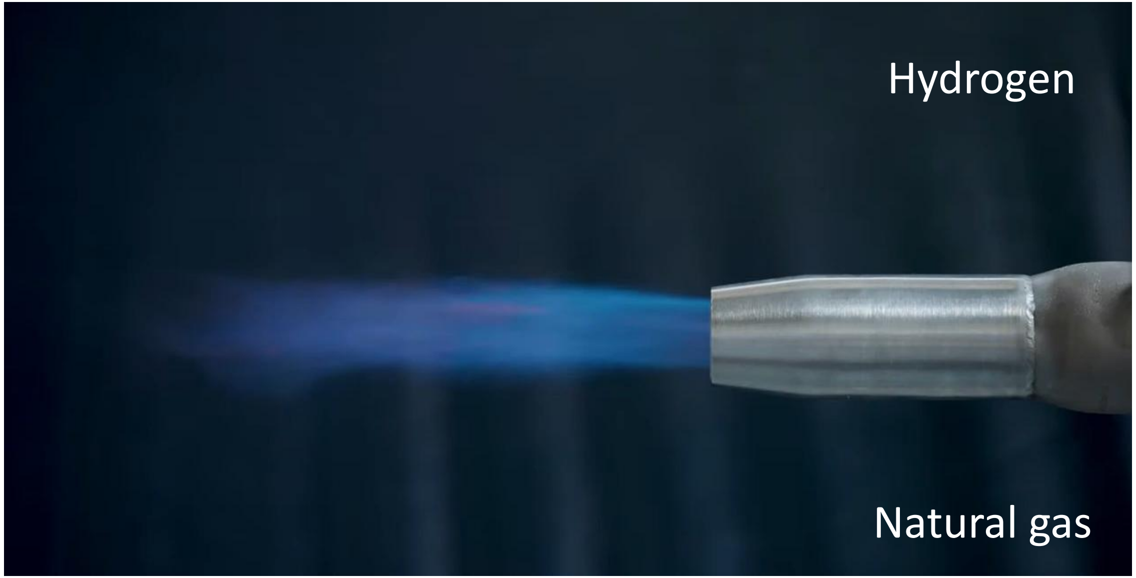




Source: Meynet, N., Grandin, G.-A., Gobin, C., Lefebvre, F., Honoré, D., Experimental characterization of hydrogen impact on the flame structure and NOx emissions inside a semi-industrial furnace, 11th European Combustion Meeting, Rouen, France, 2023

Fuel flexibility and multi-fuel applications

Dual-fuel burner

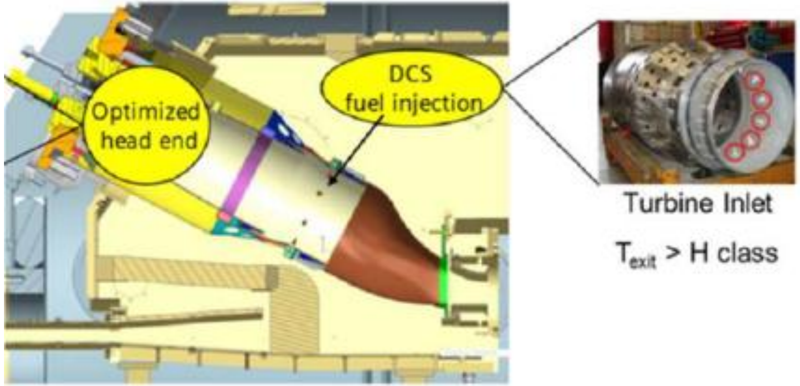


Source: KuepperSolutions

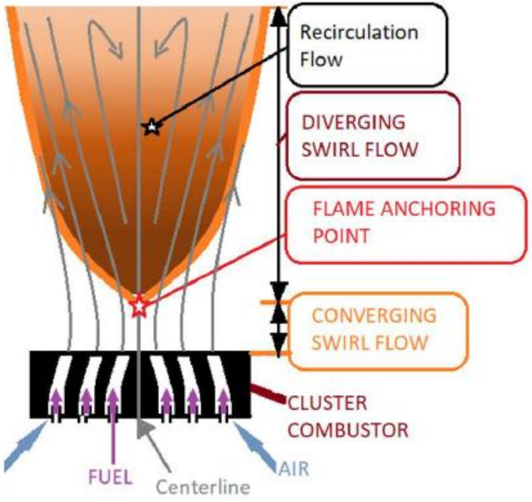
H_2/NH_3 combustion

Source: GWI

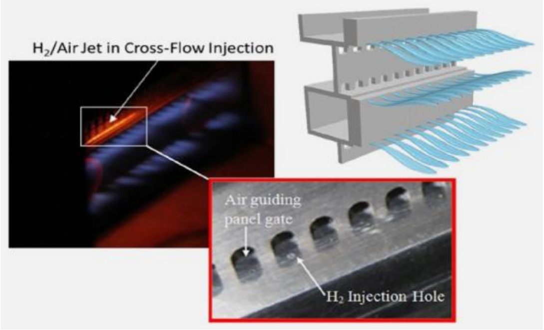
Technologies for hydrogen combustion in power plant gas turbines



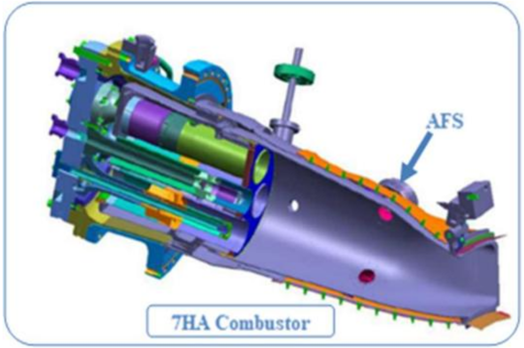
Distributed Combustion System (Siemens)



Multi-Cluster Diffusion Burner (MHI)



Micro Mix Combustion (Kawasaki)



Axial Fuel Staging (GE)

Old questions, new context: NO_X formation in hydrogen and ammonia combustion

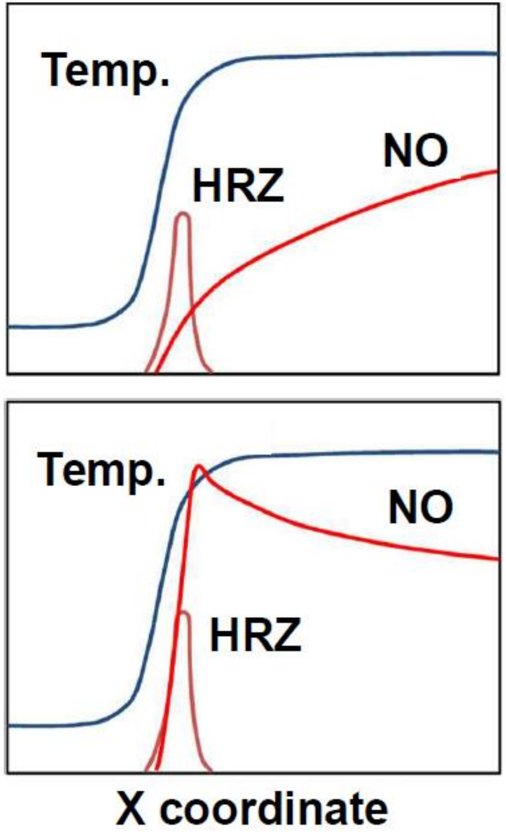
Thermal NO_X:

- air is the main N_2 source
- NO_X formation **post-flame**
- relatively long time scales, slow reaction
- main pathway for NO_X formation in hydrocarbon/**H_2** combustion

Fuel NO_X:

- N is provided by the fuel itself
- quick NO_X peak **in** the flame, decreases to chemical equilibrium
- important pathway for **NH_3** combustion

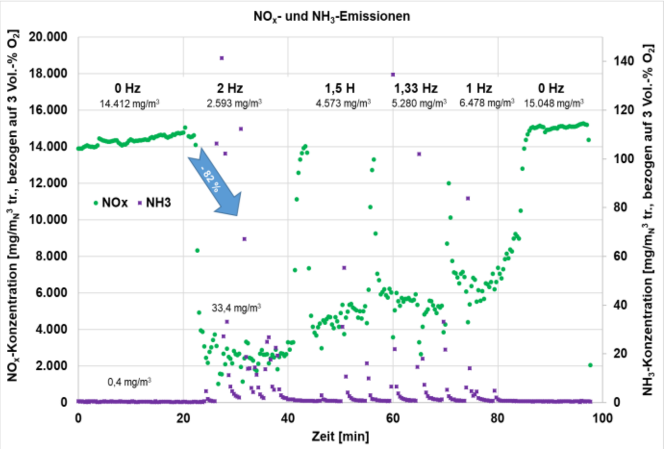
New pollutant species can become relevant, e.g. **N_2O** and NH_3 in ammonia combustion.



Images: H. Kobayashi, Tohoku University

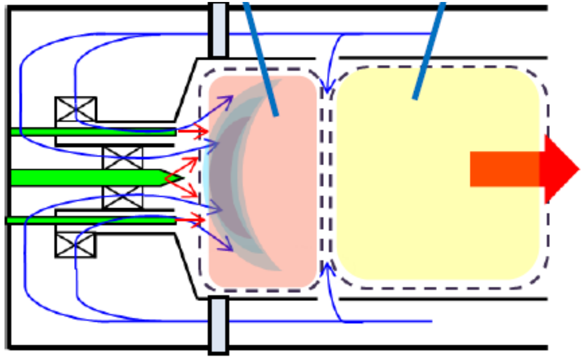
Ammonia combustion: pollutant emissions are a challenge

Source: GWI

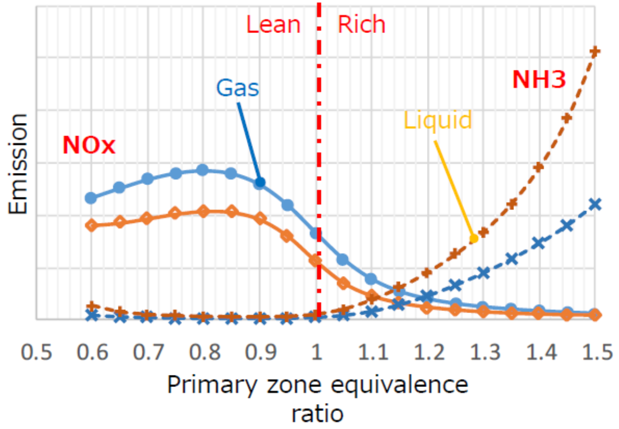


RQL staging

Source: IHI



Effect of primary zone equivalence ratio on emission



Full-scale demo projects

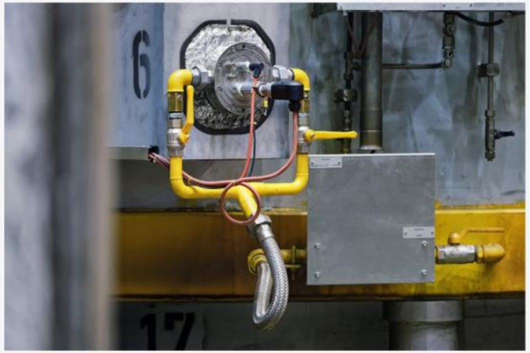
- Many challenges of new fuels have already been solved on the technological level (e. g. hydrogen in process heating), at least on the lab or semi-industrial scale.
- Others such as ammonia combustion or the use of hydrogen in heavy-duty gas turbines still require some fundamental work.
- What‘s often missing is the next step: **full-scale implementation**
- The challenges here are often less technological, but questions of logistics or cost.

First industrial-scale trials for hydrogen (and even ammonia) are underway… but they can be challenging and expensive

Press release, March 2023

Kuepper Solutions
Power. Innovation. Responsibility.
Aktuelles Produkte Mischeinheiten iRecu®

iRecu ins Spiel. Werden diese Anlagen auf unsere wasserstofffähigen Brenner umgrüstet, kann der Anlagenbetrieb je nac
durch Wasserstoff erfolgen. Diese hybride Funktionsweise der Anlagen sorgt also für Flexibilität in der Wahl der Brennst
anderen Worten: Unser Dual-Fuel-Brenner macht Anlagen H2-ready.



„Aus dem Schornstein kam statt CO_2 Wasserdampf"

World's first batch of recycled aluminium using hydrogen fueled production

Hydro has produced the world's first successful bat
hydrogen as an energy source. The test is another s
aluminium.

Press release, June 2023

World's First Successful Trial Demonstration of Using Fuel Ammonia for Combustion in a Glass Melting Furnace

TAIYO NIPPON SANSO AGC 産総研 東北大学

In June of 2023, we conducted world's first demonstration test of ammonia oxygen combustion test in glass melting furnace that produces architectural glass at AGC.

AGC
Your Dreams, Our Challenge

News Release

AGC Achieves Success in Demonstration Test of Glass Production Using Hydrogen as Fuel

Press release, October 2023

SAINT-GOBAIN

EVES THE FIRST FLAT GLASS PRODUCTION
MORE THAN 30% HYDROGEN

Press release, March 2023

EU project, started 01/2024

H2AL

DECARBONISING ALUMINIUM RECYCLING WITH HYDROGEN

OVAKO
INDUSTRY SOLUTIONS STEEL PORTFOLIO PRODUCT FORMS SERVICES SUSTAINABILITY

You are here: News and Events / Stories / First in the world to heat steel using hydrogen

First in the world to heat steel using hydrogen

Successful Demonstration Test of Ammonia Firing Conducted at Commercial Power Station

Results of demonstration test for ammonia 20% firing at Hekinan Thermal Power Station Unit 4

IHI project, Japan, 2023

HYINHEAT

EU project, started 01/2023

First industrial-scale trials for hydrogen (and even ammonia) are underway… but they can be challenging and expensive

Press release, March 2023

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TAIYO NIPPON SANSO AGC 産総研 東北大学

ammonia oxygen combustion test in glass melting

IN

LAT GLASS PRODUCTION
HYDROGEN
March 2023

project, started 01/2024

Special session on Industrial Implementation projects

Successful
of Ammoni
Commercia

Results of demonstra… Hekinan Thermal Power Station Unit 4

IHI project, Japan, 2023

THINKHEAT

EU project, started 01/2023

H2AL
DECARBONISING ALUMINIUM RECYCLING WITH HYDROGEN

Combustion remains… interesting.
And relevant!

Conclusion

- Hydrocarbons and coal have been the foundation of the modern world since the Industrial Age. They offer high energy densities, are abundantly available, and are easy and safe to handle, transport and store. **They also inevitably produce CO_2 when burned**.

- In a decarbonizing world, the **roles of fuels and combustion will change**.
  New fuels will serve as a **necessary complement** for intermittent renewables and electricity.

- New fuels bring new challenges and resurrect some old ones. **Flexibility is key**.
  Many technical issues are already (almost) solved, but the real challenge is **scaling and economics**.

- But let‘s not forget: **energy is always a means to an end**.
  Decarbonization is pointless if the energy system is no longer **fit-for-purpose**.
  Safety, **availability** and **affordability** are still just as essential as **net-zero**.

Conclusion

- **Cooperation is important**, both internationally, but also between academia, industries, infrastructure operators, authorities and policymakers.

Image: Getty

Conclusion

- **Cooperation is important**, both internationally, but also between academia, industries, infrastructure operators, authorities and policymakers.

- **Professional education** and **training** are vital tasks, but so are social outreach and **communication**. Many people still automatically associate hydrogen with the Hindenburg disaster…and yet, here we are, seriously discussing **NH_3 combustion!**

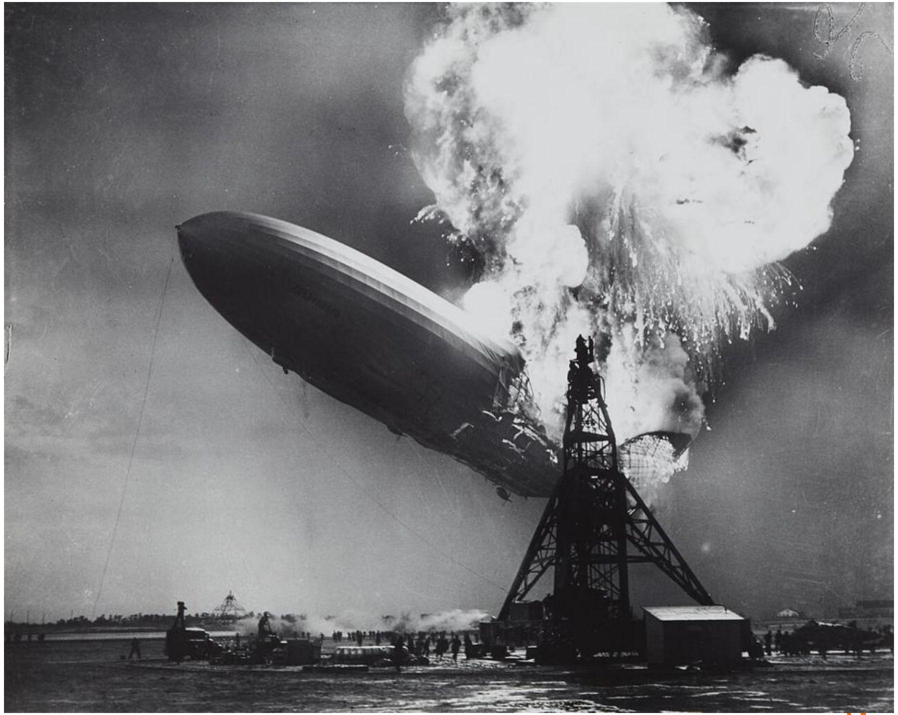

Image: WikiCommons

Conclusion

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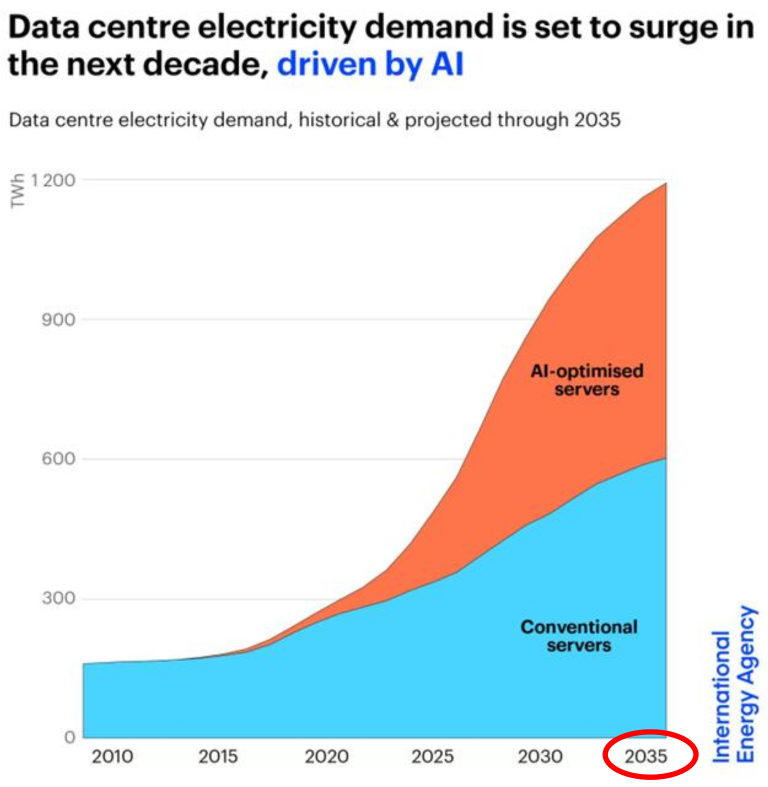
- **Professional education** and **training** are vital tasks, but so are social outreach and **communication**. Many people still automatically associate hydrogen with the Hindenburg disaster…and yet, here we are, seriously discussing **NH_3 combustion!**

- And **the next challenge** is already on the horizon:



Thank you for your attention

Dr.-Ing. Jörg Leicher

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