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Wasserstoff -Energieträger der Energiewende
“Stand und Ausblick der Elektrolysetechnologie”

—

Prof. Dr. Christopher Hebling
Fraunhofer Institute for Solar Energy Systems, Freiburg, Germany

3. Nationales Wirtschaftsforum Wasserstoff
Hamburg, 7.5.24

Global Direct Primary Energy Consumption

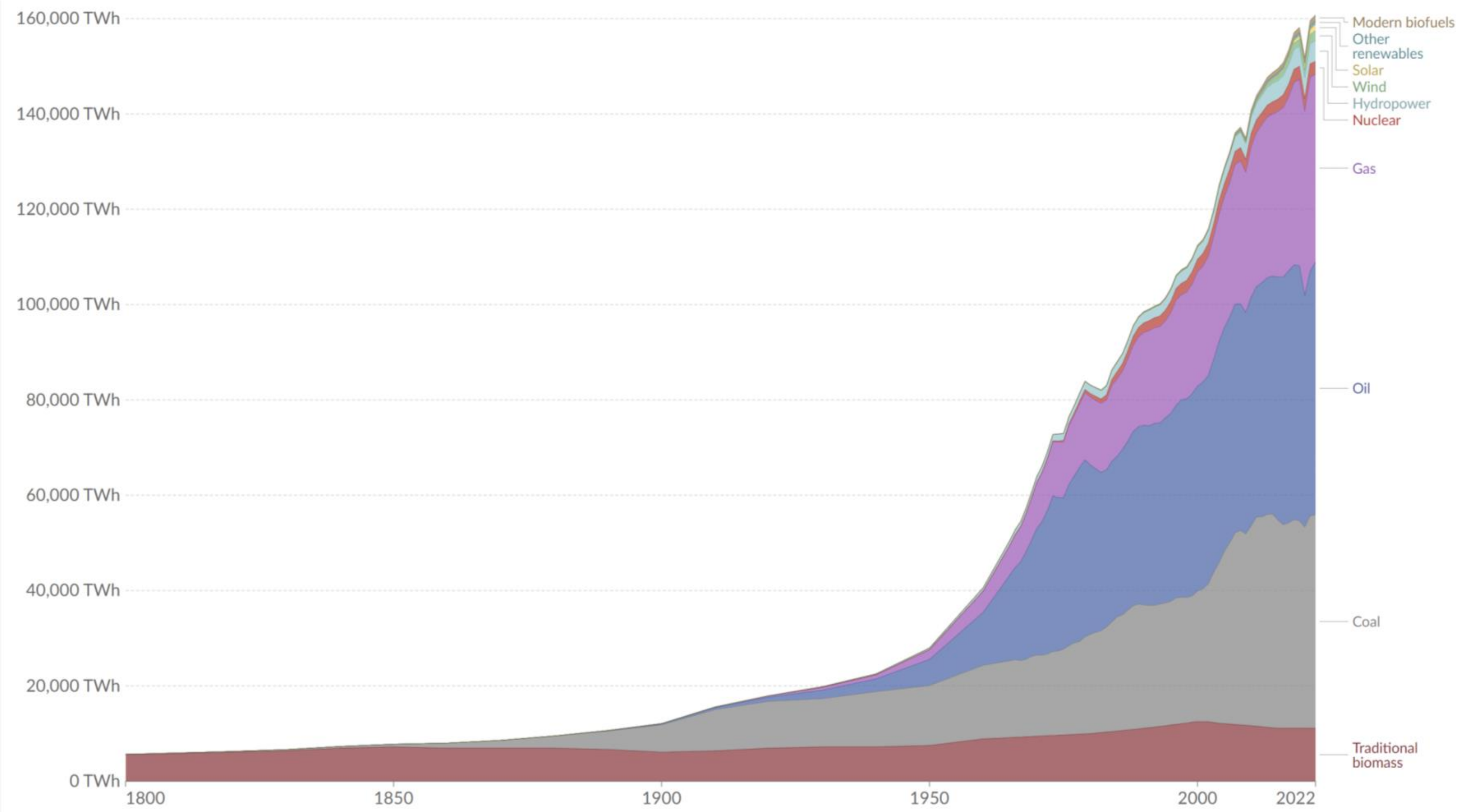
Using stored fossile energy carriers has created a carbon leakage from the geosphere to atmosphere

- Energy consumption is on an **all times-high**

- 13,5 % Renewables
- 86,5 % Fossil (and Nuclear) Energy

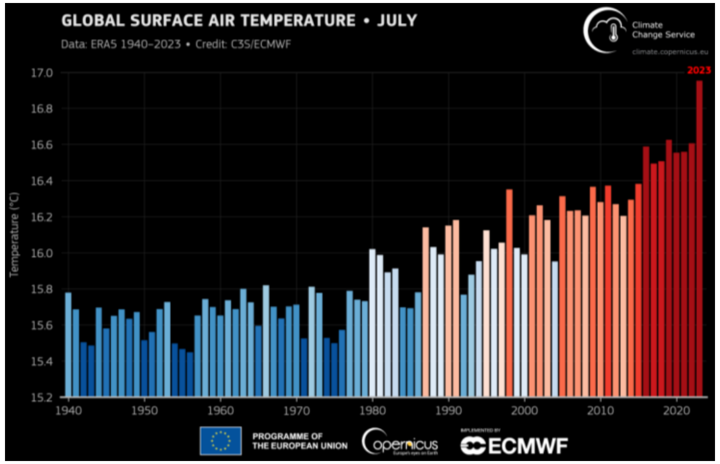
Promise of Salvation:

- **Green hydrogen and the Biosphere as a CO_2 source can close the carbon leakage**

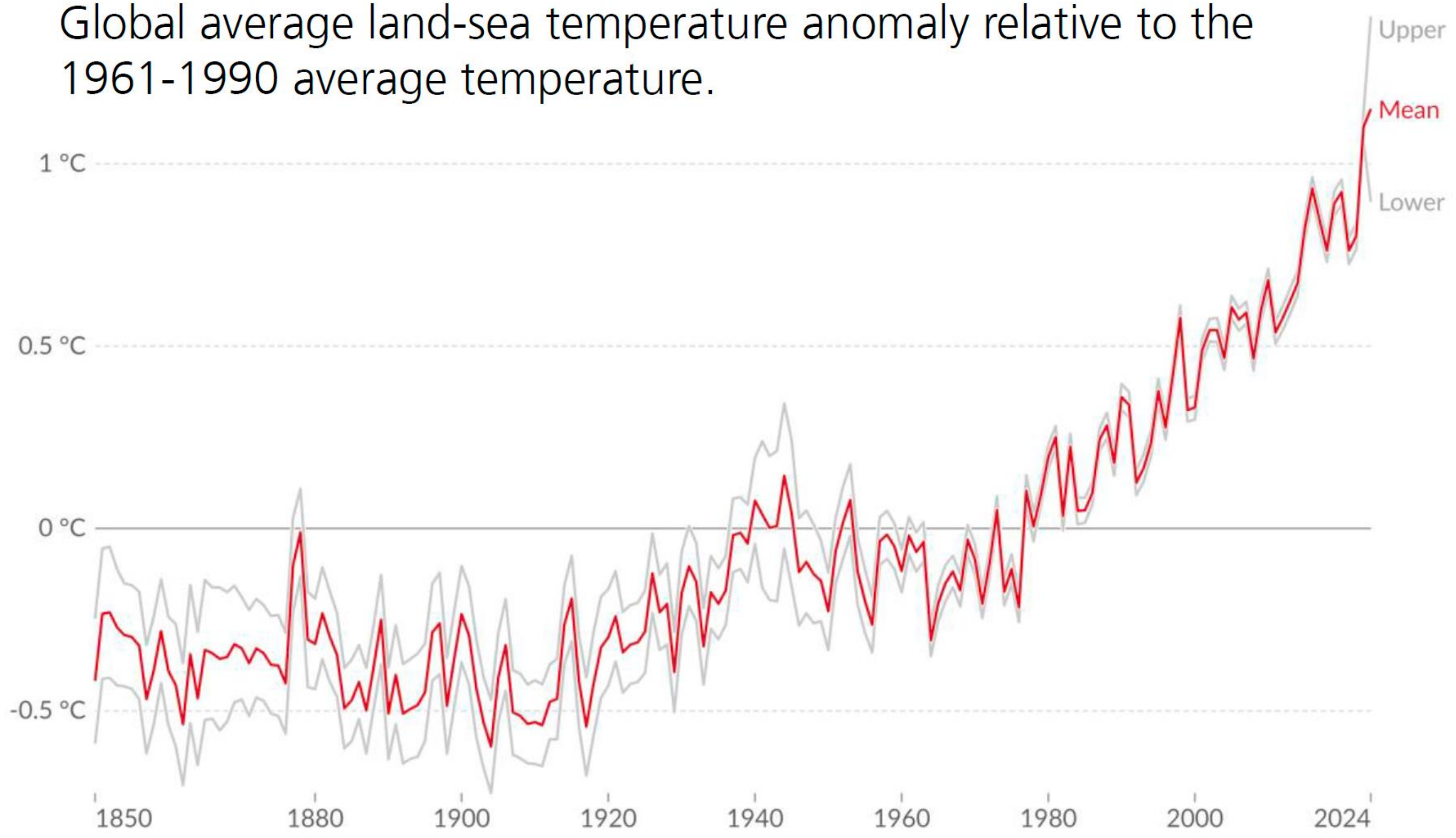


Energy Institute Statistical Review of World Energy (2023); Vaclav Smil (2017) – Our World In Data.org/energy

Global Average Land-sea Temperature Anomaly



Global average land-sea temperature anomaly relative to the 1961-1990 average temperature.



Data source: Met Office Hadley Centre (2023) OurWorldInData.org/co2-and-greenhouse-gas-emissions | CC BY
Note: The gray lines represent the upper and lower bounds of the 95% confidence intervals.

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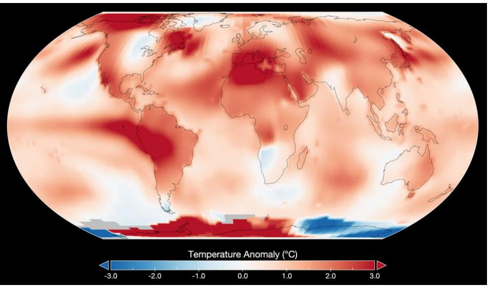
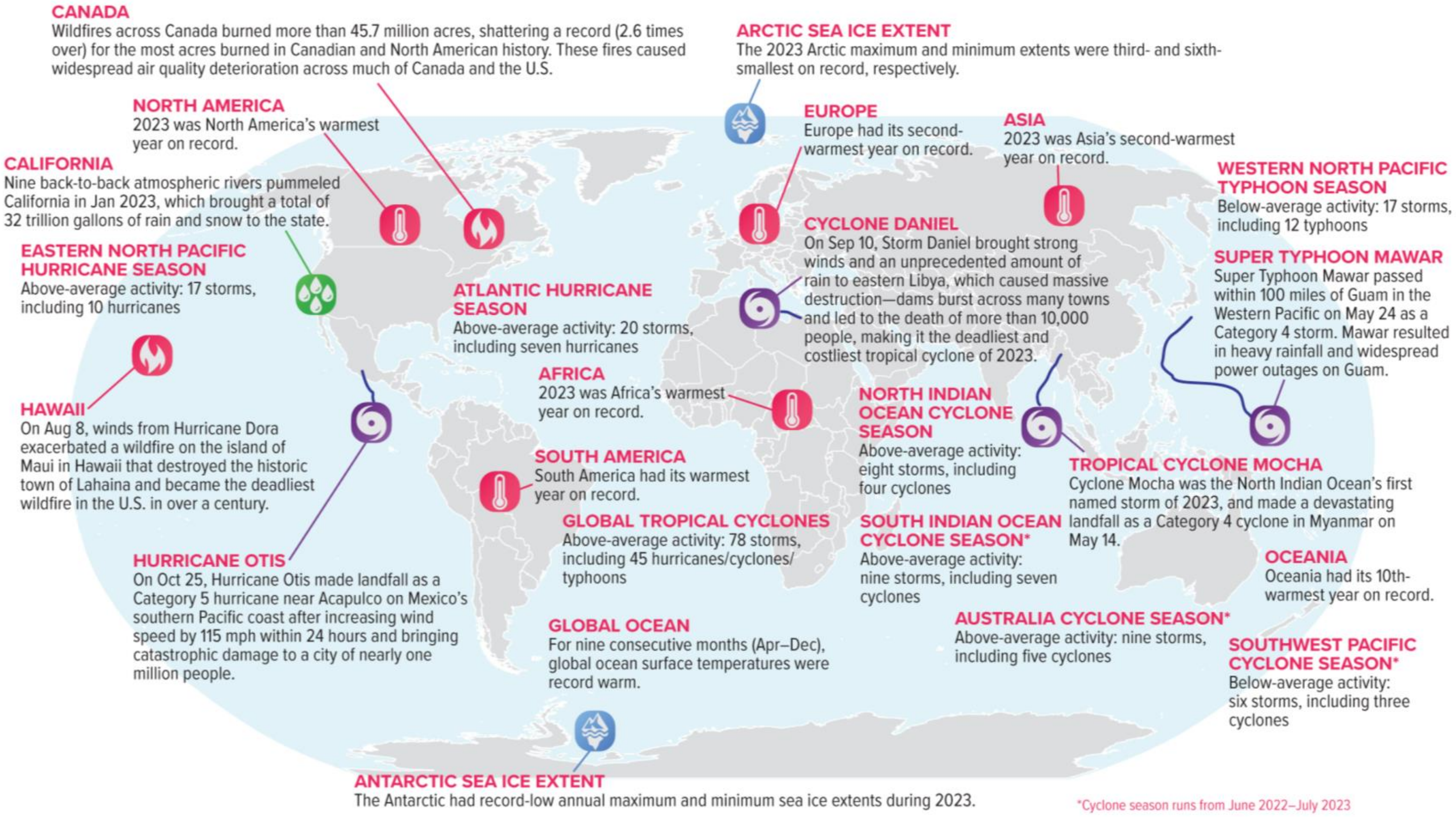
Extreme Weather Conditions as Early Warning Systems

Tipping elements at risk

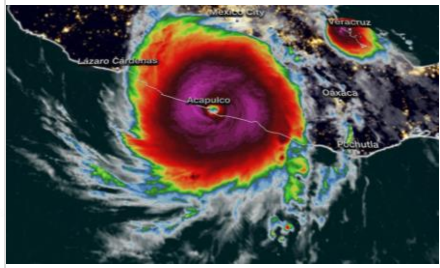
Wild Fires in Canada 2023



NASA Clocks July 2023 as Hottest Month on Record Ever Since 1880

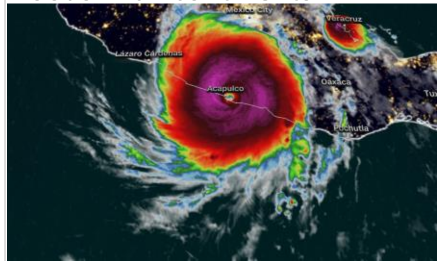


Hurricane Otis 205 mphmax



Sliding Thwaites Glacier

Floods in all continents



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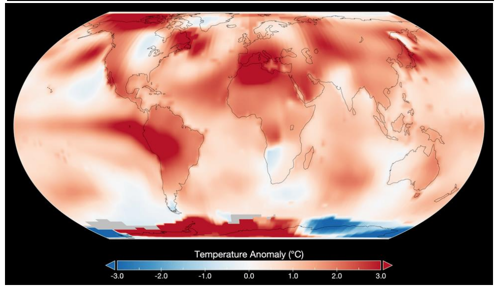
Extreme Weather Conditions as Early Warning Systems

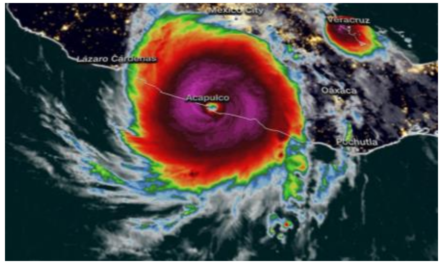
Canadian Wildfires in 2023 accounted for 23% of global accumulated wildfire CO_2 emissions

Wild Fires in Canada 2023



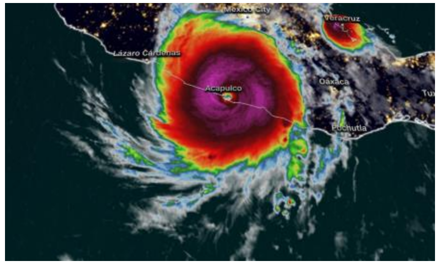
June hottest Month on Record

Hurricane Otis 205 mph max



Sliding Thwaites Glacier

Floods in all Continents

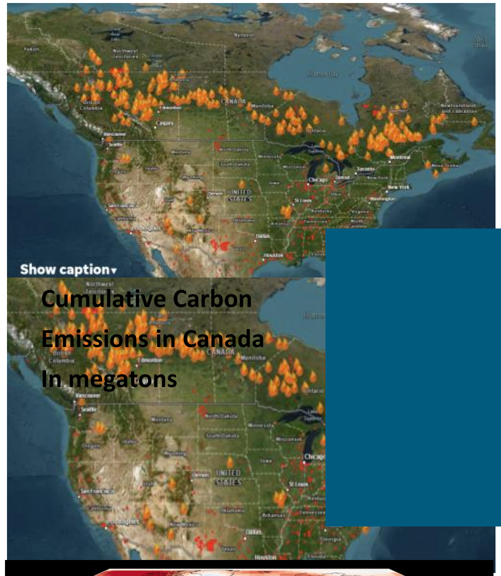


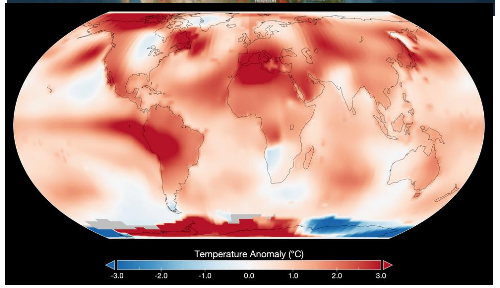
 Steffen et al. (2018). Trajectories of the Earth System in the Anthropocene. *Proceedings of the National Academy of Sciences*, *115*(33), 8252-8259.

Extreme Weather Conditions as Early Warning Systems

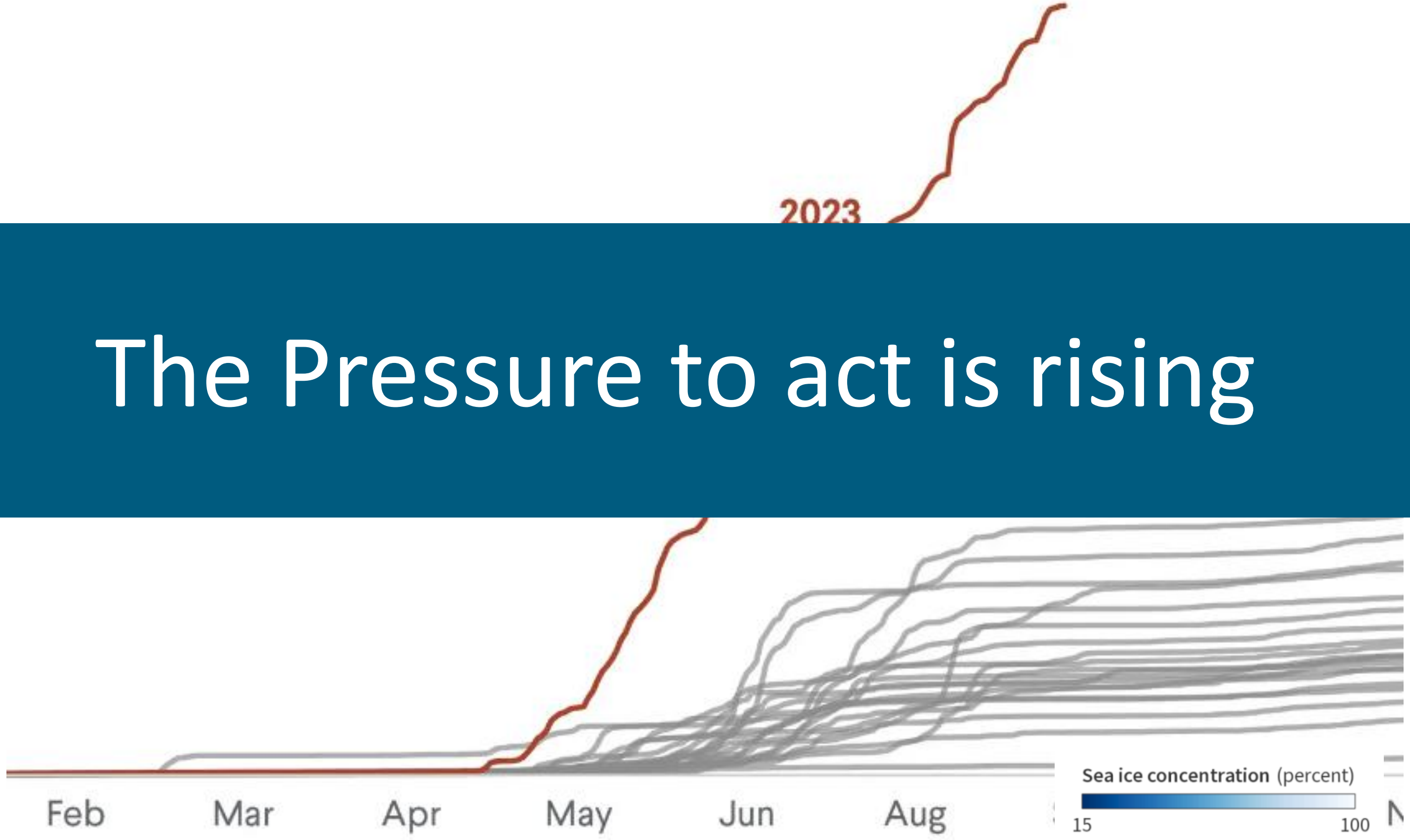
Arctic sea ice coverage in summer 2023 was the lowest ever

Wild Fires in Canada 2023



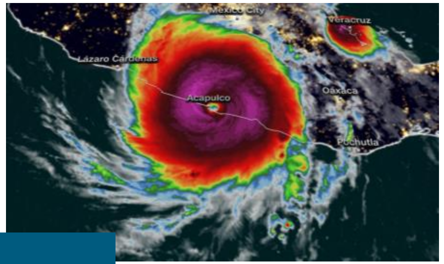


Hottest Month on Record Since 1880

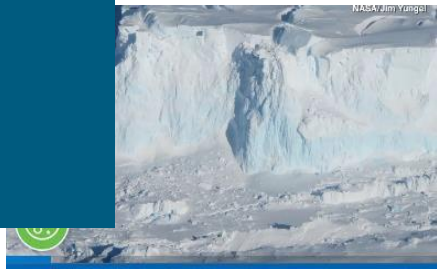


The Pressure to act is rising

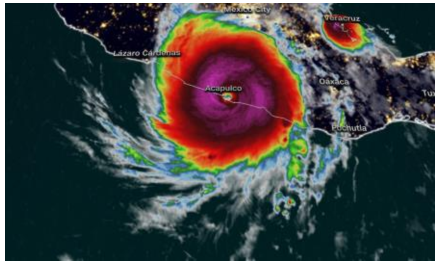
Hurricane Otis 205 mph max



…hwaites Glacier



Floods in all Continents



Steffen et al. (2018). Trajectories of the Earth System in the Anthropocene. *Proceedings of the National Academy of Sciences*, *115*(33), 8252-8259.

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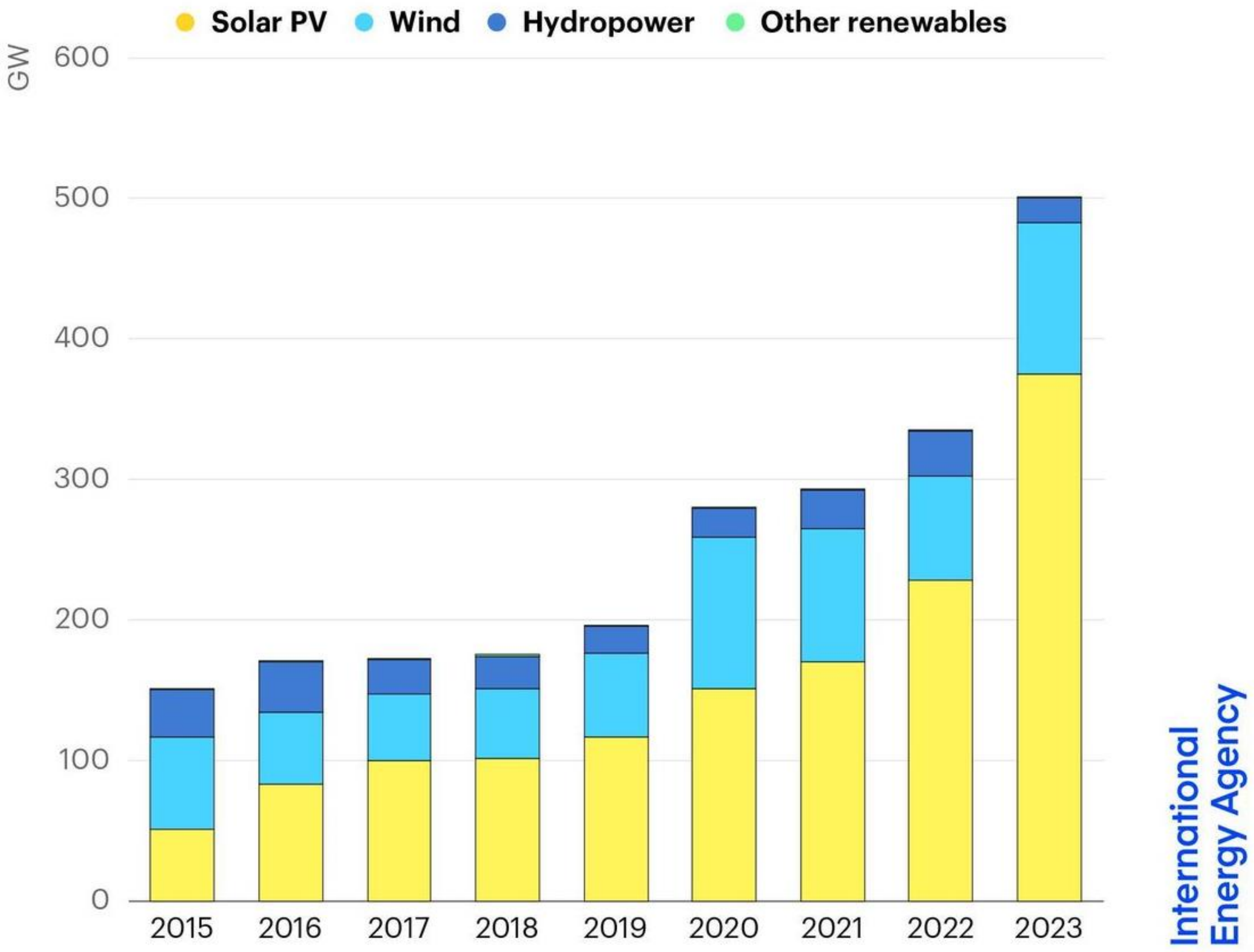
The Backbone of the Future Energy System: Renewable Energy

Global Wind and Photovoltaic Installations at like 3 TW Total Capacity Today

- **325 GW new renewable capacity in 2022**
- **473 GW new renewable capacity in 2023**
- **3870 GW Total installed renewable capacity**
- Power Purchase Agreements in **Photovoltaics @ 1 ct/kWh**
- Power Purchase Agreements in **Wind Onshore @ 2 ct/kWh**



Source: IRENA, 2023, http://resourceirena.irena.org/gateway/dashboard/

IRENA International Renewable Energy Agency

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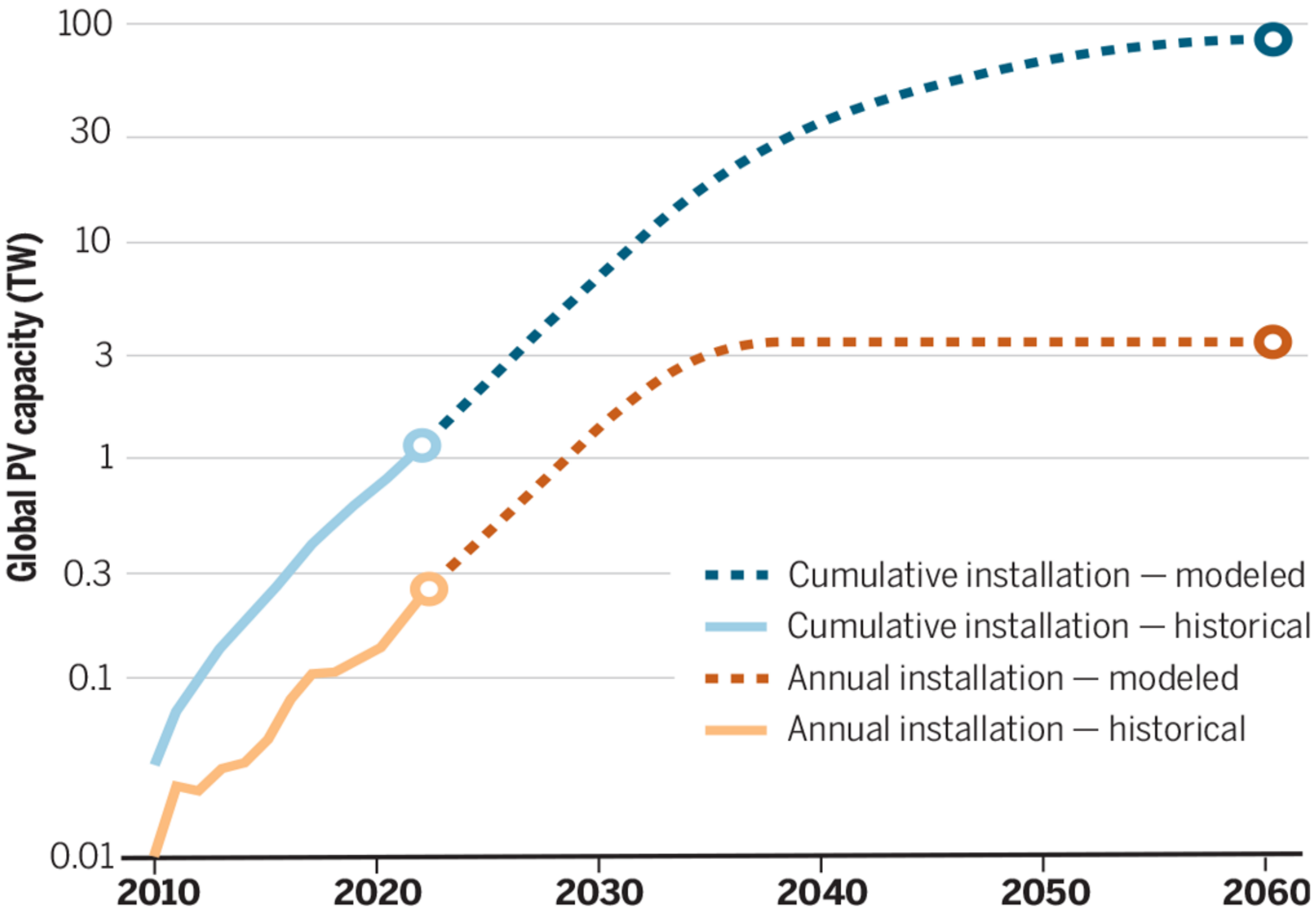
Development of future energy system

Example PV – PV installations and growth toward 75 TW by 2050



PV growth in 2004 1GW/yr
PV growth in 2010 1GW/m
PV growth in 2015 1GW/w
PV growth in 2023 1GW/d

PV growth in 2030 1GW/2h ?

- 25% **production rate growth** over the next 7 years and then reducing slowly to steady state
- Replacement needs are included by simple subtraction of installations 25 years before the modeled date

Haegel, N. et al.: Photovoltaics at multi-terawatt scale: Waiting is not an option, Science, Apr 2023, Vol 380, Issue 6640, pp. 39-42, DOI: 10.1126/science.adf6957

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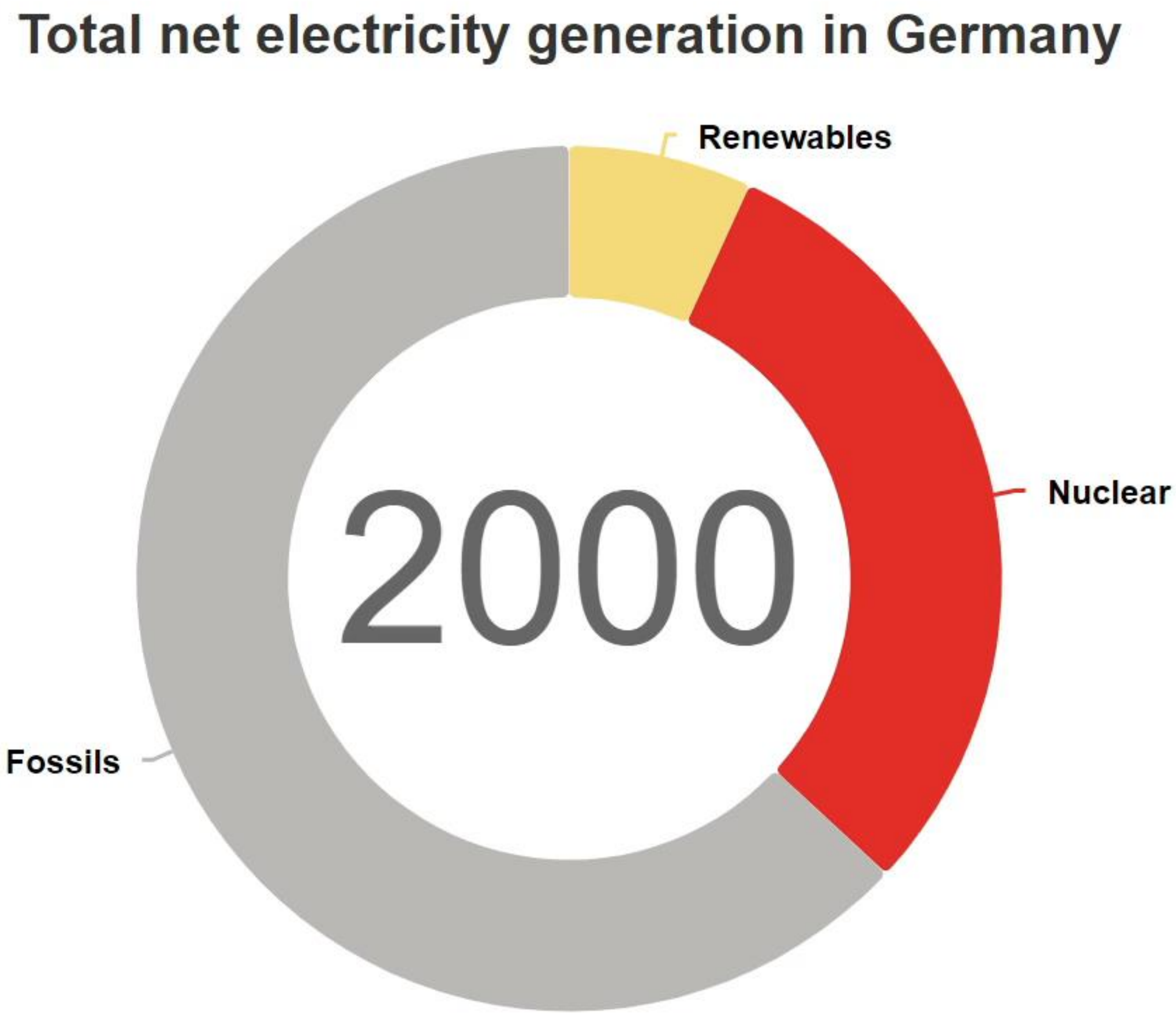
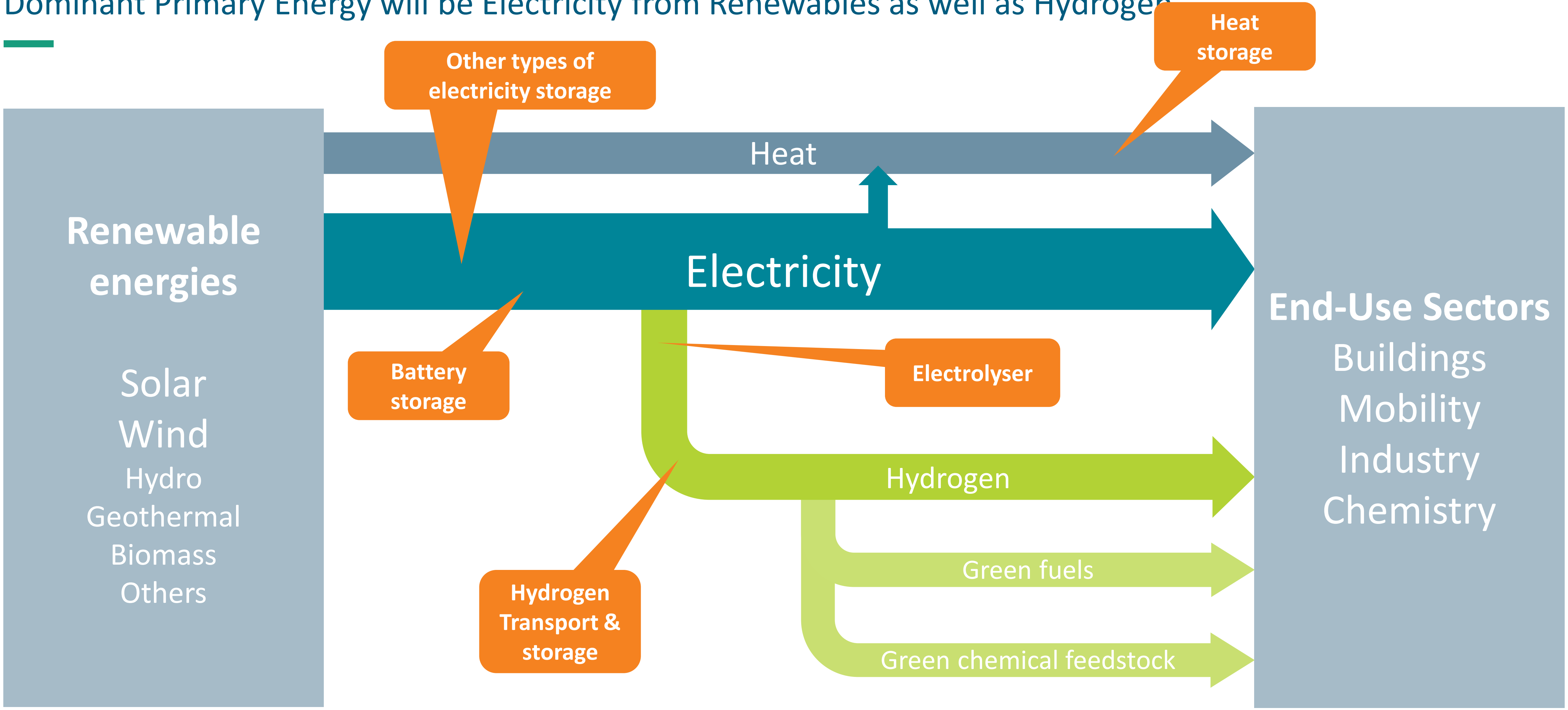
Energy System Transformation in Germany



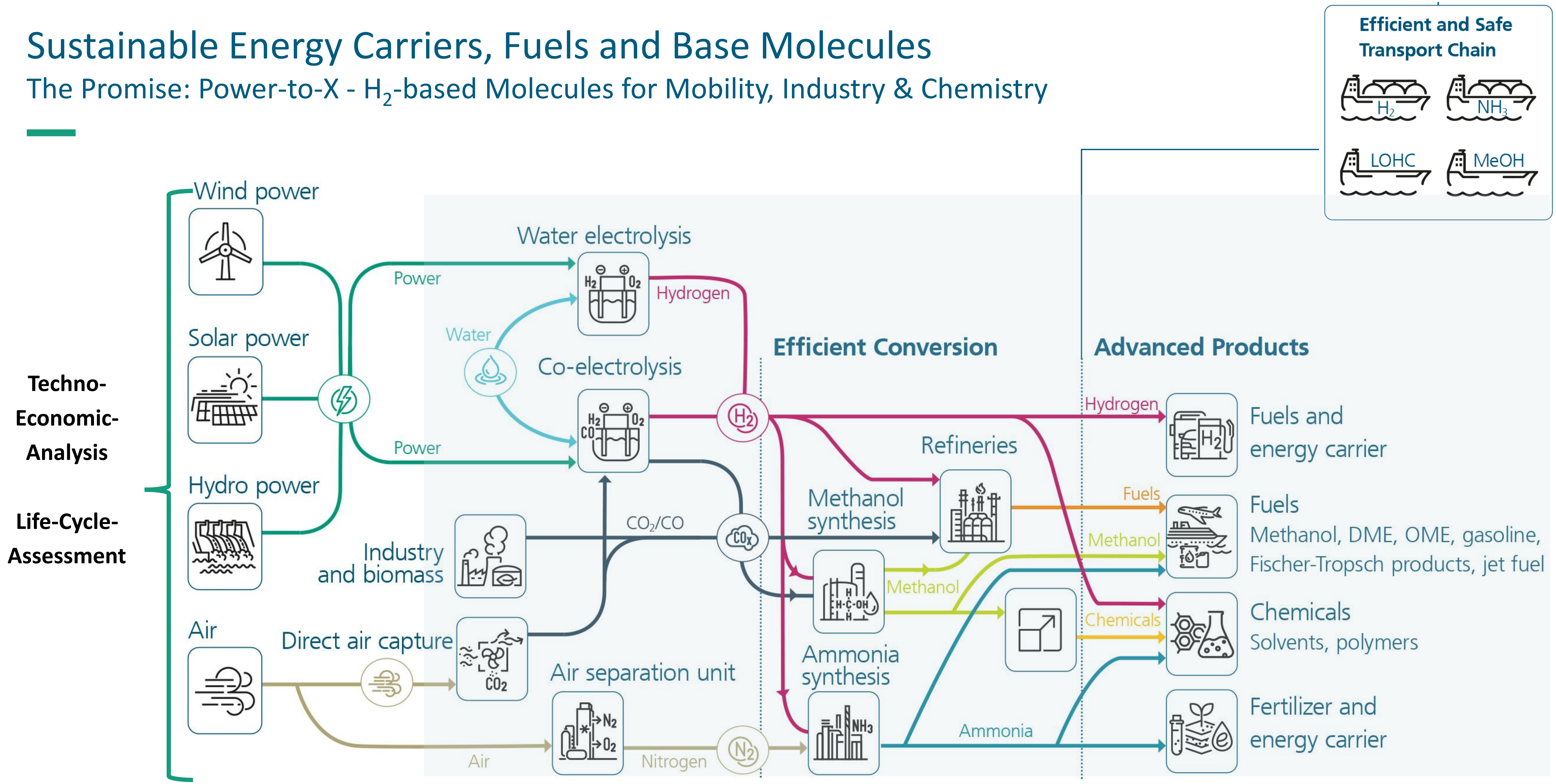
The Future Energy System

Dominant Primary Energy will be Electricity from Renewables as well as Hydrogen



Sustainable Energy Carriers, Fuels and Base Molecules

The Promise: Power-to-X - H_2-based Molecules for Mobility, Industry & Chemistry



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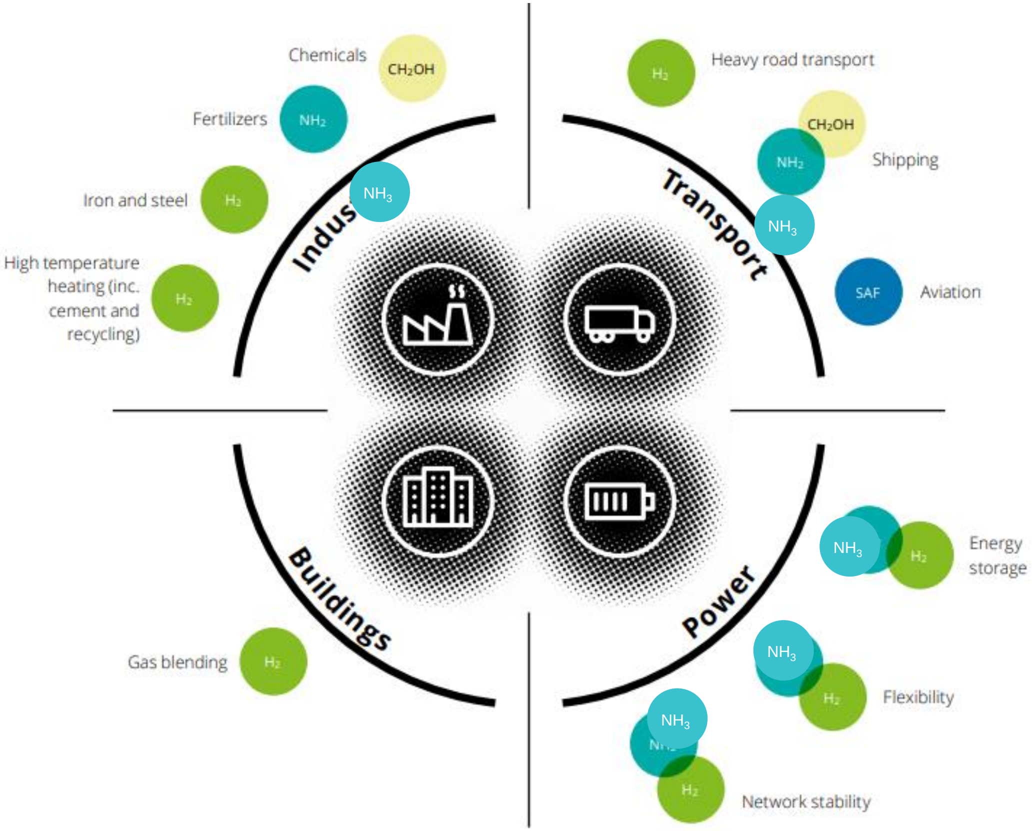
Global Green Hydrogen Outlook

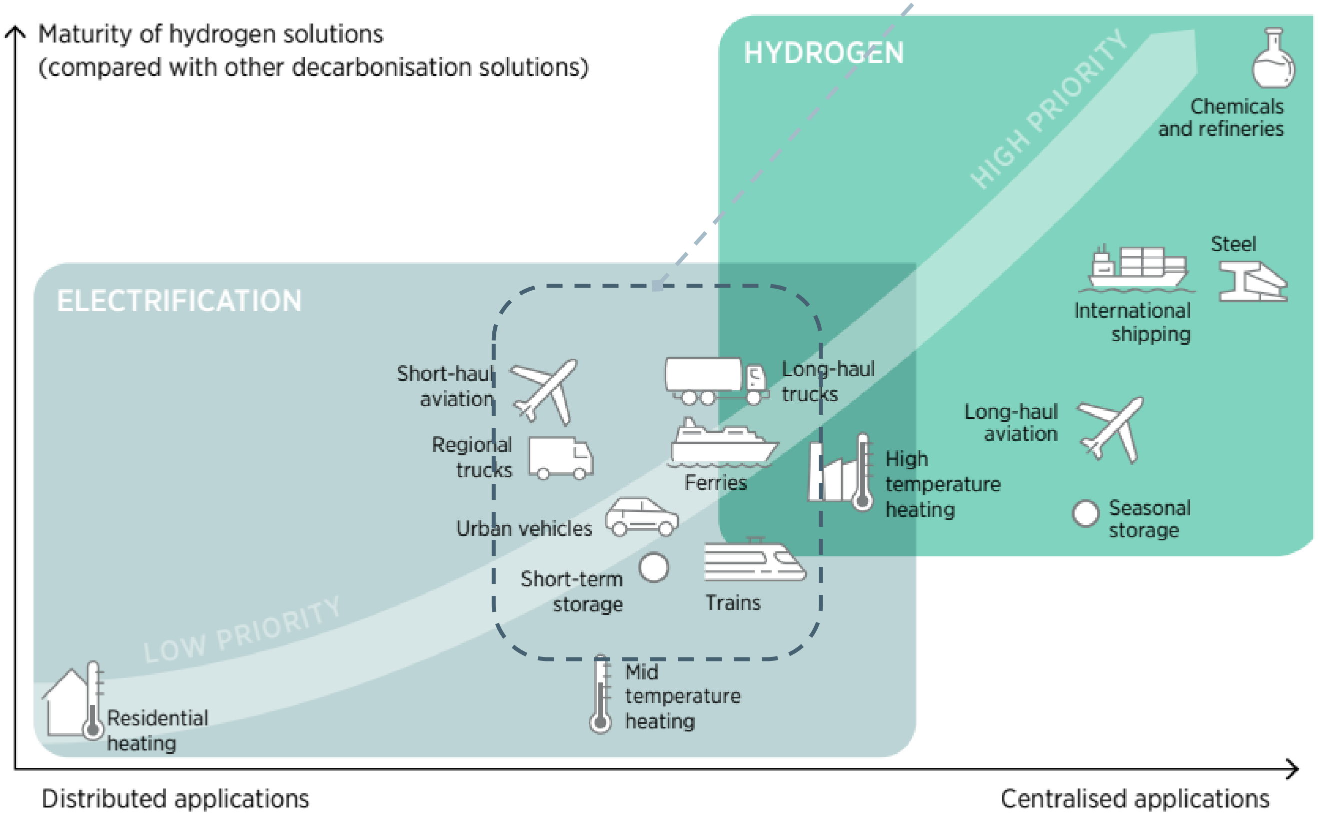
Hydrogen Demand for Climate Neutrality in 2050

Uncertainties about the limits of electrification, costs and quantities of hydrogen and e-fuels

- End Uses of clean H_2 and its derivatives



- Priority Settings for H_2-applications across the energy system



Source: Deloitte analysis based International Energy Agency (IEA)16, International Renewable Energy Agency (IRENA)17 and Hydrogen4EU.18

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> 50 National Roadmaps, Strategy Papers, R&D Programms on Hydrogen

World Energy Council – Germany, www. weltenergierat.de

> 50 National Roadmaps, Strategy Papers, R&D Programs on Hydrogen

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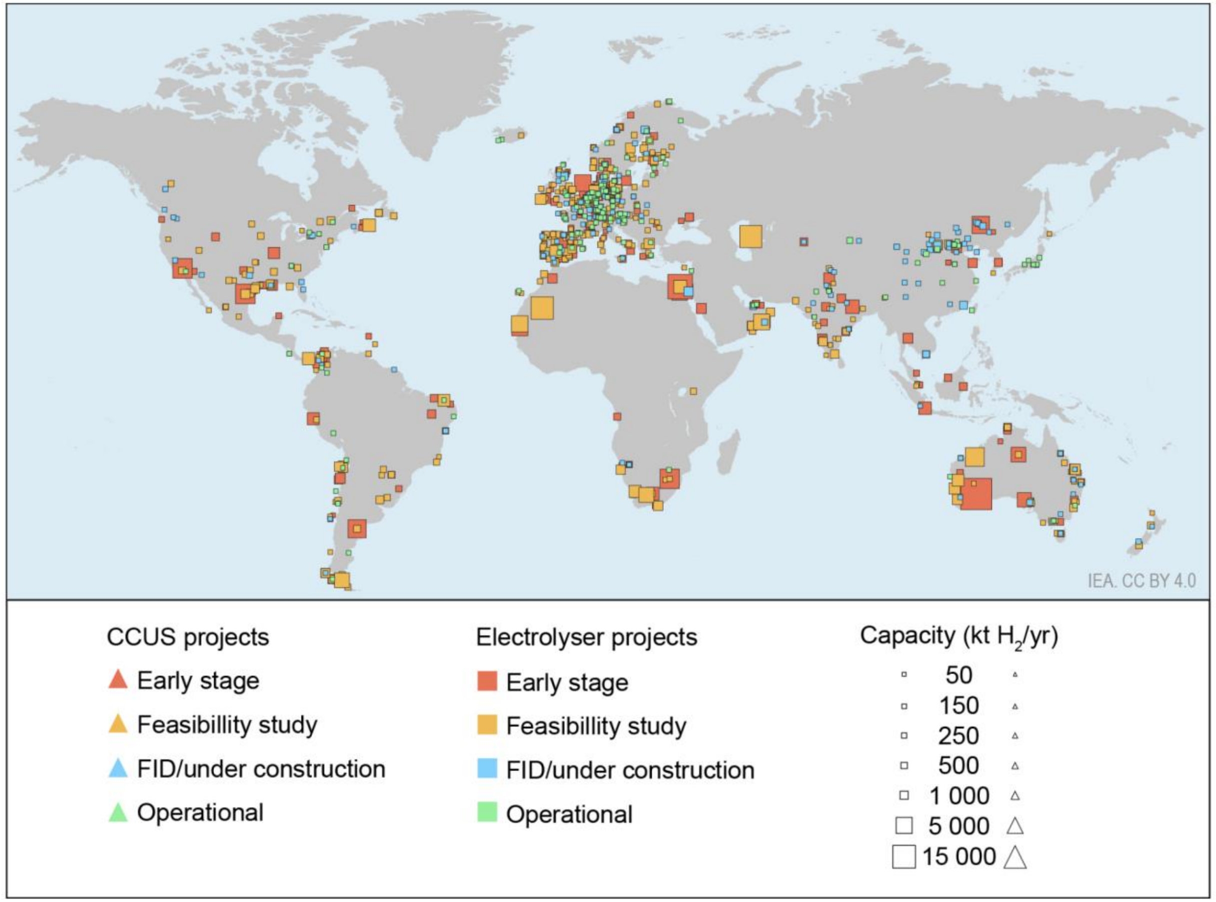
Strong Momentum Globally on Announcements

Perspective on hydrogen market development (IEA Global Hydrogen Review, 09/23)

- The number of announced projects for low-emission hydrogen production is **rapidly expanding**
- Less than 10% of projects have seen **FID** state, **China** accounts for more than **40% of the electrolysis projects** that have reached **FID globally**.
- **Carbon Contracts for Difference**, trackable, tradeable, transparent and trustworthy **guarantees of origin**
- The **potential production by 2030** from announced projects to date is **50% larger** than IEA's Review 2022.
- Annual H2-production could reach **38 Mt in 2030**.
- **27 Mt based on electrolysis** and low-emission electricity and **11 Mt on fossil fuels** with **CCUS**.
- By the end of 2023, **China's** installed electrolyser capacity reaches **1.2 GW – 50% of global capacity**. (10% in 2020)



Global Hydrogen Review – International Energy Agency 2023

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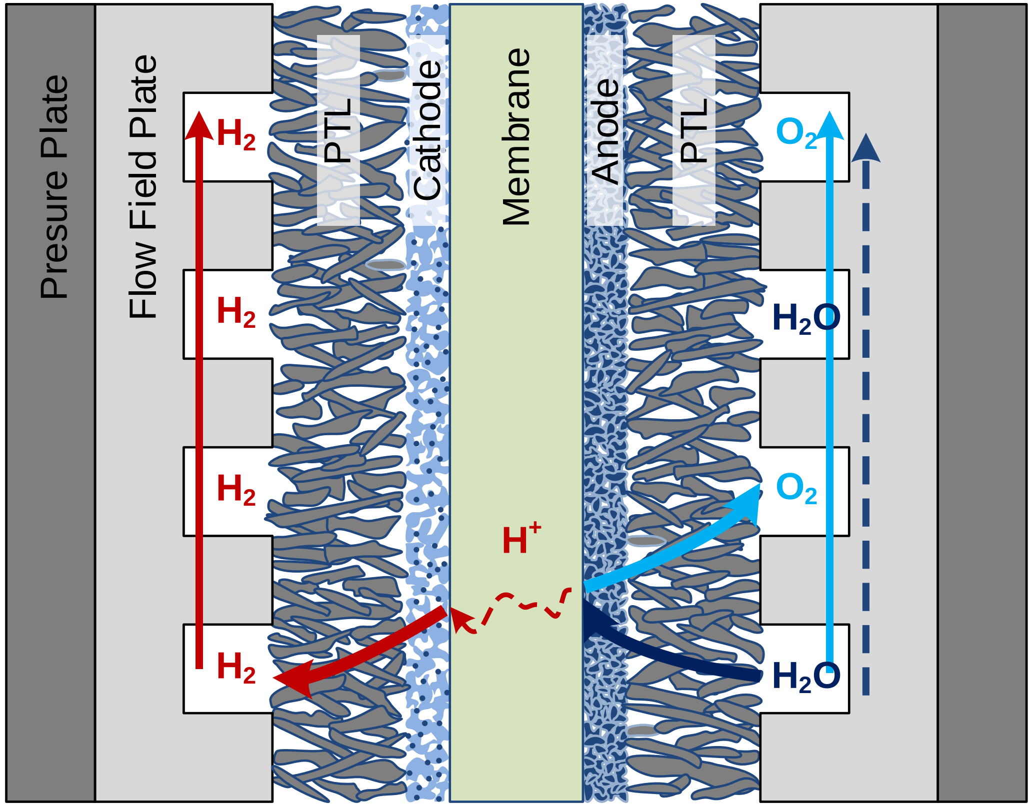
Proton exchange membrane water electrolysis (PEMWE/PEMEL)

Main cell components and state of the art materials



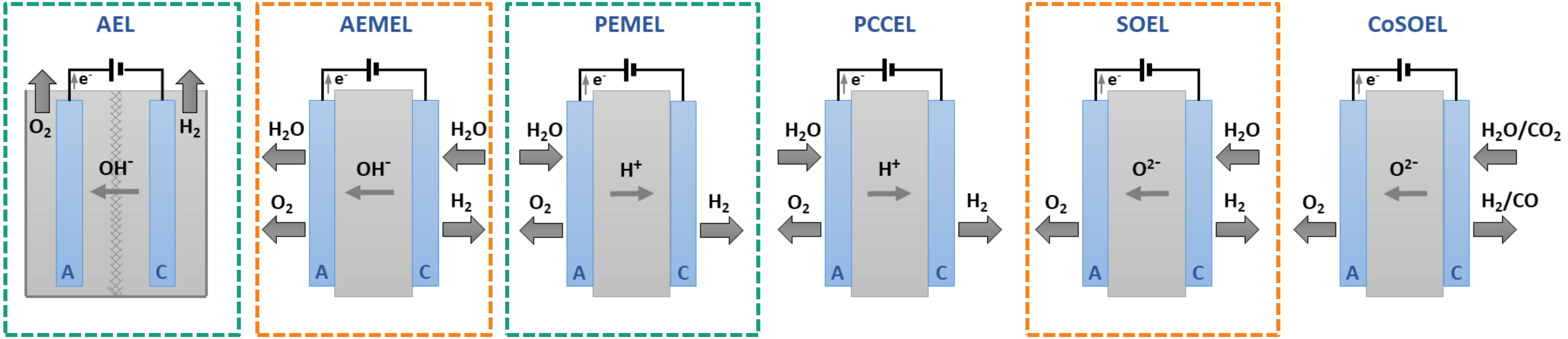
Cross section of a PEM electrolysis cell

- Membrane as solid electrolyte
  - Perfluorosulfonic acid (PFSA) ionomer
  - Typical thickness: 100 – 180 mm
- Electrodes for OER and HER
  - AN: (supported) Ir or IrOx: ~2.0 mg/cm²
  - CAT: supported Pt/C: ~ 0.5 - 1.0 mg/cm²
- Porous transport layers
  - Sintered Ti fibers/particles: 0.5 - 1.0 mm
  - Carbon paper (only at cathode)
- Bipolar plate (with flow field structures)
  - (Au or Pt coated) Ti sheet: 0.2 - 1.0 mm

Current State of Water Electrolysis Industry

Different electrolysis technologies exist but technology readiness levels vary.

Low Temperature (Water) Electrolysis			High Temperature (Steam) Electrolysis	
Alkaline Electrolysis		Proton Exchange Electrolysis		Oxygen Ion Electrolysis
Liquid Electrolyte	Polymer Electrolyte Membrane		Solid Oxid Membrane	



TRL: 8-9 | TRL: 5-7 | TRL: 7-9 | TRL: 3-4 | TRL: 4-8 | TRL: 4-6

Processes that **will**/**can** play a commercial role by 2030.

Current State of Water Electrolysis Industry

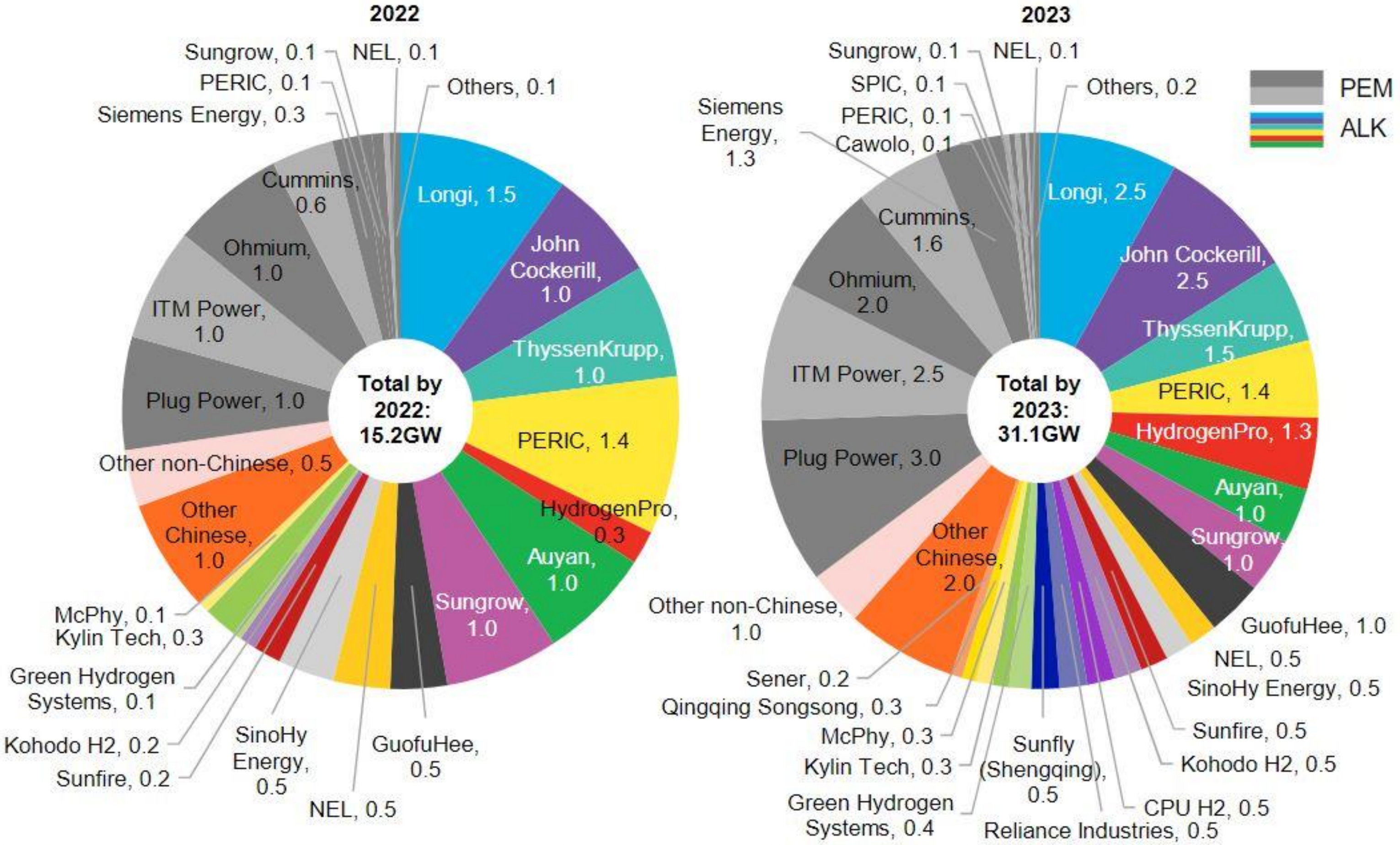
Dramatic increase in manufacturing capacities until 2030 - Green hydrogen is entering hockey stick territory

Market trends until mid 2020's

- Takeover of small technology companies by financially strong players (nearly) completed
- Extension of necessary production capacities and establishment of resilient supply chains
- Global additions reach small GW range with 2 GW in 2022 → 240 GW in 2030
- Realization of large-scale EL plants up to 100 MW with focus on AEL and PEMEL

European pain points

- Cost pressure from Chinese manufacturers
- Continuing delays to green hydrogen projects by policy hold-ups (unclear legal framework)



Source: Company filings, industry sources, BloombergNEF. Note: The values refer to year-end capacities.

BloombergNEF (2022-11): A Breakneck Growth Pivot Nears for Green Hydrogen, https://about.bnef.com/blog/a-breakneck-growth-pivot-nears-for-green-hydrogen/

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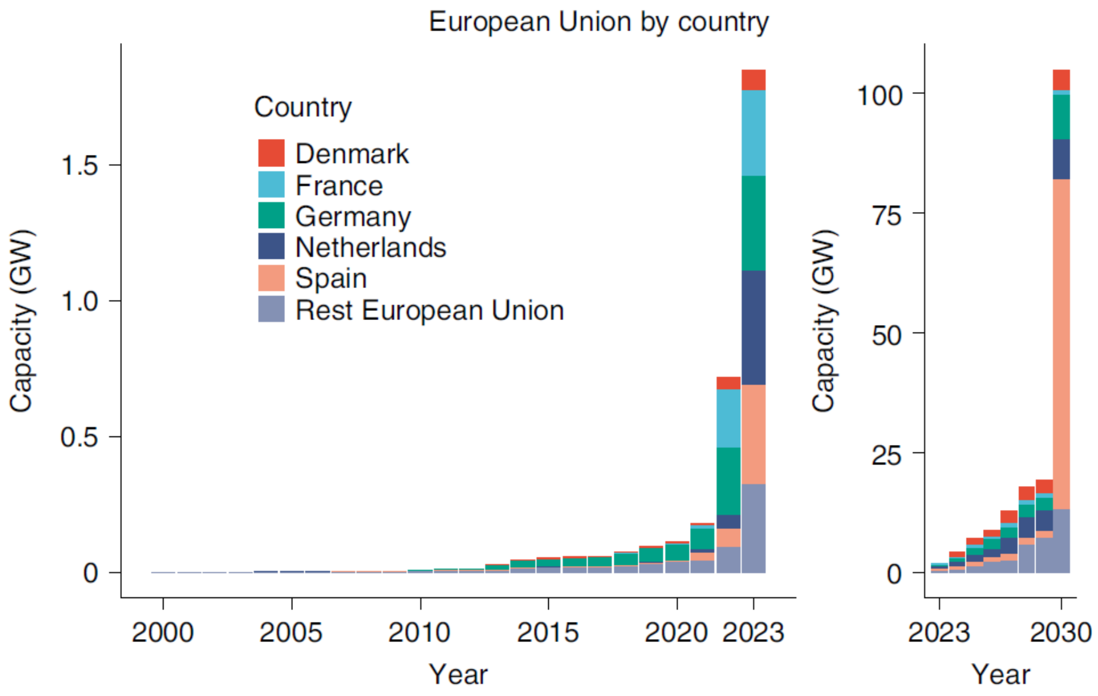
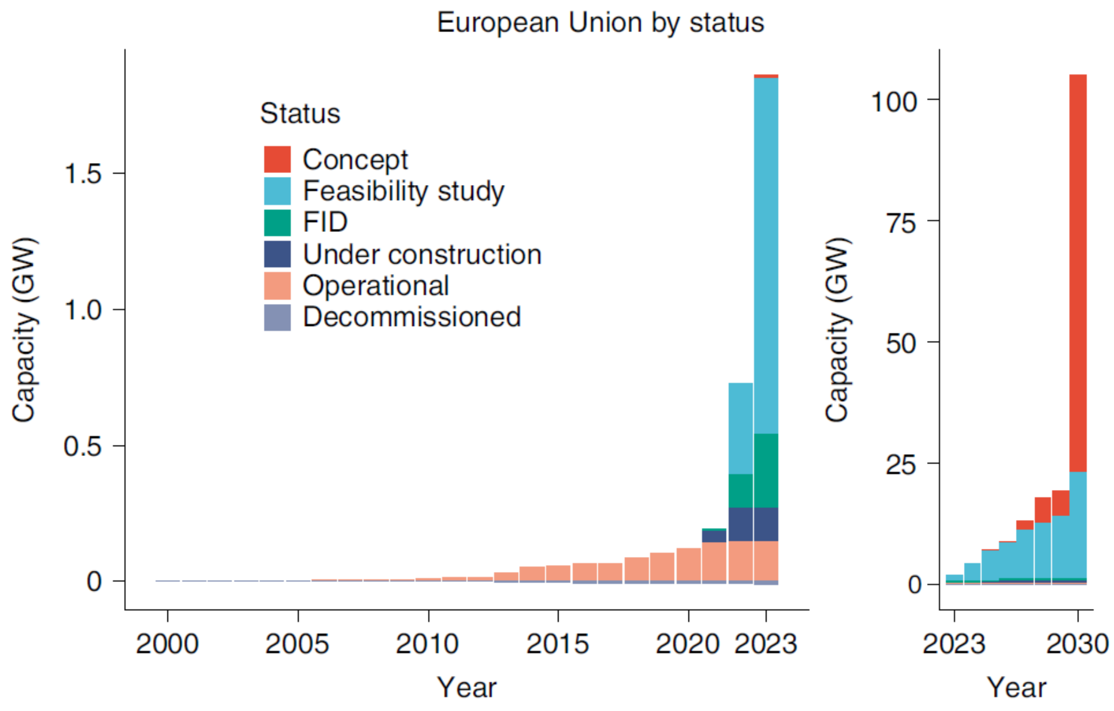
Current State of Water Electrolysis Industry

Europe: Policy support will play a crucial role to scale green hydrogen up to 2030.

European hydrogen strategies focuses on the production of green H_2 through water electrolysis coupled with renewable electricity.





Historical development and future announcements of electrolysis projects according to IEA data base

Odenweller, A., Ueckerdt, F., Nemet, G.F. *et al.* Probabilistic feasibility space of scaling up green hydrogen supply. *Nat Energy* **7**, 854–865 (2022). https://doi.org/10.1038/s41560-022-01097-4

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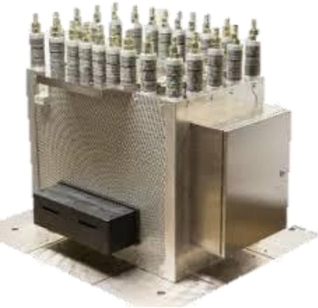
Current State of Water Electrolysis Industry

Upscaling and commercialization of PEM electrolyzers is ongoing but not an easy way.

Cummins (US) – HyLIZER series

- 30 bar_g (DP)
- E1500 stack
- Up to 2.5 MW

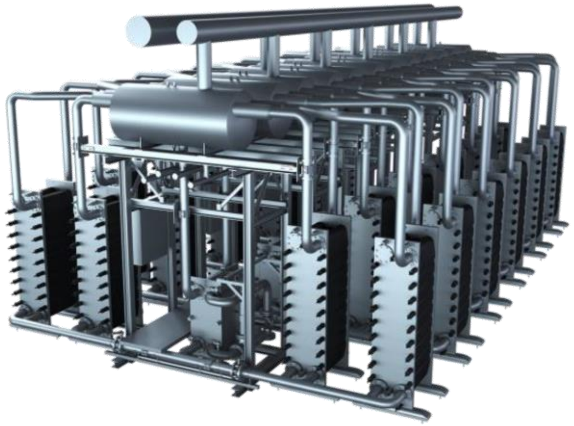


h-tec Systems (DE) – Series S450

- Up to 30 bar_g (DP)
- 450 cm²
- ~ 100 kW

Siemens Energy (DE) – Silyzer 300

- 24 modules in a full array with 17.5 MW
- Atmospheric (!)

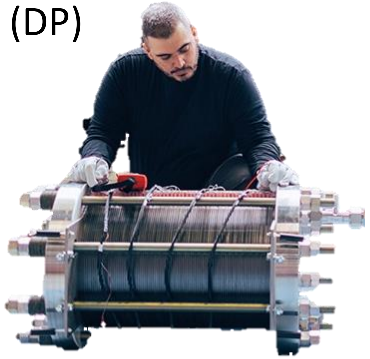


NEL (NO) – M series

- 30 bar_g (DP)
- 1,580 cm²
- 1.25 MW

Elogen (FR) – E series

- 30 bar_g / 9 bar_g (DP)
- from 50 kW up



ITM Power (UK) – MEP2.0

- 3 stacks in a 2 MW EL skid
- Pneumatic 'quick' clamping
- 30 bar_g (DP)

➔ Exemplary naming of some manufacturers, not a complete overview!

Picture credits: NEL ASA, cummins Inc., elogen SAS, h-tec Systems GmbH, ITM Power Ltd., Siemens Energy AG

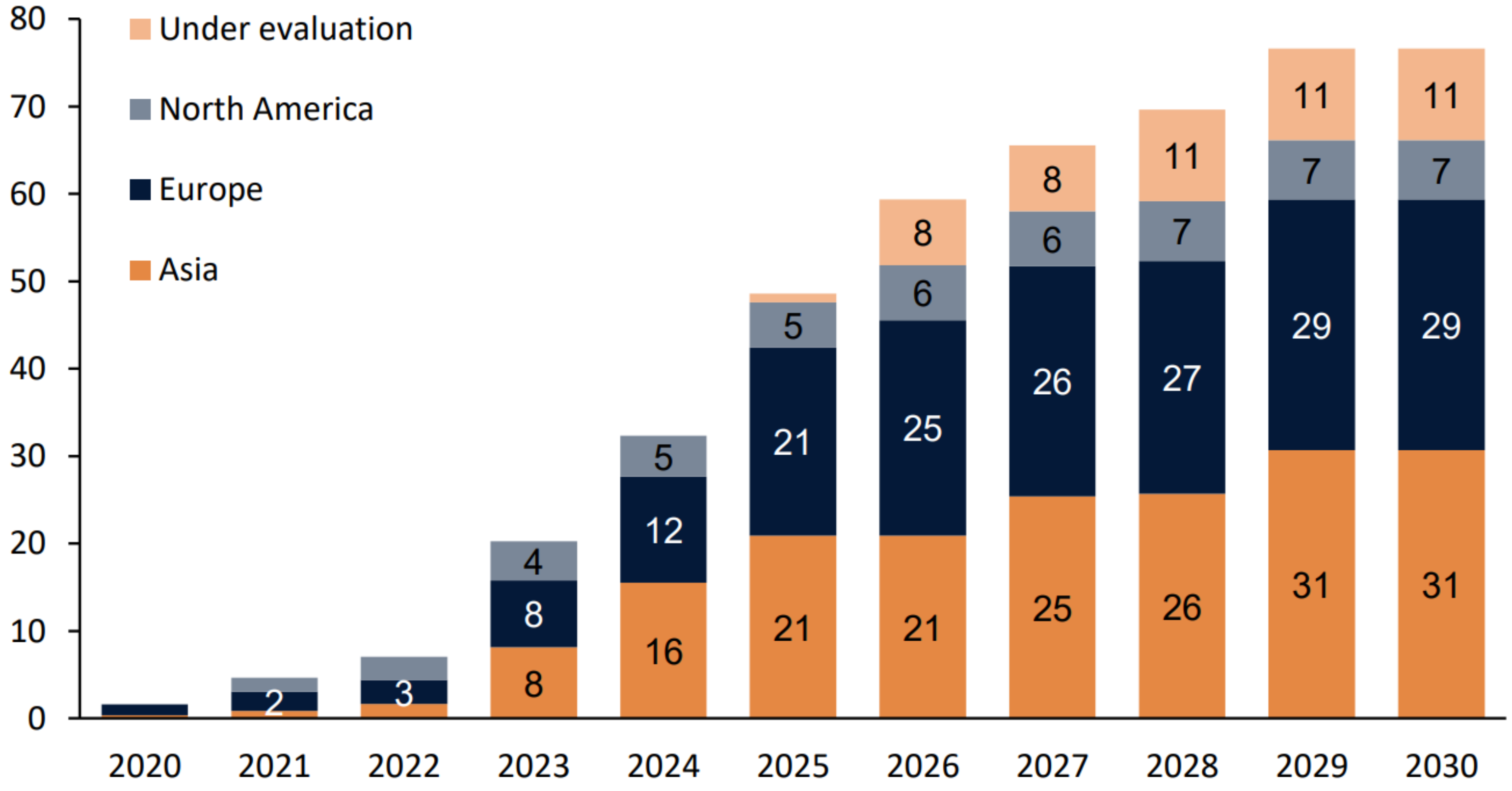
DP: differential pressure
PB: pressure-balanced

Current State of Water Electrolysis Industry

Dramatic increase in manufacturing capacities until 2030

Market trends until mid 2020's

- Realization of large-scale EL plants up to 100 MW
  - Valley of tears --> learning curves & funding
  - Focus on AEL and PEMEL
- Global additions reach small GW range
  - 2 GW in 2022 → 240 GW in 2030



Electrolyzer supplier's manufacturing capacity
In gigawatts (GW), announced annual manufacturing capacity by region

Reference: RystadEnergy (2023-01-13): Energy Transition Report Hydrogen Market Update, The hydrogen economy in 2023

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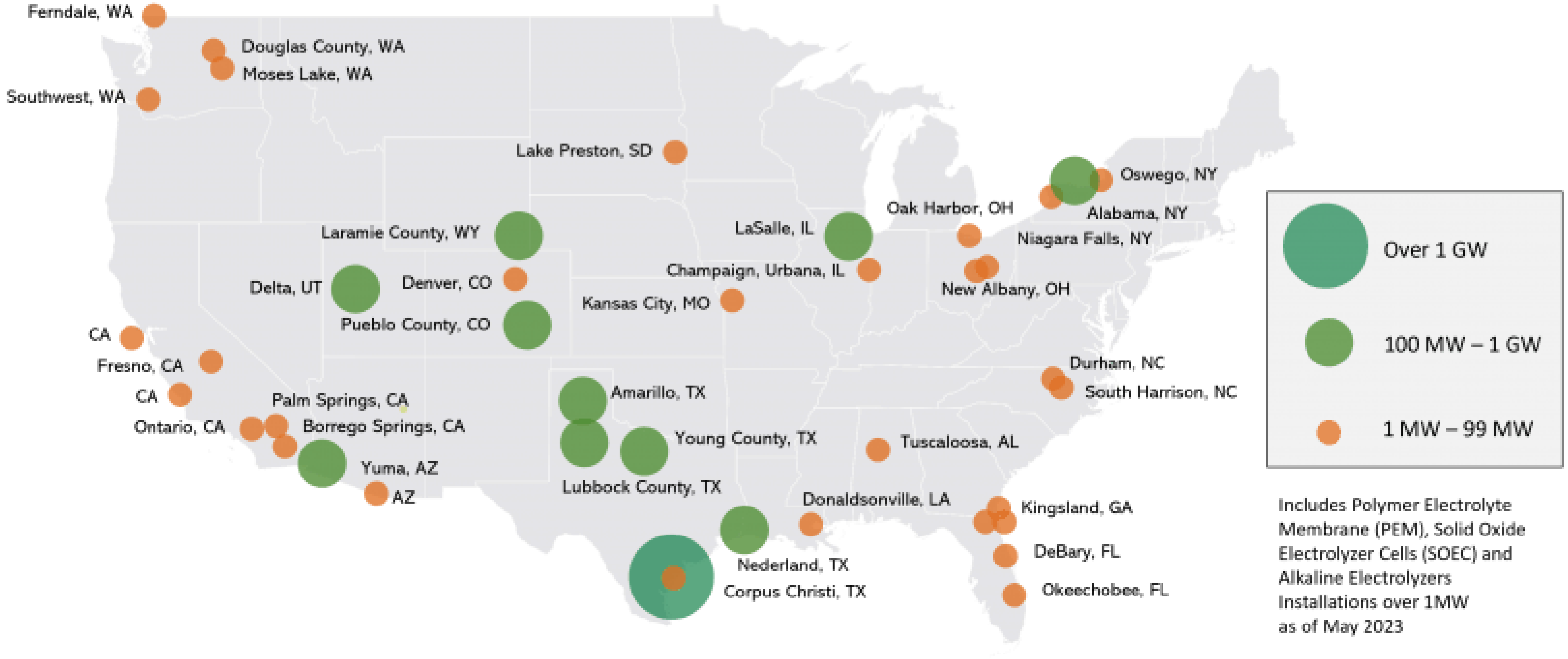
Current State of Water Electrolysis Industry

Planned and Installed Electrolyzer Capacity in the U.S.

Total 3.7 GW in Electrolyzer Capacity: Five-fold increase since 2022!



Includes Polymer Electrolyte Membrane (PEM), Solid Oxide Electrolyzer Cells (SOEC) and Alkaline Electrolyzers Installations over 1MW as of May 2023

Arjona, V. (2023), DOE Hydrogen Program Record 23003, June 2023, https://www.energy.gov/eere/fuelcells/articles/electrolyzer-installations-united-states

Development Targets for LT Water Electrolysis

European Strategic Research and Innovation Agenda 2021 – 2027

Clean Hydrogen Partnership

- Target KPI values for PEM water electrolysis defined by Hydrogen Europe and HE Research
  - for Horizon Europe (9th EU Framework Program for Research and Innovation)
  - All KPIs should be achieved at the same time
- Technological develop-ment will be evolutionary, not disruptive

No.	KPI	Unit	SoA 2020		Targets 2024		Targets 2030	
			AEL	PEMEL	AEL	PEMEL	AEL	PEMEL
1	Electricity consumption @ nominal capacity	kWh/kg	50	55	49	52	48	48
2	Capital cost	€/(kg/d) €/kW	1,250 600	2,100 900	1,000 480	1,550 700	800 400	1,000 500
3	O&M cost	€/(kg/d)/y	50	41	43	30	35	21
4	Hot idle ramp time	sec	60	2	30	1	10	1
5	Cold start ramp time	sec	3,600	30	900	10	300	10
6	Degradation	%/1,000h	0.12	0.19	0.11	0.15	0.10	0.12
7	Current density	A/cm^2	0.6	2.2	0.7	2.4	1.0	3.0
8	Use of critical raw materials as catalysts	mg/W	0.6	2.5	0.3	1.25	0.0	0.25

Clean Hydrogen Joint Undertaking (25 February 2022): Strategic Research and Innovation Agenda 2021 – 2027
hhttps://www.clean-hydrogen.europa.eu/about-us/key-documents/strategic-research-and-innovation-agenda_en

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Development Targets for LT Water Electrolysis

Goals of the US American The Hydrogen and Fuel Cell Technologies Office

U.S. DEPARTMENT OF ENERGY

- Technical targets for LT water electrolysis accord-ing to the Multi-Year Research, Development, and Demonstration Plan
- All performance, durability, and capital cost targets must be met simultaneously
- Overall central goal of low-cost hydrogen production
  - \$2/kg H2 by 2026 and
  - \$1/kg H2 by 2031
  - Electricity ≤ \$0.03/kWh

No.	KPI	Unit	SoA 2022		Targets 2026		Ultimate Targets	
	System		AEL	PEMEL	AEL	PEMEL	AEL	PEMEL
Sy	Energy Efficiency @ nominal capacity	kWh/kg	55	55	52	51	48	46
Sy	Capital cost	\$/kW	500	1,000	250	250	150	150
Sy	H_2 production cost	\$/kg	> 2.00	> 3,00	2.00	2.00	1.00	1.00
	Stack							
St	Cell performance	A/cm^2 @ V	0.5 @ 1.9	2.0 @ 1.9	1.0 @ 1.8	3.0 @ 1.8	2.0 @ 1.7	3.0 @ 1.6
St	Electrical efficiency	kWh/kg	51	51	48	48	45	43
St	Av. degradation rate	%/1,000h	0.17	0.25	0.13	0.13	0.13	0.13
St	Total PGM content (both electrodes)	mg/cm^2 (g/kW)	--	3.0 (0.8)	--	0.5 (0.1)	--	0.125 (0.03)

Water Electrolyzer Technical Targets from the Hydrogen and Fuel Cell Technologies Office
https://www.energy.gov/eere/fuelcells/hydrogen-production-related-links#targets

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Development Targets for LT Water Electrolysis

Comparison of the EU SRIA targets with US DOE goals: Who is more ambitious?

U.S. DEPARTMENT OF ENERGY

Ambition mapping

- Europe is more ambitious (light green)
- Parity between EU and US (light blue)
- US is more ambitious (orange)
- US is much more ambitious (magenta)

No.	KPI	Unit	SoA 2022		Targets 2026		Ultimate Targets	
	System		AEL	PEMEL	AEL	PEMEL	AEL	PEMEL
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Water Electrolyzer Technical Targets from the Hydrogen and Fuel Cell Technologies Office
https://www.energy.gov/eere/fuelcells/hydrogen-production-related-links#targets

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Summary, Statements & Conclusion (I)

The market launch of electrolysis will not fail because of the technology.

1. Water electrolysis is on its way to becoming a gigawatt industry. All companies are currently massively expanding their manufacturing capacities.

2. There is no real technical showstopper visible until 2030+ (materials, scale-up, lifetime, costs). Technologies can complement each other. But learning curve still has to be overcome.

3. Current hurdles for electrolysers: no investment security, supply chain bottlenecks, shortage of skilled workers, lack of standardization and norming

4. However, a successful market ramp-up will only work with suitable boundary conditions (availability of RE and market framework incl. business models for green hydrogen).

Summary, Statements & Conclusion (II)

- There is a **dual structure of local electrons and remote derivatives of hydrogen** in world markets

- **Circularity** becomes key

- Different **cultures, markets and industry sectors** have different challenges and needs and thus, react differently
- **Behavioral changes and societal norms** contribute more than technical efficiency
- Put the **people into the center** of the energy system transformation
- The best **innovations, processes and technologies** are meaningless when we don‘t understand how they **affect the life of human being** and how we communicate, accompany and control these changes best

- **A global sustainability assessment is needed which acknowledges the planetary boundaries**

- International politics must develop **clear pathes and targets for GHG neutrality** and set-up an effective **regulatory framework** (taxes, levies, incentives, etc.) to achieve the targets.

Thank you for your attention!

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International Initiatives

Greater coherence by means of global activities is needed to increase impact

IAHE, 1974
Objective: Dissemination
Activities: WHEC, IJHE

Hydrogen TCP, 1977
Objective: Collaboration on R&D
Activities: Tasks

IEA Technology Collaboration Programme Advanced Fuel Cells

AFC TCP, 1990
Objective: Collaboration on R&D
Activities: Tasks

IPHE, 2003
Objective: RCS
Activities: Certification, LCA, carbon footprint

MISSION INNOVATION
CLEAN HYDROGEN MISSION

MI, 2015 (COP21, Paris)
Objective: reach GW
Activities: Hydrogen Valleys + Gas Grid WG

Hydrogen Council, 2017 (Davos)
Objective: Mobilize CEOs
Activities: Reports, Hydrogen Insights

HYDROGEN INITIATIVE
AN INITIATIVE OF THE CLEAN ENERGY MINISTERIAL

CEM H2I, 2019 (CEM 10)
Objective: Collaboration on policies, programs, projects
Activities: WGs

CLEAN HYDROGEN MISSION

MI 2.0, 2021-2022
Objective: 2USD/kg green H_2 by 2030
Activity: Hydrogen Valleys (100 by 2030)

RD20
Research and Development 20 for Clean Energy Technologies

Founded in 2019 by Prime Minister Abe in Japan, fostering
International Collaboration of leading Research Institutions of the G20 countries
Partnerships between industry, academia and politics
Activity: Annual conference and leaders meeting

International Energy Agency
IRENA International Renewable Energy Agency
WORLD ECONOMIC FORUM
UNIDO

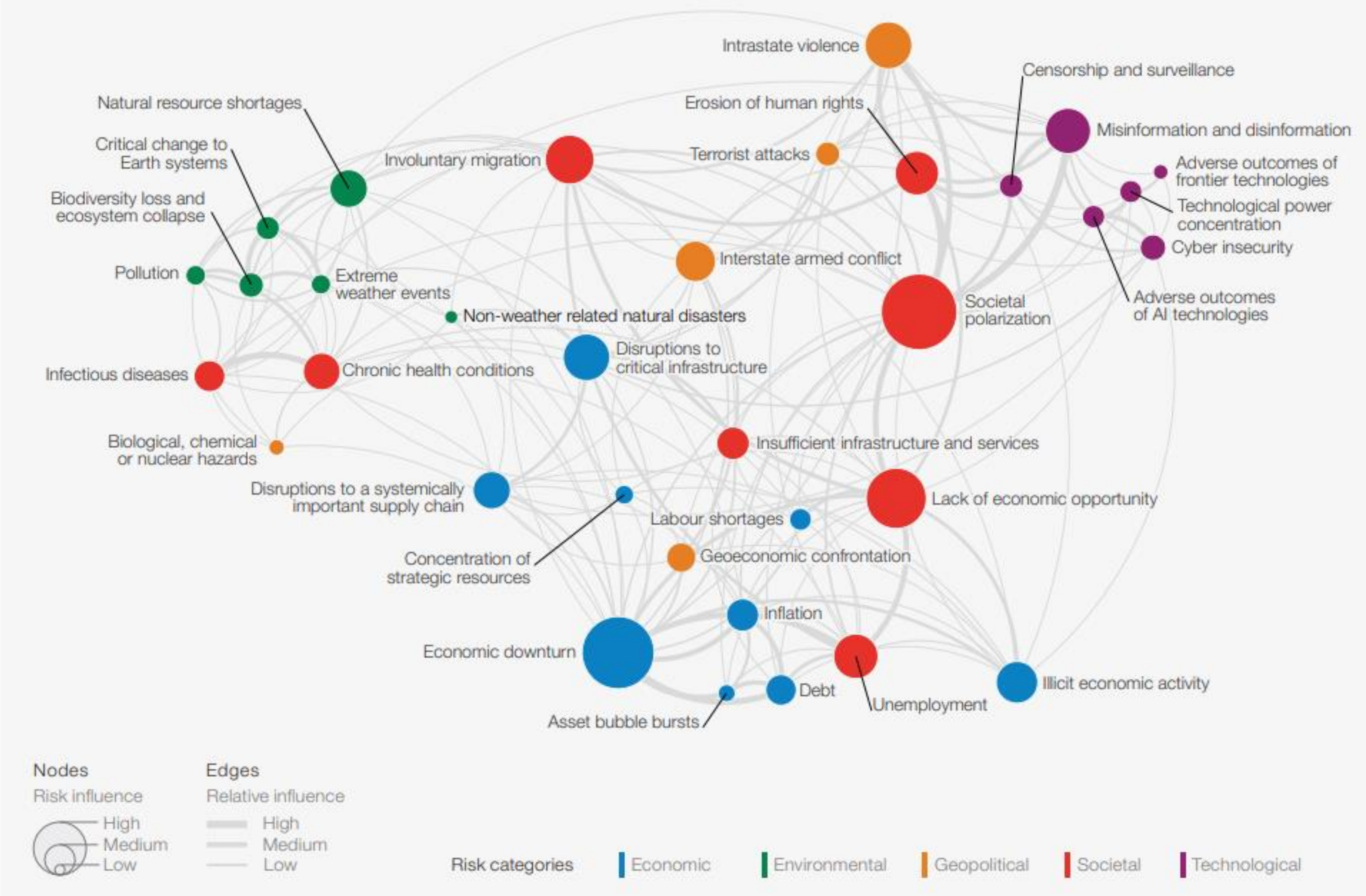
Hydrogen TCP
Fraunhofer ISE

Global risks landscape

Overlaps of Economic, Societal, Geopolitical, Environmental and Technological Crises

- **The Top Global Risks in 2024/25**
  - 1st Misinformation
  - 2nd Extreme Weather events
  - 3rd Societal/ Political Polarization
  - 4th Cyber Insecurity
  - 5th Interstate armed conflict

- Rising Risk of **Divided Societies**
  - Emotions and Ideologies overshadow facts
  - Manipulative narratives can infiltrate the public discourse



The Global Risks Report 2024 from World Economic Forum

Fraunhofer ISE

IEA - Global Hydrogen Review 2023, incl. Clean Hydrogen Ministerial and Hydrogen Initiative (An Initiative of the Clean Hydrogen Ministerial)

- Demand remains concentrated in traditional uses in refining and the chemical industry and mostly met by hydrogen produced from unabated fossil fuels
- To meet climate ambitions, there is an urgent need to switch hydrogen use in existing applications to low-emission hydrogen and to expand use to new applications in heavy industry or long-distance transport.
- 2020 China accounted for less than 10% of global electrolyser capacity, in 2022 installed capacity in China grew to more than 200 MW, representing 30% of global capacity, end of 2023, China's installed electrolyser capacity is expected to reach 1.2 GW – 50% of global capacity
- Equipment and financial costs are increasing, putting projects at risk and reducing the impact of government support for deployment. Inflation is increasing capital and financial costs, threatening the bankability of projects across the entire hydrogen value chain, which are capital intensive
- Governments have started to make funding available to support the first large-scale projects, but slow implementation of support schemes is delaying investment decisions. North America and Europe have taken the lead in implementing initiatives to encourage low-emission hydrogen production
- Electrolyser manufacturers have announced ambitious expansion plans. Around 14 GW of manufacturing capacity are available today, half of which is in China. Electrolyser production in 2022 is estimated to be just over 1 GW. Manufacturers have announced plans for further expansion, aiming to reach 155 GW/year of manufacturing capacity by 2030
- Hydrogen demand reached a historical high in 2022, but it remains concentrated in traditional applications. Global hydrogen use reached 95 Mt in 2022, a nearly 3% increase year-on-year, with strong growth in all major consuming regions except Europe