

What Do We Need in PEM Water Electrolysis to Achieve Our 2030 Targets: A Review of Key Challenges

Tom Smolinka

Berlin Electrolyser Conference

artloft.berlin, December 6th, 2023

www.ise.fraunhofer.de



The Fraunhofer Institute for Solar Energy Systems ISE

Performing research for the energy transition for over 40 years.



The Institute in Numbers

Institute Directors

Prof. Dr. Hans-Martin Henning

Prof. Dr. Andreas Bett

Employees ca. 1400

Budget 2022 (preliminary)

Operation €107.0 million

Investment € 12.3 million

Total €119.3 million

Founded in 1981

The Fraunhofer Institute for Solar Energy Systems ISE

Hydrogen and batteries are integral components of the energy transition!



Photovoltaics

- Silicon Photovoltaics
- III-V and Concentrator Photovoltaics
- Perovskite and Organic Photovoltaics
- Photovoltaic Modules and Power Plants

Energy Efficient Buildings

Solar Thermal Power Plants and Industrial Processes

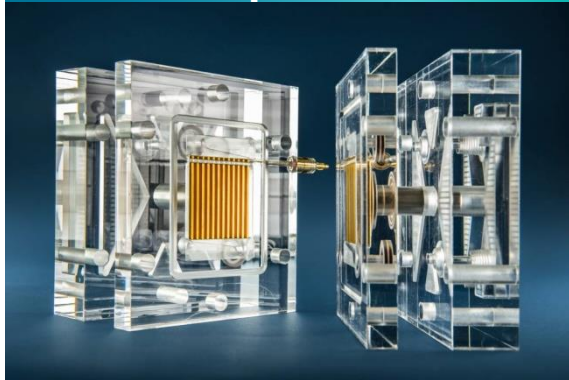
Hydrogen Technologies and Electrical Energy Storage

Power Electronics, Grids and Smart Systems

The Fraunhofer Institute for Solar Energy Systems ISE

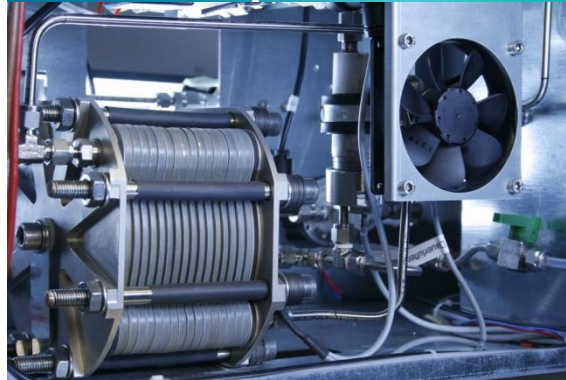
Research field: Electrochemical hydrogen production and hydrogen infrastructure

Characterisation of Materials and Components



- Electrochemical characterisation
- Investigation of life-time / accelerated stress tests
- Ex-situ analysis

Development of PEM Water Electrolysis Components



- CCM manufacturing
- New cell concepts
- Laboratory PEM stacks
- Control strategies

Power to Gas



- Dynamic system modelling of PtG systems
- Development of system and plant concepts
- H2 yield assessment

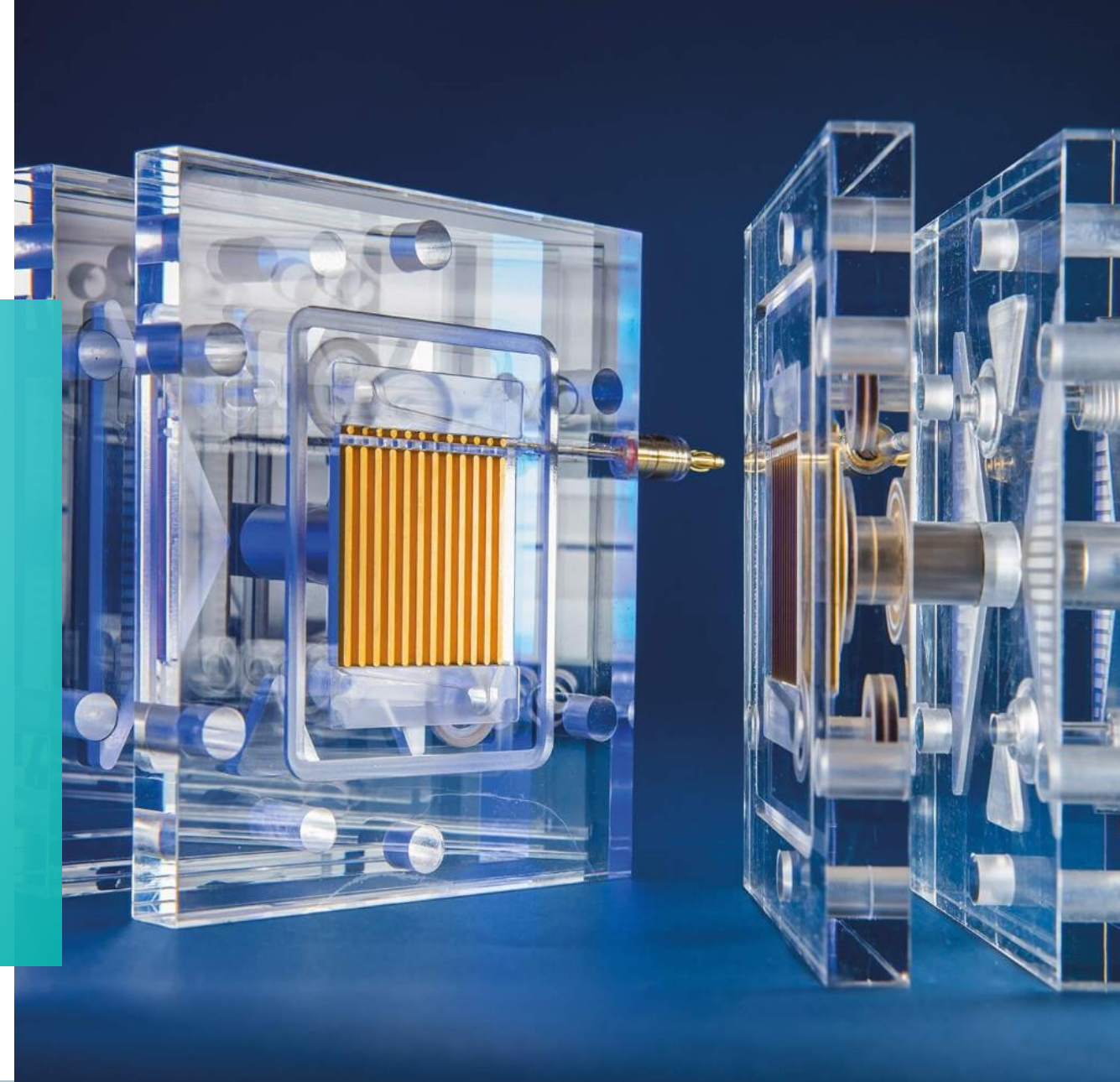
Hydrogen Infrastructure



- Technology consulting
- Techno economic analysis /market survey
- Roll out H2 technologies
- Life cycle assessment

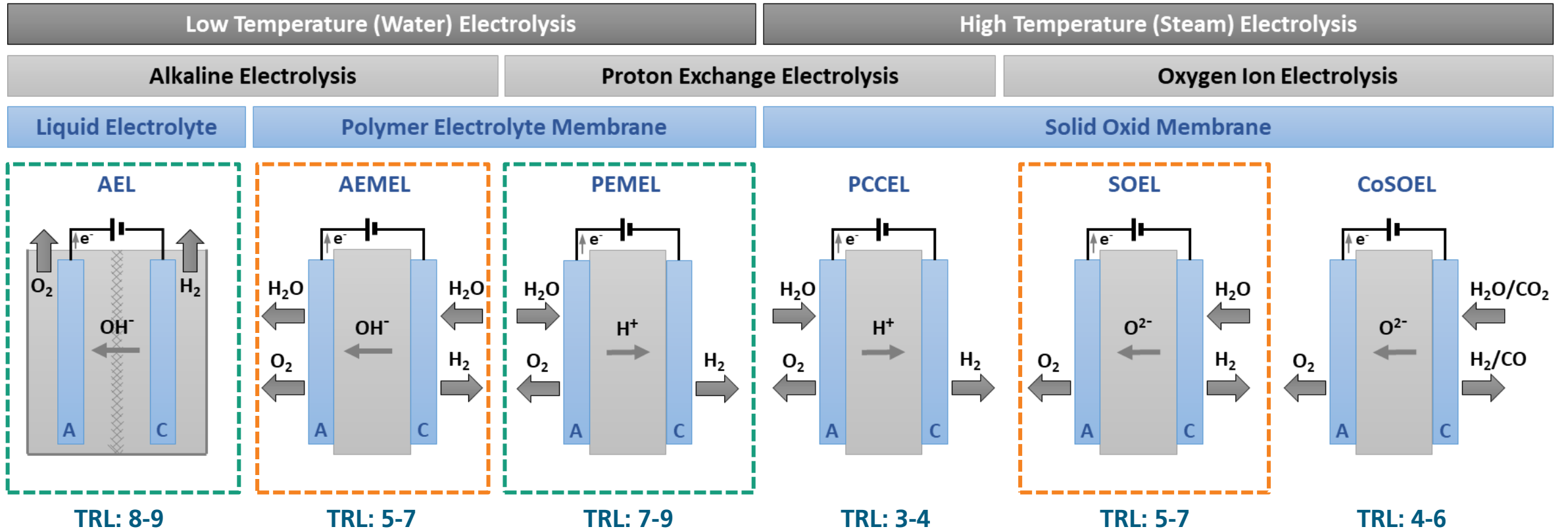
Outline of the Talk

1. Introduction to Fraunhofer ✓
2. Current state of WE industry
3. PEM water electrolysis
4. R&D goals in Europe and US America
5. Development trends in PEM Water Electrolysis
6. Examples for key challenges
7. Conclusion and summary



Current State of Water Electrolysis Industry

Different electrolysis technologies exist but technology readiness levels vary.



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

Current State of Water Electrolysis Industry

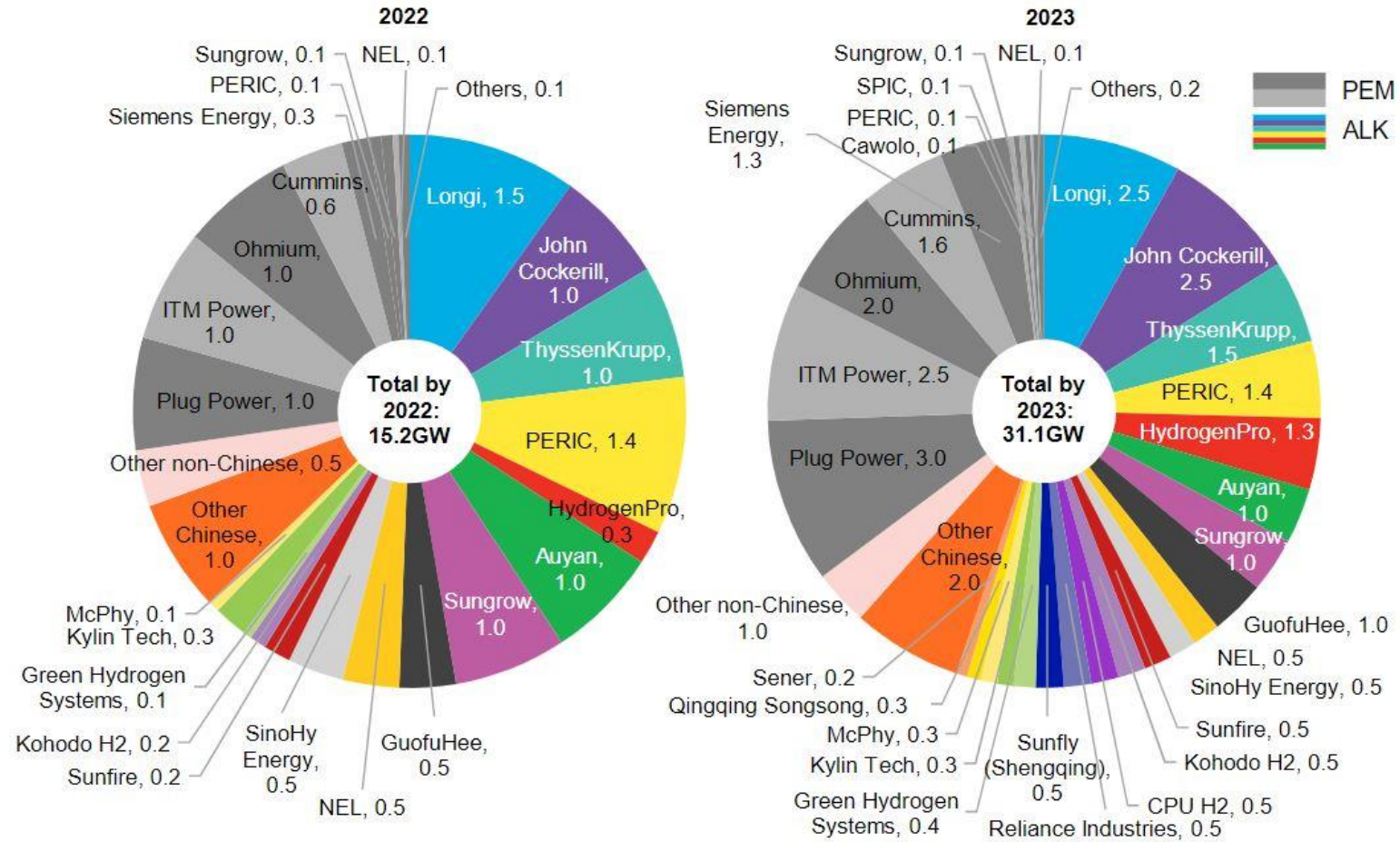
Dramatic increase in manufacturing capacities until 2030

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/>

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



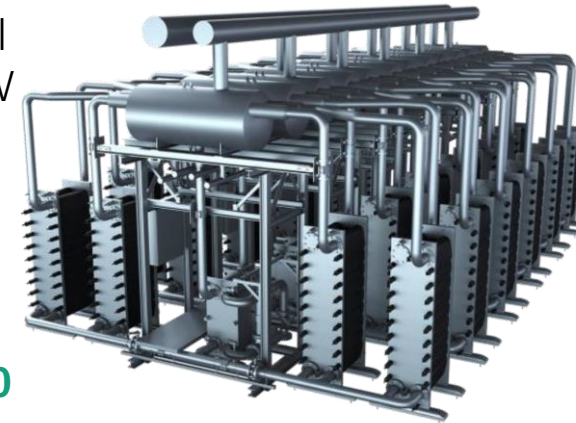
h-tec Systems (DE) – Series S450

- 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 (!)



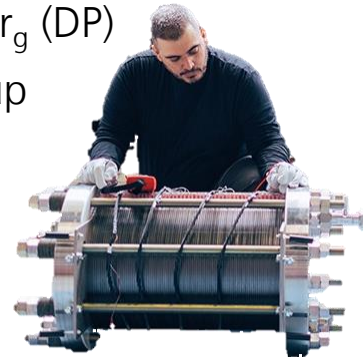
NEL (NO) – M series

- 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)

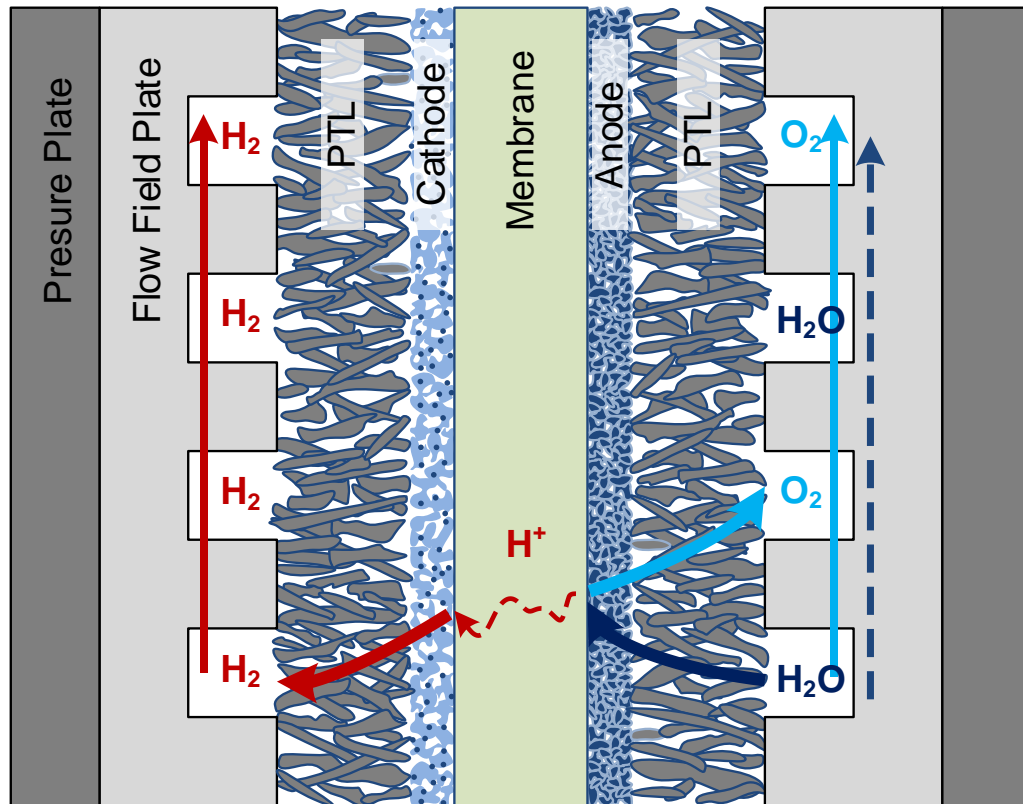


→ Exemplary naming of some manufacturers, not a complete overview!

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

Proton exchange membrane water electrolysis (PEMWE/PEMEL)

Main cell components and state of the art materials

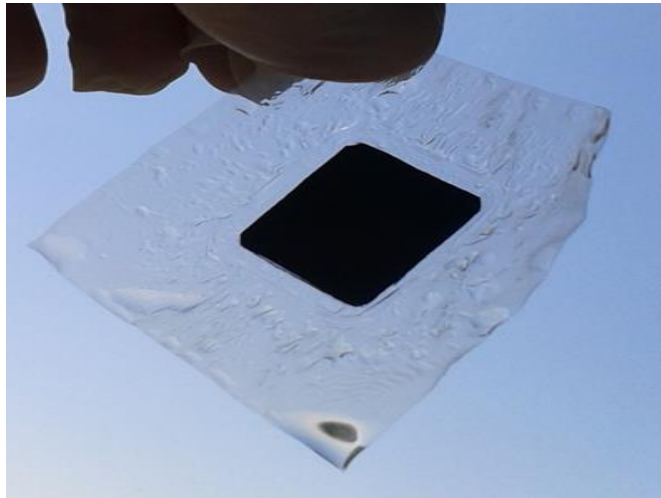


Cross section of a PEM electrolysis cell

- Membrane as solid electrolyte
 - Perfluorosulfonic acid (PFSA) ionomer
 - Typical thickness: 100 – 180 μm
- 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

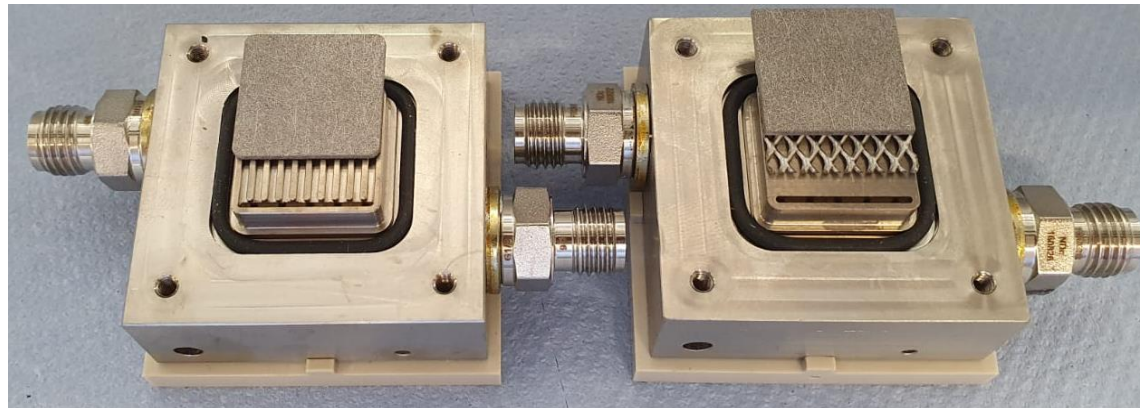
Proton exchange membrane water electrolysis (PEMWE/PEMEL)

Main cell components and state of the art materials



Membrane electrode assembly (MEA) (© Fraunhofer ICT)

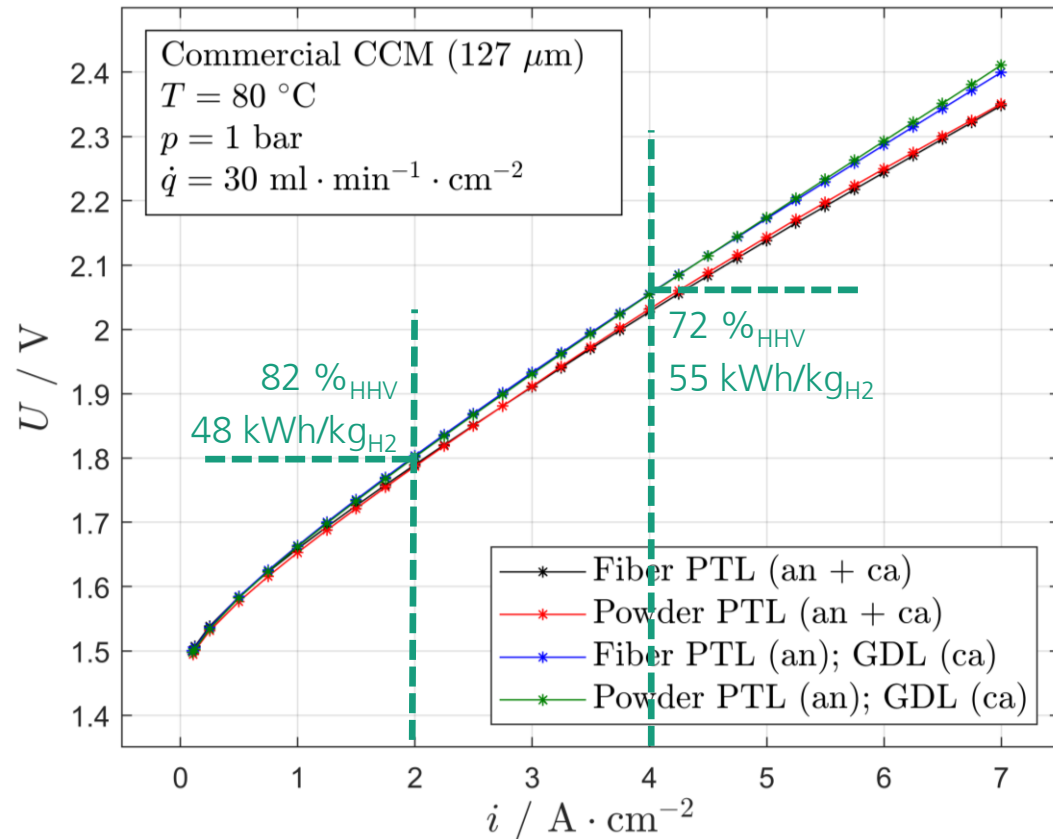
Different cell configurations with PTLs, spacers and flow fields (© Fraunhofer ISE)



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Proton exchange membrane water electrolysis (PEMWE/PEMEL)

Main cell components and state of the art materials and performance



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Polarization curve of different PTL setups measured with Fraunhofer ISE laboratory reference cell

Development Targets for LT Water Electrolysis

European Strategic Research and Innovation Agenda 2021 – 2027



- 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 development 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
https://www.clean-hydrogen.europa.eu/about-us/key-documents/strategic-research-and-innovation-agenda_en

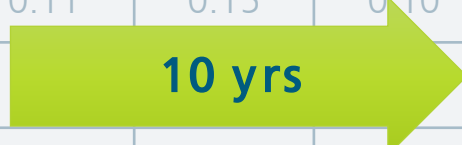
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Goals of the US American The Hydrogen and Fuel Cell Technologies Office



- Technical targets for LT water electrolysis according 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	
			AEL	PEMEL	AEL	PEMEL	AEL	PEMEL
	System							
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
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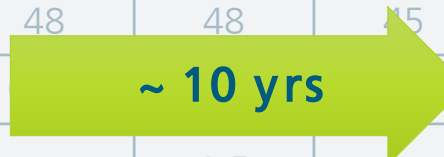
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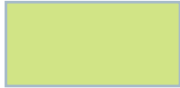
Development Targets for LT Water Electrolysis

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

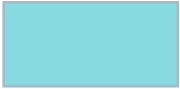


Ambition mapping

- Europe is more ambitious



- Parity between EU and US



- US is more ambitious



- US is much more ambitious



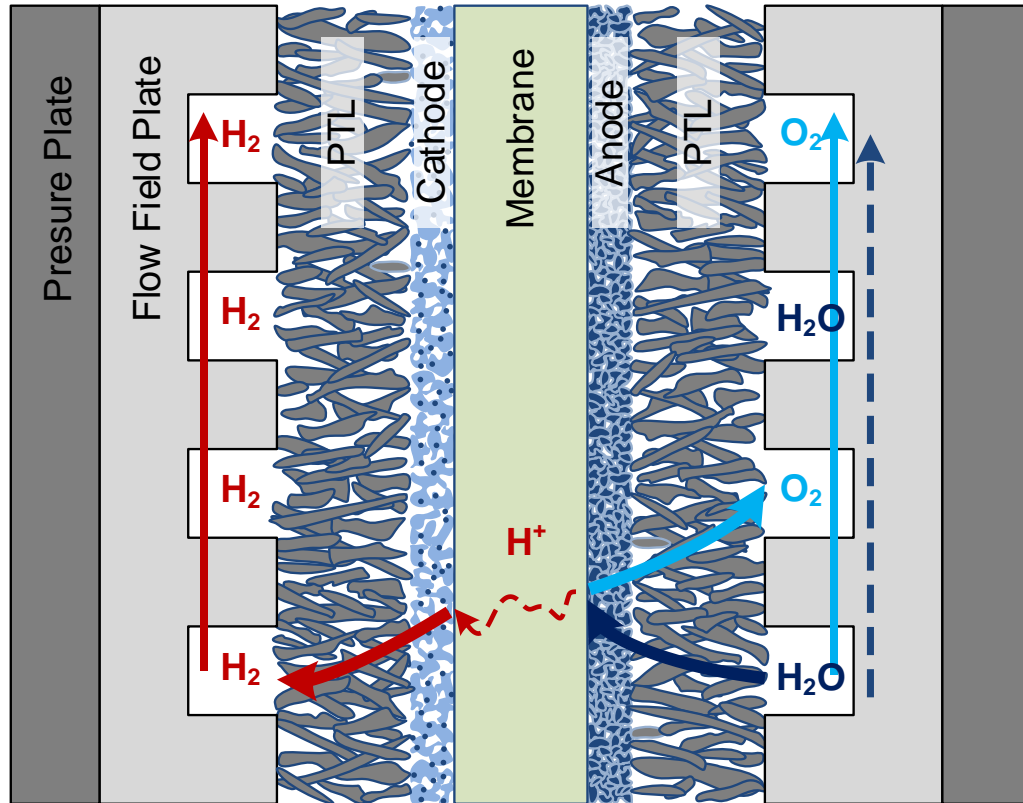
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Development Trends in PEM Water Electrolysis

Main cell components and state of the art materials

Already known

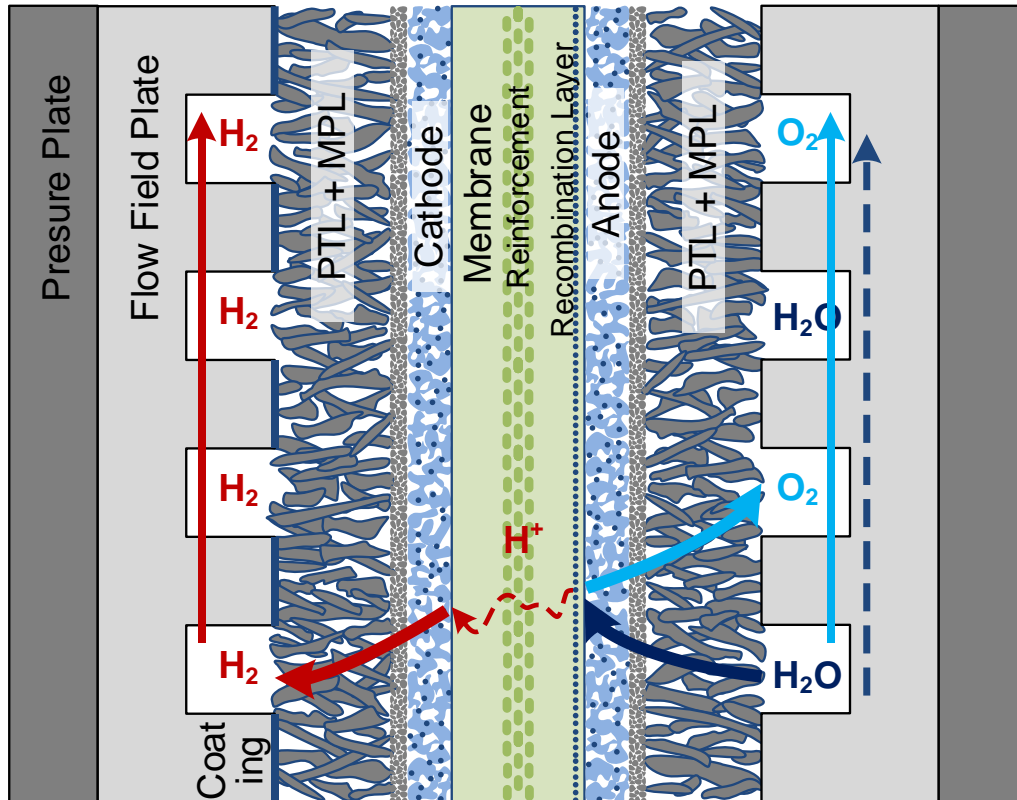


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Development Trends in PEM Water Electrolysis

Main cell components and state of the art materials → **next generation 2025+**

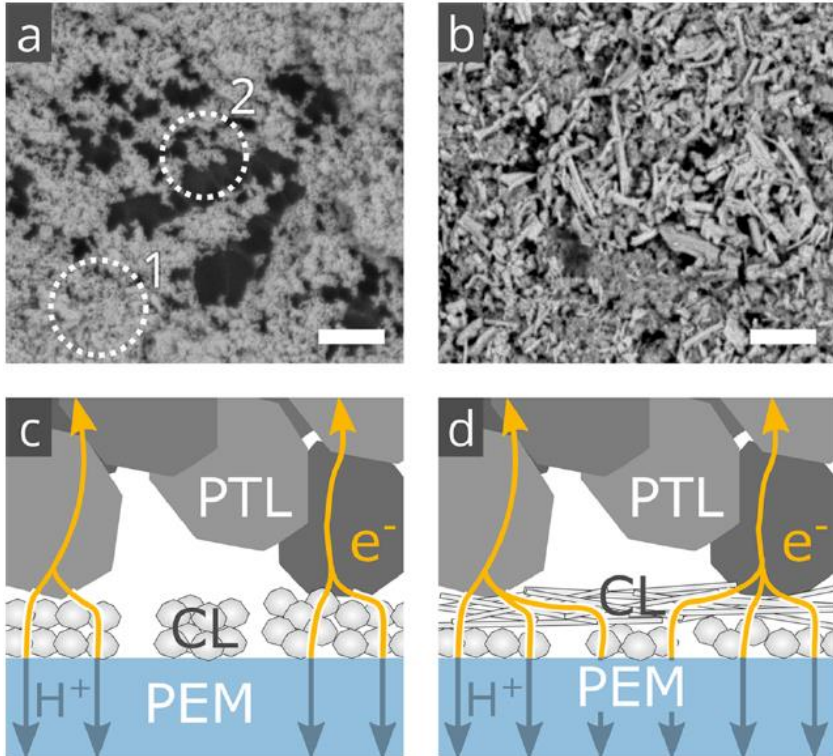


Cross section of an advanced PEM electrolysis cell

- Membrane as solid electrolyte
 - Perfluorosulfonic acid (PFSA) ionomer → **PFAS ban**
 - Typical thickness: 100 – 180 μm < **100 μm**
 - **With recombination layer**
- Electrodes for OER and HER
 - AN: supported Ir or IrOx: $\sim 2.0 \text{ mg/cm}^2$ **0.4-1.0 mg/cm^2**
 - CAT: supported Pt/C: $\sim 0.5-1.0 \text{ mg/cm}^2$ **0.1-0.5 mg/cm^2**
- Porous transport layers
 - Sintered Ti fibers/particles: 0.5 - 1.0 mm \sim **300 μm**
 - Carbon paper (only at cathode)
- Bipolar plate (with flow field structures)
 - (Au or Pt coated) Ti sheet: 0.2 - 1.0 mm \sim **300 μm**
 - **Highly integrated & mass-produced half-cell compounds**

Key Challenges in PEM Water Electrolysis

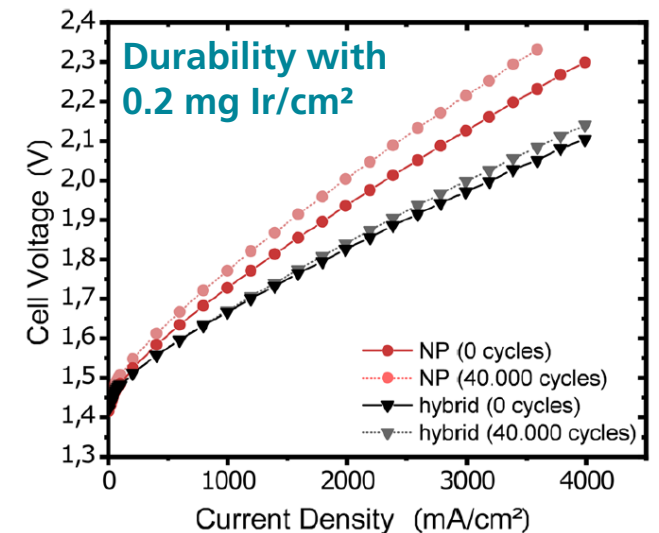
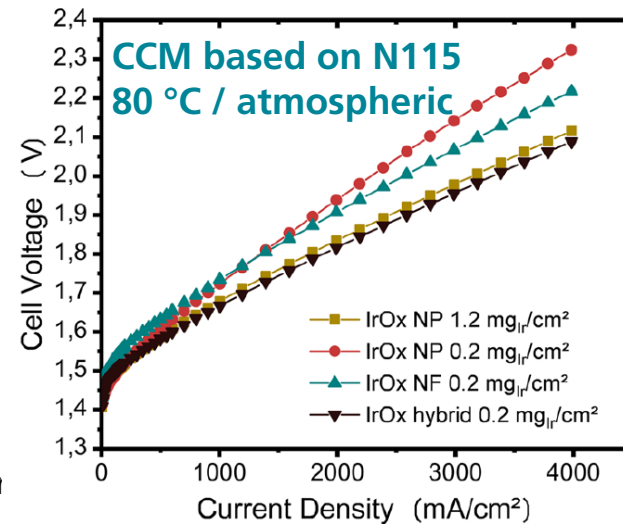
Various promising approaches exist to reduce the PGM loading.



Low loaded (0.2 mg Ir/cm²) electrodes
Left: nanoparticle catalyst layer with electronically disconnected islands (2)
Right: nanofiber interlayer of IrOx hybrid anode with nanoparticle catalyst layer

Efficient and stable low iridium loaded anodes by hybrid electrode layers (Hegge et al. 2020)

- Ultra low loadings results in thin catalyst layer with poor electrical contact to the the porous transport layer
- New electrode design: combining the advantage of good electric contact and high porosity of IrOx nanofibers with high surface area of IrOx nanoparticles



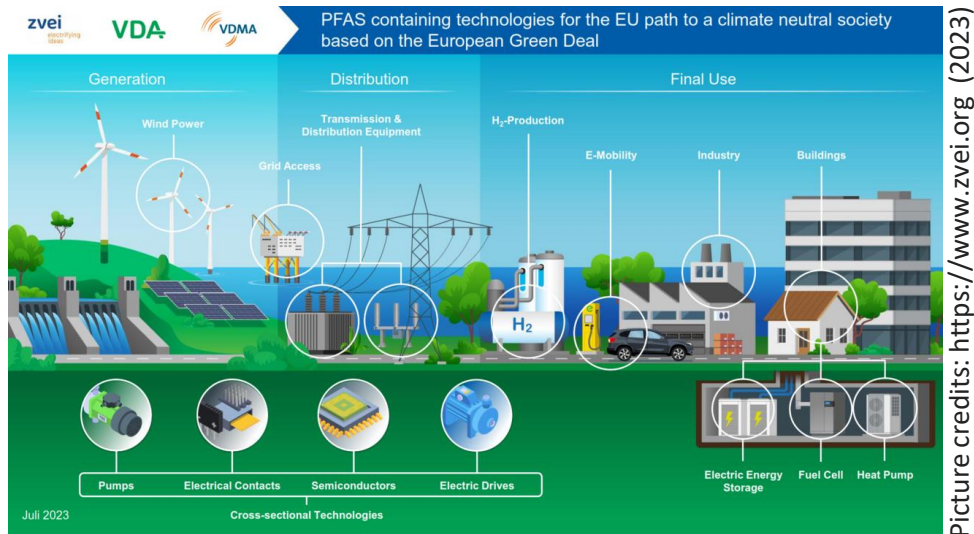
Hegge et al. (2020) ACS Appl. Energy Mater. 2020, 3, 8276–8284

Key Challenges in PEM Water Electrolysis

Alternative fluorine-free membranes with a long life-time remain a major challenge.

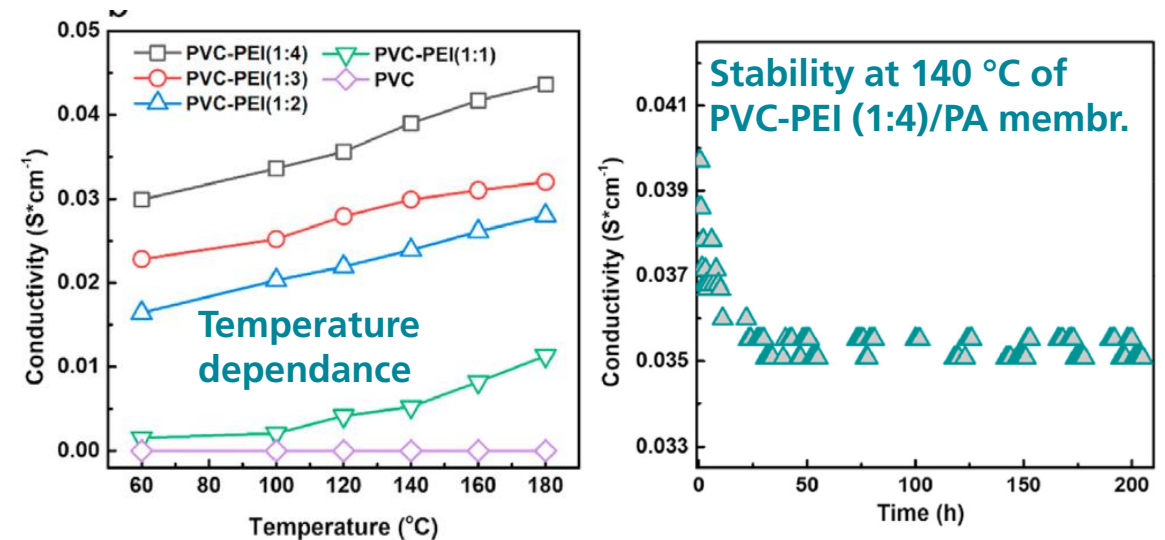
Impending ban on PFAS in the EU

- proposal for the restriction of PFAS (per- and polyfluoroalkyl substances) submitted to the European Chemicals Agency (ECHA) in Februar 2023 → Draft PFAS restriction in 2024
- Exemption or transition period is demanded for PFSA (perfluorosulfonic acid) materials in H₂ technologies



Alternative materials to PFSA membrane (Yin et al. 2023)

- Proton conductive PVC-PEI hybride membrane are realized by cross-linking of PVC and PEI with high temperature stability at 100 °C - 180 °C
- Conductivity, mechanical pattern and long-term stability remains an issue



Yin et al. (2023), Int. J. Hydrogen Energy 48 (2023) 24 – 34

Conclusion and Summary

Take home messages

Water electrolysis is on its way to becoming a GW industry and, in addition to the alkaline process, PEM electrolysis in particular will play an important role by 2030!

1.

All companies are currently massively expanding their manufacturing capacities. However, unclear political and legal framework conditions are leading to persistent delays in green hydrogen projects and thus to a slowdown in the market ramp-up.

2.

The European development targets for 2030 are less ambitious than those of the US American Department of Energy in the USA. The DOE has set more ambitious targets for stack and system costs in particular, as well as for reducing PGM content.

3.

PEM electrolysis is currently undergoing considerable improvements at cell level. Despite a considerable reduction in the amount of material used in a cell, very high performance values and efficiencies can be achieved.

4.

The impending PFAS ban at European level would be a significant setback for the market ramp-up of PEM electrolysis. There are currently no adequate replacement materials for the membranes.

Thanks a lot for your kind
attention!



Contact

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