PEM Water Electrolysis: Insights in Different Technology Options

Tom Smolinka
Cluster Brennstoffzelle BW: Electrolysis Workshop
ZSW, Stuttgart, December 12th, 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

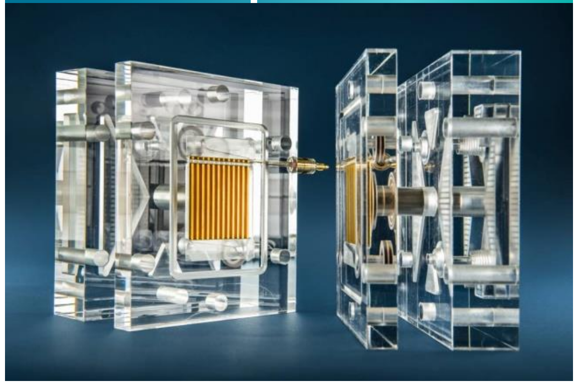
Hydrogen Technologies and Electrical Energy Storage

Power Electronics, Grids and Smart Systems

The Fraunhofer Institute for Solar Energy Systems ISE

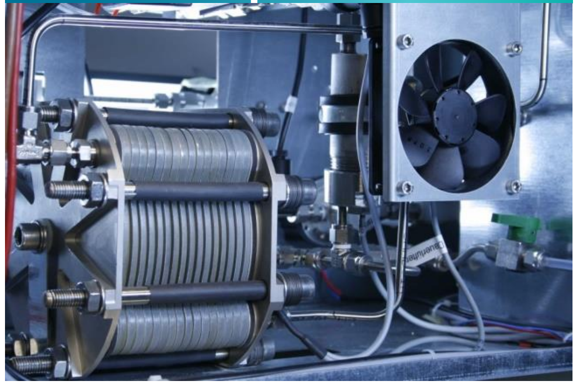
Research field: Electrochemical hydrogen production and hydrogen infrastructure

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

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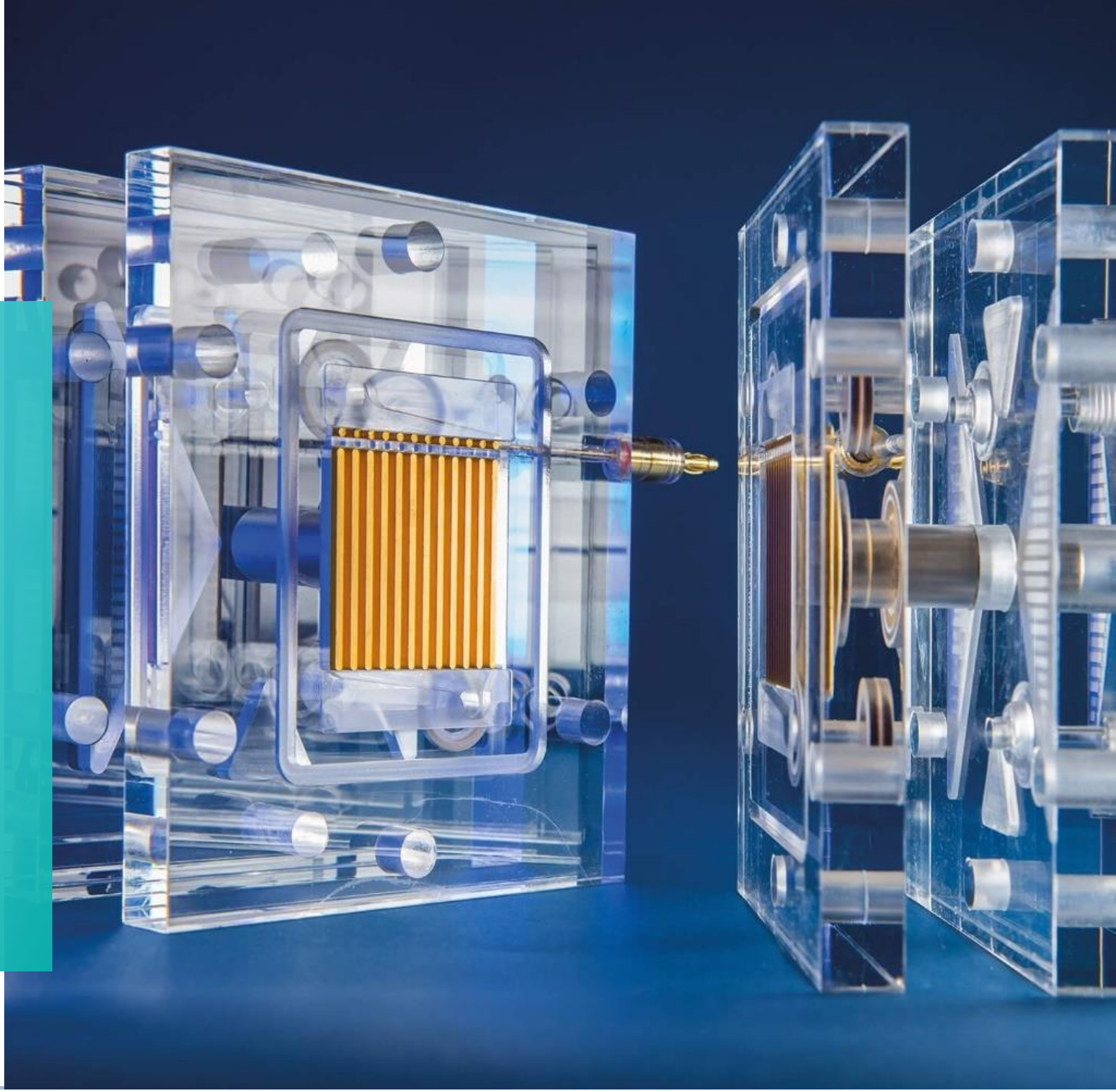
Outline of the Talk

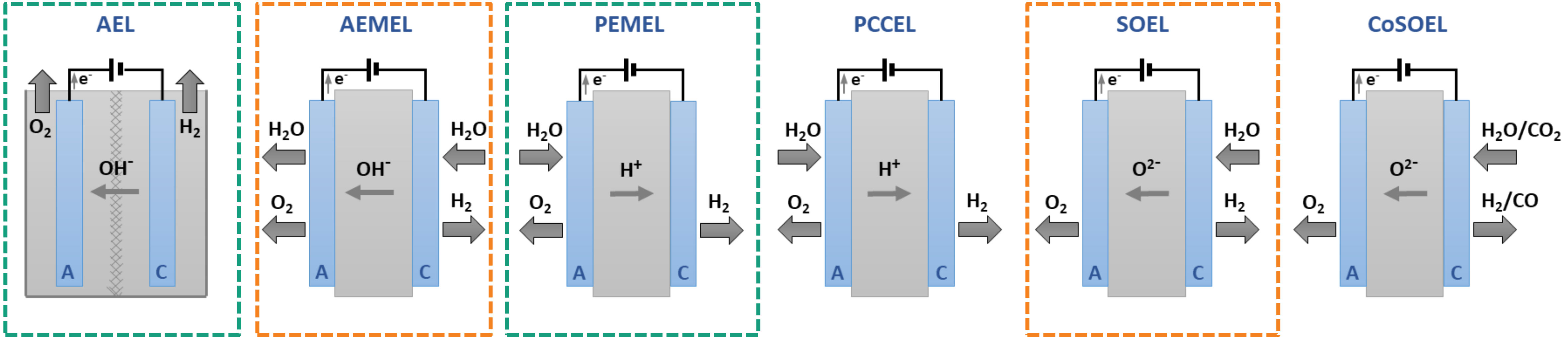
1. Introduction to Fraunhofer ✓
2. Current state of WE industry
3. PEM water electrolysis: Components & cells
4. PEM Water Electrolysis: Systems
5. Conclusion and summary



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	



AEL	AEMEL	PEMEL	PCCEL	SOEL	CoSOEL
TRL: 8-9	TRL: 5-7	TRL: 7-9	TRL: 3-4	TRL: 5-7	TRL: 4-6

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

Current State of Water Electrolysis Industry

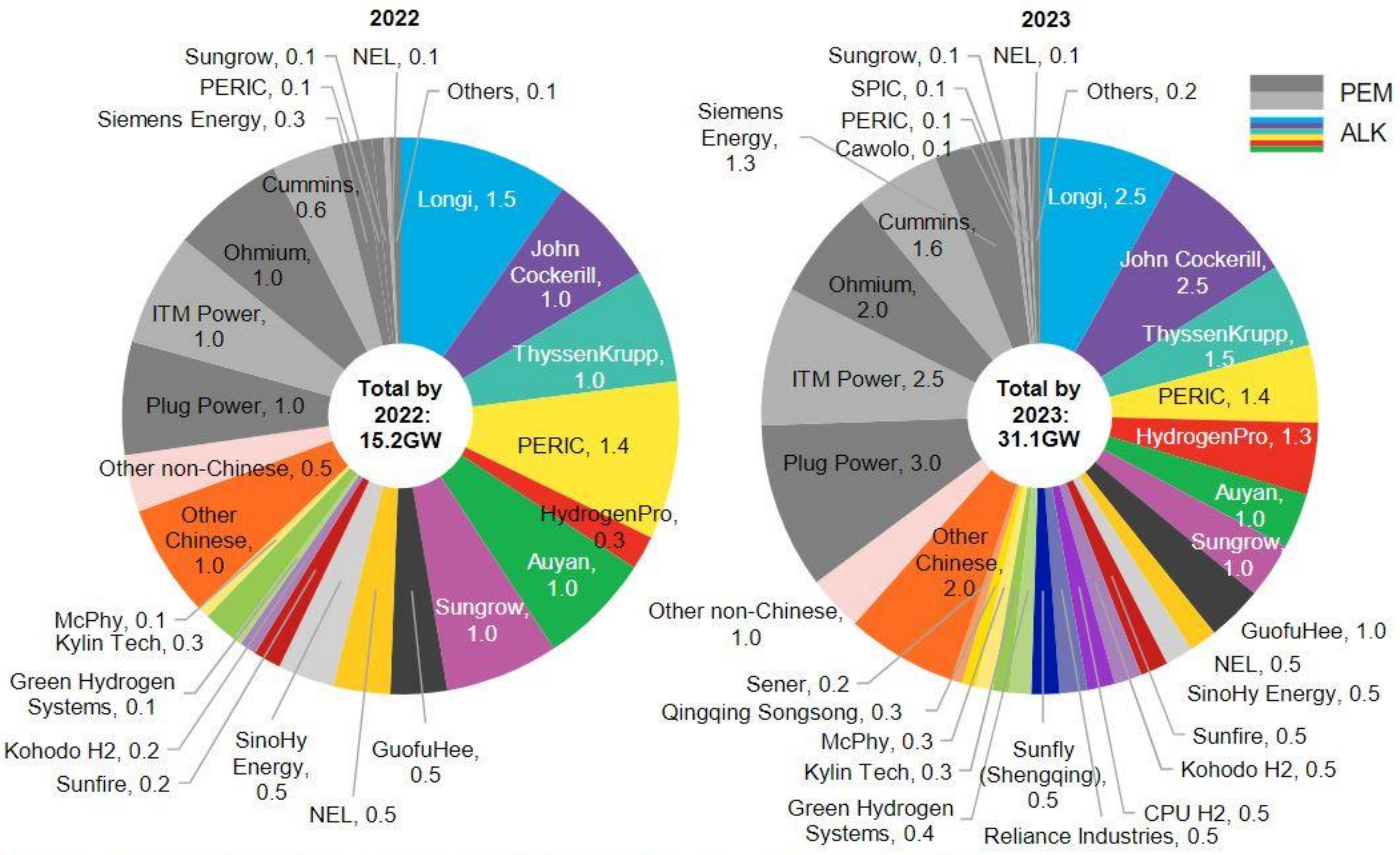
Dramatic increase in manufacturing capacities is announced until 2030.

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/

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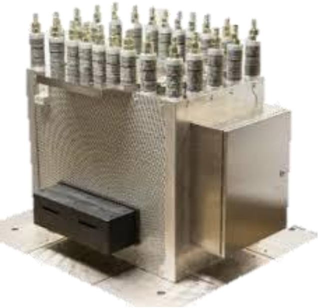
Current State of Water Electrolysis Industry

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

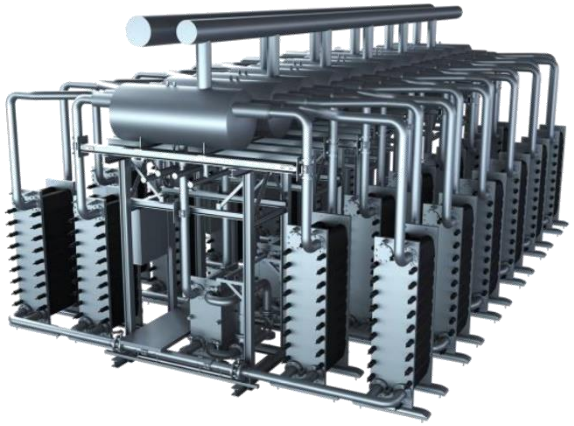
- Up to 30 bar_g (DP)
- 450 cm²
- ~ 100 kW

Hydrogen is now.
H-TEC SYSTEMS

Siemens Energy (DE) – Silyzer 300

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

SIEMENS energy



NEL (NO) – M series

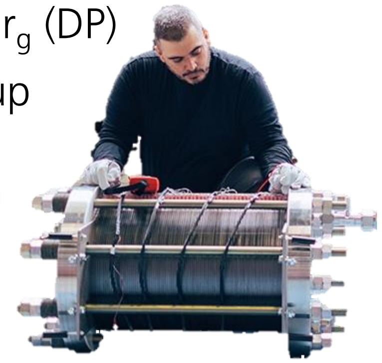
- 30 bar_g (DP)
- 1,580 cm²
- 1.25 MW

nel

Elogen (FR) – E series

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

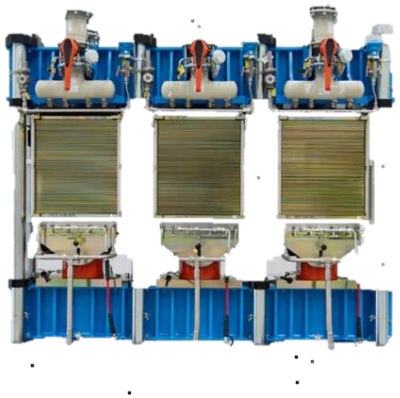
elogen
Empowering a sustainable world



ITM Power (UK) – MEP2.0

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

ITM POWER
Energy Storage | Clean Fuel



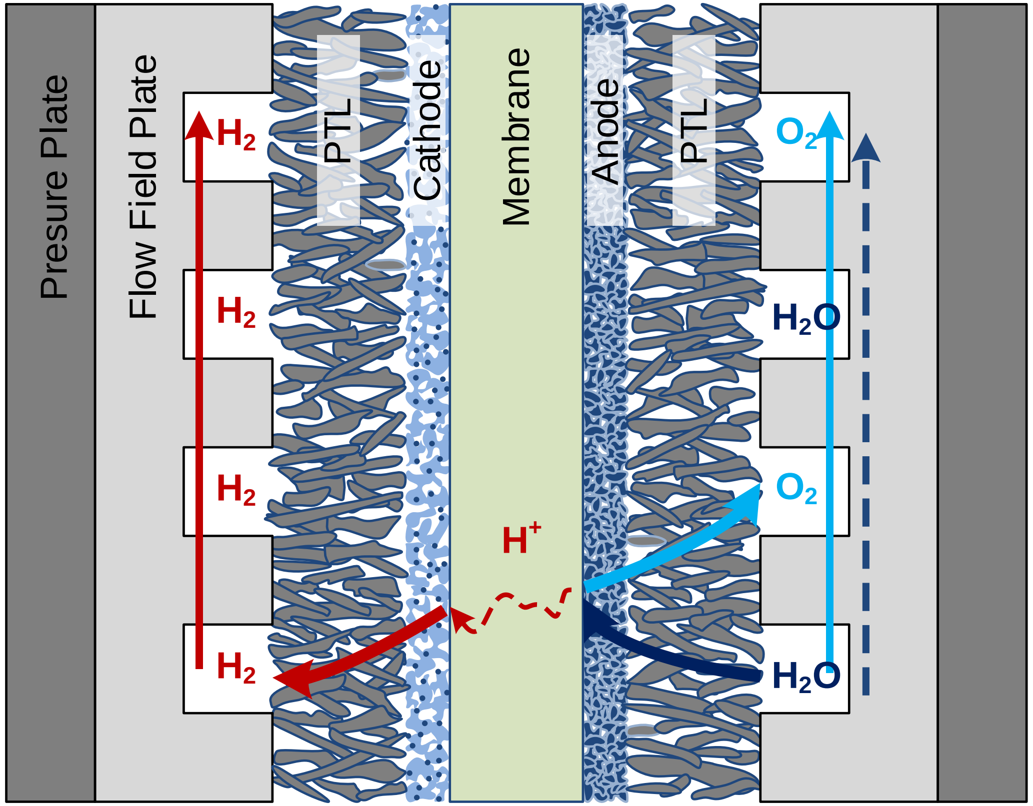
➔ Exemplary naming of some manufacturers, not a complete overview!

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

DP: differential pressure
PB: pressure-balanced

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

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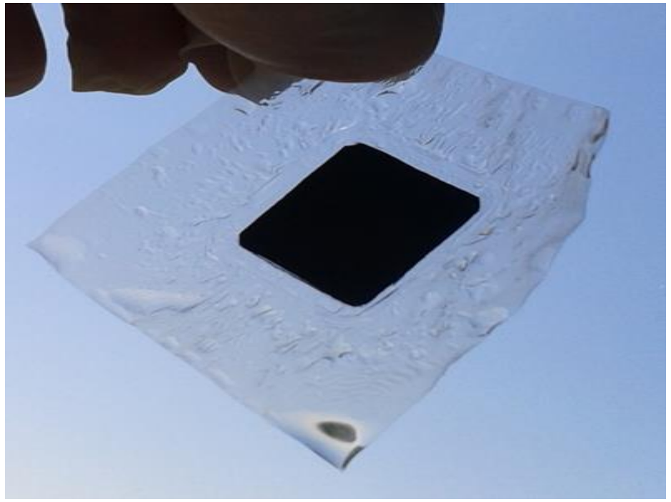
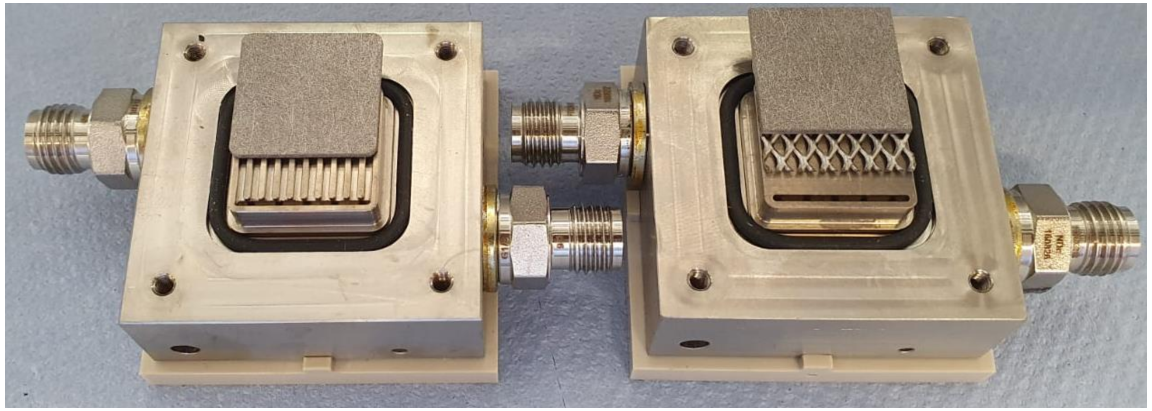


Membrane electrode assembly (MEA) (© Fraunhofer ICT)

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



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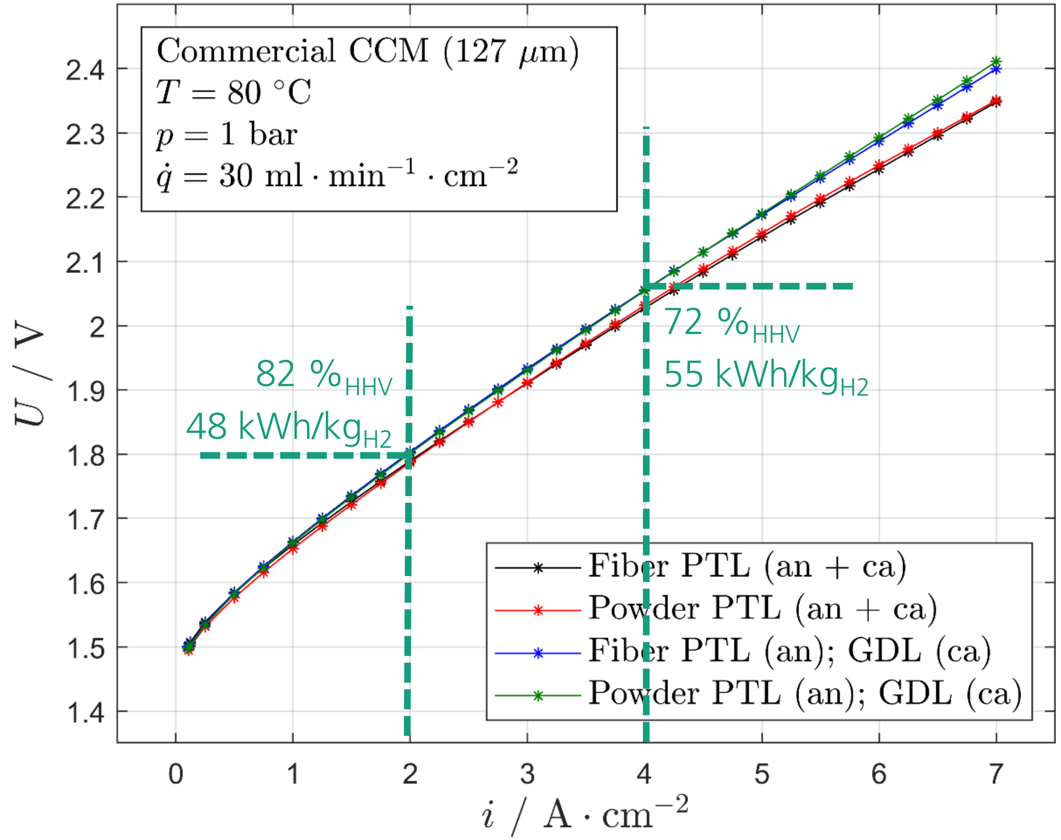
Proton exchange membrane water electrolysis (PEMWE/PEMEL)

Main cell components and state of the art materials and performance



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

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  - Typical thickness: 100 – 180 mm
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Proton exchange membrane water electrolysis

Evolution of stack designs for membrane water electrolyzers

a) Laboratory style

- 30 – 300 cm²

b) No milled plates

- 100 – 600 cm²

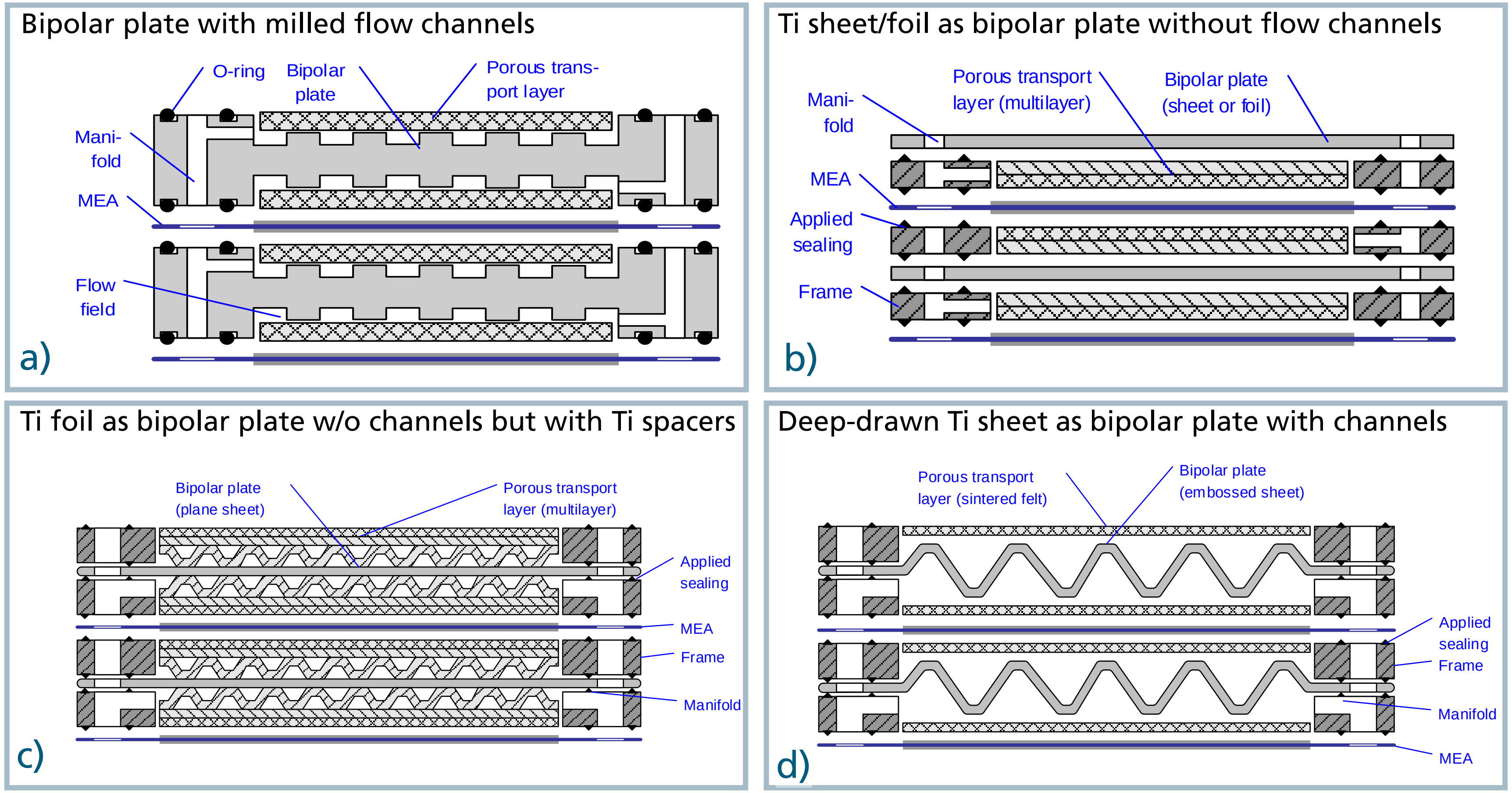
c) Additional spacers

- 300 – 1,000 cm²

d) Embossed/deep-dawn plates with channels

- 500 – 5,000 cm²

- Area specifications are only rough guide values



Reference: Fraunhofer ISE

BPP: Bipolar plate
BoS Balance of stack
MEA: Membrane electrode assembly
PTL: Porous transport layer

Proton exchange membrane water electrolysis

Evolution of stack designs for PEM water electrolysis → Examples

a) Laboratory style

- 30 – 300 cm²

b) No milled plates

- 100 – 600 cm²

c) Additional spacers

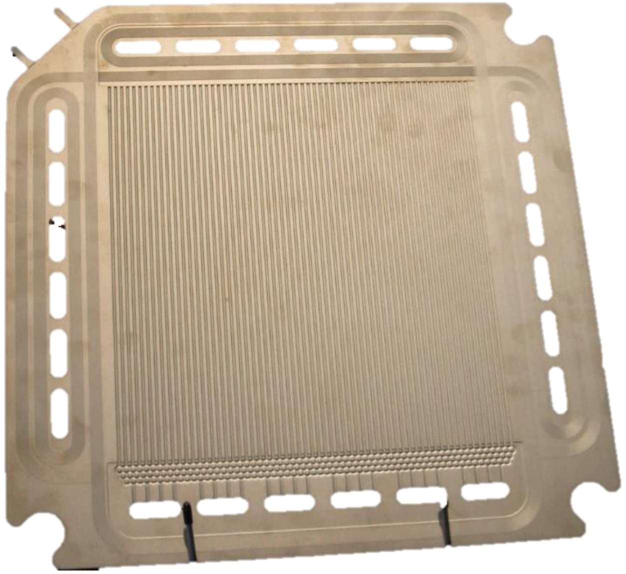
- 300 – 1,000 cm²

d) Embossed/deep-dawn plates with channels

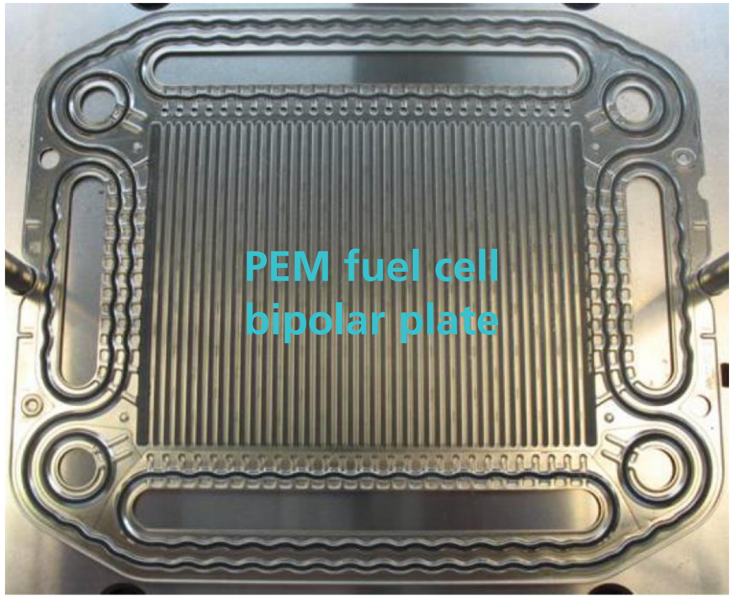
- 500 – 5,000 cm²

- Area specifications are only rough guide values

© Fraunhofer ISE (2002)



© Proton OnSite (2012)



© Dana – REINZ-Dichtungs-GmbH (2017)

Reference

BPP: Bipolar plate
BoS Balance of stack
MEA: Membrane electrode assembly
PTL: Porous transport layer

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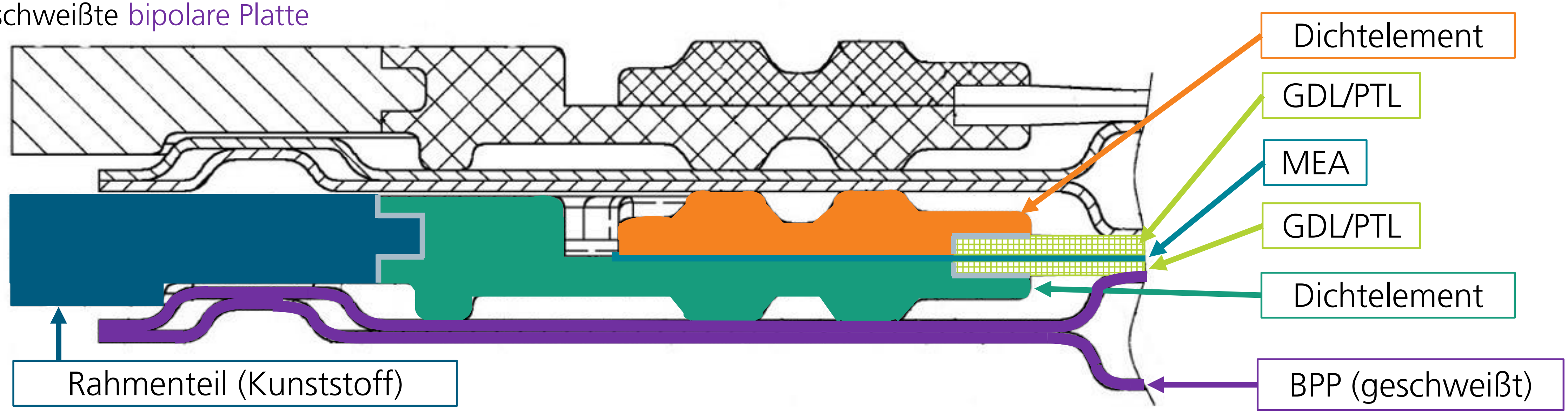
Proton exchange membrane water electrolysis

Modern cell and stack design is much more complex!

ElringKlinger AG / WO 2021/122164 A1 / 2021

- Dichtelement mit stoffschlüssiger Verbindung zur GDL (PTL) und einem Rahmenteil
- Silikon im Spritzguss
- Geschweißte bipolare Platte

- Dichtungen im Kraftschluss
  - Membrane gegen Dichtelemente
  - Dichtelemente gegen BPP



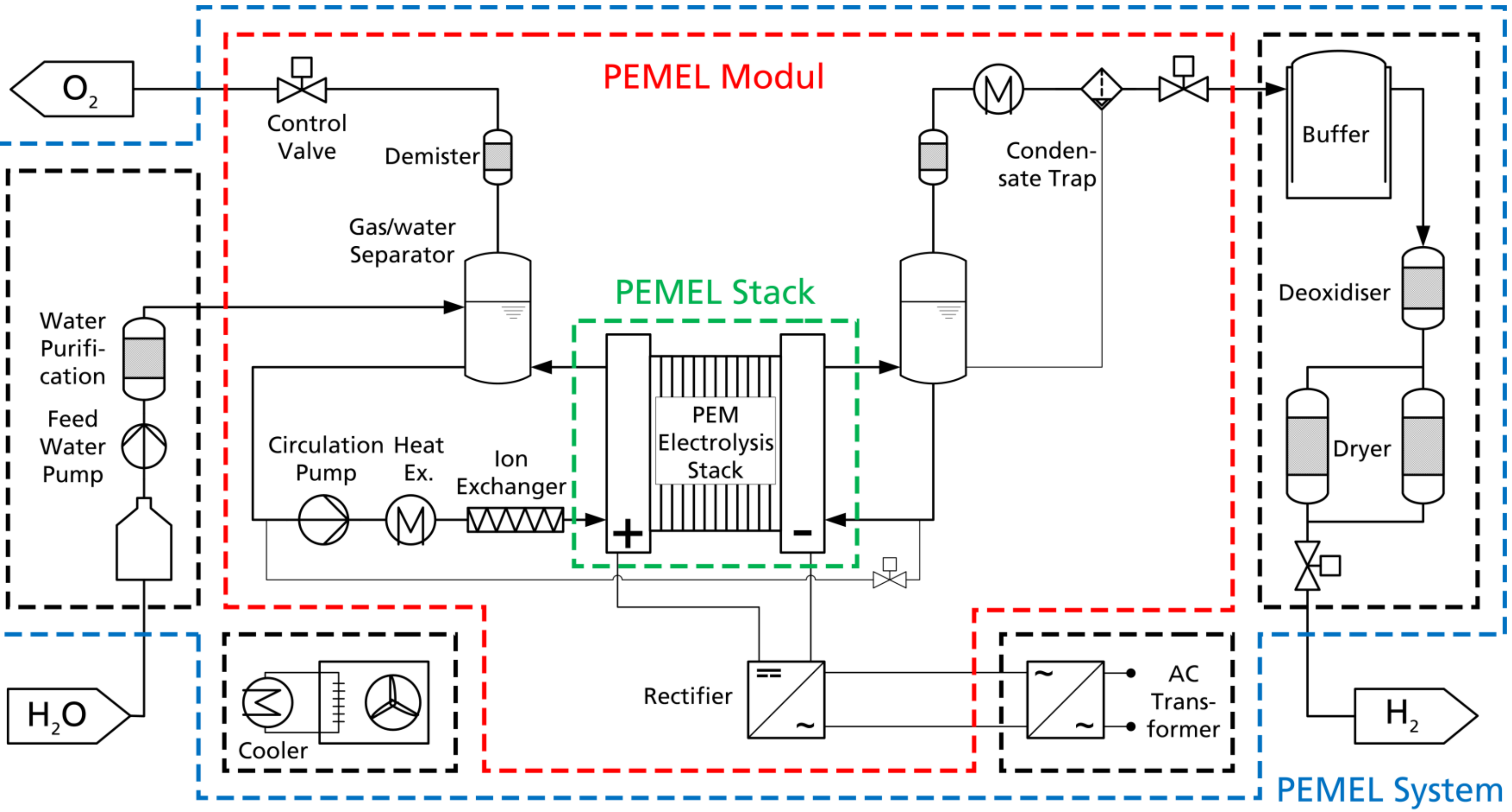
Reference

BPP: Bipolar plate
BoS Balance of stack
MEA: Membrane electrode assembly
PTL: Porous transport layer

PEM Water Electrolysis System

Basic system layout & main system components

- Stack as electrochemical reactor
- PEM electrolysis module
  - Circulation loop anode (fluidic and thermal management)
  - Gas water separators, demisters and control valves
  - Rectifier
- Subsystems
  - Water feed and purification
  - Recooling unit
  - AC connection
  - Hydrogen treatment

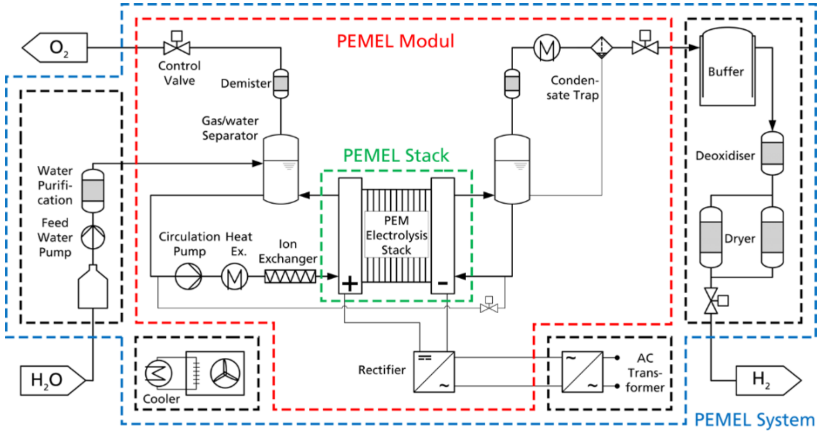


Picture credits: Fraunhofer ISE (2014)

PEM Water Electrolysis System

Basic system layout & main system components

- Component diagram of a PEMWE system



Picture credits: Fraunhofer ISE (2014)

PEM water electrolysis system

- 1.0 PEM electrolysis stack
  - 1.1 Membrane electrode assembly
    - 1.1a Membrane
    - 1.1b Cathode
    - 1.1c Anode
  - 1.2 PTL Anode
  - 1.3 PTL Cathode
  - 1.4 Bipolar plate
    - 1.4a Sheet/plate
    - 1.4b Coating
  - 1.5 Sealing / gasket
  - 1.6 Cell frame
  - 1.7 Endplates / compression hardware
- 2.0 Thermal and fluid management
  - 2.1 Gas & liquid loops
  - 2.2 Gas water separators
  - 2.3 Heat exchanger
  - 2.4 Circulation pump
  - 2.5 Ion exchange resin
  - 2.6 Control valves
- 3.0 System controls
- 4.0 Power electronics (Rectifier)
- 5.0 System BoP
  - 5.1 Water purification
  - 5.2 Recooling unit
- 6.0 Hydrogen conditioning
  - 6.1 Gas dryer / chiller
  - 6.2 De-oxygen unit

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PEM Water Electrolysis System

Typical example of a small system

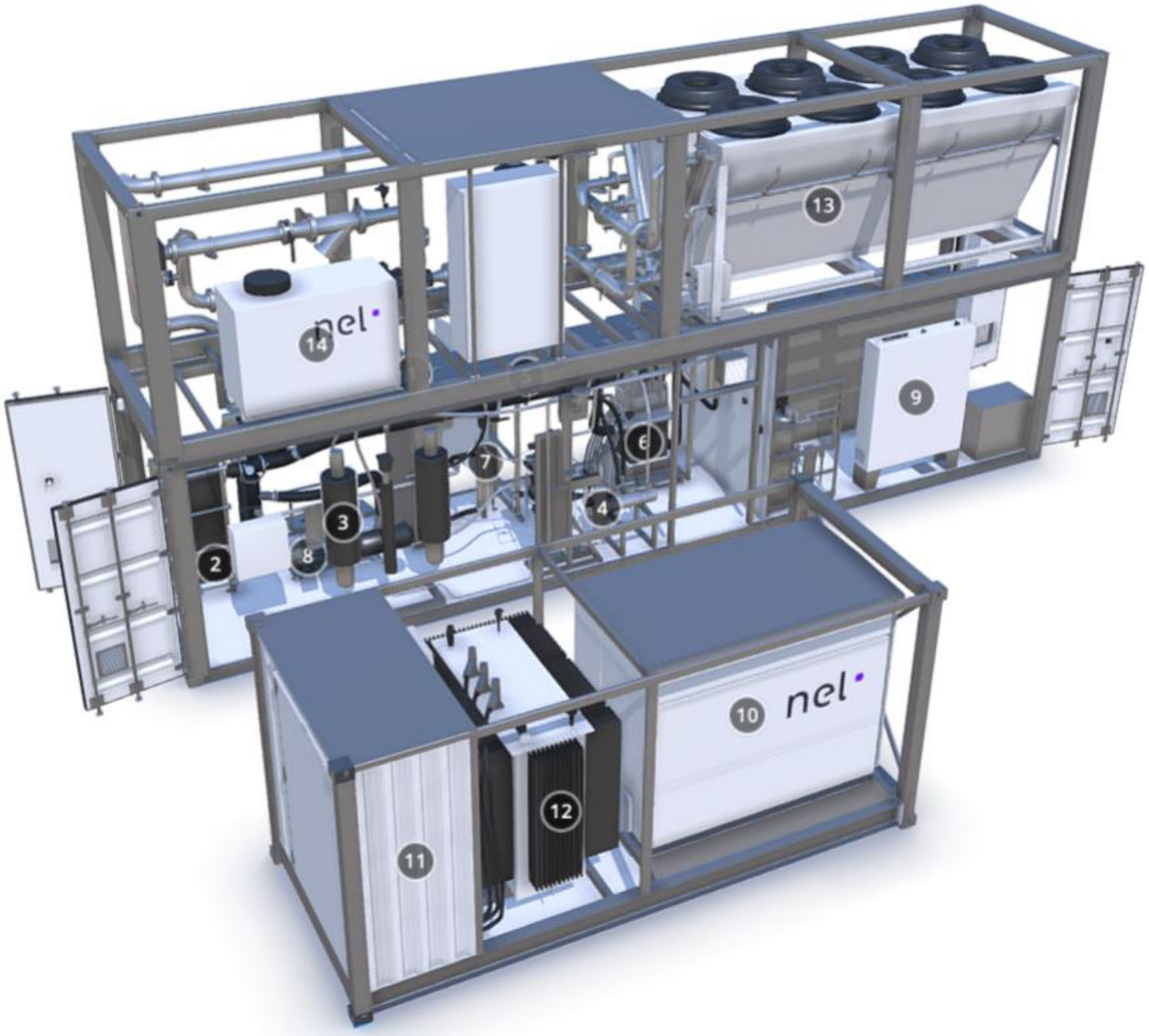
- H-TEC PEM electrolyzer ME450
- Containerized solution
- 1 MW nominal load with 9 stacks
- Hydrogen production: 450 kg/d

Picture credits: h-tec systems (2023), https://www.h-tec.com/en/products/detail/h-tec-pem-electrolyser-me450/me450/

PEM Water Electrolysis System

Typical example of a small system

- NEL Hydrogen M series containerized
- Outdoor solution for single digit MW systems with up to 1 t/d
- 1. Combustible gas detector
- 2. Heat exchanger
- 3. Hydrogen gas dryer
- 4. Hydrogen phase separator
- 5. Oxygen phase separator
- 6. Cell stack 1.25 MW
- 7. DI water polish bed
- 8. Circulation pump
- 9. Control panel
- 10. Rectifier / 11. MV input / 12. Transformer
- 13. Thermal control system / 14. Chiller



Picture credits: Nel Hydrogen (2023), https://nelhydrogen.com/product/m-series-containerized/

PEM Water Electrolysis System

Typical example of a medium-sized system

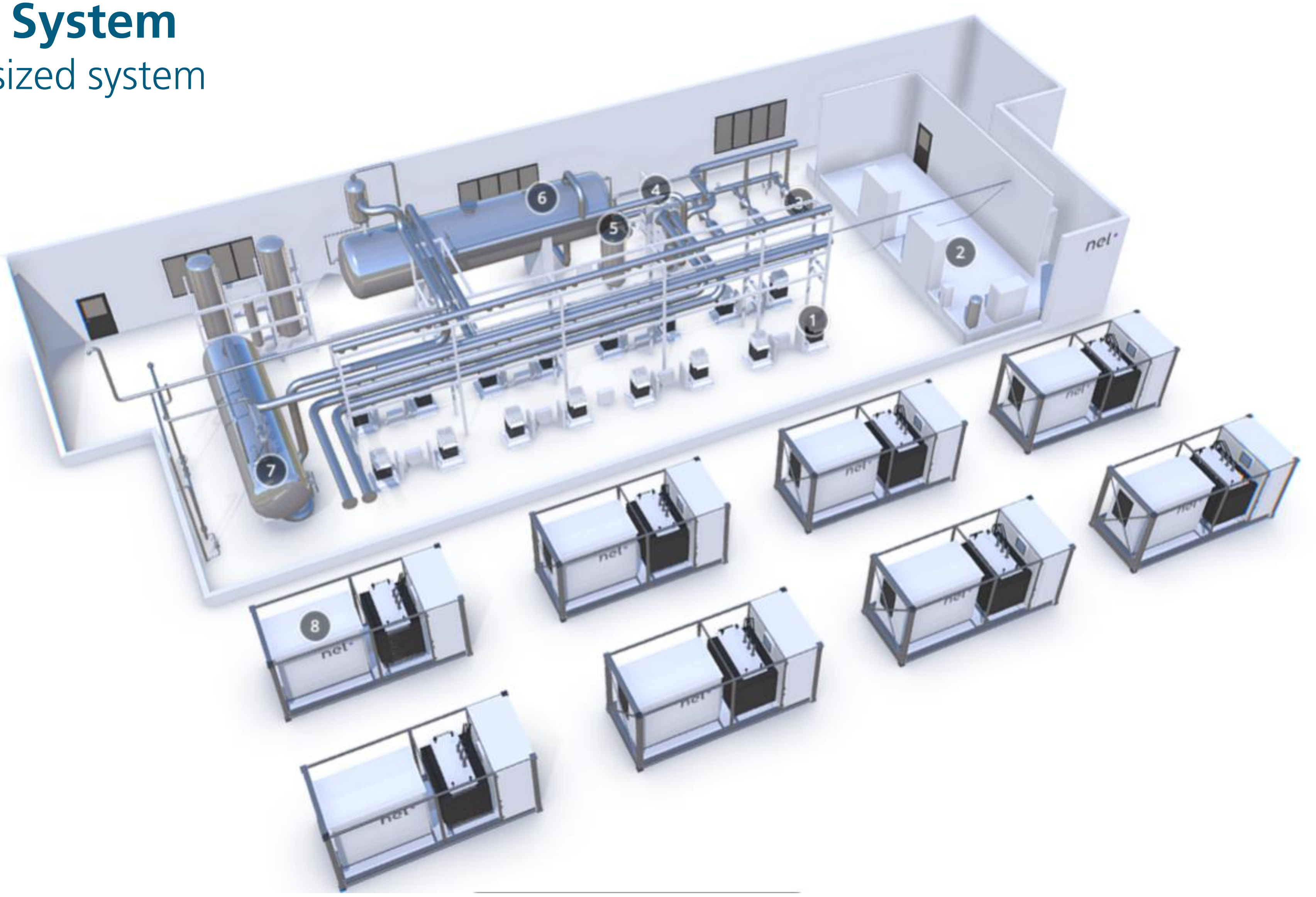
- H-TEC PEM Electrolyzer Modular Hydrogen Platform
- Indoor solution
- Combination of 10 MW blocks to multi-MW systems
- Numbering of stacks, here 4 arrays à 24 stacks

Picture credits: h-tec systems (2023), https://www.h-tec.com/en/products/detail/h-tec-pem-electrolyser-me450/me450/

PEM Water Electrolysis System

Typical example of a medium-sized system

- NEL Hydrogen M series
- 20 MW indoor solution
- 2 arrays à 8 x 1.25 MW stacks
  - 1. Cell stacks
  - 2. Control room
  - 3. Circulation pumps
  - 4. Heat exchanger
  - 5. DI water polish bed
  - 6. Oxygen phase separator
  - 7. Hydrogen phase separator
  - 8. Transformer and rectifier



Picture credits: NEL Hydroegen (2023), https://nelhydrogen.com/product/m-series-3/

PEM Water Electrolysis System

Typical example of a medium-sized system in reality

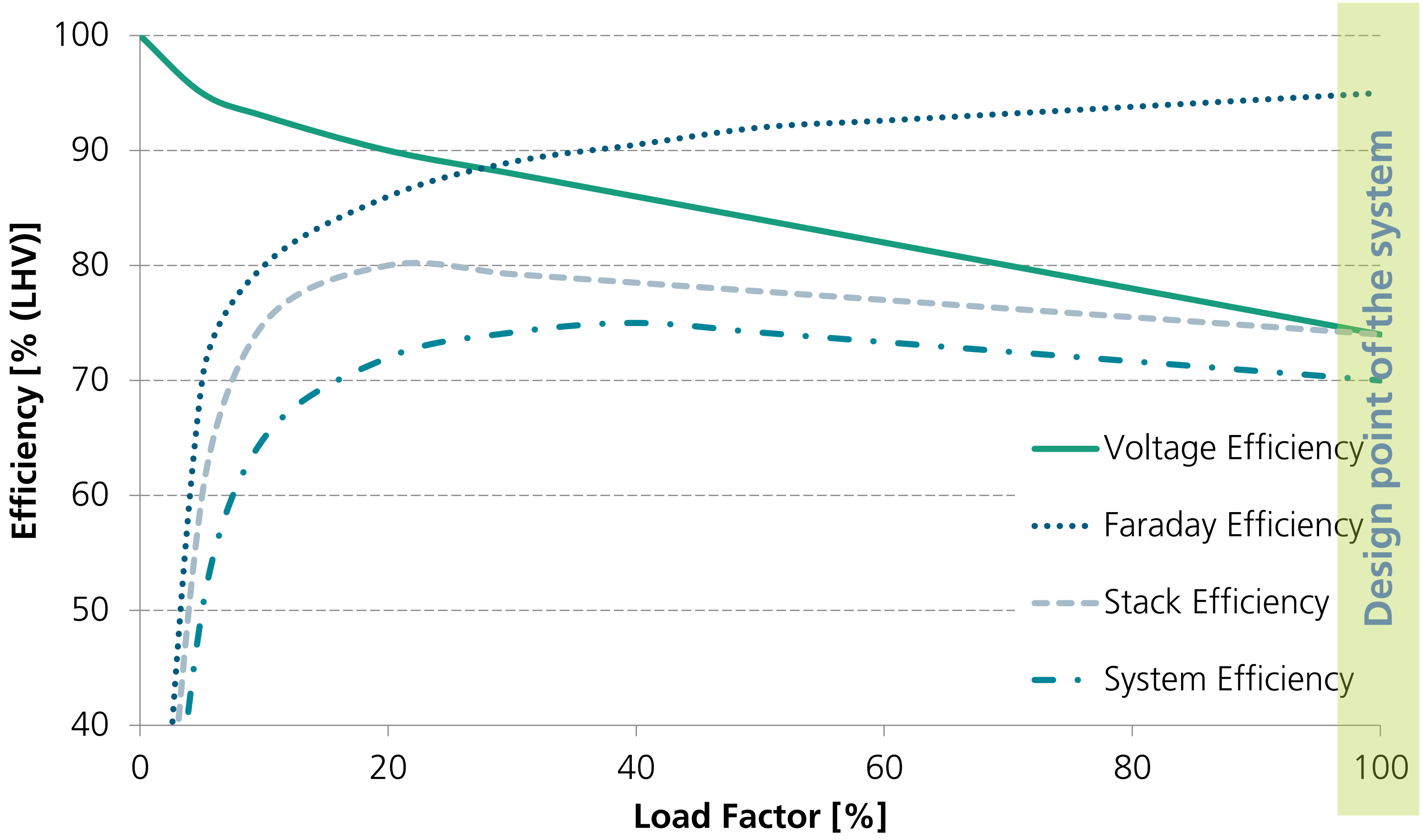
- ITM Power 10 MW PEMWE system
- Shell Refinery in Wesseling / DE
- European REFHYNE project

Picture credits: Refhyne (2020), https://www.refhyne.eu/construction-progressing-at-the-refhyne-site/

PEM Water Electrolysis System

Overall efficiency

- Voltage efficiency can reach theoretically 100% at 0% load
- Voltage efficiency and Faraday efficiency result in cell/stack efficiency
- System efficiency also includes balance of plant and several load dependent efficiency curves
- Real behaviour depends on many parameters
- System can be optimized for a specific applications
- Numbers shown here are only an example (Fraunhofer model)
- Keep in mind: drifting of the efficiency during operation

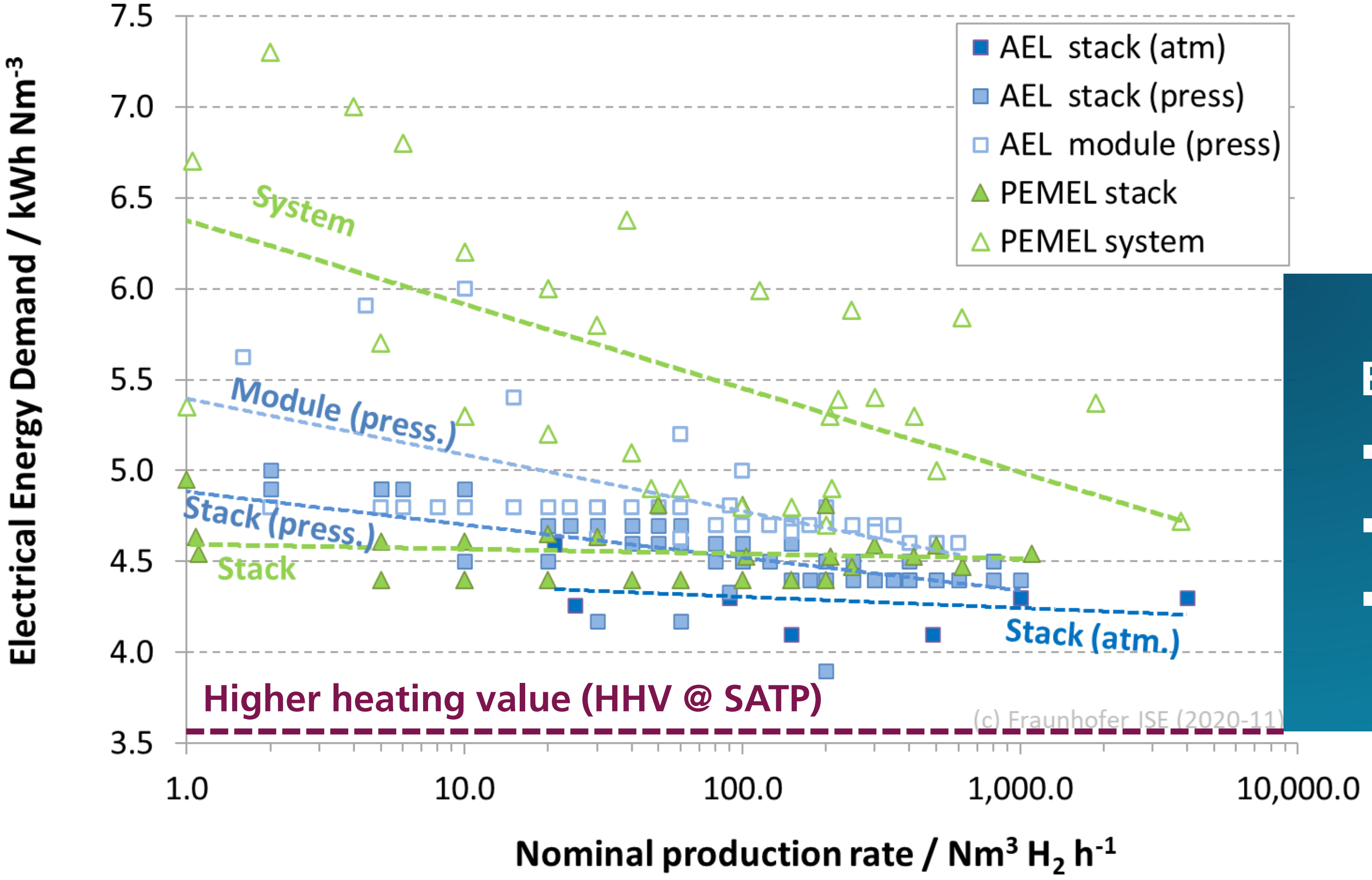


Picture credits:

Fraunhofer ISE

PEM Water Electrolysis System

The efficiency for electrolysers depends on the system size.



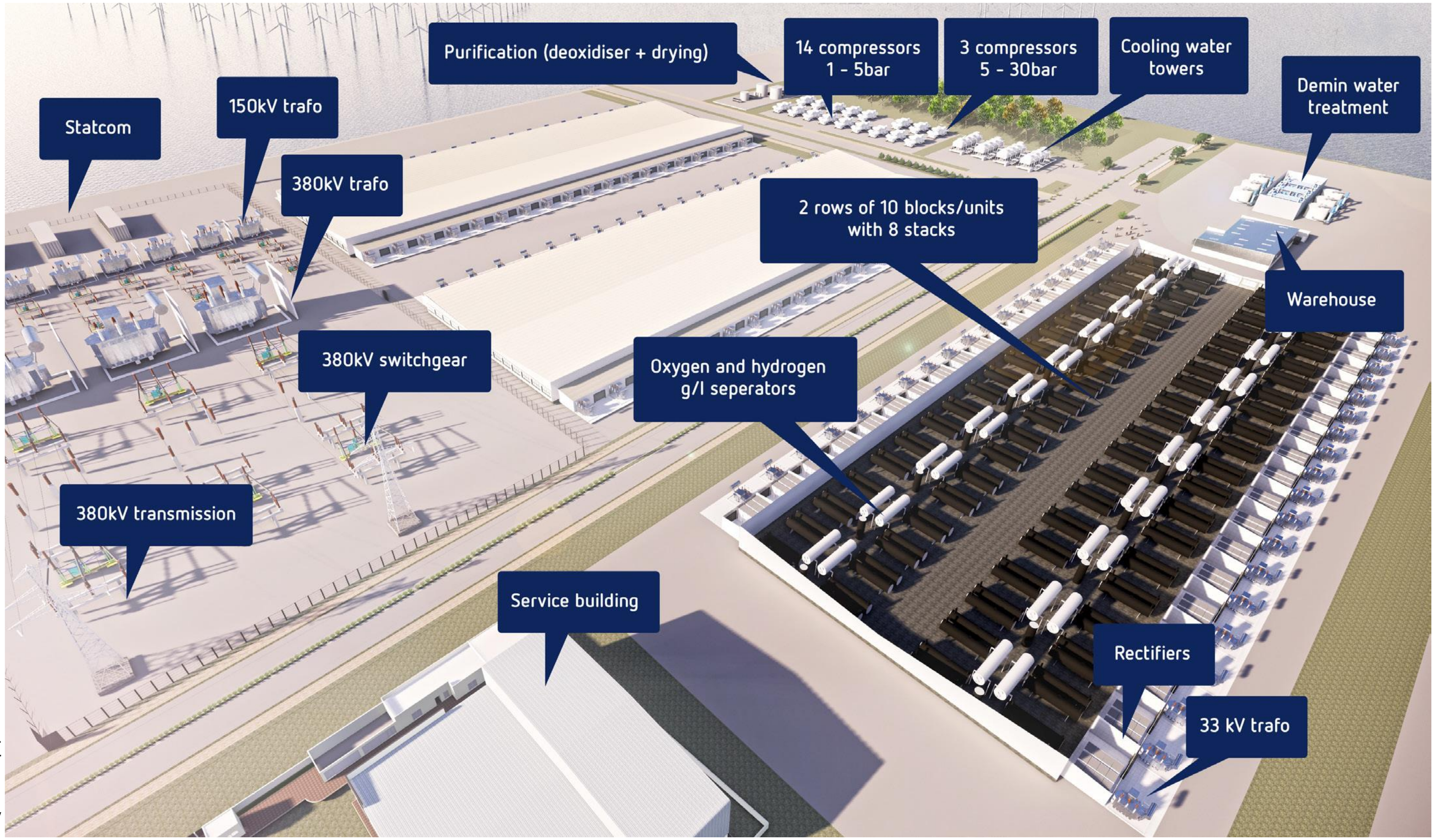
Electrical energy demand at rated power

- Manufacturer specifications (2010 – 2020)
- No standardized definition of efficiency
- No significant reduction expected in the future

Gigawatt Water Electrolysis Systems

Large-scale installations will be following up the numbering up approach.

- How can be achieved larger hydrogen production capacities?
  - Scale up cell area
  - Numbering up cells in a stack
  - Numbering up stacks in a system / plant



Artist impression of a state-of-the-art 1 GW green hydrogen plant based on alkaline technology

ISPT (2020): Gigawatt green hydrogen plant, state-of-the-art design and total installed capital costs. Report, Institute for Sustainable Process Technology, Amersfoort (The Netherlands) 2020

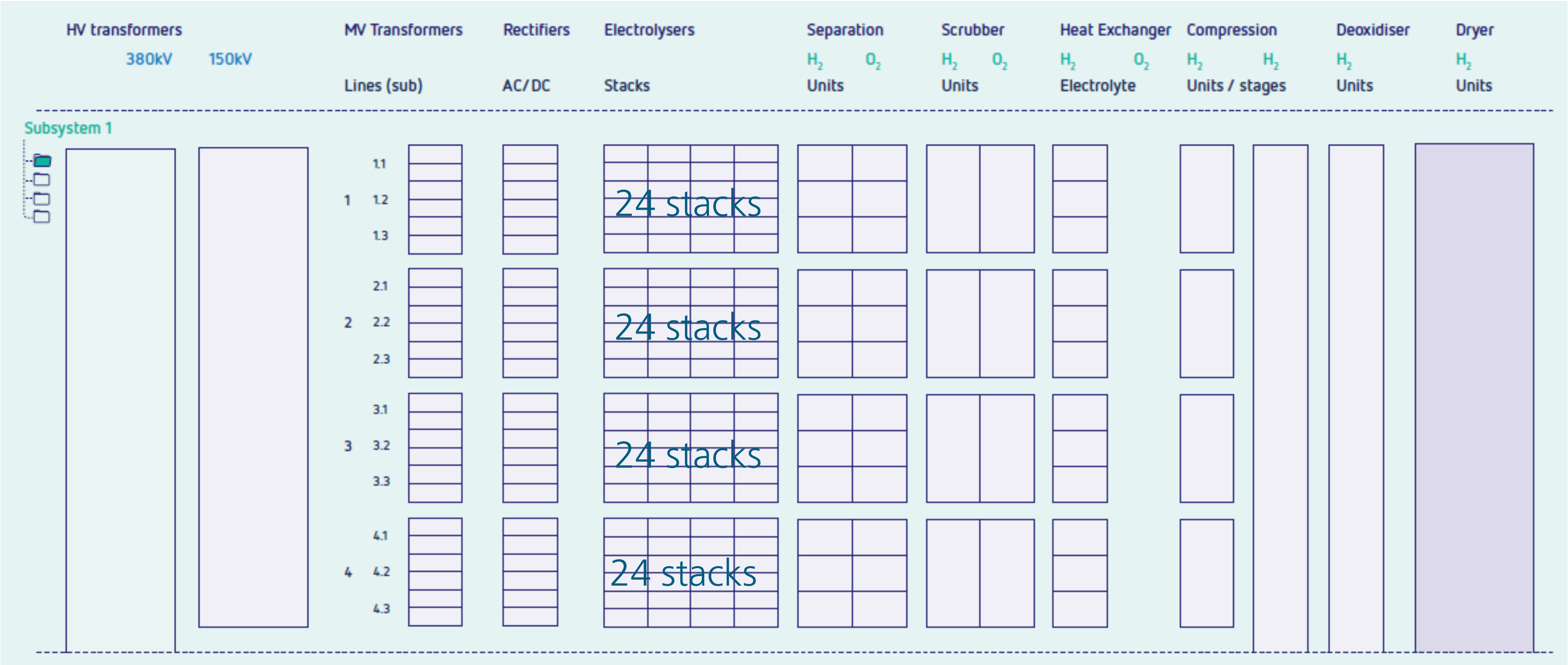
Gigawatt Water Electrolysis Systems

Large-scale installations will be following up the numbering up approach.

© ISPT (2022)

- Central components are combined in a modular design
  - Cost saving
  - Application determines requirements for redundancy and partial load range

Alkaline electrolysis system



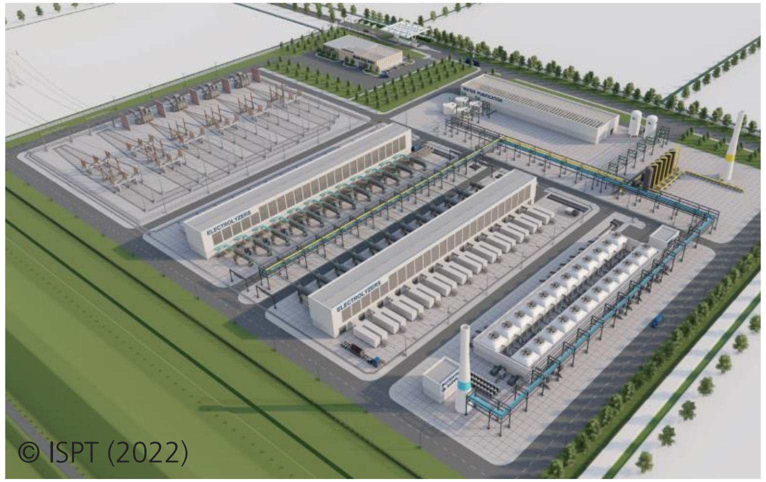
Modular design of a state-of-the-art 1 GW green hydrogen plant based on alkaline technology

ISPT (2020): Gigawatt green hydrogen plant, state-of-the-art design and total installed capital costs. Report, Institute for Sustainable Process Technology, Amersfoort (The Netherlands) 2020

Gigawatt Water Electrolysis Systems

Large-scale installations will be following up the numbering up approach.

PEM electrolysis system



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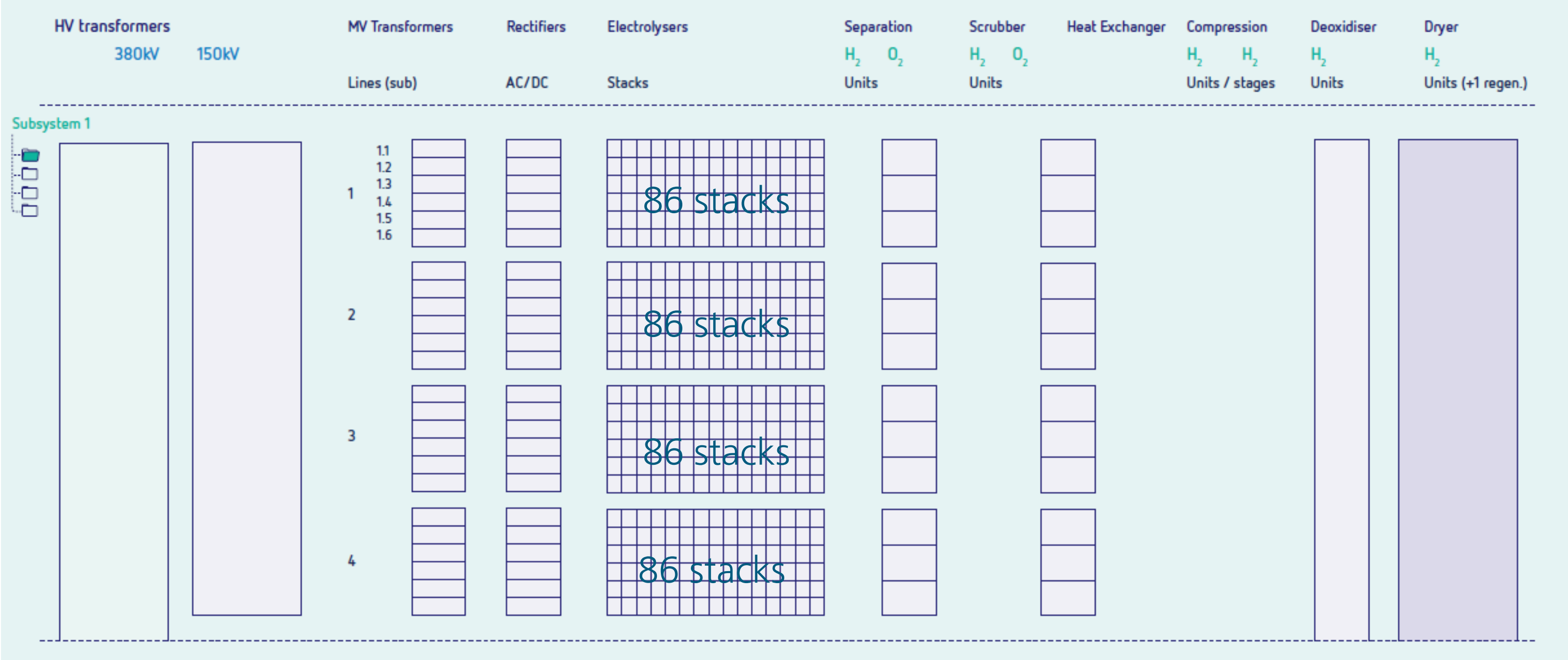
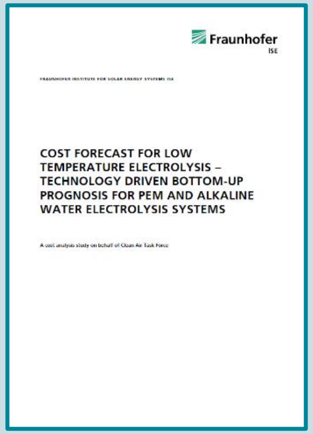


Modular design of a state-of-the-art 1 GW green hydrogen plant based on PEM technology

ISPT (2020): Gigawatt green hydrogen plant, state-of-the-art design and total installed capital costs. Report, Institute for Sustainable Process Technology, Amersfoort (The Netherlands) 2020

Further reading

More insights can be found here:

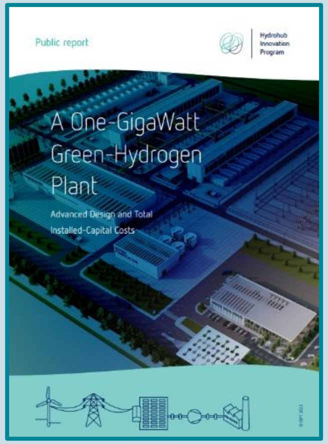


Bottom up cost model for AEL and PEM water electrolysis (CATF study):

https://www.ise.fraunhofer.de/en/press-media/press-releases/2022/towards-a-gw-industry-fraunhofer-ise-provides-a-deep-in-cost-analysis-for-water-electrolysis-systems.html

Similar study for a 1 GW electrolysis plant concepts (by ISPT, Netherlands)

https://ispt.eu/media/Public-report-gigawatt-advanced-green-electrolyser-design.pdf

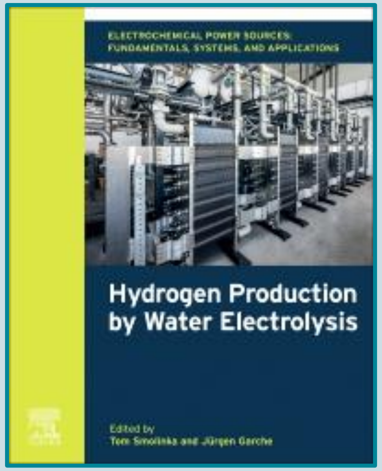


Study IndWEDe – Industrialization of water electrolysis in Germany (by NOW / Fraunhofer)

https://www.now-gmbh.de/wp-content/uploads/2020/09/indwede-studie_v04.1.pdf

General introduction to water electrolysis for hydrogen production (Elsevier book)

Paperback ISBN: 9780128194249
eBook ISBN: 9780128194256



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 and no technical showstopper is visible until 2030+ (materials, scale-up, lifetime, costs).

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

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

4. A successful market ramp-up will only work with suitable boundary conditions (availability of RE and market framework incl. business models for green hydrogen). The impending PFAS ban in Europe would be a significant setback for PEMWE.

Thanks a lot for your kind attention!

Contact

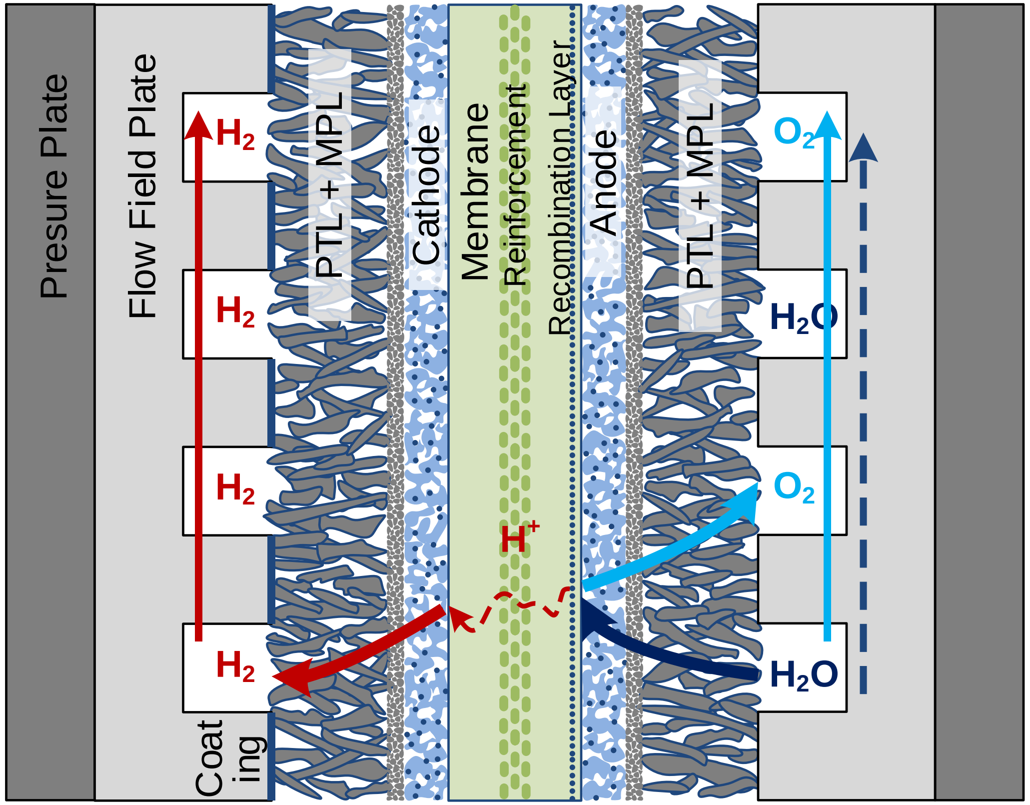
Dr. Tom Smolinka
Business Area Hydrogen Technologies
tom.smolinka@ise.fraunhofer.de

www.ise.fraunhofer.de
www.pem-electrolysis.de

Development Trends in PEM Water Electrolysis

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

Backup slide



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: ~2.0 mg/cm² **0.4-1.0 mg/cm²**
  - CAT: supported Pt/C: ~ 0.5-1.0 mg/cm² **0.1-0.5 mg/cm²**
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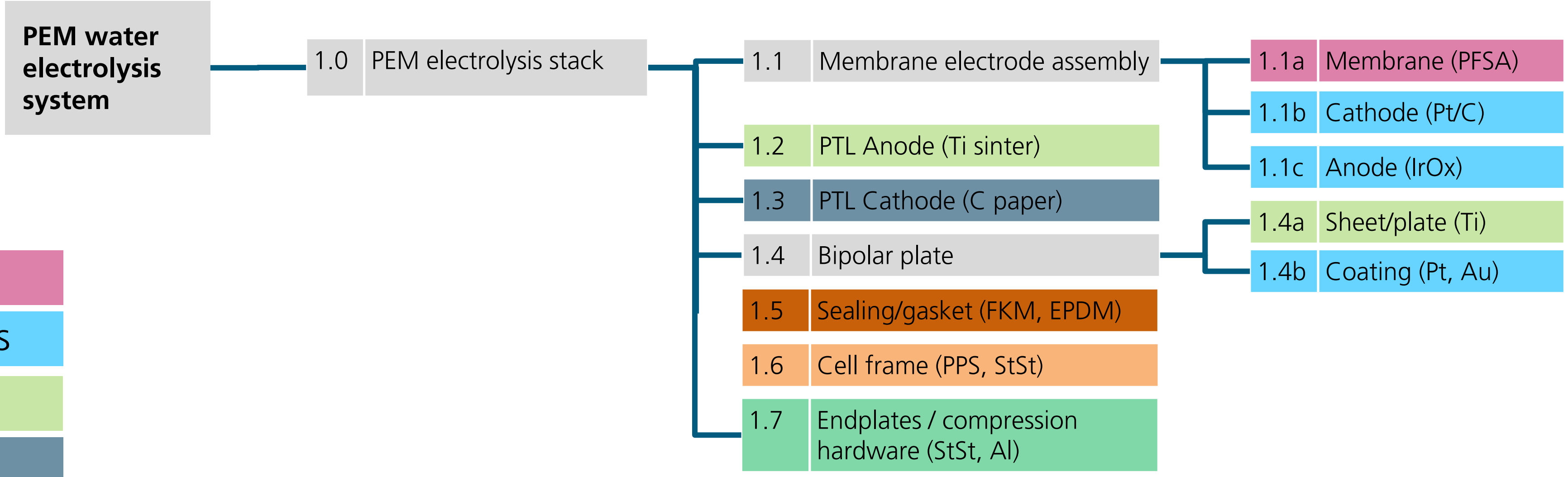
  - Sintered Ti fibers/particles: 0.5 - 1.0 mm **~ 300 µm**
  - Carbon paper (only at cathode)
- Bipolar plate (with flow field structures)
  - (Au or Pt coated) Ti sheet: 0.2 - 1.0 mm **~ 300 µm**
  - **Highly integrated & mass-produced half-cell compounds**

PEM Water Electrolysis System

Basic system layout & main system components

Backup slide

- Component diagram of a PEMWE system
- Most common materials used in PEMWE stacks
  - Perfluorosulfonic acid
  - Nobel metals as PGM elements
  - Transition metals as titanium
  - Carbon
  - Stainless steel and aluminium as construction material
  - Elastomers
  - Thermoplastics



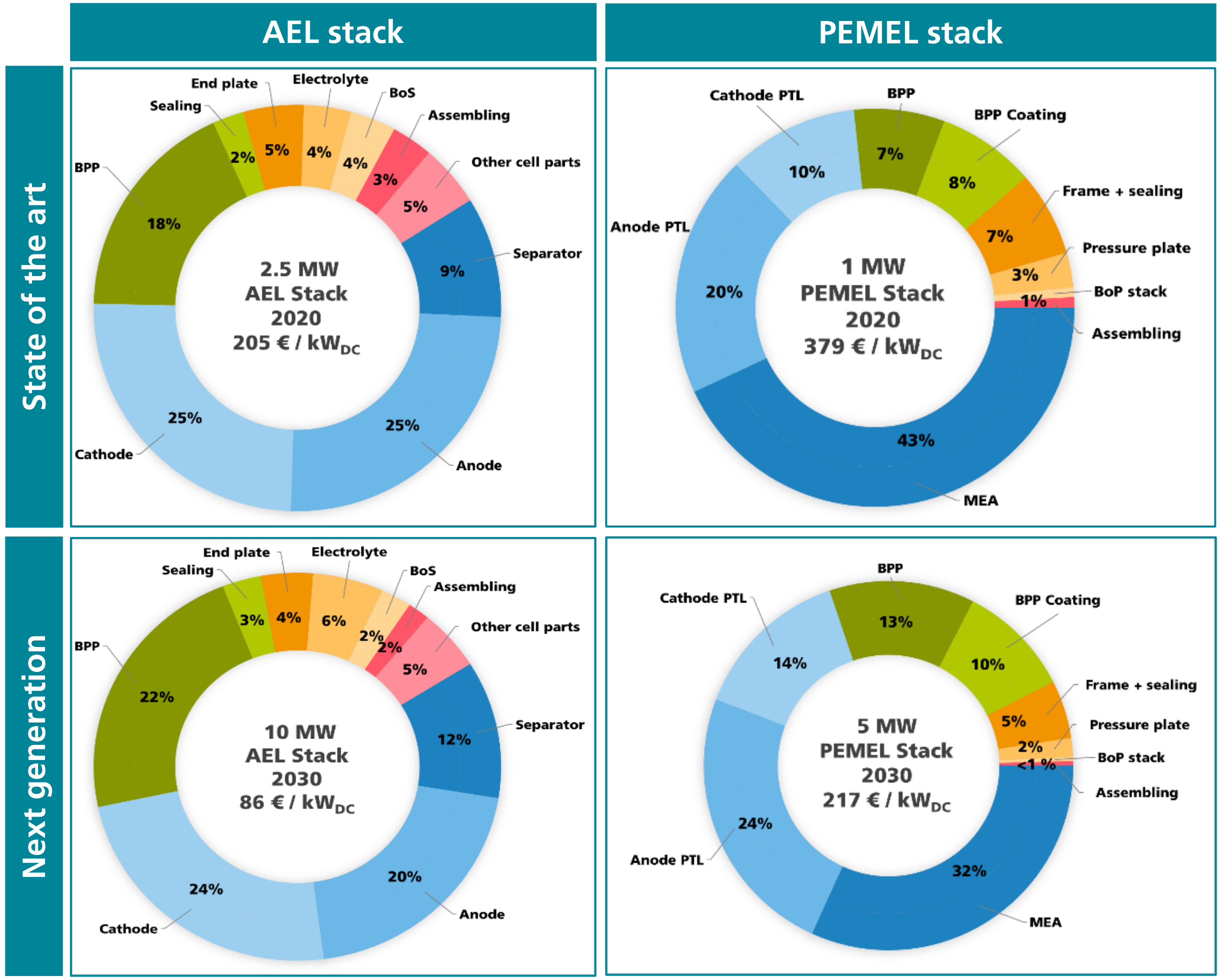
EPDM	: Ethylene propylene diene monomer rubber
FKM	: Fluoroelastomer as Viton©
FFKM	: Perfluoro-elastomer (fluorinated elastomer)
PFSA	: Perfluorosulfonic acid as Nafion©
PGM	: Platinum Group Metals
PTFE	: Polytetrafluoroethylene as Teflon©
StSt	: Stainless steel

Picture credits: Fraunhofer ISE (2014)

Cost structure analysis of stacks in alkaline and PEM water electrolysis

CATF study: Main results for state of the art and future stack designs

- Cost drivers AEL stacks
  - electrodes (anode/cathode)
  - bipolar plates (cell compartments)
- Cost drivers PEMEL stacks
  - membrane electrode assembly (CCM)
  - porous transport layer anode (Ti based)
- Prediction of future costs
  - Scale-up and technology progress results in a cost reduction of some 50 %
  - AEL stacks can also be produced more cost-effectively in the future



Cost breakdowns of state of the art electrolysis stacks (2020) and future electrolysis stacks (2030) for AEL and PEMEL

Reference: CATF study

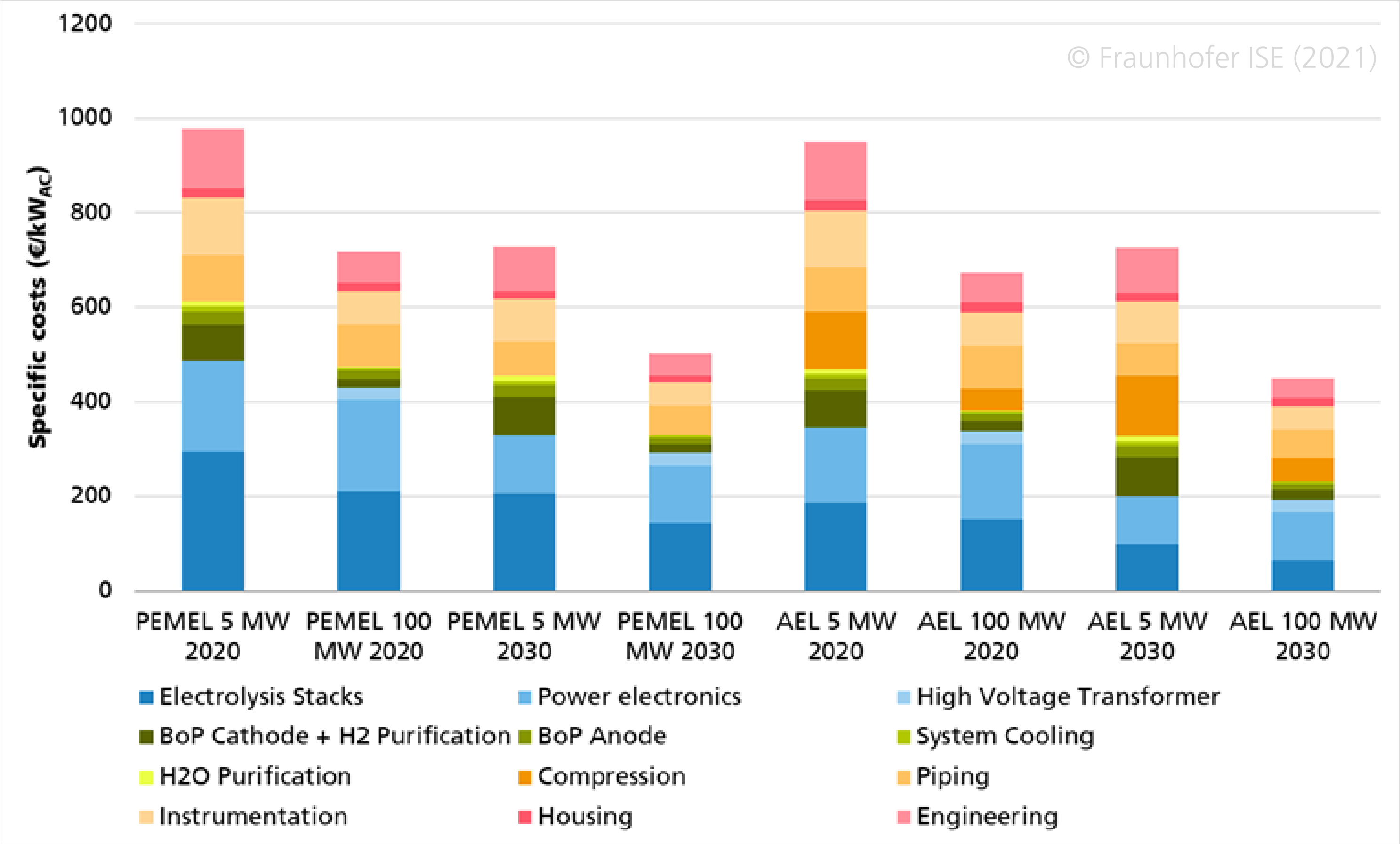
BPP: Bipolar plate
BoS Balance of stack
MEA: Membrane electrode assembly
PTL: Porous transport layer

Cost structure analysis of stacks in alkaline and PEM water electrolysis

Backup slide

CATF study: Stack costs do not dominate the system costs alone.

- System costs are made up of many individual components such as stack, gas and water treatment, cooling systems and power electronics
  - Stack main cost driver
  - Rectifier and transformer second most expensive components
- Small systems significantly more expensive than larger ones
- AEL systems will also lead to lower system costs in the future
- Almost cost parity between AEL and PEMEL systems if hydrogen compression is taken into account



Reference: CATF study

Fraunhofer ISE

Development Targets for LT Water Electrolysis

European Strategic Research and Innovation Agenda 2021 – 2027

Backup slide

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 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/cm²	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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No.	KPI	Unit	SoA 2020		Targets 2024		Targets 2030	
			AEL	PEMEL	AEL	PEMEL	AEL	PEMEL
1	Electricity consumption @ nominal capacity	kWh/kg	50	**55**	[illegible]	[illegible]	[illegible]	**48**
2	Capital cost	€/(kg/d)	1,250	**2,100**	[illegible]	[illegible]	[illegible]	**1,000**
		€/kW	600	**900**	480	700	400	**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
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10 yrs

10 yrs

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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

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- 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	
	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/cm² @ 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/cm² (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

Backup slide

Development Targets for LT Water Electrolysis

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U.S. DEPARTMENT OF ENERGY

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	System		AEL	PEMEL	AEL	PEMEL	AEL	PEMEL
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~ 10 yrs

~ 10 yrs

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Development Targets for LT Water Electrolysis

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

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U.S. DEPARTMENT OF ENERGY

Ambition mapping

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

No.	KPI	Unit	SoA 2022		Targets 2026		Ultimate Targets	
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