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Hydrogen at Scale

Key items for R&D&I in electrolysis?

Outline

- R&D targets: 100 % efficiency
- Activities to realize implementation plan → check on goals

- KPIs form IP related to electrolysis
  - AEC
  - PEMEC
  - SOEC

"Recent developments and advances in electrolysis: from concepts to materials to systems".

- How can we reduce the energy consumption and costs for hydrogen?
  - translate KPIs into research objectives/goals
- How to get hydrogen in large quantities?
  - What are size limitations in cells and systems?
- How can electrolysis efficiently be integrated into other (downstream processes)?
  - Can we learn more from fuel cell technology?

- Aim of the WS: have a list of ideas/approaches to be work on for input to joint JP workshop next year, but also for input to HE and Horizon Europe calls.

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Hydrogen at scale?

- Green Deal:
  - 100 MW electrolyser

- Clean Hydrogen for Europe HE & HER strategy:
  - 2 times 40 GW Electrolyser strategy 2030
  - Reduced to 1 times 40 GW in European Hydrogen Strategy

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General consideration Electrolysis vs Fuels Cells

- Design criteria: 100 % efficiency → thermos neutral potential 1.23 V (LHV), 1.48 (HHV) → 200-500 mV cell overvoltage (electrodes + electrolytes)
  - Overvoltage and efficiency → energy demand → electricity costs → OPEX
  - Current density: → production rate / time/ unit → CAPEX

  - SOEC: high current densities → lower cell voltage than thermos neutral
    - heat required: → exergy analysis for different kinds of energy rather than efficiency analysis
    - Robust materials/ Interfaces
  - AEC: higher overpotential → lower efficieny than 100%
    - Catalysts, electrolytes and cell design → gas diffusion electrodes vs immersed electrodes
  - PEMEC: higher overvoltages → lower efficiency than 100%
    - Catalysts & supports, electrolyte durability

Comparison high and low temperature water electrolysis

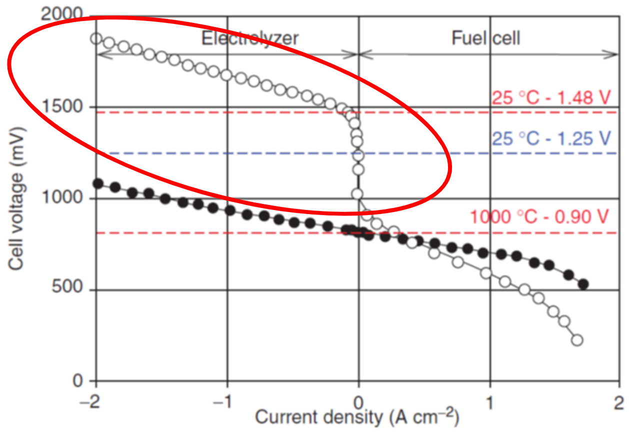

Figure 2.13 Experimental water electrolysis polarization curves measured at (o) 90 °C and (•) 1000 °C.

Electrolysis KPIs

- KPI tables in implementation plan:
  - Most values are for fuel cell operation or related to both.
  - But there are fundamental differences:
    - Heat management is in principle simpler for electrolysis
    - Voltage gradient over the cell is higher

Some questions for large scale hydrogen production:

- How fast are the electrode reactions and transport rates (ions, electrons gases (in liquids)
- How large can electrolysers be built → difference between ELY and FC
  - thermal management?
  - structural mechanical robustness
  - large cell areas (squaremeters) & currents → electrode design → equal potential distribution?
- How fast are the dynamics (cell, stack, systems?)

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Electrolytes

No.	Parameter	Unit	Applicable technology (e.g. PEMFC, SOEC, AEC, etc.)	Applicable conditions (e.g. T, J, #cycles, …)	SoA 2018	Target 2030	Corresponding FCH JU MAWP KPIs (e.g. A.1.1 no.1)
8	Increase of performance through the adoption of innovative binders	%	Low-temperature FC & Electrolyser technologies		Reference	>25%	A.1.8 no.4 ,5 A.1.9 no. 7,8

- SOEC:
  - Electrolyte supported designs help → thermoneutral conditions?

- AEC: electrolytes for gas diffusion electrode concepts?
  - thinner more robust diaphragms
  - Anion conducting membranes → Low TRL
- AEC advanced
  - hybrid immobilized aqueous electrolytes → very low TRL
    - Scale-up of ceramic separators
- PEMEC: polymer durability & costs → KPI above

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Electrodes and Catalysts

No.	Parameter	Unit	Applicable technology (e.g. PEMFC, SOEC, …)	Applicable conditions (e.g. T, J, #cycles, …)	SoA 2018	Target 2030	Corresponding FCH JU MAWP KPIs (e.g. A.1.1 no.1)
1	Area-Specific Resistance	Ωcm²	All cell technologies	At respective operation temperature	0.25	<0.1	A.1.8 no.1,5 A.1.9 no.1,8 A.1.10 no.1
2	Current density	A/cm²	Fuel Cell	At respective operation temperature, 50 mV overpotential (FC anode) 100 mV (FC cathode)	0.3	0.8	A1.13 no.6 A1.14 no.6 A1.15 no.6
			Electrolysis	100 mV (cathode) 200 mV (anode)	0.6	>1	A.1.8 no.4 A.1.9 no.7 A.1.10 no.7
3	Catalysts/electrode durability	hours	All cell technologies	Under relevant operation conditions	5000-10000	>40000	A.1.8 no.4, 3 A.1.9 no.7, 3 A.1.10 no.7, 4
4	Precious metal loading	mg/cm²	PEM fuel cells/electrolyzers	Under relevant operation conditions	0.25	<0.1	A.1.9 no.9
5	Sulfur Tolerance of Anodes	ppm	SOFC	700°C-900°C	0 ppm for Ni-YSZ	10	A.1.13 no.4,5,8
6	Redox cycling ability	No.	SOFC	600-900 C	10	>100	A.1.13 no.4,5,8
7	Carbon Tolerant fuel electrodes for co-electrolysis (ASR)	Ω.cm²	SOE	700°C-900°C P =1- 10 bar	>1	0,1	A.1.10 no. 4

Electrodes and catalysts

- AEC
  - Improved anodes (revised anode design)
  - Higher efficiency and productivity
- Advanced HTP
  - Robust anodes

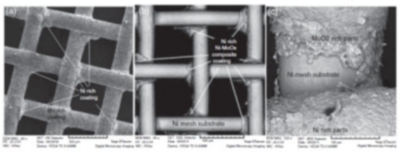
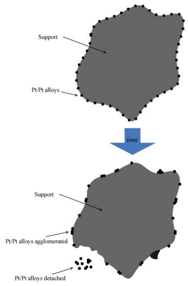


Figure 4.10 Catalyst (Ni–MoOx and Ni–MoO$_2$)-coated Ni mesh before (a) and after 'service life' test. (b) NiMoOx coating and (c) Ni–MoO$_2$ coating.

- PEMEC
  - Improved anodes (oxygen electrode)
  - Precious metal free catalysts



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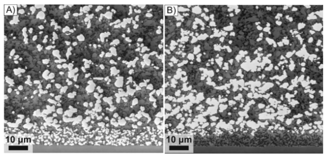


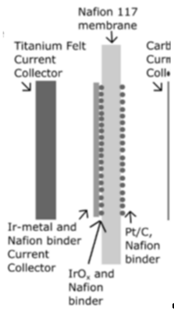
- SOEC
  - More robust electrodes (especially fuel electrode), allowing for higher current densities
    - Ceria/ceramic based electrode(s)?
    - Modified Ni-based fuel electrode?

1-year test SOEC, H_2O electrolysis at 800 °C, microstructure after 1 year at OCV (A) and at -1 A/cm^2. (M. Mogensen et al., Fuel Cells, 2017)

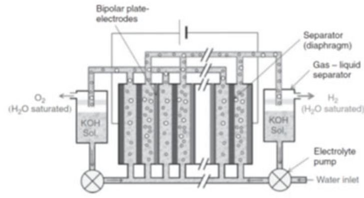
Stack materials & design

No.	Parameter	Unit	Applicable technology (e.g. PEMFC, SOEC, ...)	Applicable conditions (e.g. T, J, #cycles, ...)	SoA 2018	Target 2030
13	Interconnect lifetime	hours	PEMFC,PEMEC,AEC			>40 000
14	Interconnect cost target	€/kW	PEMFC,PEMEC,AEC			<3
15	Electrical conductivity	S/cm	PEMFC,PEMEC,AEC			>100
16	Interconnect lifetime	hours	SOFC, SOEC		40k	>100k
17	Interconnect (w/o Cr-barrier layer) cost target	€/kW	SOFC (for SOEC, divide by 3)	Small series	1300-1800	<300
18	Cost target Cr-barrier coating	€/kW	SOFC (for SOEC, divide by 3)		1050	30
18a	Cost target Cr-barrier coating	€/kW	SOFC (for SOEC, divide by 3)	MCF by APS	1050	120
19	ASR of Protective coating for the interconnect at the Fuel Side	mΩ.cm²	SOE (steam electrolysis)	700°C – 750°C (ASC) 800°C -900°C (ESC) Steady state	-	<10
20	ASR of Anti coking protective coatings for the interconnect at the fuel side	mΩ.cm²	SOE co-electrolysis	700°C – 750°C (ASC) 800°C -900°C (ESC) Steady state	-	<10
22	SOFC sealing life time	Thermal cycles	SOFC, SOEC	Ambient – 700°C	<100	200-1000 (TBD, 2 different inputs provided)
23	Cost of stack sealant	€/kW	SOFC (for SOEC, divide by 3 to 4)	Small series production	500	45
24	Cost of electrode contact material	€/kW	SOFC (for SOEC, divide by 3 to 4)	Mesh of Nickel wire	70	5
25	ASR of electrode-contact-layer	mOhm/cm²	SOFC, SOEC	At xxx°C	40	20

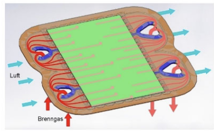
Stack materials and design



- Materials
  – Protective coatings → relevant for all electrolysis technologies
    - Corrosion → AEC PEMEC (?)
      – Coated steels
      – Cr evaporation → SOEC
  – Separators thinner diaphragms→AEC
  – Sealing materials → mostly SOEC?
  – Contacting layers → mostly SOEC
- Scaling up cell size: → SOEC
  - Robust support materials
  - Metal supported designs
  - Monolithic stack design



- Design
  – AEC
    - Load flexibility
    - Reduced leak currents
    - Gas diffusion electrodes
    - Prototyping
  – PEMEC
    - Hydrogen cross over



  – SOEC
    - Metal supported designs
    - Monolithic stack design
    - Automated assembly

Systems

No.	Parameter	Unit	Applicable technology (e.g. PEMFC, SOEC, …)	Applicable conditions (e.g. T, J, #cycles, …)	SoA 2018	Target 2030	Corresponding FCH JU MAWP KPIs (e.g. A.1.1 no.1)
			Balance of Plant (BoP) components				
1	Corrosion rate	μA/cm²	BoP parts in alkaline or acidic media	n.a.		< 0.1	A.1.8-9 no.3 (O&M) A.1.13-15 no.5 (MTBF)
	Oxidation mass gain	mg/1000 hrs	Steel components in HT systems	Operating conditions		< 0.2	A.1.10 no.4 (O&M) A.1.13-15 no.5 (MTBF)
2	Cost of materials	€/kg	All BoP parts	n.a.		< 5	A.1.8-9 no.2 (CAPEX) A.1.10 no.3 (CAPEX) A.1.13-15 no.1 (CAPEX)
3	Cumulative Cr evaporation from BOP parts	kg/m² for 1000 hrs	Steel components in HT systems	n.a.		< 0.0002	A.1.13-15 no.2 (Lifetime)
4	Coating resistance	hrs	Heat exchangers	n.a.		> 40kh	A.1.13-15 no.5 (MTBF)
5	Coating costs	€/m²	Coatings and linings for corrosion resistance in alkaline and acidic media in BoP	n.a.		< 700	A.1.8-9 no.2 (CAPEX) A.1.10 no.3 (CAPEX) A.1.13-15 no.1 (CAPEX)
6	Influence of coating on funtional properties of the parts	%	Coatings and linings for corrosion resistance in alkaline and acidic media in BoP	n.a.		< 10	A.1.8 no.1 A.1.9 no.1 A.1.13 no.6,7 A.1.14 no.6, 7 A.1.15 no.6, 7
7	Degradation	%	Catalysts/support for reforming and POX	n.a.		< 10	A.1.13-15 no.2 (Lifetime)
			BoP integration				
8	BoP Cost	€/kW	Total system, All FC & electrolyser technologies	n.a.		< 400	A.1.8 no.2 A.1.9 no.2 A.1.10 no.3 A.1.13 no.1 A.1.14 no.1 A.1.15 no.1
9	Footprint reduction	%	Total system, All FC & electrolyser technologies	n.a.		> 15	A.1.9 no.6
10	System efficiency gain	%	Total system, All FC & electrolyser technologies	n.a.		> 3	A.1.8 no.1 A.1.9 no.1 A.1.13 no.6,7 A.1.14 no.6, 7 A.1.15 no.6, 7

AEC ThyssenKrupp

Systems

- System design
  - Load flexibility
  - Size/footprint
  - Overall efficiency
  - Power range (stack vs system vs application)
  - Gaseous or liquid feed (HT EC)
  - Product separation (SOEC-> condensation for phase separation?)
- Centralized systems
  - Operation in industrial environment?
- Decentralized systems
  - Public, individual operation

- BoP components
  - Robustness: Corrosion (AEC, HT materials)
  - Failure tolerance
    - Reformer
    - Power electronics
- Forward integration
  - HTP-AEC & SOEC
    - downstream P2X thermal integration)
  - Hydrogen storage (& use FC systems)
    - Thermal management between electrolyser and e.g. solid storage
    - Integration into filling stations (700 bar)

Modelling

- Materials
  - KPI 6 Prediction of cellcomponent models based on ab-initio properties calculations
  - Artifical intelligence for development of new materials
  - Density Functional Theory
- Multiphysics approaches?
  - What can we learn from FuelCells?
  - System modelling?

No.	Parameter	Unit	Applicable technology (e.g. PEMFC, SOEC, ...)	Applicable conditions (e.g. T, J, #cycles, ...)	SoA 2018	Target 2030	Corresponding FCH JU MAWP KPIs (e.g. A.1.1 no.1)
Diagnostics hardware and software							
Modelling and validation							
6	Predictability of cell component model based on ab-initio properties calculation and material properties characterization	%	All cell technologies	All conditions	<80	90	A.1.1 no. 1,3 A.1.2 no. 1,3 A.1.3 no. 1,3 A.1.4 no. 1,2,4 A.1.5 no. 4, 5 A.1.8 no. 4,5,6 A.1.9 no. 4,5,6 A.1.10 no. 5,7 A.1.13 no. 3, 5 A.1.14 no. 3, 5 A.1.15 no. 3, 5