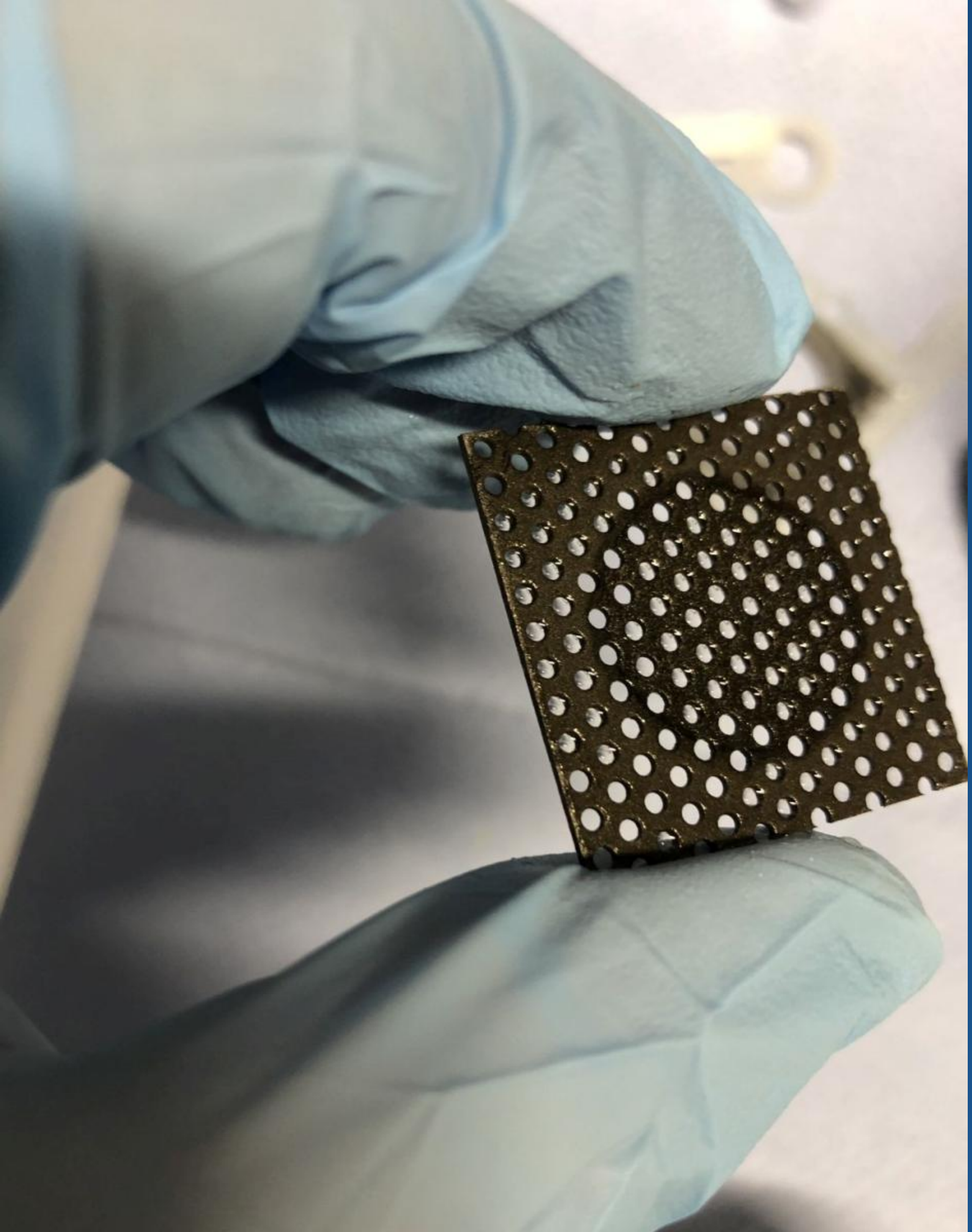


Electrodes for Alkaline Electrolyzers

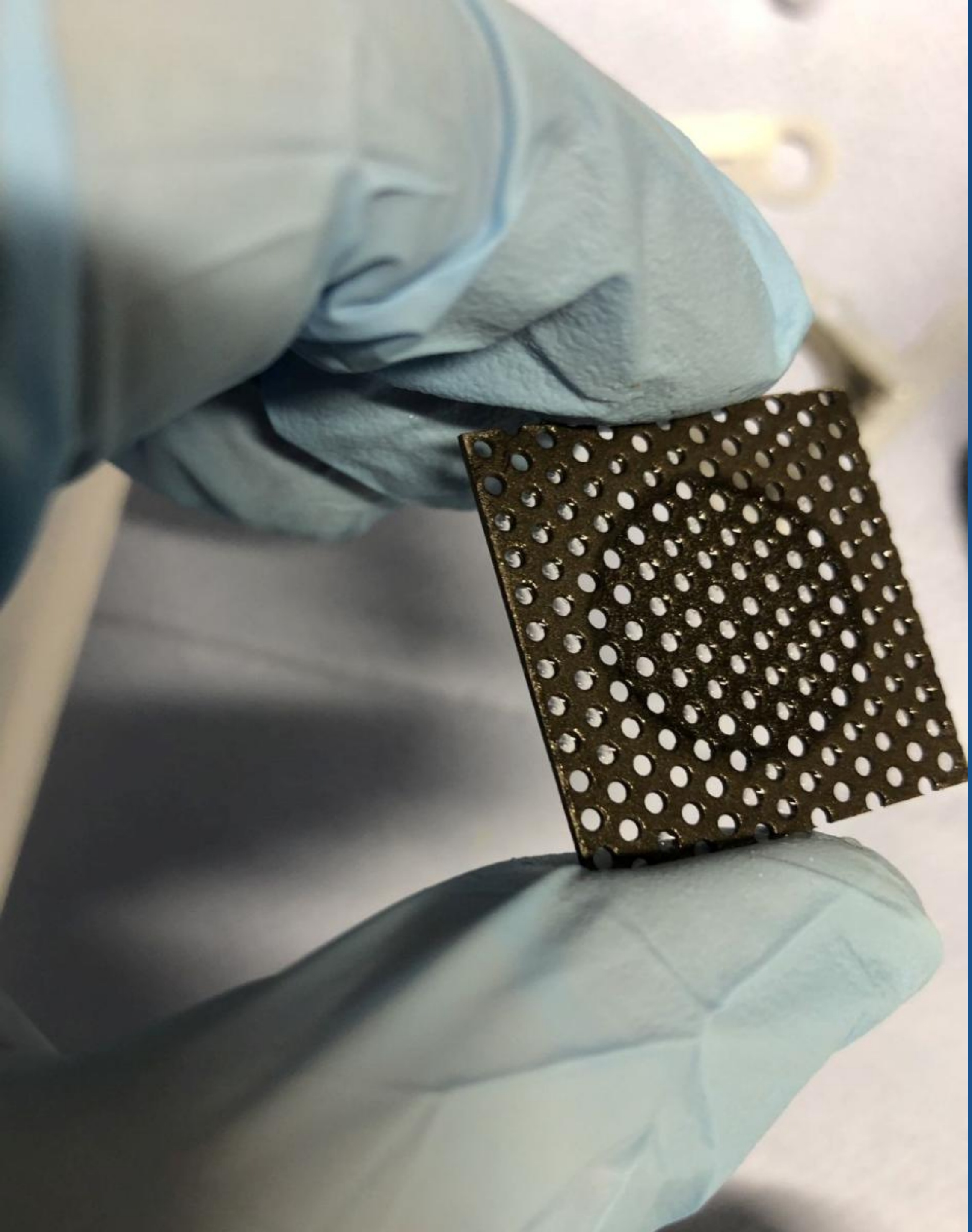
Mission Hydrogen Webinar

Dr. Marc-Simon Löffler

M.Sc. Verena Kindl

M.Sc. Philipp Spieth

Dipl.-Ing. (BA) Thomas Ottitsch



Electrodes for Alkaline Electrolyzers

Mission Hydrogen Webinar

- How can efficiency and current density be increased by electrode coatings?
- What are the effects on hydrogen production costs?
- What are the technical requirements for coatings?
- What are the main coating processes?
- How can coatings be tested and validated?

AGENDA

1 **ZSW**

2 **Alkaline Electrolysis**

3 **Electrode design and coating processes**

4 **From fundamental research to market-readiness**

5 **Summary**

Dr. Marc-Simon Löffler
Head of department
Electrolysis & eFuels

M.Sc. Verena Kindl
Senior scientist
Stack development

Dipl.-Ing. (BA) Thomas Ottitsch
Team manager
ElyLab test field

M.Sc. Philipp Spieth
PhD student
Electrode characterization

AGENDA

ZSW – At a Glance

- **Non-profit organization with ~350 employees, approx. 50 MM€ annual budget and 85% external funding.**
- **2 locations in Stuttgart and Ulm, Baden-Württemberg, Germany**
- **Applied research & development on new energy technologies:**

– Photovoltaic: materials, thin film technologies (CIGS) & application systems

– Batteries & Supercapacitors: materials, production technologies, systems, qualification

– Renewable Fuels: Electrolysis, Direct Air Capture, eFuels

– Fuel Cells: stack-technology, component, systems, production technologies, test centre

– Energy politics & economics

– **Technology transfer**

www.zsw-bw.de

WIND ENERGY

PHOTOVOLTAICS

BATTERIES

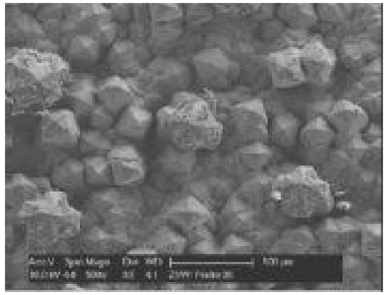
HYDROGEN

FUEL CELLS

ENERGY POLICY

ZSW – Electrolysis research

Development of alkaline electrolysis technology since 2012 (> 150 man-years of experience).





materials
- catalysts & coatings
- material screening
- accelerated stress testing

components
- electrode development
- electrode packages
- cell frames

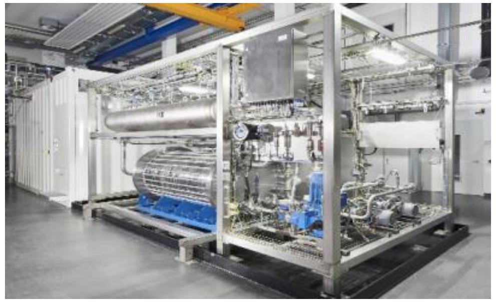
stacks & manufacturing
- stack designs up to MW scale
- from 100 cm² up to 10.000 cm² electrode area

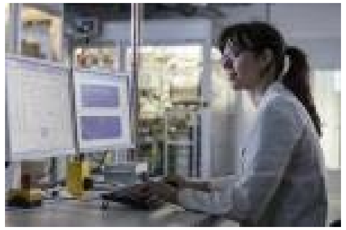
systems & test field
- system designs up to MW scale
- ElyLab test field

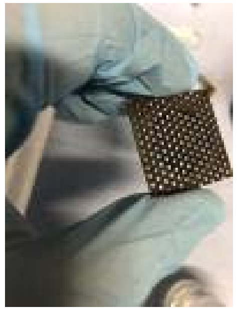
digitalization & AI
- stack-integrated sensors
- data monitoring
- data analysis applying AI
- digital twins

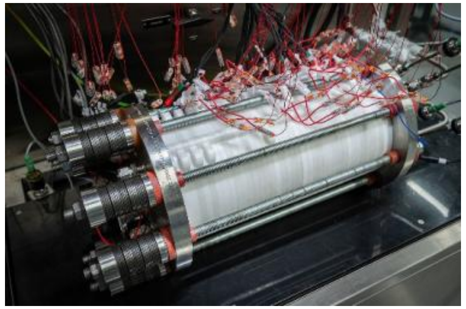
ZSW – Supporting the market ramp-up

ZSW is offering technology, consulting & testing services .







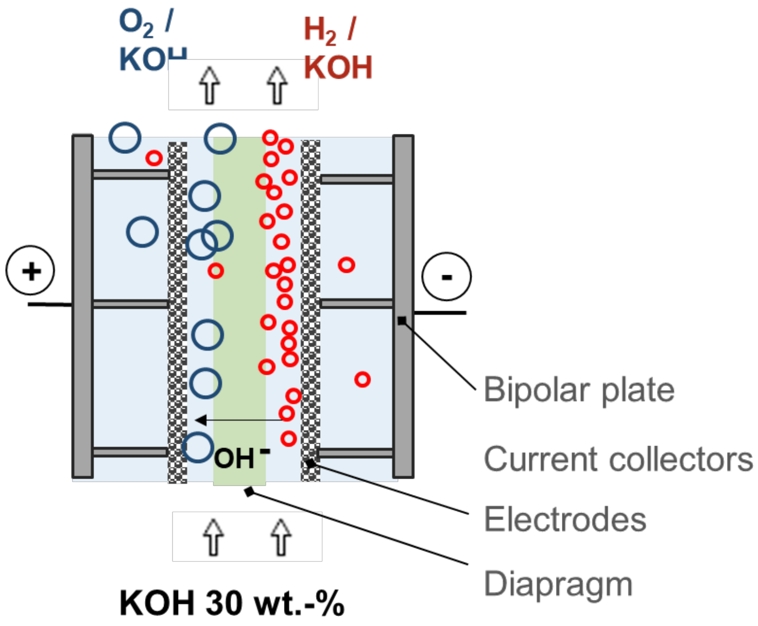


- ZSW´s technologies as a springboard to market.
- Consulting services for system, stack and component development.
- Testing services from 1 cm^2 coating prevalidation up to MW stack testing
- Competent partner in R&D funding projects

AGENDA

Alkaline electrolysis – overview

The alkaline technology is (alongside PEM) a key pillar for the electrolysis market ramp-up



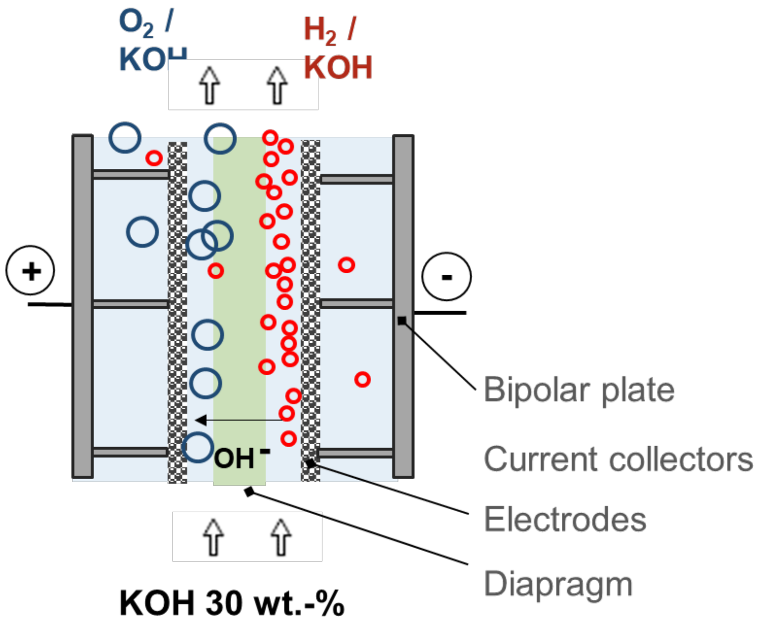
$$(-)\ Kathode \quad 2H_2O + 2e^- \rightarrow H_2 + 2OH^-$$

$$(+)\ Anode \quad 2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^-$$

- \+ Mature, well-proven technology
- \+ Easy to scale on stack level
- \+ No rare PGM metals needed
- \+ Lower CAPEX compared to PEM
- o Dynamic operation is feasible!
- – ~ Factor 3-4 lower power density, larger footprint compared to PEM
- – Slow cold start behaviour
- – Limited load range

Alkaline electrolysis – overview

The alkaline technology is (alongside PEM) a key pillar for the electrolysis market ramp-up



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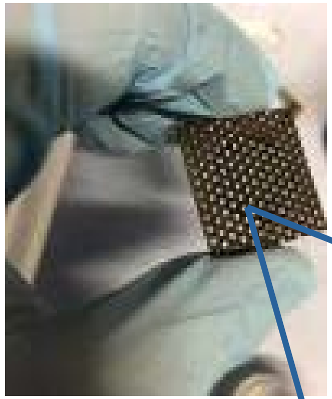
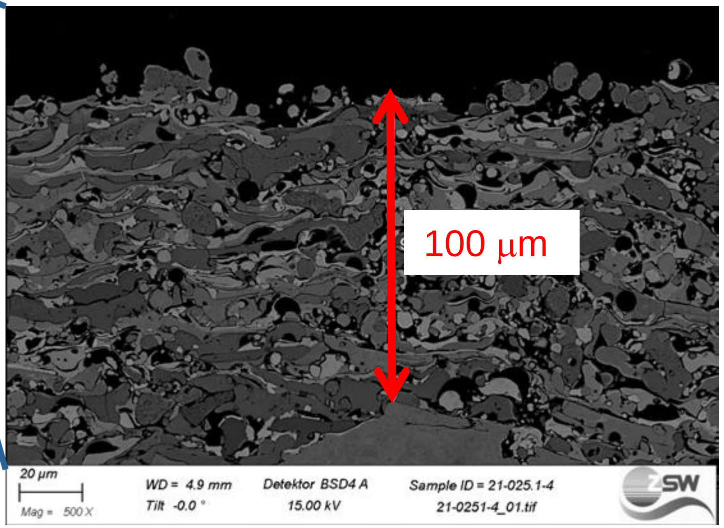
Alkaline Electroysis – cost effects of electrode coating

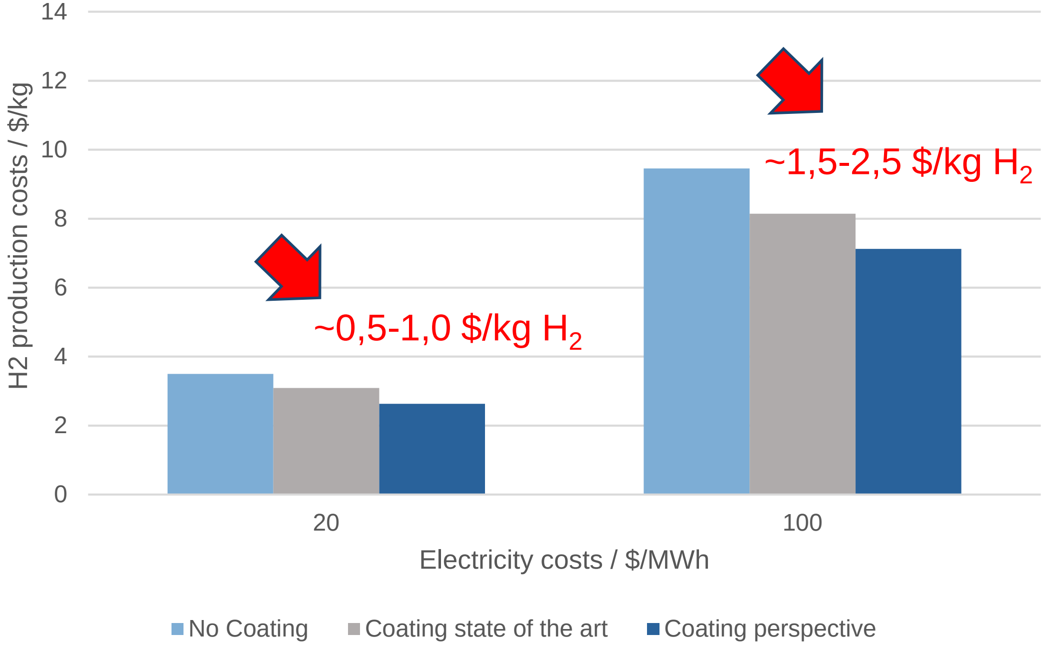
100 µm can make the difference!



Raney-Ni coating on Ni substrate



Example: 1 MW AEL 30 bar , 4000 h annual full load time

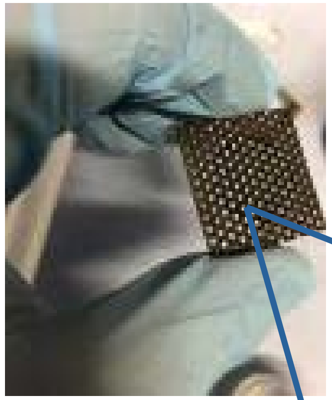


- No coating, plain Ni substrate
- Raney-Ni coating state of the art: 1,8 V @600 mA/cm² ~500-1000 $/m²
- Raney-Ni coating perspective: 1,8 V @1000 mA/cm² *, <100 $/m²

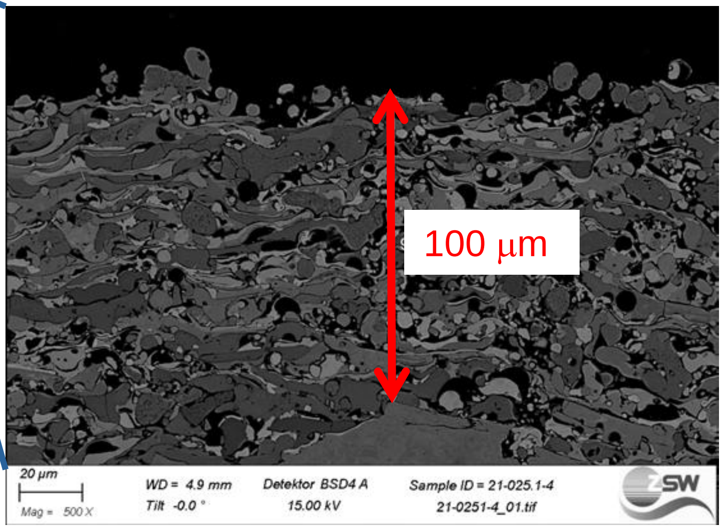
* Clean Hydrogen JU, 2022

Alkaline Electroysis – cost effects of electrode coating

100 µm can make the difference!



Raney-Ni coating on Ni substrate



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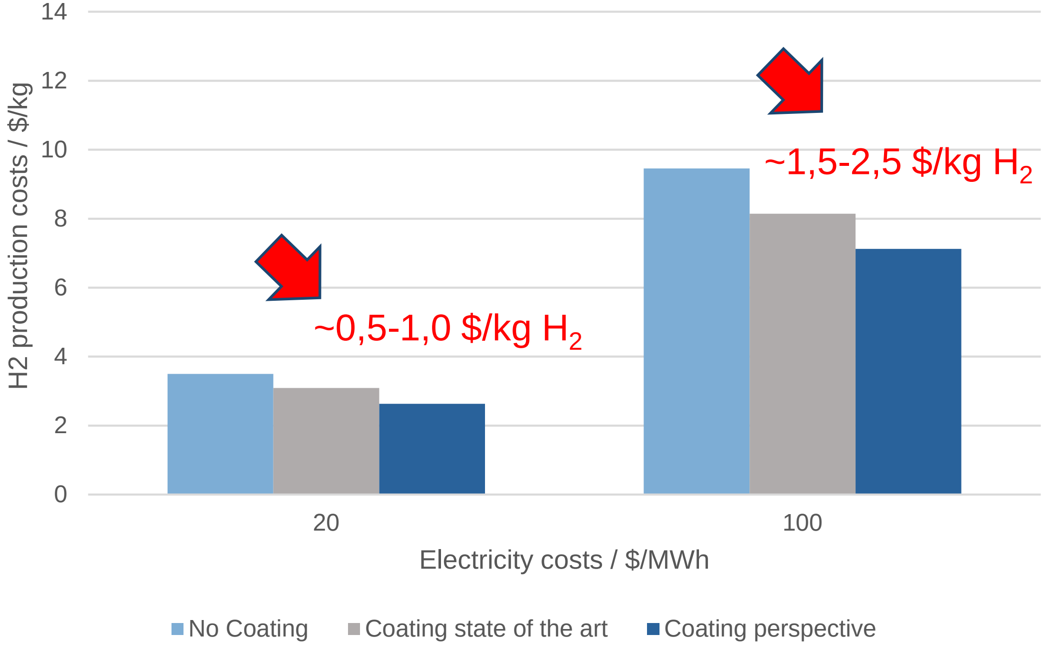


Positive cost effect regardless of the electricity costs:

- Plus ~2-4 % of CAPEX
- Minus ~15-25 % of H_2 production costs

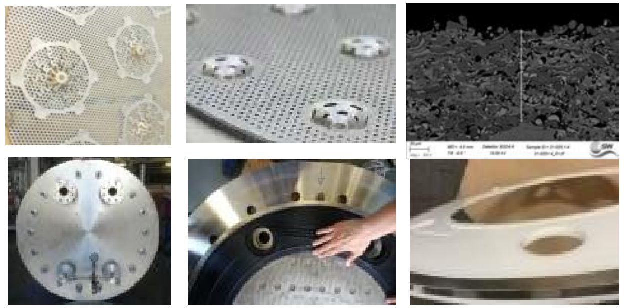
Alkaline Electrolysis – electrode coating market potentials

How many m² of electrode and coatings are we talking about?

- **1 $\mathbf{MW_{el}}$** electrolysis: example ZSW-technology, 30 $\text{bar}_{\ddot{u}}$
- 2 x 0,5 MW_{el} stack: In total ~240 cells with ~3,000 cm² cell area (state of the art)
  ~1,800 cm² cell area (perspective 2030)
- Electrode area per MW: In total **~150 m² cathode + anode area (state of the art)**
  ~90 m² cathode + anode area (perspective 2030)

Electrolysis system

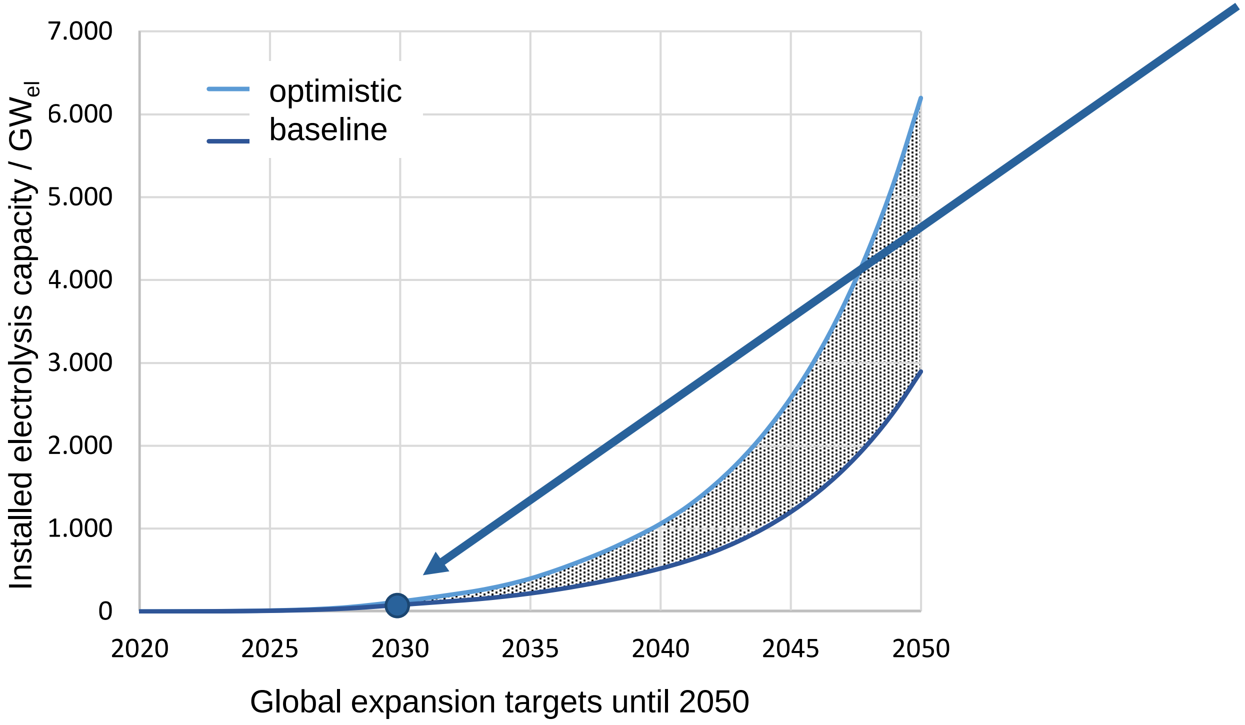
Electrolysis stack



stack components

Alkaline Electrolysis – electrode coating market potentials

Market and sales potentials of electrode coatings



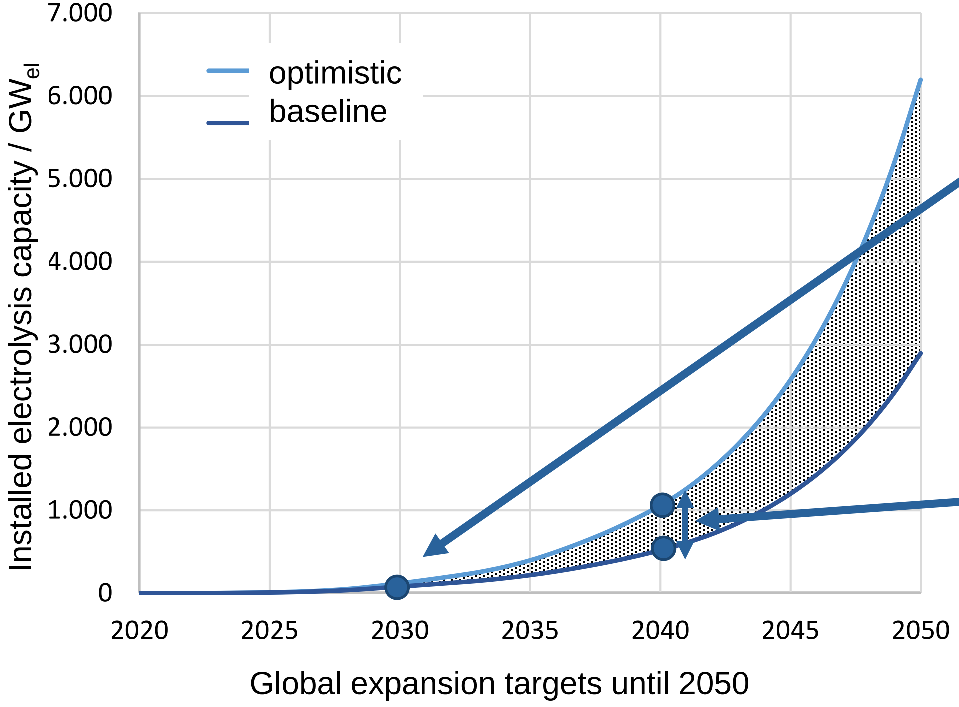
2030: ~100 GW

- with an AEL share of 40%
- ~ 3,6 Mio. m² of coatings (anode + cathode)
- @100 $/m^2_{coating}$ = ~360 Mio.$ in total

** Baseline development based on the Sustainable Development Scenario (SDS) of the IEA World Energy Outlook 2019. Optimistic development based on the evaluation of current scenarios taking into account the European Union's decision to be climate neutral by 2050.

Alkaline Electrolysis – electrode coating market potentials

Market and sales potentials of electrode coatings



2030: ~100 GW

- with an AEL share of 40%
- ~ 3,6 Mio. m² of coatings (anode + cathode)
- @100 $/m$^2_{coating}$ = ~360 Mio.$ in total

2040: ~500-1000 GW

- with an AEL share of 40%
- ~ 18-36 Mio. m² of coatings (anode + cathode)
- @50 $/m$^2_{coating}$ = ~900-1800 Mio.$ in total

** Baseline development based on the Sustainable Development Scenario (SDS) of the IEA World Energy Outlook 2019. Optimistic development based on the evaluation of current scenarios taking into account the European Union's decision to be climate neutral by 2050.

AGENDA

1 ZSW

2 Alkaline Electrolysis

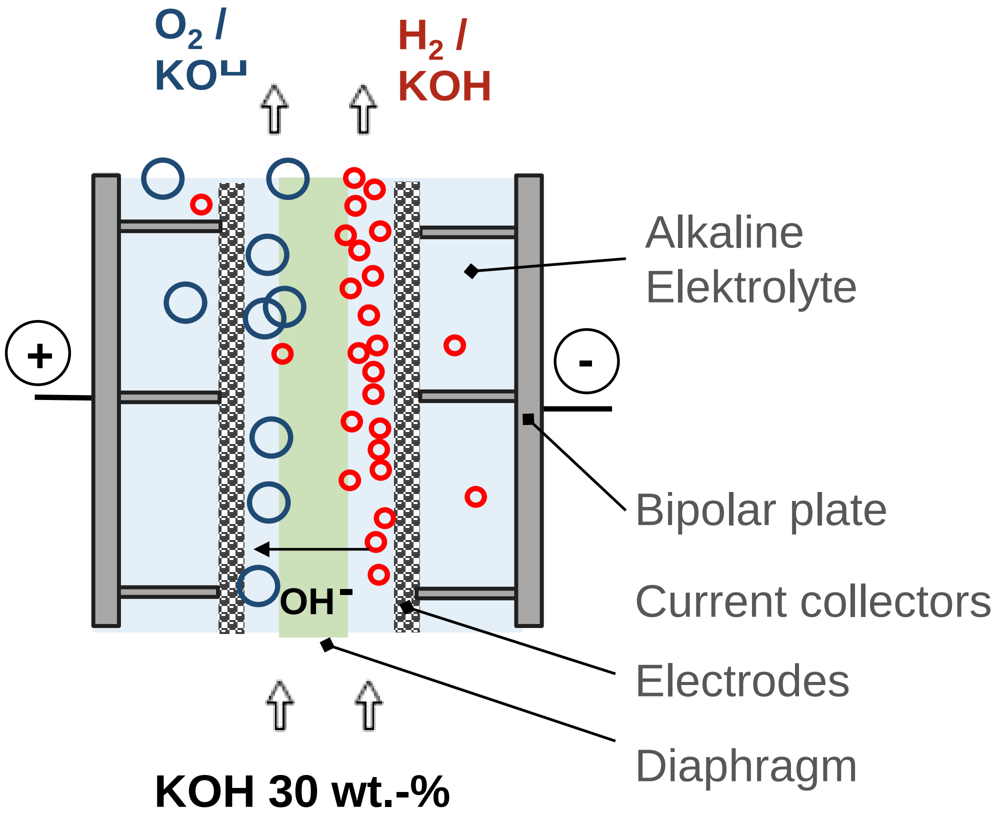
3 Electrode design and coating processes

4 From fundamental research to market-readiness

5 Summary

Electrodes

Electrode are core components and coating is core process in AEL electrolysis.

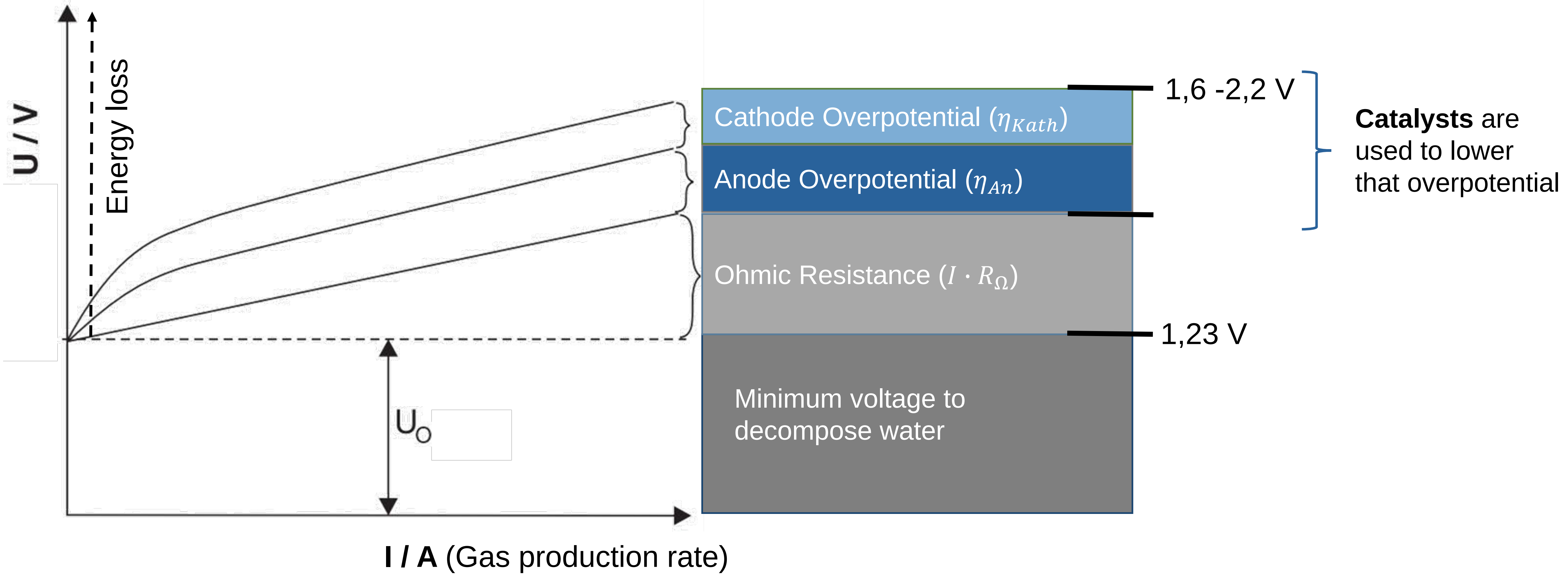


$$(-)\ Kathode\quad 2H_2O + 2e^- \rightarrow H_2 + 2OH^-$$

$$(+)\ Anode\quad 2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^-$$

Electrodes

Both the anode and cathode overpotentials have a major influence on stack efficiency.



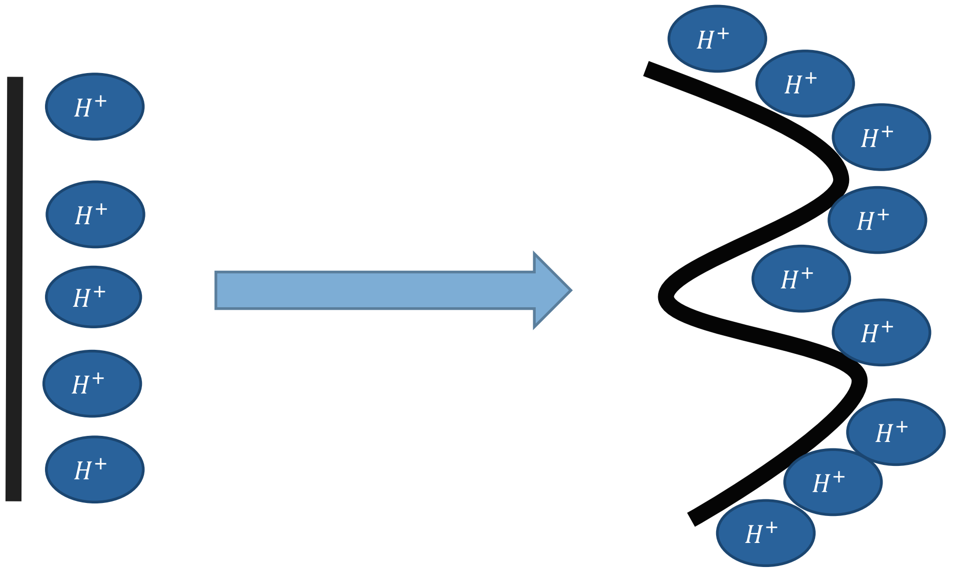
The cell efficiency strongly depends on the gas production rate !

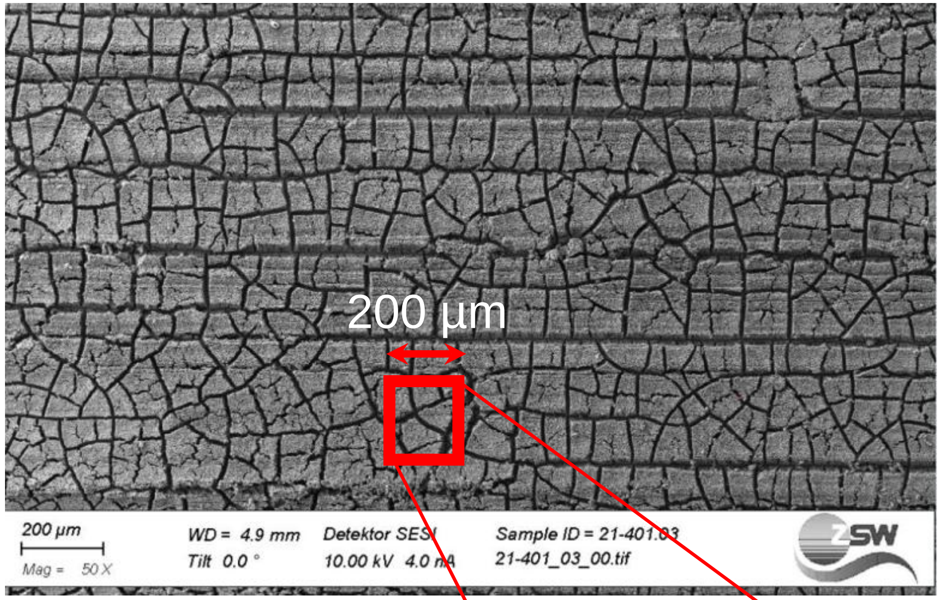
Electrode coatings

Basics and technical requirements

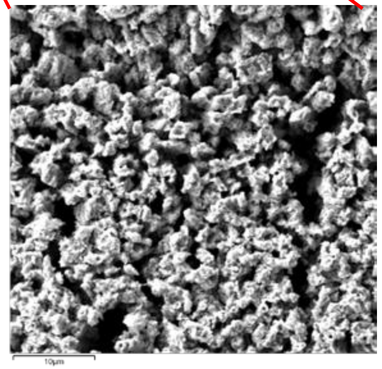
Plan surface

Cracked porous surface





High porous nickel surface



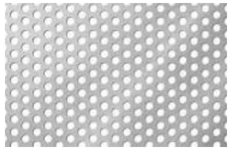
- High surface area = high catalytic activity
- Long term stability (standard life span is 10 years)
- Scalability (suitable for serial production / electrode area/ 2030 ~100GW 3.6 mio m²)
- Low manufacturing costs (perspective 100 $/m²)
- Avoidance of critical raw materials

Electrode coatings

Overview main substrates, catalysts and coating technologies

Substrates

Perforated plate

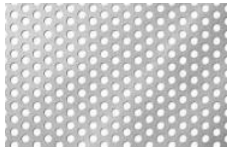


Expanded metal sheet

Metal foam

Electrode coatings

Overview main substrates, catalysts and coating technologies

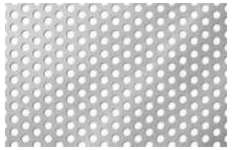
Substrates	*Coating composition*
Perforated plate  Expanded metal sheet  Metal foam 	**Nickel based catalyst coatings** Ni-Al / Ni-Al-Mo Ni-Zn / Ni-S/ Ni-Fe….. Noble metal based catalysts (Pt, IrO2/ RuO2) Mixed Oxides containing Ni and Co

Electrode coatings

Overview main substrates, catalysts and coating technologies

Substrates

Perforated plate



Expanded metal sheet

Metal foam

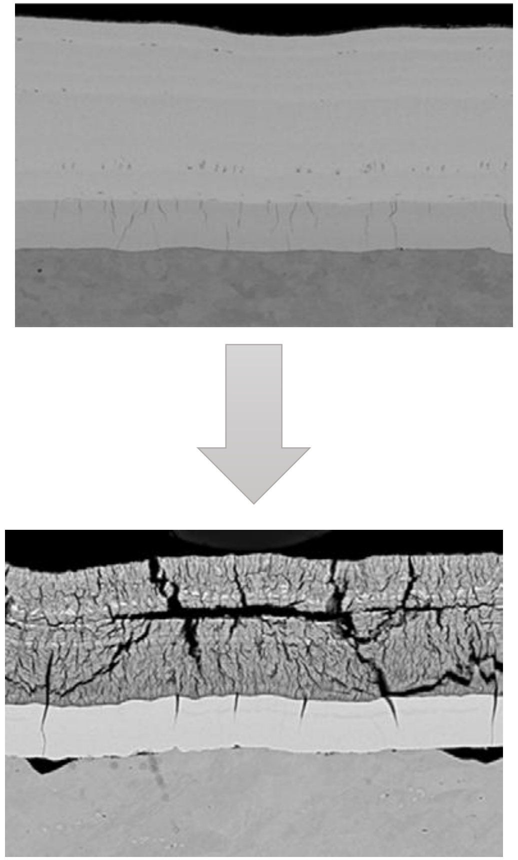
Coating composition

Nickel based catalyst coatings
Ni-Al / Ni-Al-Mo
Ni-Zn / Ni-S/ Ni-Fe…..

Noble metal based catalysts
(Pt, IrO2/ RuO2)

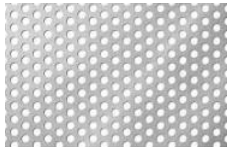
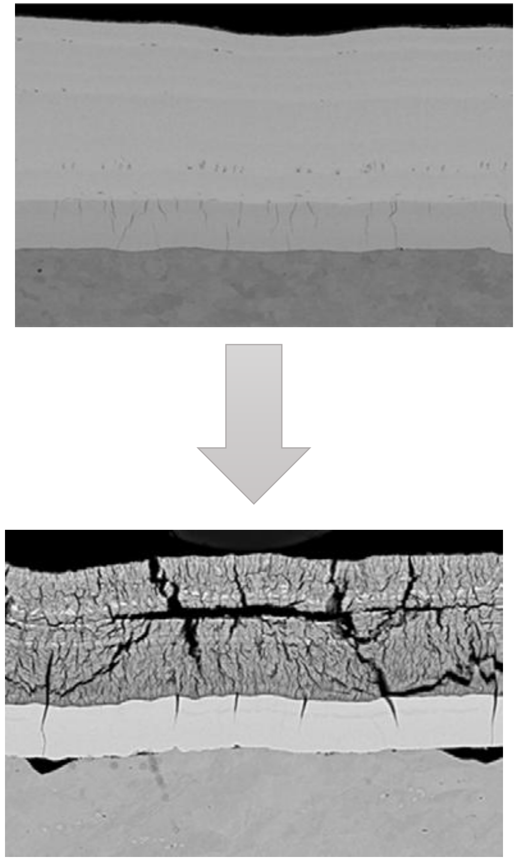
Mixed Oxides containing Ni and Co

Activation



Electrode coatings

Overview main substrates, catalysts and coating technologies

Substrates	*Coating composition*	*Activation*	*Preparation method*
Perforated plate  Expanded metal sheet  Metal foam 	**Nickel based catalyst coatings** Ni-Al / Ni-Al-Mo Ni-Zn / Ni-S/ Ni-Fe….. Noble metal based catalysts (Pt, IrO2/ RuO2) Mixed Oxides containing Ni and Co		Electrodeposition Thermal spraying Hot Pressing / Rolling Sand blasting Physical vapor deposition Hot dip galvanisation

Electrode coatings

Benchmark of coating technologies and their potential

Aspect	Electro-deposition
Maturity for AEL (TRL)	
Manufacturing costs	
Coating time	
Flexibility layer thickness	
Efficiency potential	
Flexibility coating area / geometry	
Flexibility coating composition	
Risk of substrate distortion	

\+ 0 -

Electrode coatings

Benchmark of coating technologies and their potential

Aspect	Electro-deposition	Thermal Spraying (APS)
Maturity for AEL (TRL)	+	+
Manufacturing costs	o	o
Coating time	-	o
Flexibility layer thickness	+	+
Efficiency potential	+	+
Flexibility coating area / geometry	+	o
Flexibility coating composition	+	+
Risk of substrate distortion	+	-

+ o -

Electrode coatings

Benchmark of coating technologies and their potential

Aspect	Electro-deposition	Thermal Spraying (APS)	Hot Pressing /Rolling
Maturity <u>for AEL </u>(TRL)	🟢	🟢	🟢
Manufacturing costs	⚪	⚪	⚪
Coating time	🟡	⚪	🟡
Flexibility layer thickness	🟢	🟢	🟢
Efficiency potential	🟢	🟢	🟢
Flexibility coating area / geometry	🟢	⚪	🟡
Flexibility coating composition	🟢	🟢	🟢
Risk of substrate distortion	🟢	🟡	🟢

\+ o -

Electrode coatings

Benchmark of coating technologies and their potential

Aspect	Electro-deposition	Thermal Spraying (APS)	Hot Pressing /Rolling	(Sand blasting)
Maturity for AEL (TRL)	🟢	🟢	🟢	🟢
Manufacturing costs	⚪	⚪	⚪	🟢
Coating time	🟡	⚪	🟡	🟢
Flexibility layer thickness	🟢	🟢	🟢	🟡
Efficiency potential	🟢	🟢	🟢	🟡
Flexibility coating area / geometry	🟢	⚪	🟡	🟢
Flexibility coating composition	🟢	🟢	🟢	🟡
Risk of substrate distortion	🟢	🟡	🟢	⚪

+ o -

Electrode coatings

Benchmark of coating technologies and their potential

Aspect	Electro-deposition	Thermal Spraying (APS)	Hot Pressing /Rolling	(Sand blasting)	PVD
Maturity <u>for AEL </u>(TRL)	+	+	+	+	+
Manufacturing costs	o	o	o	+	o
Coating time	-	o	-	+	-
Flexibility layer thickness	+	+	+	-	-
Efficiency potential	+	+	+	-	+
Flexibility coating area / geometry	+	o	-	+	o
Flexibility coating composition	+	+	+	-	+
Risk of substrate distortion	+	-	+	o	-

+ o -

Electrode coatings

Benchmark of coating technologies and their potential

Aspect	Electro-deposition	Thermal Spraying (APS)	Hot Pressing /Rolling	(Sand blasting)	PVD	Hot Dip Galvanization
Maturity for AEL (TRL)	🟢	🟢	🟢	🟢	🟢	⚪
Manufacturing costs	⚪	⚪	⚪	🟢	⚪	🟢
Coating time	🟡	⚪	🟡	🟢	🟡	⚪
Flexibility layer thickness	🟢	🟢	🟢	🟡	🟡	🟡
Efficiency potential	🟢	🟢	🟢	🟡	🟢	⚪
Flexibility coating area / geometry	🟢	⚪	🟡	🟢	⚪	🟢
Flexibility coating composition	🟢	🟢	🟢	🟡	🟢	🟡
Risk of substrate distortion	🟢	🟡	🟢	⚪	🟡	🟡

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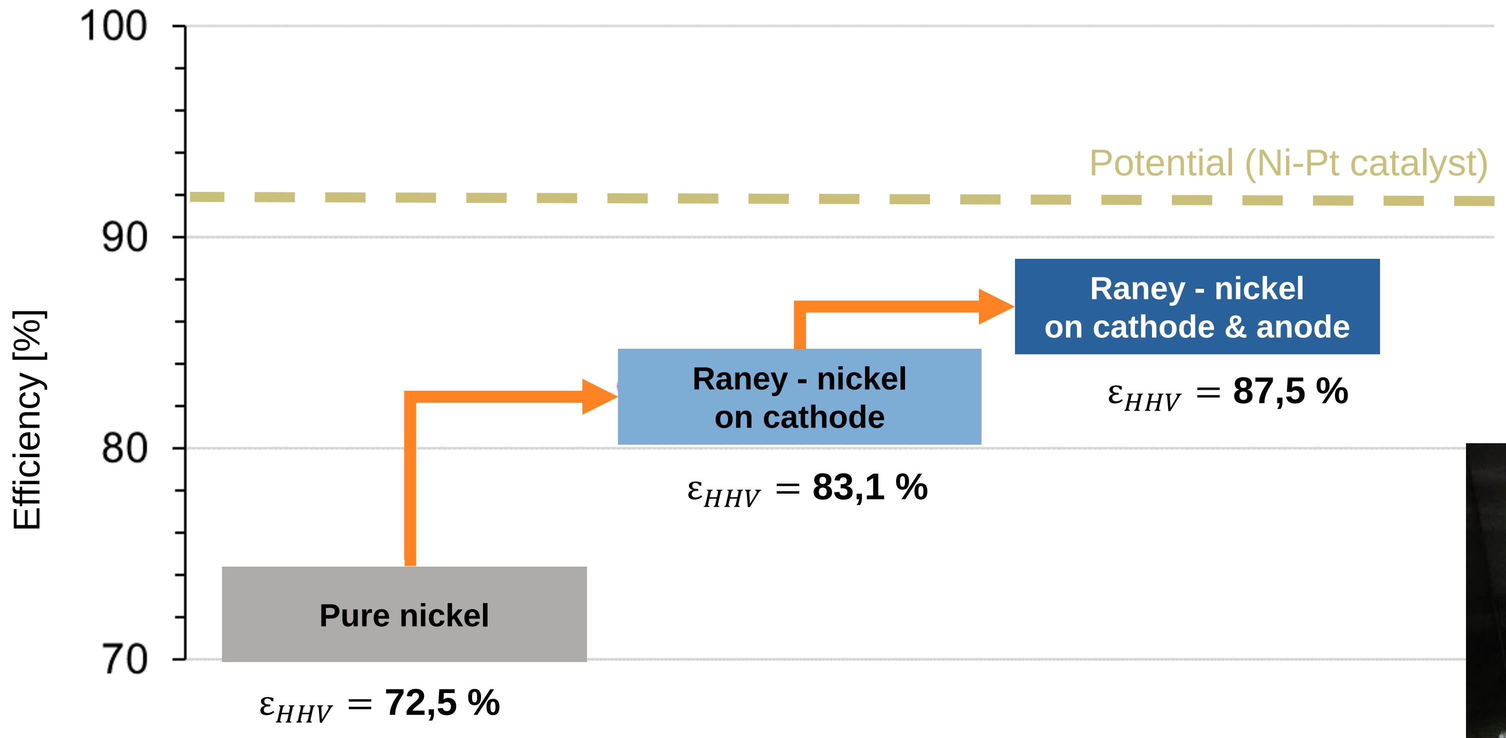
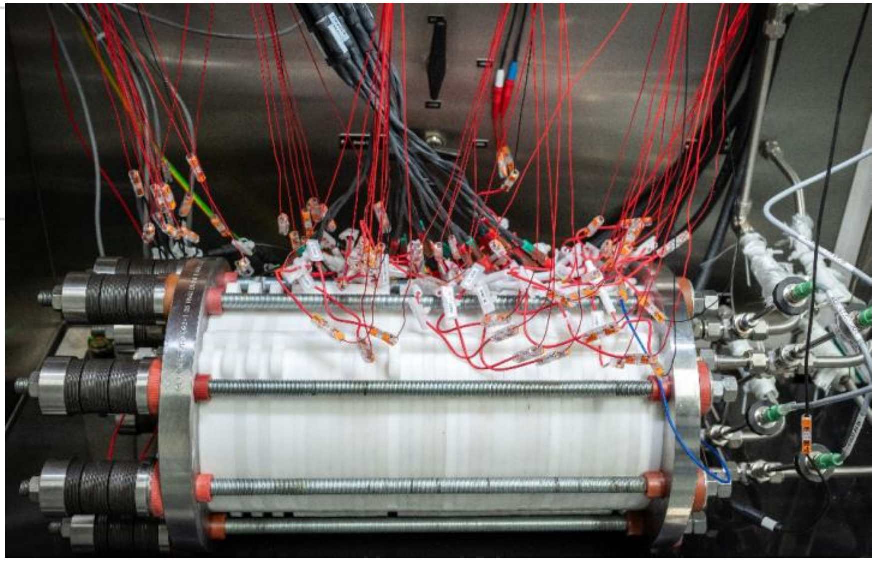
Electrode coatings

Coatings can improve the efficiency significantly





Cell voltage was measured from electrode to electrode in a zero gap design with Zirfon UTP 500 diaphragm at 70°C /10 barg and 400 mA/cm² to reduce the effect of ohmic overpotentials.

AGENDA

From fundamental research to market-readiness

A variety of analytical steps and testing are required from material analysis to megawatt stacks.

Electrode characterisation and material analysis

Prevalidation cell components (up to 30 bar, 100 cm², 1-10 kW)

Short and full stack testing (up to 30 bar, up to 40.000 cm², up to 0,5 MW)

Relevant for developers:
Galvanostatic, CV, LSV, EIS

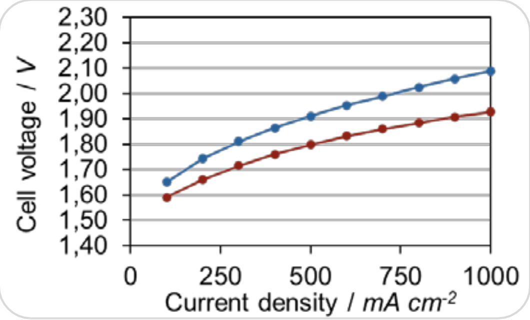
Relevant for industrial application:
Galvanostatic, (EIS)

Material analytics: SEM, EDX, XRD, ...

From fundamental research to market-readiness

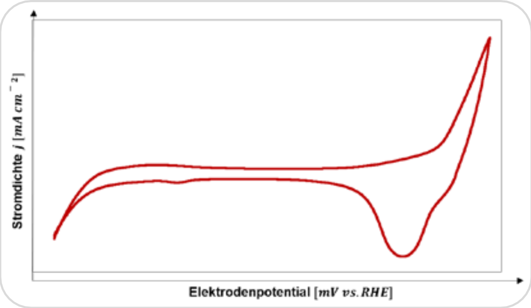
Of the different kinds of analytics, galvanostatic measurements are most relevant for end users.

What is happening? | **Why** does it happen?



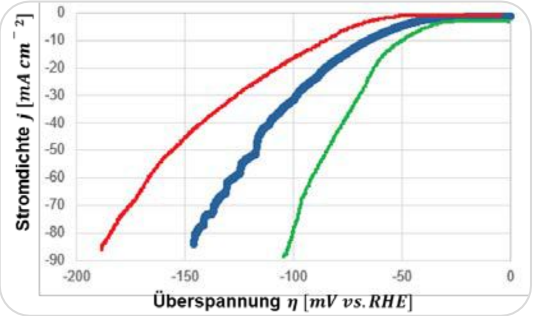
Galvanostatic

- Small, medium & large scale
- Relevant in all phases of development and operation
- Overpotential
- Cell voltage
- Polarisation curve (Ui)
- Degradation rate



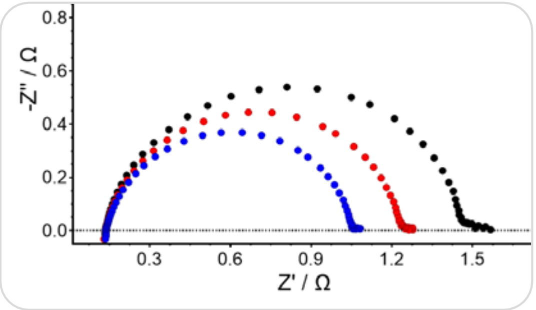
CV

- Small scale
- Relevant for development
- Change in surface area (Cdl, ECSA)
- Critical potentials for the electrode (oxidation and reduction peaks)



LSV

- Small scale
- Relevant for development
- Change in kinetics (exchange current density, tafel slope)
- Limits of reaction cycle:
  - Rate determinant step



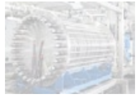
EIS

- Small & medium scale
  Large scale in development
- Relevant for development
- Change in surface area (Cdl, ECSA)
- Change in kinetics (exchange current density, tafel slope)
- Limits of reaction cycle:
  - Rate determinant step
  - Limits by diffusion

From fundamental research to market-readiness

Electrode characterisation & material analysis

- Catalytic activity of anodes/cathodes
- Combination of catalyst and electrode substrate
- Layer adhesion
- Material characteristics
- Determination of stressors
- Degradation behavior, AST protocols



Electrode characterisation and material analysis

Prevalidation cell components (up to 30 bar, 100 cm², 1-10 kW)

Short and full stack testing (up to 30 bar, up to 40.000 cm², up to 0,5 MW)

From fundamental research to market-readiness

Pre-validation cell components (up to 30 bar, 100 cm², up to 10 kW)

- Cell behaviour anode/membrane/cathode in application orientated operation
- In relation to temperature, pressure, volume flow
- Internal cell resistances (eg. EIS)
- Response towards different operating profiles (eg. Rapid ramp up)

Electrode characterisation and material analysis

Prevalidation cell components (up to 30 bar, 100 cm², 1-10 kW)

Short and full stack testing (up to 30 bar, up to 40.000 cm², up to 0,5 MW)

From fundamental research to market-readiness

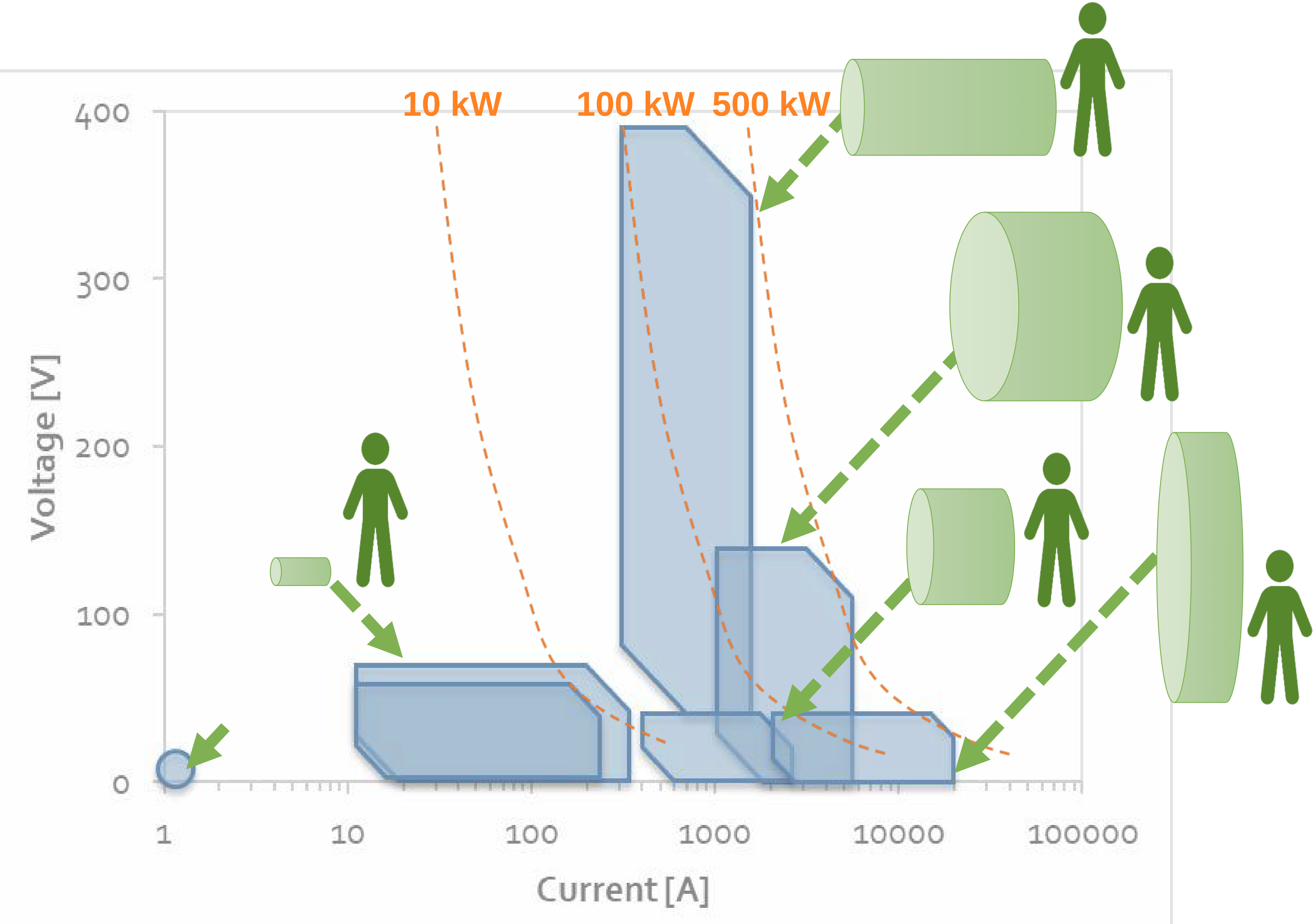
Short- and Fullstacktesting (up to 30 bar, up to 20.000 A, 0,5 MW)

- Influence of design details of electrode/cell packages and stack design in industrial scale
- Validation of pressure tightness, gas purity & stack efficiency

Electrode characterisation and material analysis

Prevalidation cell components (up to 30 bar, 100 cm², 1-10 kW)

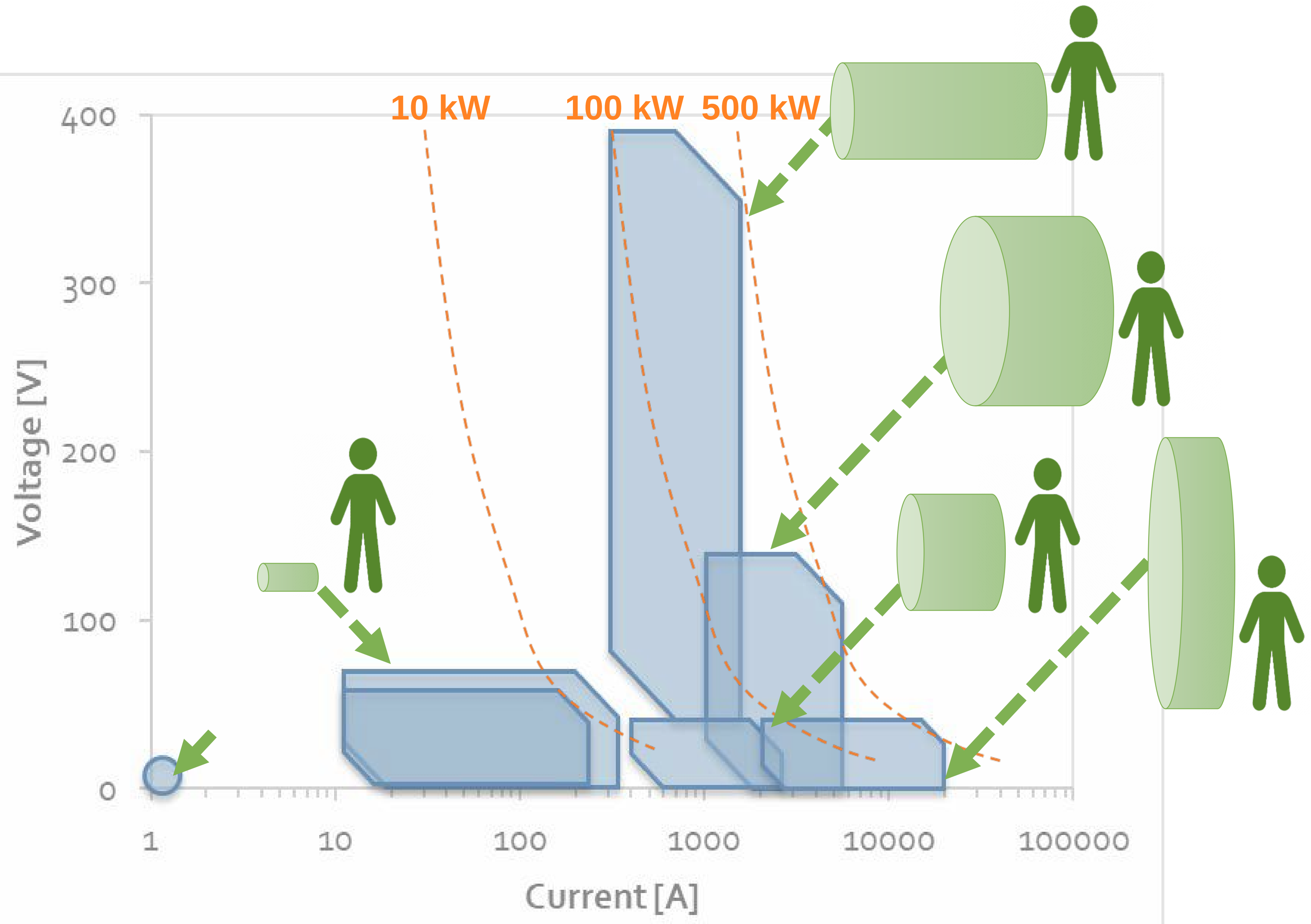
Short and full stack testing (up to 30 bar, up to 40.000 cm², up to 0,5 MW)



10 kW
100 kW
500 kW
400
300
200
100
0
Voltage [V]
1
10
100
1000
10000
100000
Current [A]

ElyLab test field at
ZSW Stuttgart:

- 10 test rigs of different sizes (…and growing)
- All kinds of analytics to characterize electrodes
- Experienced scientists running the tests
- Development of testing methods and test protocols (e.g. AST-protocols)



ZSW proposal for
for electrode/catalyst validation:

- ~ 100 cm² active area
- Stack design allowing single cell voltage measurement (on anode, cathode & BPP)
- Standardized test protocols oriented on JRC guidelines:
    - 2-week test, focus on performance (see table):
        - 1st week performance
        - 2nd week load cycles
    - Longer tests for durability analysis:
        - x-thousands hours
        - High current

Day	Subject of assessment	Description	Parameters & parameter variations
1	Performance	conditioning & reference conditions	
2		EIS	[redacted]
3		temperature variation	[redacted]
4		pressure variation	[redacted]
5		electrolyte flow variation	[redacted]
6		reference conditions	
7		reference conditions	
8		EIS	[redacted]
9	Load cycles	3 cycles (reference, load, shut off)	[redacted]
10		3 cycles (reference, load, shut off)	[redacted]
11		3 cycles (reference, load, shut off)	[redacted]
12		3 cycles (reference, load, shut off)	[redacted]
13		3 cycles (reference, load, shut off)	[redacted]
14		3 cycles (reference, load, shut off)	[redacted]
15	Performance	EIS & reference conditions	[redacted]

AGENDA

Summary

Electrode coatings in alkaline electrolysis significantly increase efficiency and reduce hydrogen costs.

Hydrogen production costs can be reduced by ~20% regardless of the electricity procurement costs.

Assuming a market share of 40% for alkaline electrolysis, the sales potential 2030 for electrode coatings is approx. 360 Mio.$.

There are a large numbers of coating processes with varying degrees of technological maturity and specific advantages and disadvantages and development needs.

ZSW has a test field and a variety of qualification methods for validating electrode substrates & coatings along all development stages.

MANY THANKS FOR YOUR INTEREST.

Marc-Simon Löffler marc-simon.loeffler@zsw-bw.de

Verena Kindl verena.kindl@zsw-bw.de

Philipp Spieth philipp.spieth@zsw-bw.de

Thomas Ottitsch thomas.ottitsch@zsw-bw.de