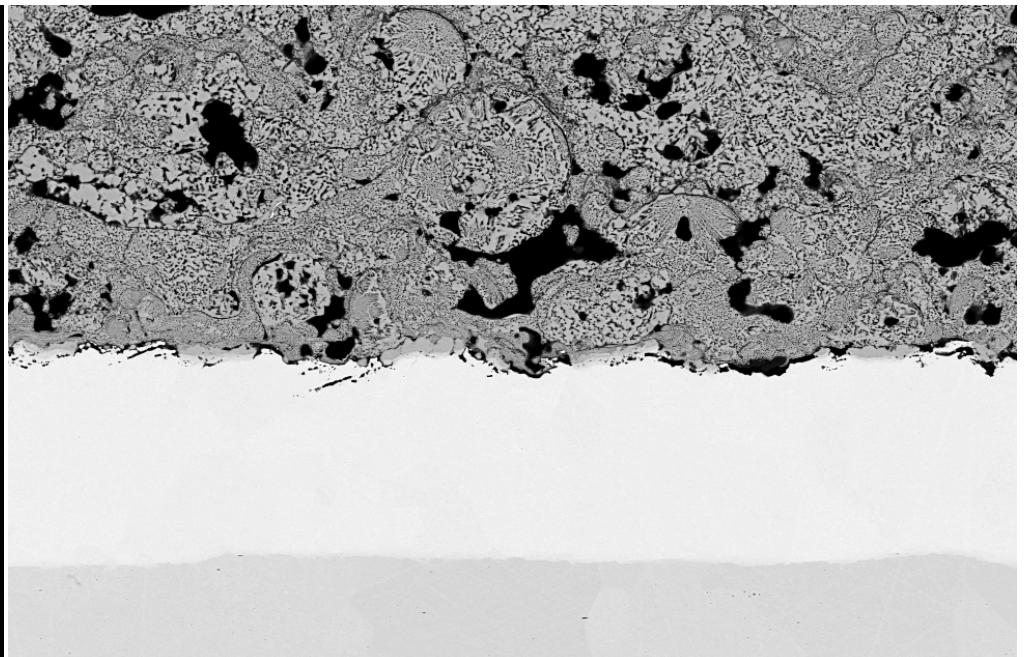
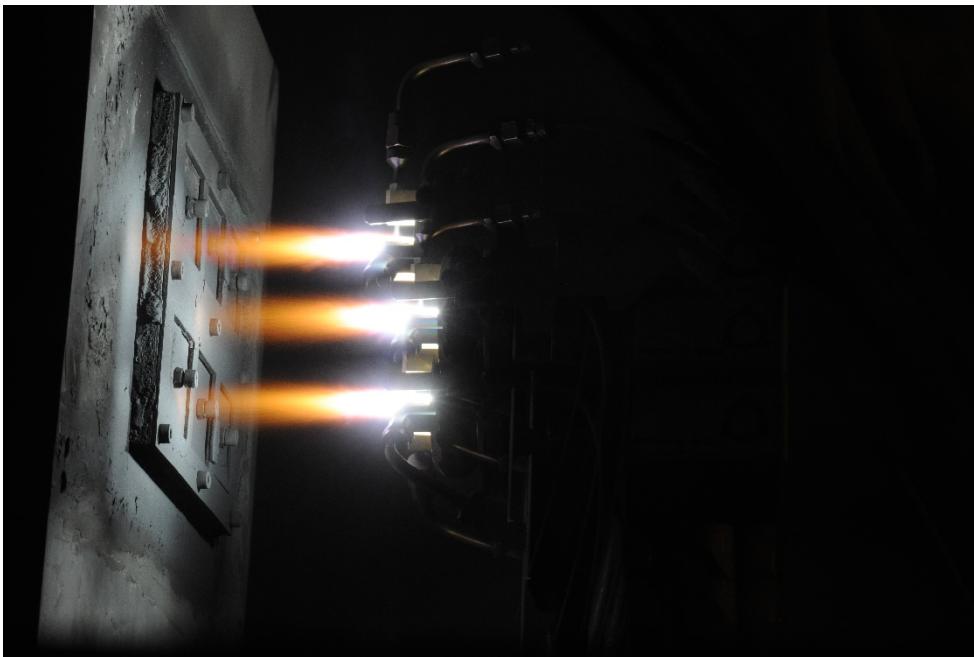


# „Elektrolyse made in Baden-Württemberg“ Innovationen für den Elektrolyseblock



## Free-standing Raney-Nickel Electrodes by Plasma Spraying

Asif Ansar, Fatemeh (Sanaz) Razmjooei



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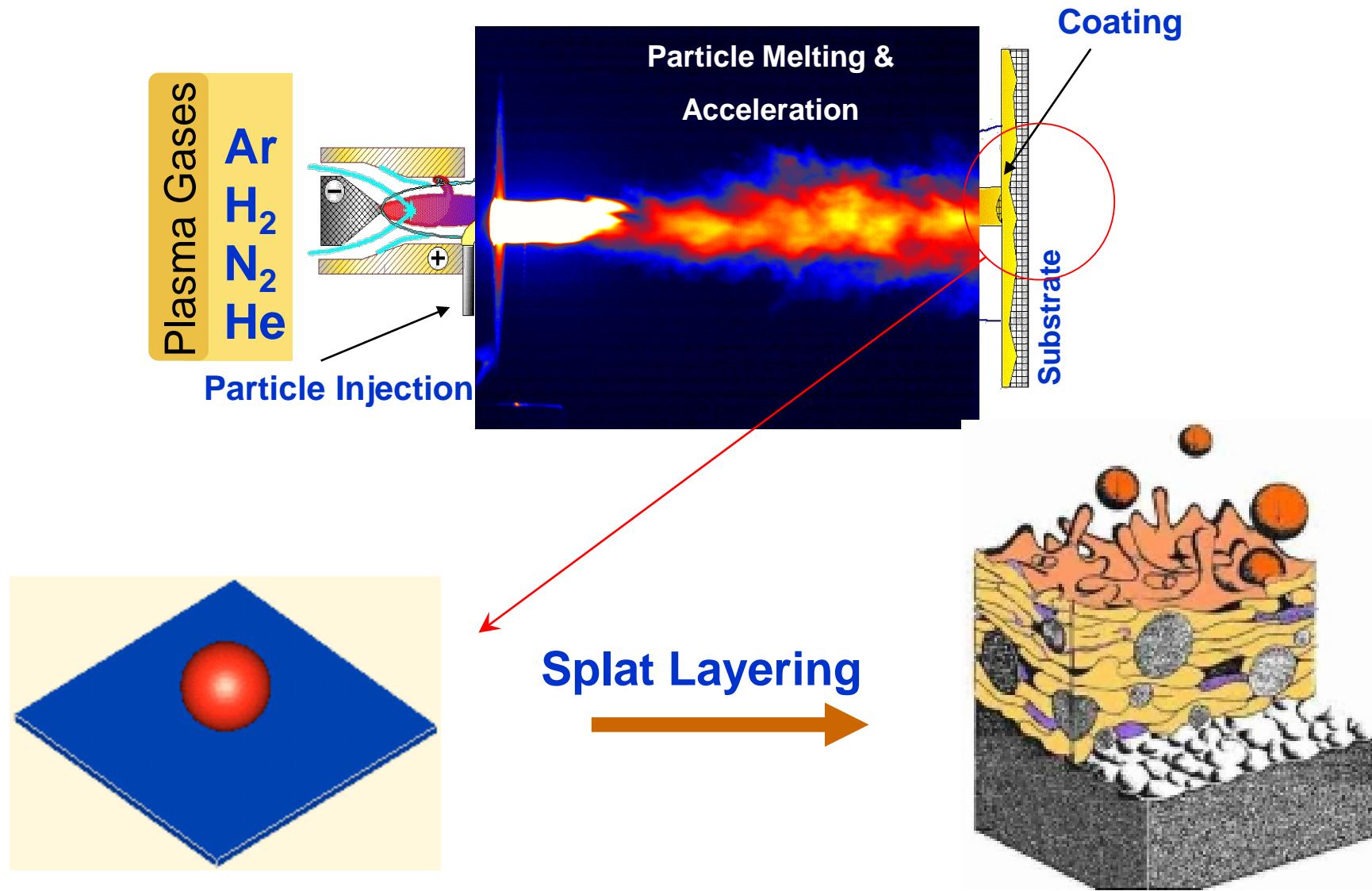
Hahn  
Schickard

DLR

DIFF  
DEUTSCHE INSTITUTE FÜR  
TEXTIL+FASEFFORSCHUNG

ZSW

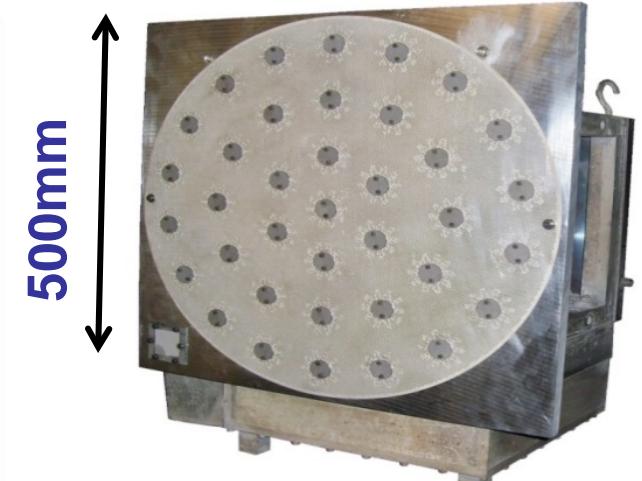
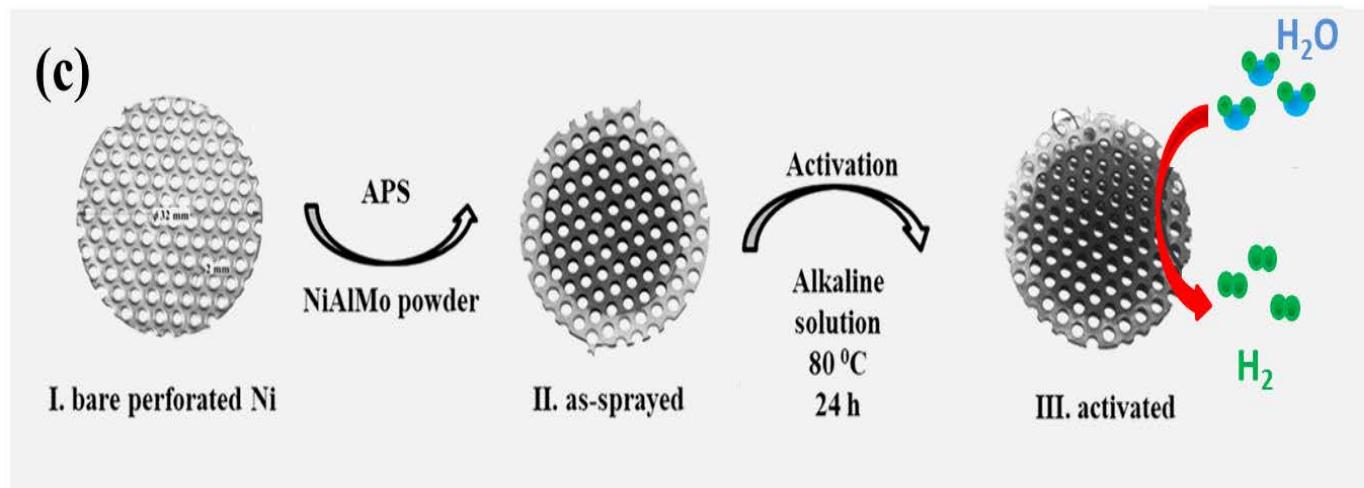
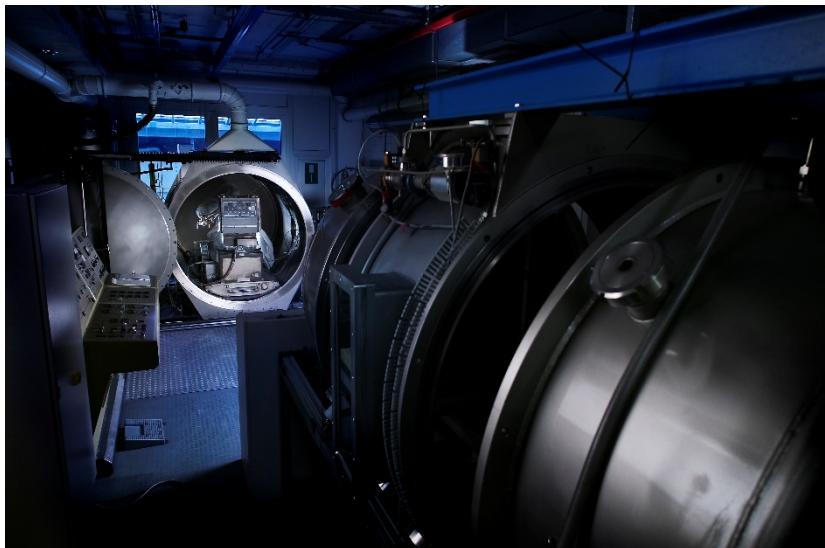
# Plasma Spray: Working Principle



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# Plasma Spray: DLR Equipment and Electrodes Fabrication



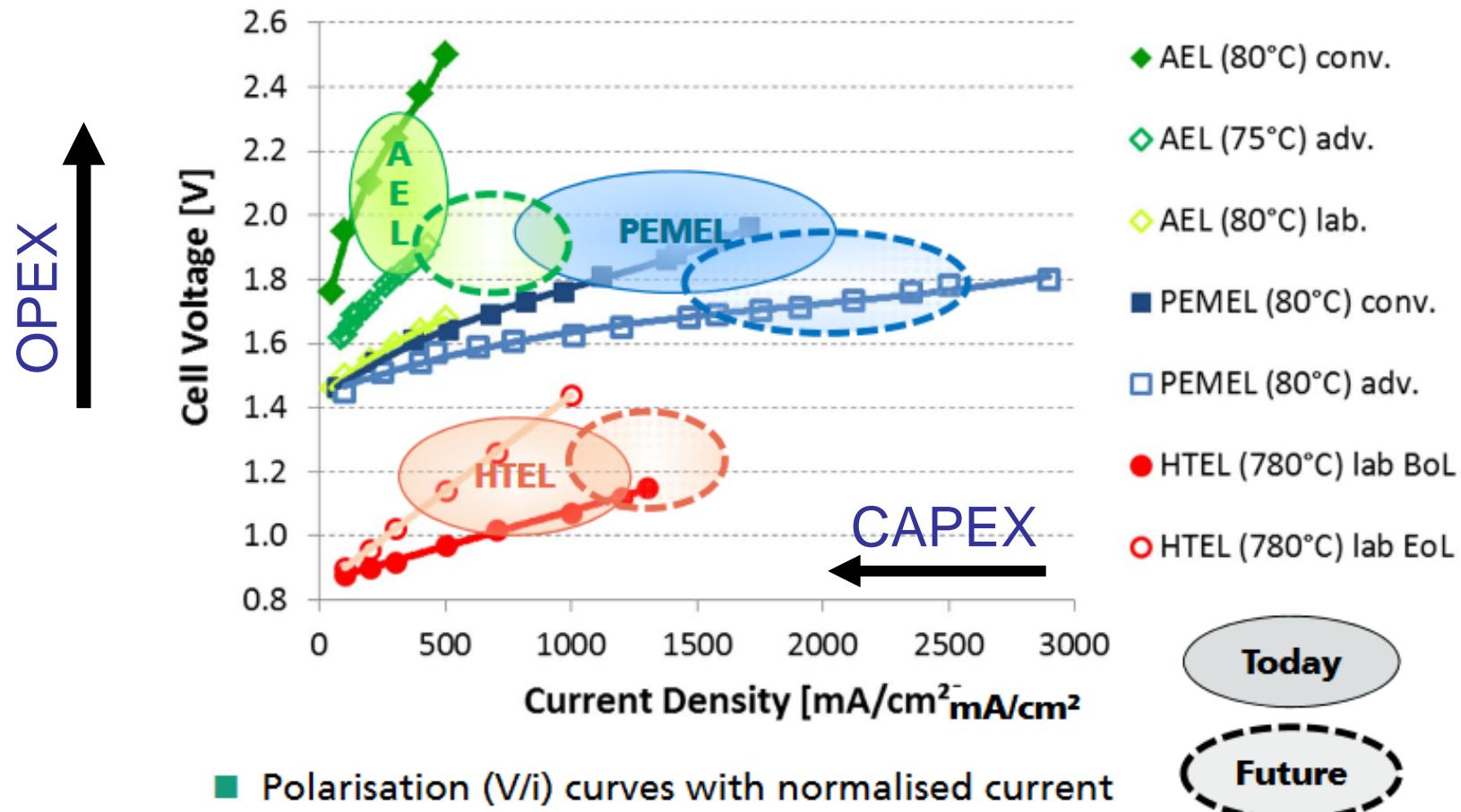
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# Comparison of different Electrolysers

## (1) Performance and Efficiency of Water Electrolysis

Comparison of different EL technologies at stack level.



Source:

<http://www.fch.europa.eu/sites/default/files/2%20Water%20Electrolysis%20Status%20and%20Potential%20for%20Development.pdf>



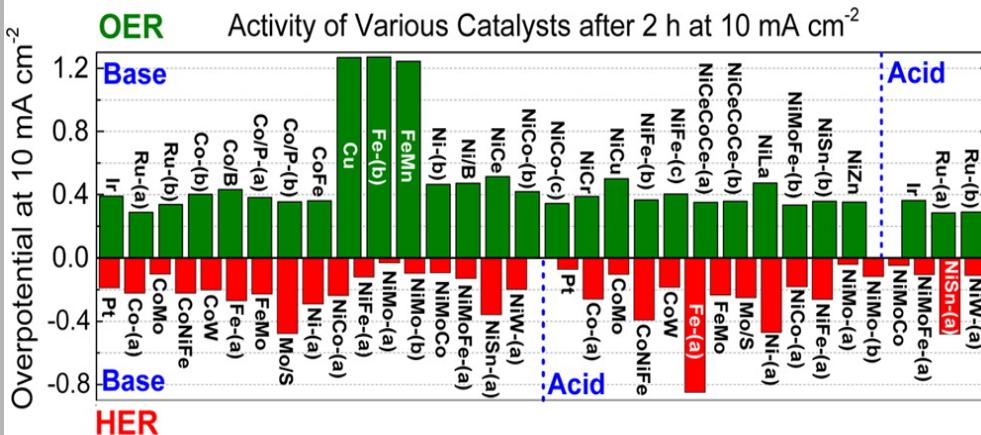
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# Catalyst benchmark for AWE

	Best known catalyst	Best non-noble metal catalyst
HER	Pt	Ni / NiMo
OER	Ir / Ru	Ni / NiFe / NiCo



C.C.L. McCrory, S. Jung, I.M. Ferrer, S.M. Chatman, J.C. Peters,  
T.F. Jaramillo, Journal of the American Chemical Society, 137  
(2015) 4347-4357

Electrode	Performance	Conditions	References
Pt/C	$0.6 \text{ mA cm}^{-2}$ exchange current density	0.1 M KOH, thin film	Ref 31
Polished Ni	422 mV overpotential at $75 \text{ A cm}^{-2}$	0.5 M KOH, SCE, $3.14 \text{ mm}^2$ disk electrode	Ref 60
Co/C	$1.1 \times 10^{-2} \text{ mA cm}^{-2}$ exchange current	0.1 M NaOH w/o ME nanoflakes	Ref 34
Ni <sub>1</sub> Co <sub>9</sub> /C	$9.1 \times 10^{-3} \text{ mA cm}^{-2}$ exchange current	0.1 M NaOH w/o ME nanoflakes	Ref 34
Raney Ni	100 mV overpotential at $500 \text{ mA cm}^{-2}$	28 wt% KOH, 80°C	Ref 47
Ni-Cr Raney	80 mV overpotential at $500 \text{ mA cm}^{-2}$	28 wt% KOH, 80°C	Ref 47
Ni <sub>64</sub> W <sub>36</sub>	$1.6 \times 10^{-6} \text{ mA cm}^{-2}$ exchange current density	0.1 M NaOH	Ref 51
MmNi <sub>3.3</sub> Co <sub>0.75</sub> Mn <sub>0.4</sub> Al <sub>0.27</sub>	88 mV overpotential at $200 \text{ mA cm}^{-2}$	Ni foam substrate and Ni–Mo coating, 30 wt% KOH	Ref 54
LaNi <sub>4.9</sub> Si <sub>0.1</sub>	84 mV overpotential at $200 \text{ mA cm}^{-2}$	Ni foam substrate and Ni–Mo coating, 30 wt% KOH	Ref 54
Ti <sub>2</sub> Ni	60 mV overpotential at $200 \text{ mA cm}^{-2}$	Ni foam substrate and Ni–Mo coating, 30 wt% KOH	Refs 12 and 54
Ni <sub>60</sub> Mo <sub>40</sub>	$29 \text{ mA cm}^{-2}$ 59 mV overpotential at $250 \text{ mA cm}^{-2}$	30 wt% KOH, 70°C, nanocrystalline fcc, mechanical alloyed	Ref 62
Ni-S	$39.2 \text{ mA cm}^{-2}$ 90 mV overpotential at $150 \text{ mA cm}^{-2}$	28 wt% NaOH, electrodeposited, thiourea	Ref 40
Fe-Mo	$20.4 \times 10^3 \text{ mA cm}^{-2}$	Fe(20%)–Mo(60%), 1 M NaOH, 25°C	Ref 57
Ni-(Ebonex-Ru)	$597 \text{ mA cm}^{-2}$ 156 mV at $100 \text{ mA cm}^{-2}$	Ni-Ti <sub>4</sub> O <sub>7</sub> -Ru, 1 M NaOH at 25°C	Ref 63
Pd/Au	NA	Pd/Au(111)	Ref 56
Ni-Sn	NA	Alloy coating deposited on Ni mesh	Ref 64
Ni-S-Co	70 mV at $150 \text{ mA cm}^{-2}$	80°C, electrodeposition	Ref 41
Ni <sub>3</sub> Al	$1.9 \text{ mA cm}^{-2}$	6 M KOH	Ref 36
Ni <sub>3</sub> Al-Mo	$13 \text{ mA cm}^{-2}$	6 M KOH	Ref 37
Ni-S-Mn	$97.5 \text{ mA cm}^{-2}$	30% KOH, amorphous alloy	Ref 43
Ni <sub>81</sub> P <sub>16</sub> C <sub>3</sub>	$2.11 \text{ mA cm}^{-2}$ 125.4 mV at $250 \text{ mA cm}^{-2}$	1 M NaOH, 25°C	Ref 39
Ni <sub>62</sub> Fe <sub>35</sub> C <sub>3</sub>	$24.5 \text{ mA cm}^{-2}$ 112.6 mV at $250 \text{ mA cm}^{-2}$	1 M NaOH, 25°C	Ref 65
Ni-Co	$29 \text{ mA cm}^{-2}$	0.5 M NaOH, 25°C, electrodeposited	Ref 66
Fe <sub>94</sub> P <sub>4</sub> Ce <sub>2</sub>	$0.075 \text{ mA cm}^{-2}$	1 M NaOH, 25°C	Ref 45

Bodner et al., WIREs Energy Environ 2014, doi: 10.1002/wene.150



# Selected Catalyst

Raney Ni

100 mV overpotential at  $500 \text{ mA cm}^{-2}$

28 wt% KOH, 80°C

Ni<sub>3</sub>Al–Mo

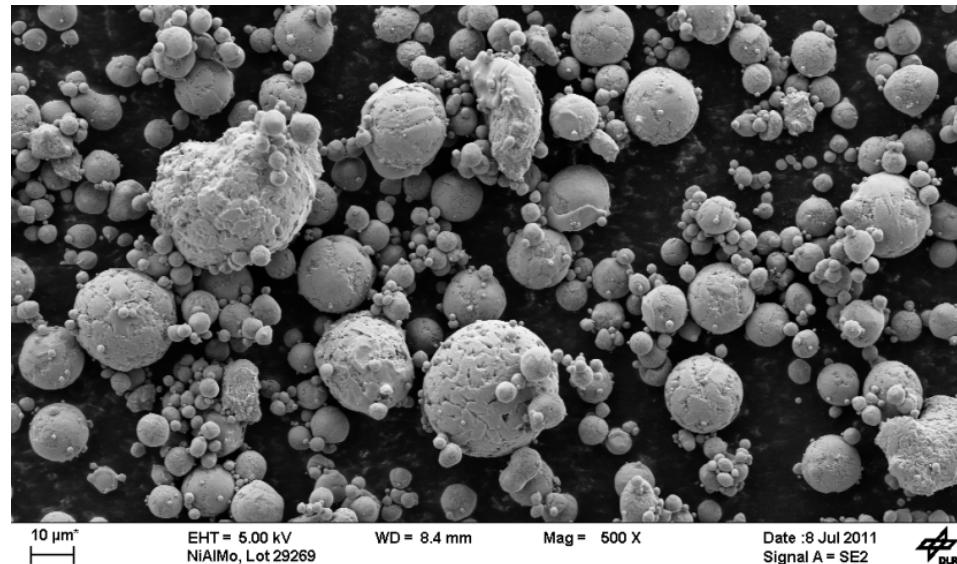
13 mA cm<sup>-2</sup>

6 M KOH



HER  
NiAlMo alloy

OER  
NiAl alloy

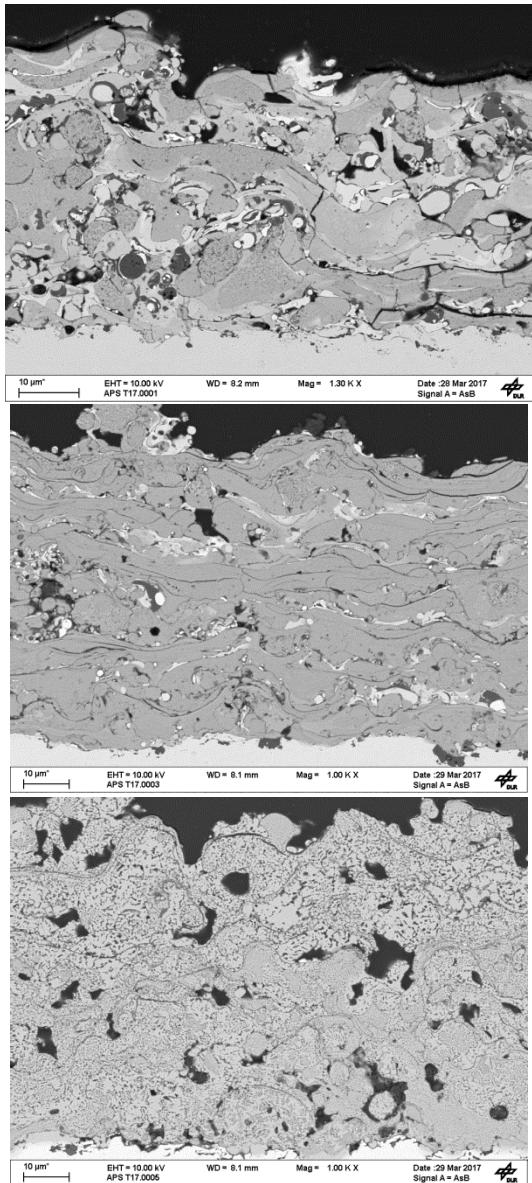


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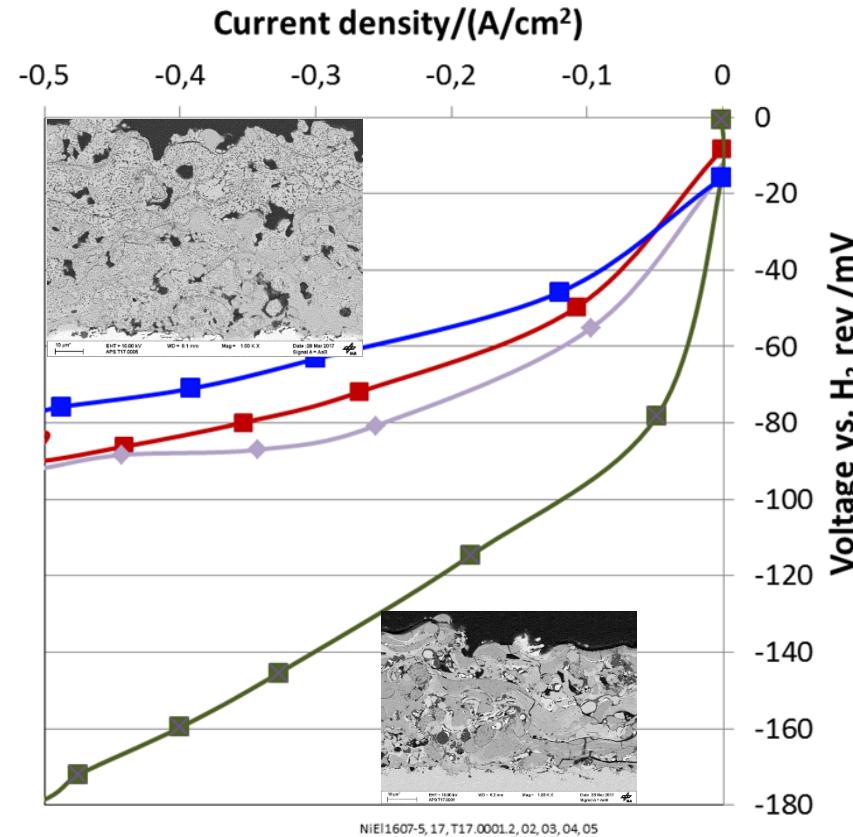
# Process Optimization



Plasma enthalpy

NiAlMo coating with  
different particle enthalpy

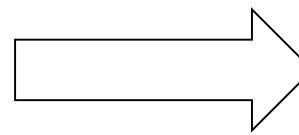
**NiAlMo on Nickel-plated punched hole sheet IR-corrected  
after 20 h cathodic operation**



# Performance Test with DLR Electrodes – continuous improvement

2017

1,8V @ 0.6 A/cm<sup>2</sup> with Zirfon



2019

1,8V @ 0.72 A/cm<sup>2</sup> with Zirfon

6M KOH, 80°C, Zirfon

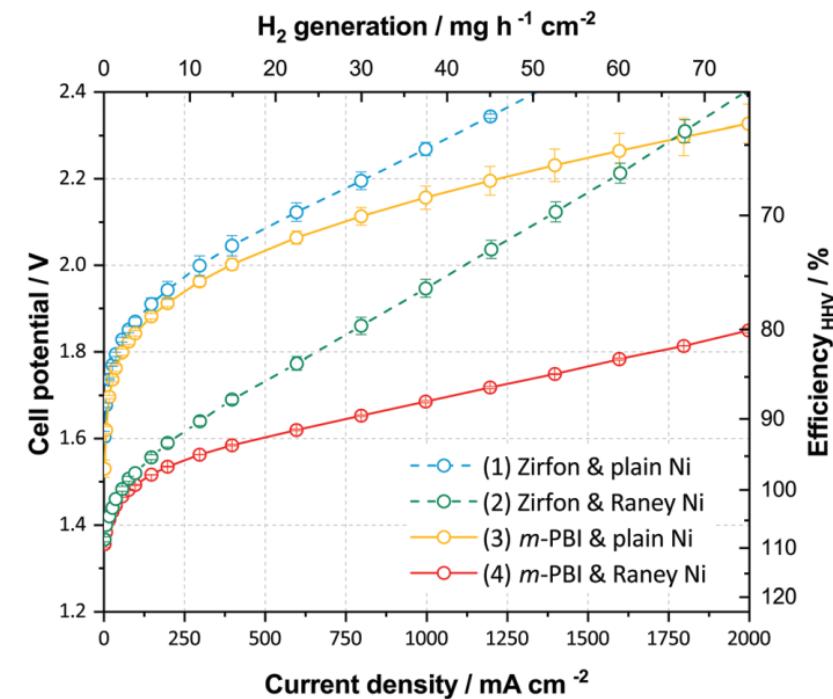
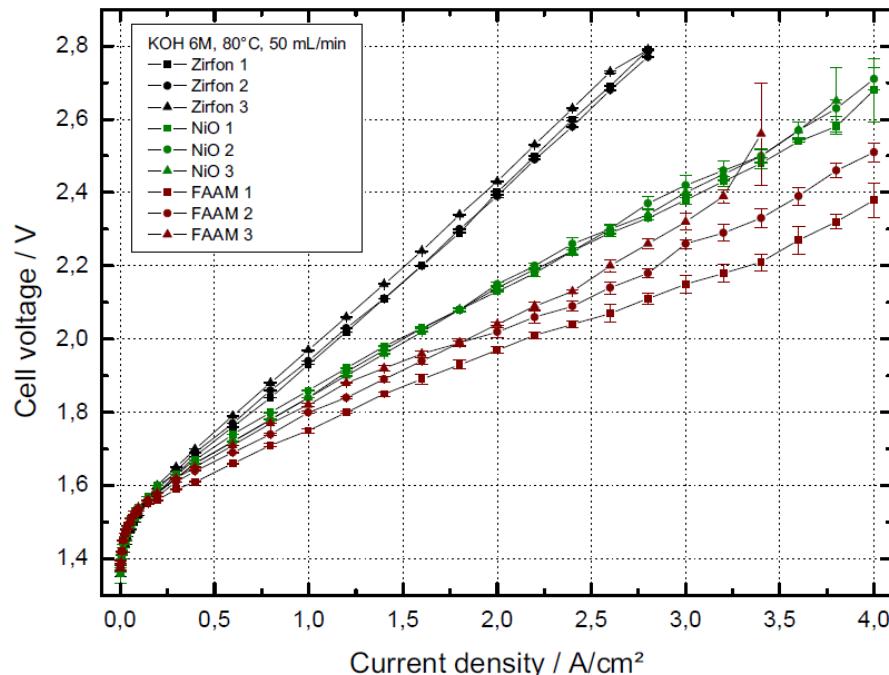


Fig. 3 Electrochemical cell performance in 24 wt% KOH and 80 °C. Cell polarization for four different cell configurations. Error bars represent variation between two or three cells. Cells are (cathode/separator/anode): (1) Ni-foam/Zirfon™ PERL diaphragm/Ni-perforated plate; (2) RANEY®-type-NiMo/Zirfon™ PERL diaphragm/RANEY®-type-Ni; (3) Ni-foam/40 µm m-PBI membrane/Ni-perforated plate; and (4) RANEY®-type-NiMo/40 µm m-PBI membrane/RANEY®-type-Ni.



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# Performance Test with DLR Electrodes – continuous improvement

2020: 1,8V @ 1.1 A/cm<sup>2</sup> with Zirfon at 70°C

**Results will be made public soon.**

**Stay tuned for our upcoming publication**



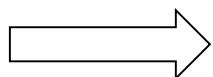
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# Cost Analysis

	VPS	APS
Yield per day	3 m <sup>2</sup>	3 m <sup>2</sup>
CAPEX	2,8 million €	0,480 million €
Depreciation time	10 years	10 years
Machine cost per day	1272 €	218 €
Other operating costs per day	212 €	196 €
Machine + other operating cost per m <sup>2</sup>	494 €	138 €
Staff cost per day	528 €	528 €
<b>Coating cost per m<sup>2</sup></b>	<b>670 €</b>	<b>314 €</b>



Potential to further reduce another 30-45% with economy of scale

# Conclusion

Plasma sprayed non-noble freestanding electrodes have potential to operate AWE

- at 1.1 A/cm<sup>2</sup> (1.8V) with Zirfon at 70°C
- above 2 A/cm<sup>2</sup> (1.8V) with new generation membranes
- The performance should be now demonstrated in stacks and in-field tests
- The cost of plasma sprayed catalyst layer is estimated to be about 300 €/ m<sup>2</sup> (approx 15 €/kW) with potential to be below 200 €/m<sup>2</sup> (approx 10 €/kW)

