Investigation of hybrid all-Fe Redox Flow Batteries

by Coupling Experiments and Simulations

International Flow Battery Forum, Budapest, 17.06.2026

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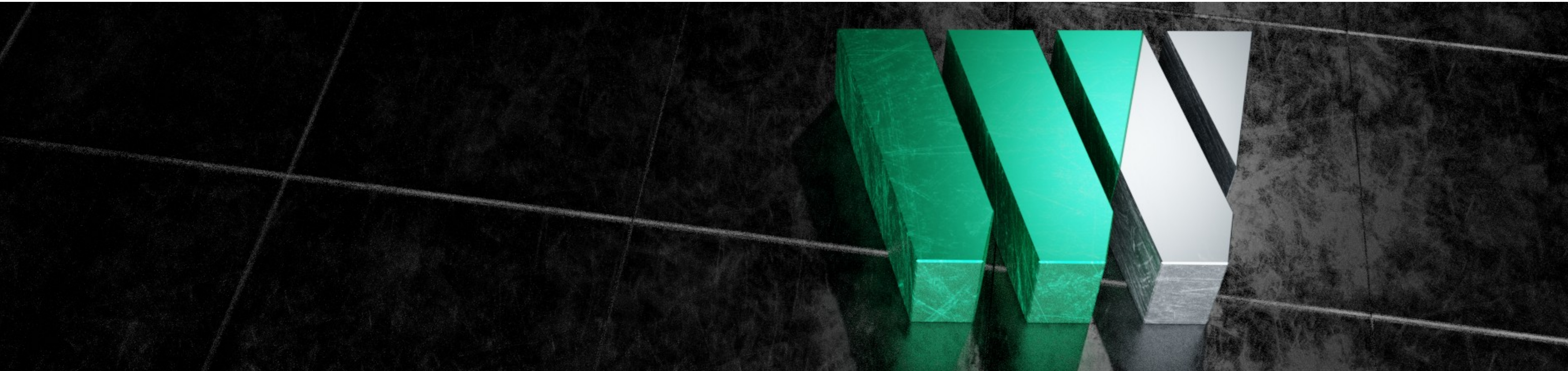
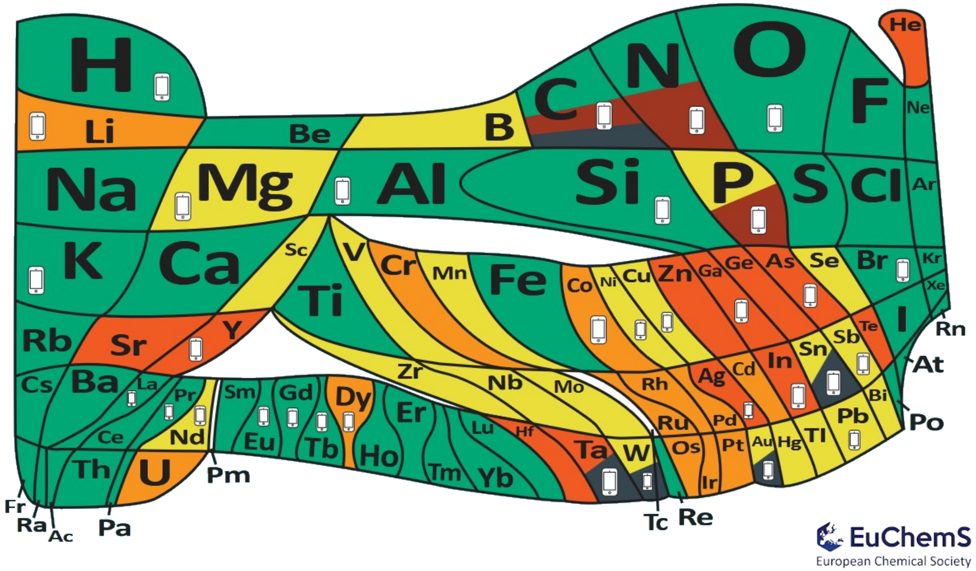


Advantages of Iron

[3]

Ecology:



[1]

- Serious threat over the next 100 years
- Rising threat from increased use
- Limited availability, future supply risk
- Plentiful supply
- Serious global problems through overuse
- From conflict resources

Economy:

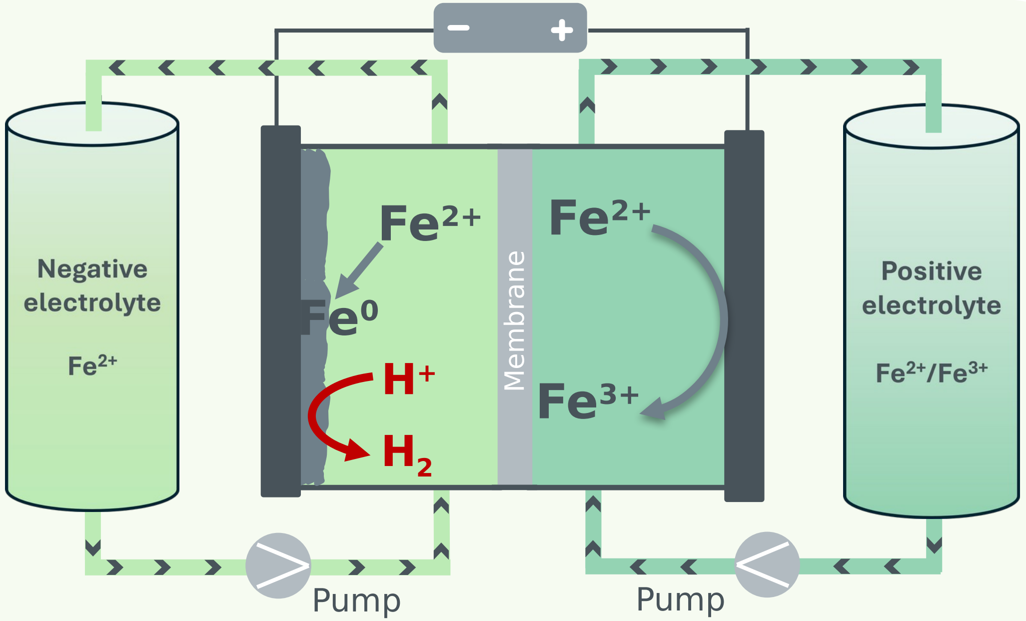
[2]

Fe: 100 USD/t **V: 18,000-36,000 USD/t**

✓ Iron is abundant, inexpensive and non-toxic

[1] https://www.euchems.eu/euchems-periodic-table/ accessed: 03.06.26
[2] https://www.marketindex.com.au/iron-ore accessed: 03.06.26

Hybrid all-Iron Redox Flow Batteries



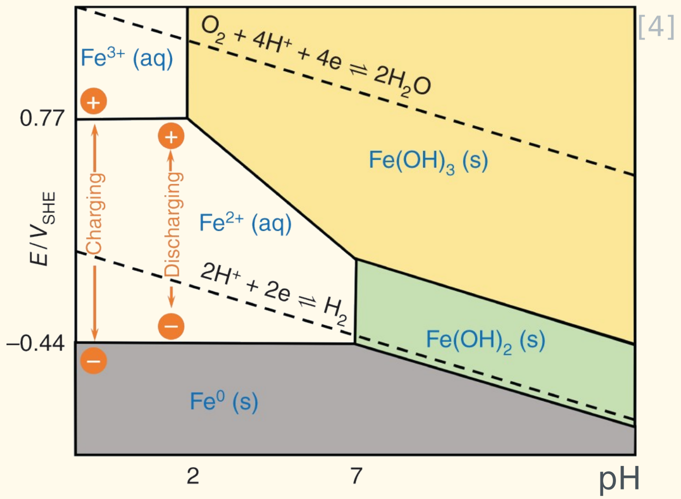
Pos. electrode: $Fe^{2+} \rightarrow Fe^{3+} + e^-$ $E^0 = +0.77\ V_{SHE}$

Neg. electrode: $Fe^{2+} + 2e^- \rightarrow Fe\ (s)$ $E^0 = -0.44\ V_{SHE}$

Cell reaction: $3\ Fe^{2+} \rightarrow 2\ Fe^{3+} + Fe\ (s)$ $\Delta E^0 = 1.21\ V_{SHE}$

Hydrogen Evolution Reaction (HER):

$2\ H^+ + 2e^- \rightarrow H_2$ 0.00 V_{SHE}

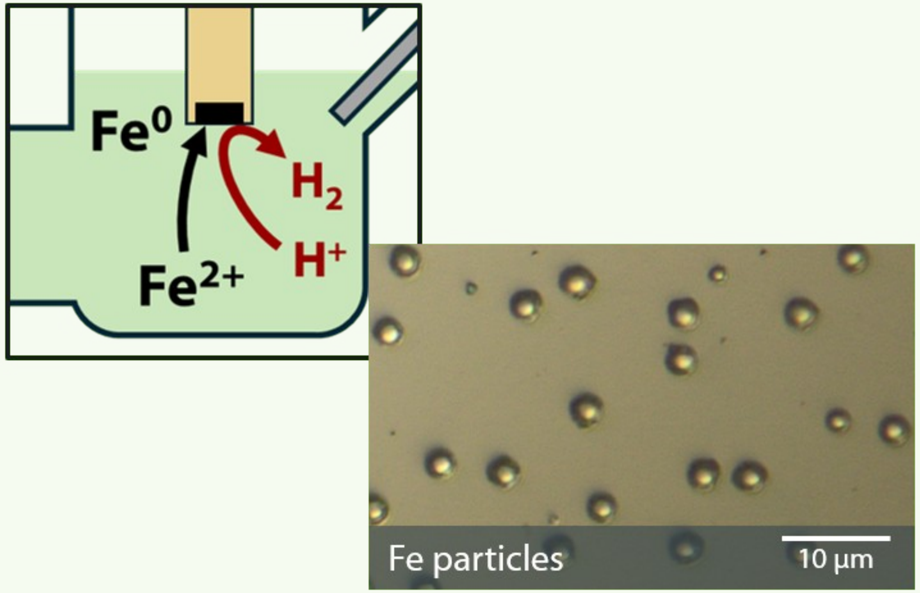


- Increase of pH
- Iron hydroxide precipitation
- Capacity fade

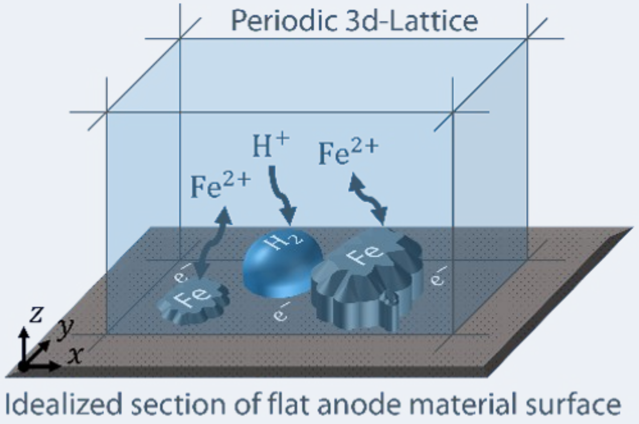
[4] R. F. Savinell et al., Chapter 35 "Fe/Fe flow battery" in "Flow Batteries: From Fundamentals to Applications", edited by C. Roth, J. Noack, M. Skyllas-Kazacos, Wiley-VCH, Weinheim, **2022**.
[5] J. Noack et al., "Studies on Fe/Fe Redox Flow Batteries with Recombination Cell", J. Electrochem Soc., 167, 160527, **2020**.

Combining experiments and simulations

- Characteristics of iron plating and stripping
- Mitigation of Hydrogen Evolution Reaction (HER)



In constant exchange

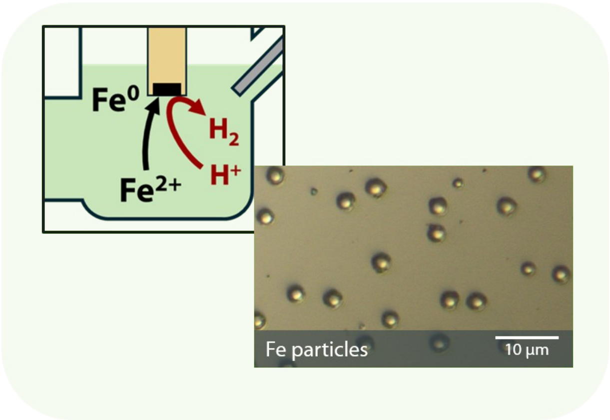


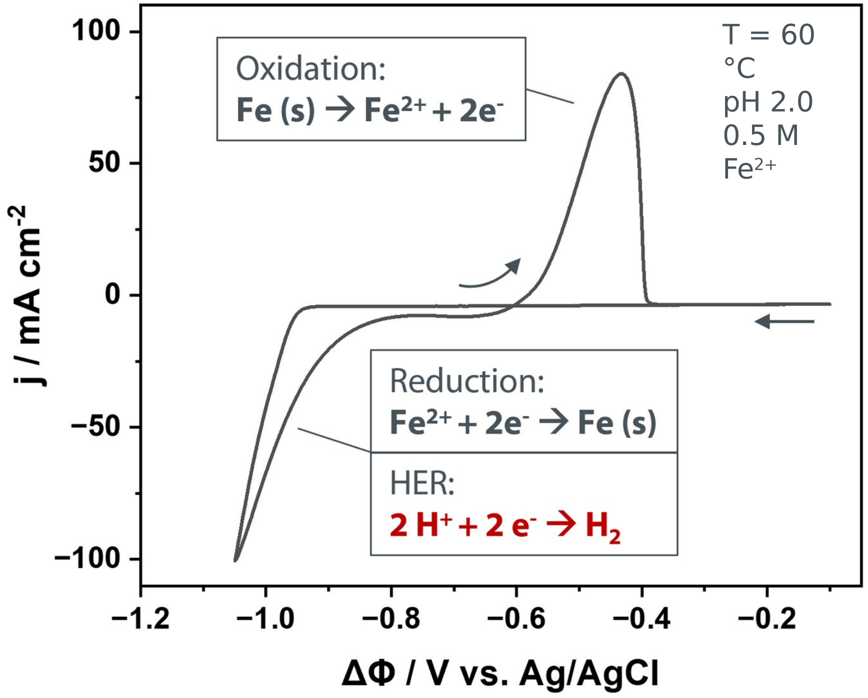
Kinetic Monte Carlo (kMC) Modeling

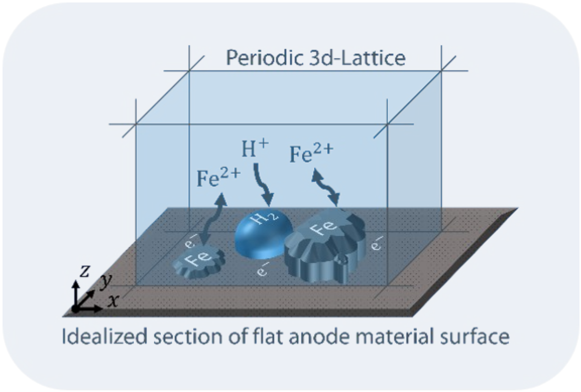
Steffen Zappe

Combining experiments and simulations cyclic voltammetry

- Characteristics of iron plating and stripping
- Mitigation of Hydrogen Evolution Reaction (HER)







Kinetic Monte Carlo (kMC) Modeling

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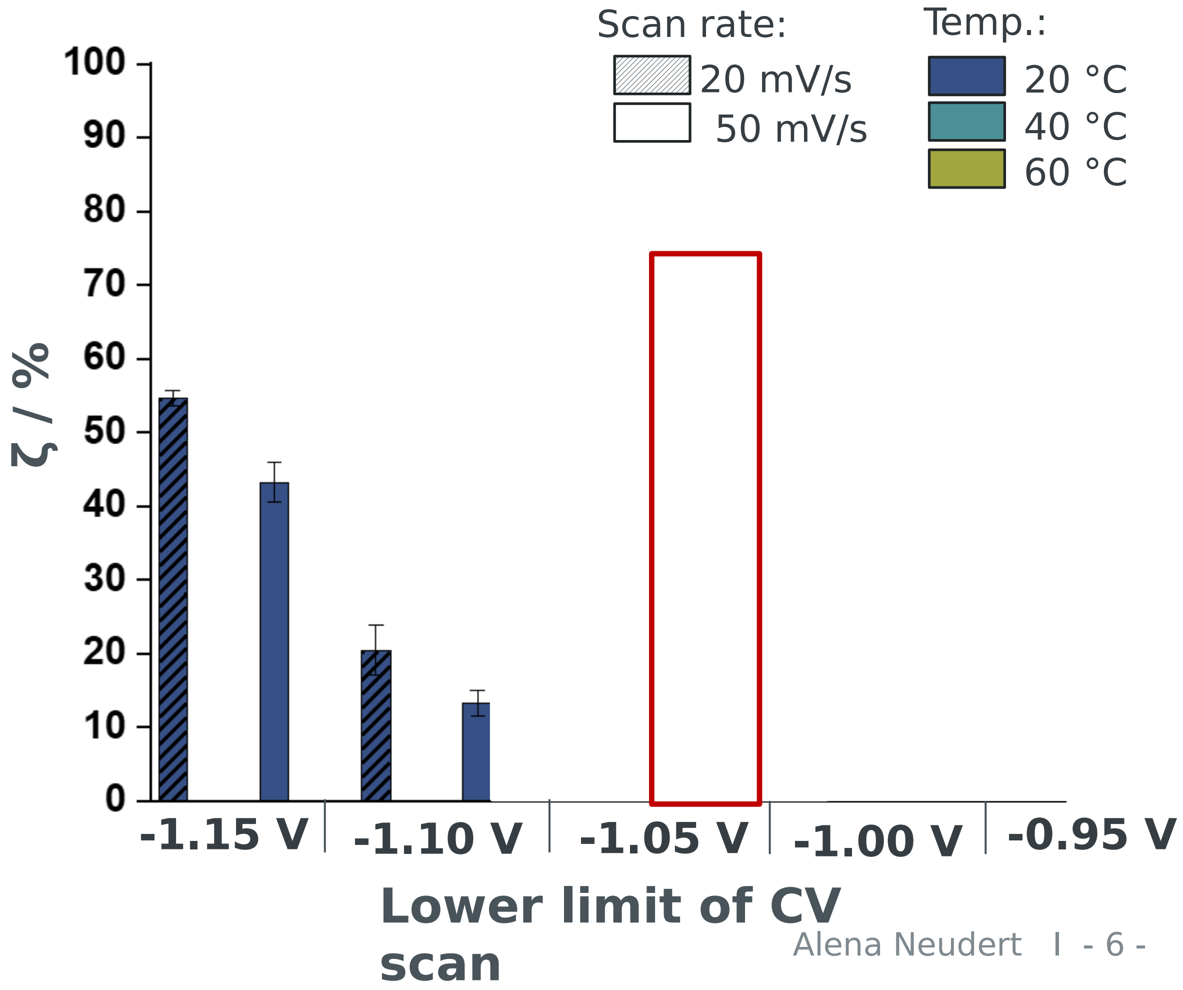
Temperature dependence of iron plating and stripping

Lower limit of CV scan	Scan rate: 50 mV s⁻¹			Scan rate: 20 mV s⁻¹		
	20°C	40°C	60°C	20°C	40°C	60°C
	—	—	—	—	—	—
-0.90 V	—	—	—	—	—	✓
-0.95 V	—	—	✓	—	✓	✓
-1.00 V	—	✓	✓	—	✓	✗
-1.05 V	—	✓	✗	✓	✗	✗
-1.10 V	✓	✗	✗	✓	✗	✗
-1.15 V	✓	✗	✗	✗	✗	✗
-1.20 V						

— Kinetically inhibited ✓ Stable operation ✗ Iron delamination



Charge going into iron redox reaction:

$$\zeta = \frac{\int j\,(Fe_{ox})dt}{\int j\,(Fe_{red}+HER)dt}$$

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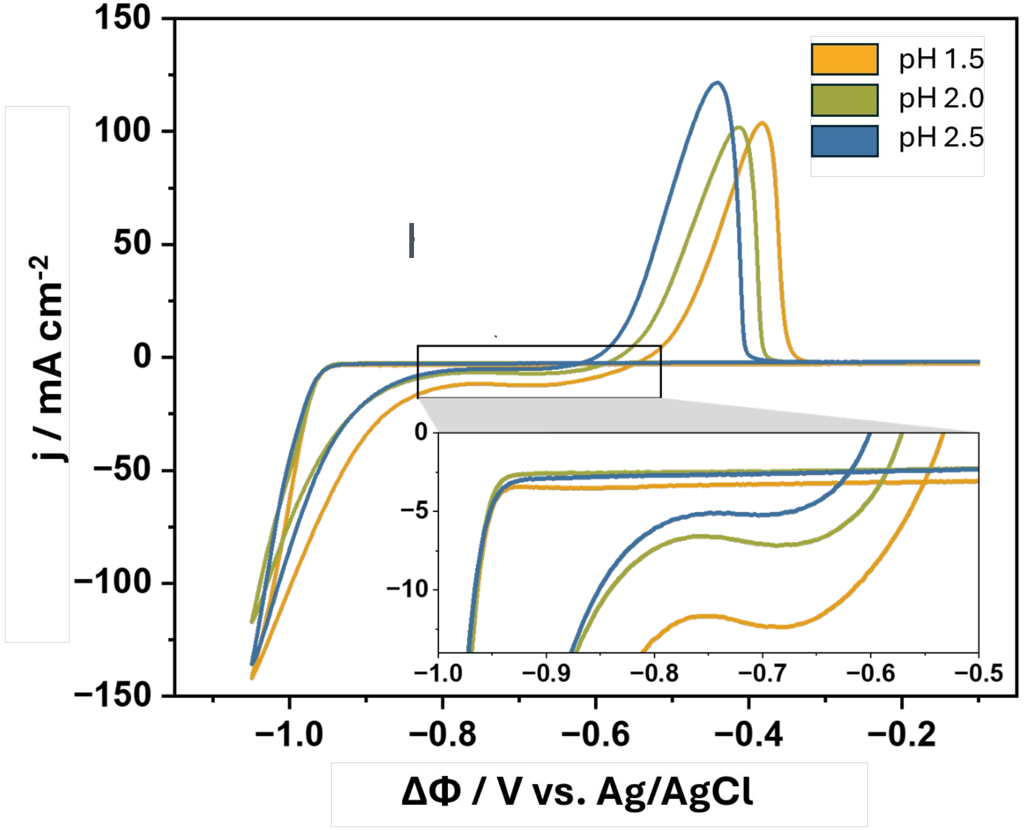
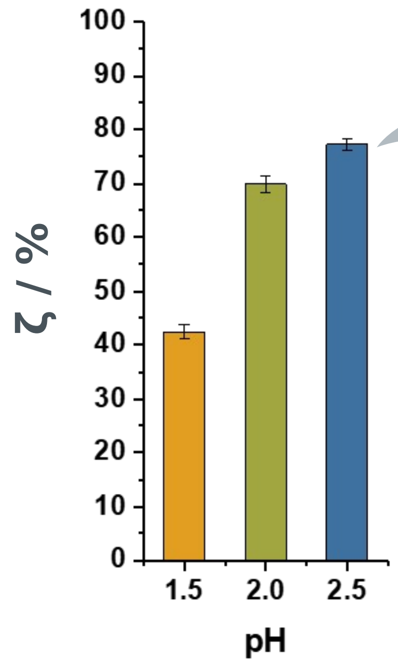
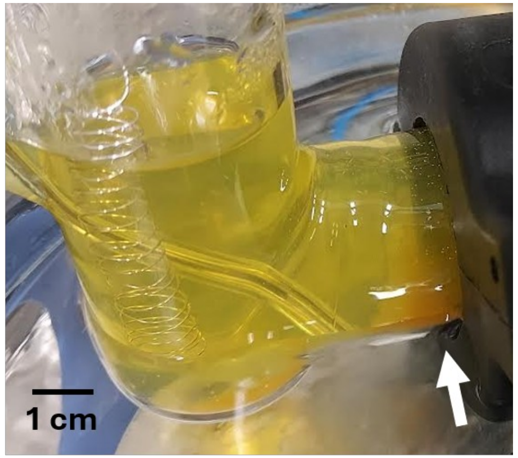
Effect of pH variation on Fe red/ox and HER







- pH increase leads to:
  - less hydrogen evolution
  - increased charging efficiency
- iron hydroxides start to form at pH 2.5

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Iron morphology evolution

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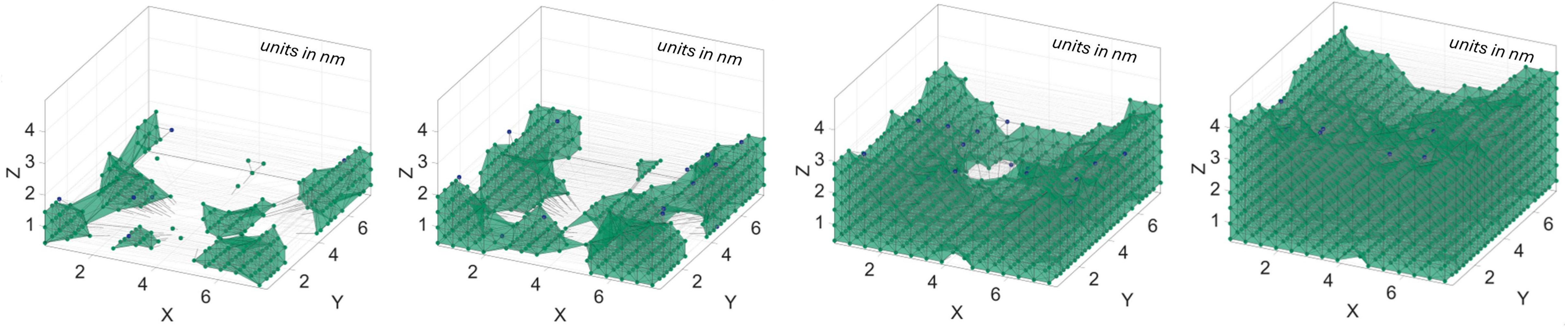

Nucleation of iron seeds

→ HER is enhanced

Growth into larger clusters

Formation of continuous iron film

→ HER is mitigated

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Deconvolution of simultaneous iron plating and HER

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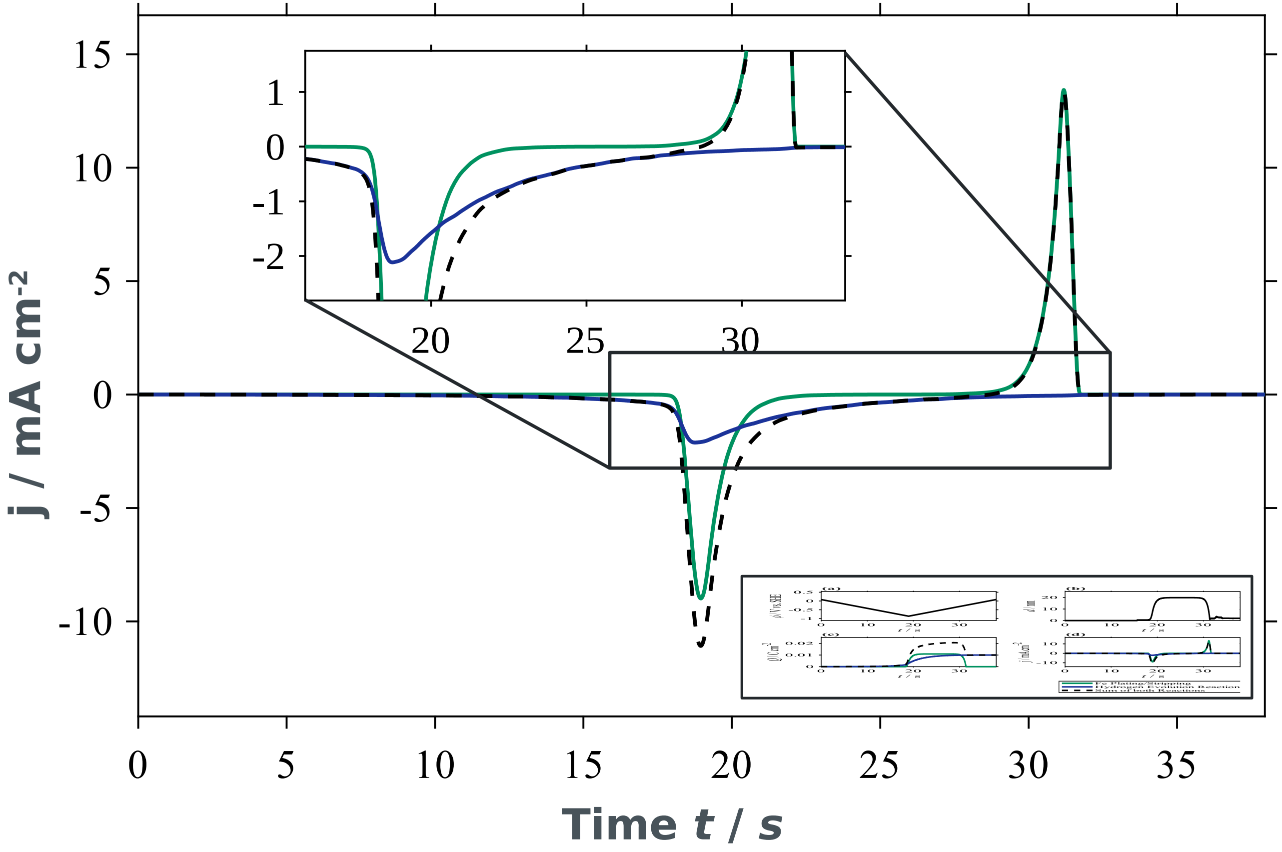
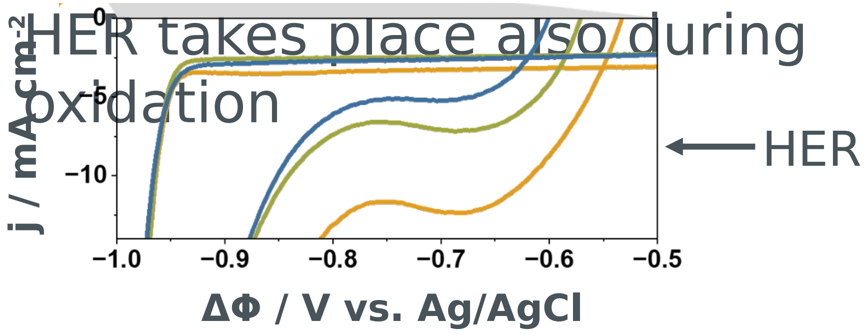


- HER dominates initially during reduction
- Iron plating becomes more dominant with lower applied potentials
- HER takes place also during oxidation



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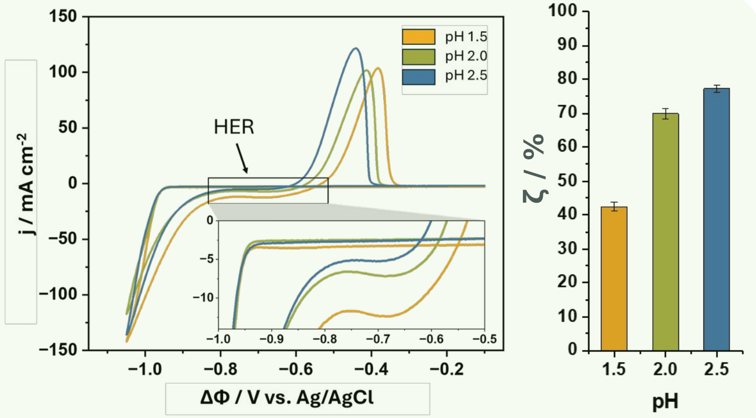
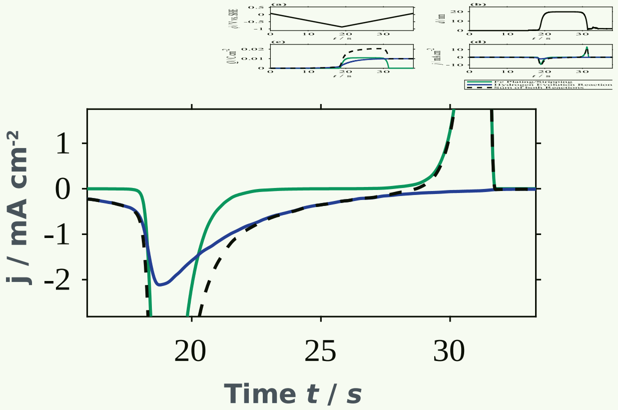
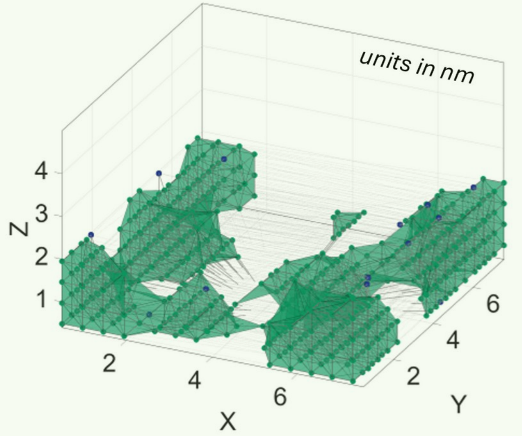
Conclusions & Outlook



- Applied potential, temp., pH and iron conc. significantly affect the **iron plating efficiency vs. HER**



- kMC enables **separation of iron reduction/oxidation and HER currents**



- Model provides **insights into iron morphology** (layer thickness, porosity) and its impact on the HER

- Homogeneous plating can mitigate HER → improvement of electrode material and electrode structure
- Combining kMC with continuums model for influence of diffusion in the electrolyte

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Travel Grant

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www.gdch.de/elektrochemie

GDCh Division of Electrochemistry

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Battery Management Methods

Methoden des Batteriemanagements

Thank you for your attention!

More questions or remarks?
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