Reactive Metals for Large-scale, Seasonal Energy Storage

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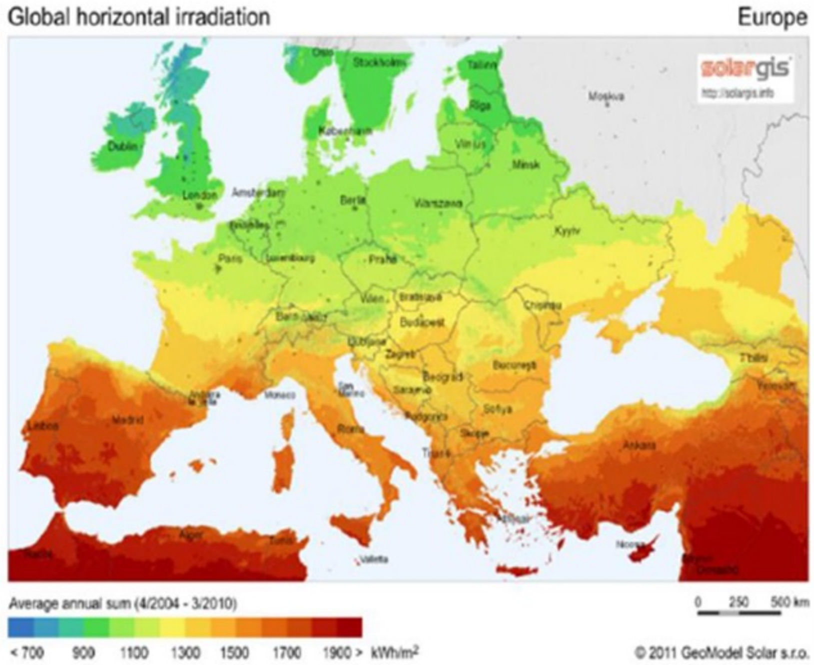
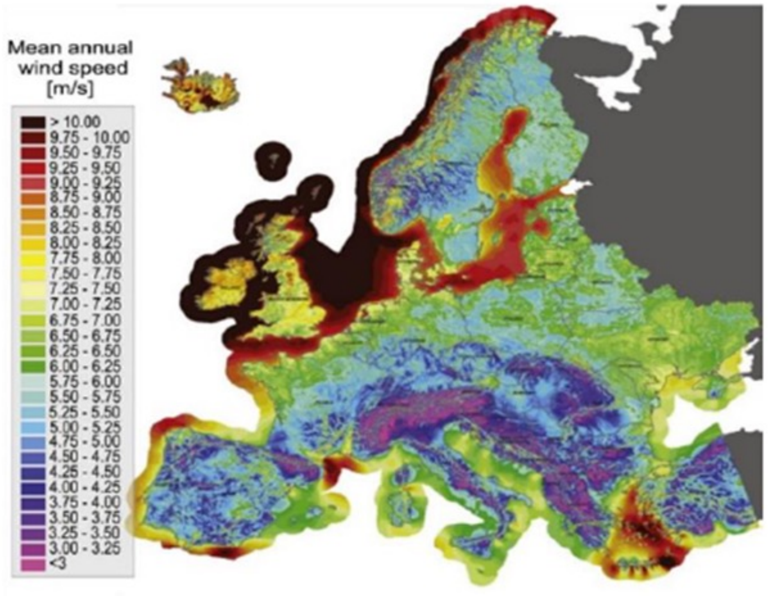
Decarbonising Europe by 2050

On 28 **November 2018**, the European Commission presented its **strategic long-term vision for a climate-neutral economy by 2050**



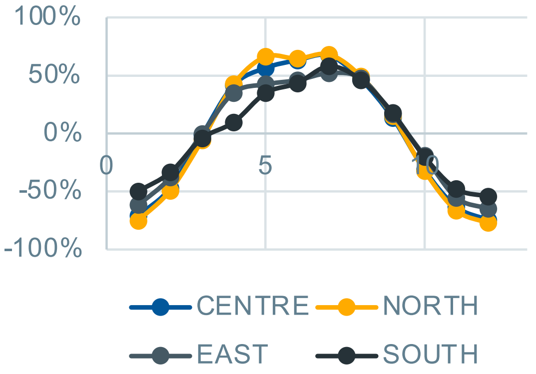


Source: Solargrids, Ad v. Wijk (TU DELFT)

Renewable Energy in Europe is far more than sufficient for the EU needs, but Energy storage is needed

Decarbonising Europe by 2050: Why Energy Storage is needed?

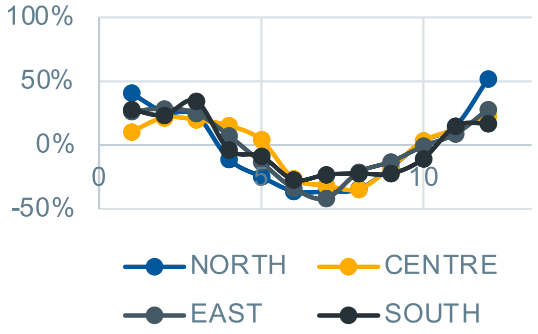
Long-term RES fluctuation (Elaboration over 2015-20 generation data (ENTSO-E))



Solar energy

Energy storage capacity needs over annual generation

Centre	North	East	South
24%	25%	20%	17%



Wind energy

Energy storage capacity needs over annual generation

Centre	North	East	South
11,7%	9,2%	10,4%	10,1%

Energy storage is needed to match solar and wind generation variation in all European areas

https://transparency.entsoe.eu/generation/r2/actualGenerationPerProductionType/show;

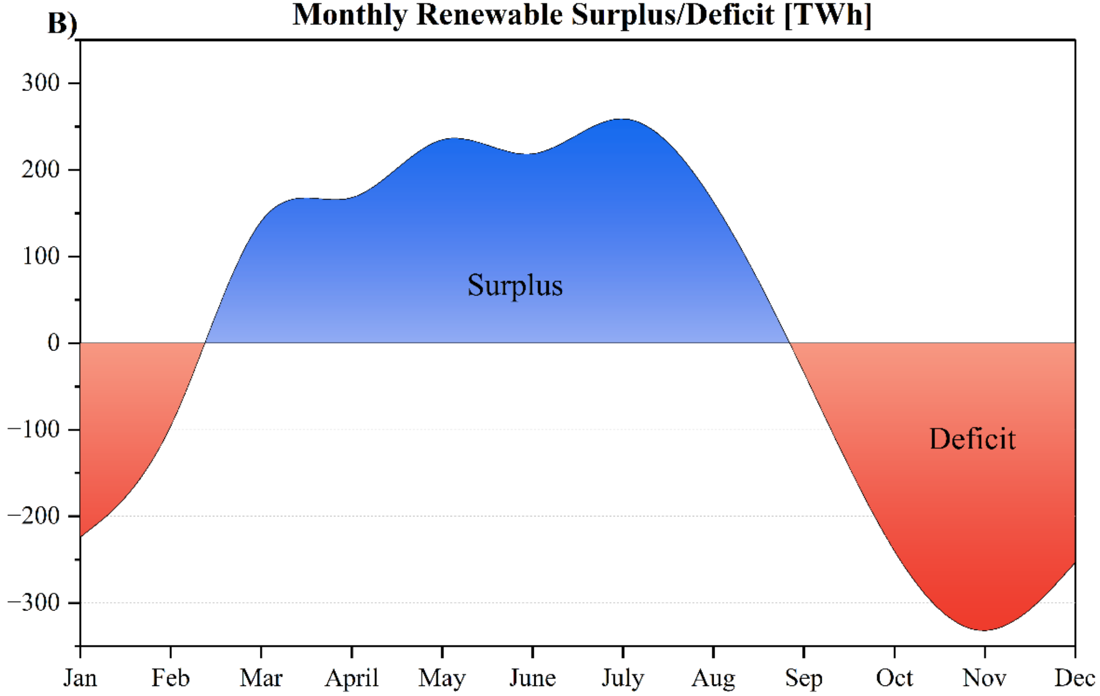
Barelli L., Passerini S. and coll., Adv. Mater. Technol. (2024), 230220

Decarbonising Europe by 2050: Why Energy Storage is needed?

Assumptions:

21399.2 TWh European primary energy consumption (2018)
36% Energy Storage cycle efficiency
5.8% POWER GRID LOSSES

Renewable Energy	Share	North Europe	Central Europe	South Europe
PV	**45%**	**0.3**	**0.15**	**0.55**
WIND	**45%**	**0.65**	**0.05**	**0.30**
Bio-mass & others	10%			

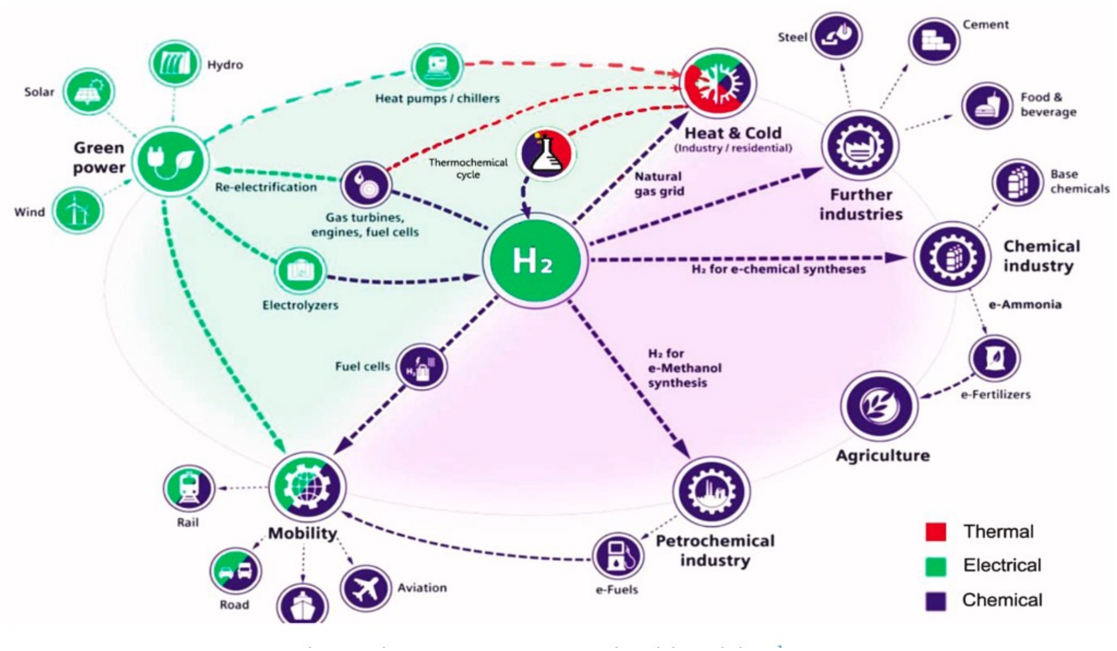


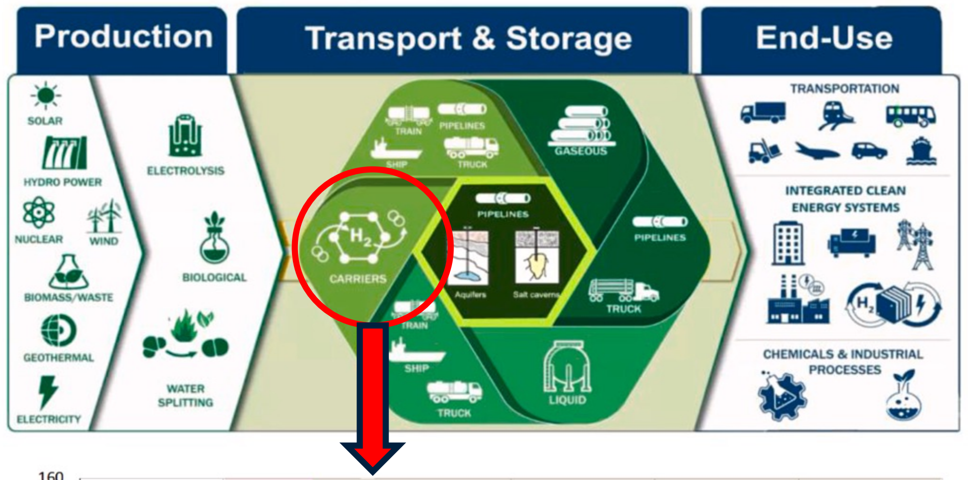
Energy storage capacity for EU energy independence

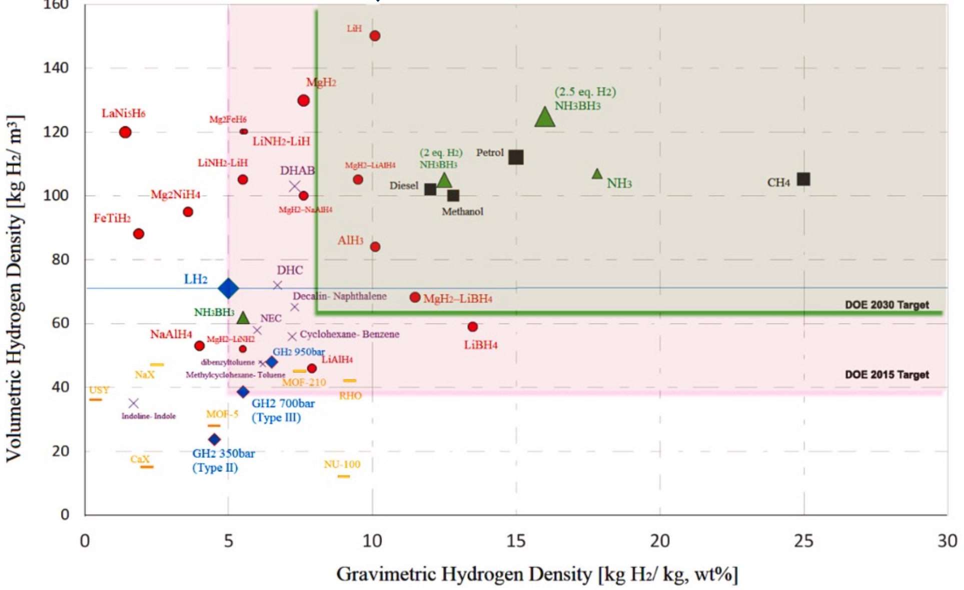
Seasonal: 1270 TWh   Weekly: 112 TWh   Daily: 19 TWh

Barelli L., Passerini S. and coll., Adv. Mater. Technol. (2024), 2302206

Addressing the Energy Storage Demands: Hydrogen



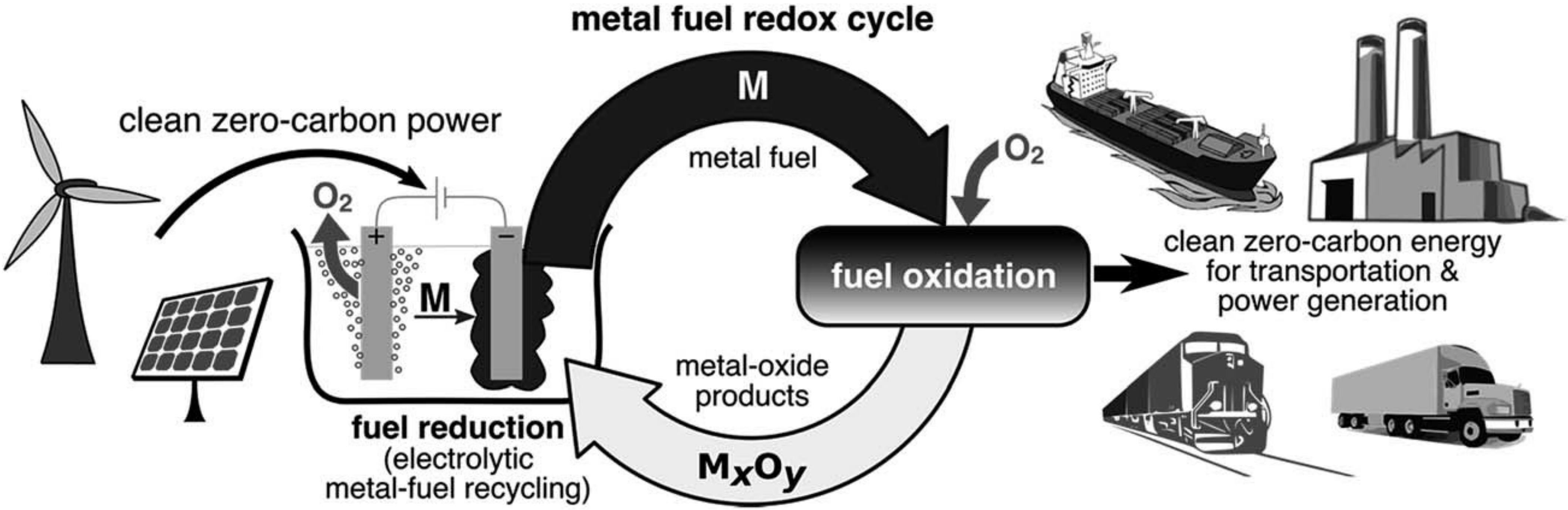




Hydrogen is certainly an excellent approach since it can be readily used in many applications, …
but storage is still an issue strongly limiting the performance

A.S. Mehr et al, *Int. J. Hydrogen Energy* (2024) 70, 786–815.

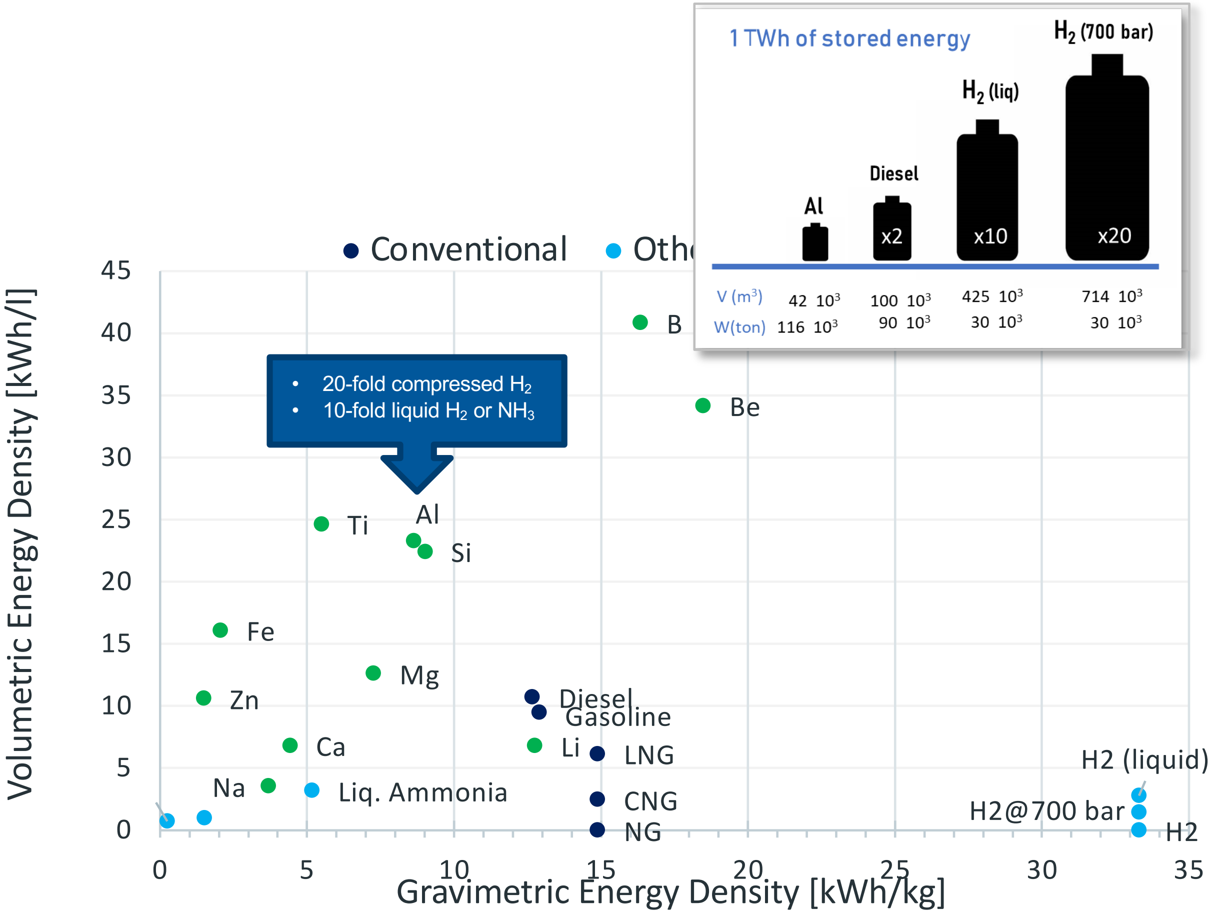
Addressing the Energy Storage Demands: Reactive Metals



Abundant reactive metals (Al, Fe, Mg, Ca, Si, Na, …) can store large amounts of energy

P. Julien, J. M. Bergthorson, *Sustainable Energy Fuels* (2017) 1, 615.
D. J. Durbin and C. Malardier-Jugroot, *Int. J. Hydrogen Energy* (2013) 38, 14595–14617.

Addressing the Energy Storage Demands: Reactive Metals

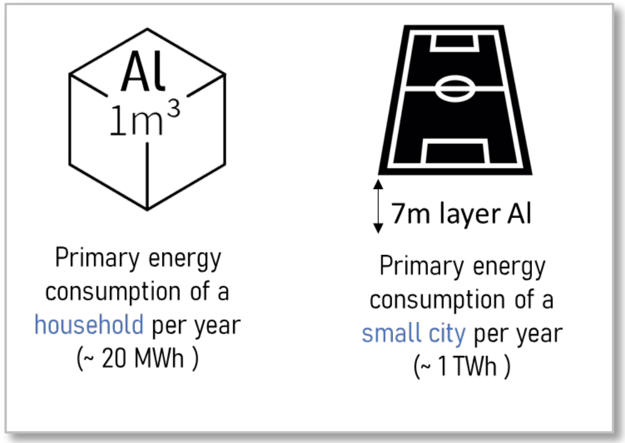


- 20-fold compressed H_2
- 10-fold liquid H_2 or NH_3

	Al	Diesel	H_2 (liq)	H_2 (700 bar)
V (m^3)	42 10^3	100 10^3	425 10^3	714 10^3
W(ton)	116 10^3	90 10^3	30 10^3	30 10^3

Requirements:

- Abundance
- High volumetric density
- High energy content
- High stability for storage
- No critical raw materials
- No toxicity or hazard risk
- CO_2 emission free
- No PFAs
- Local availability & Transportability
- Recyclability



Primary energy consumption of a household per year (~ 20 MWh)

Primary energy consumption of a small city per year (~ 1 TWh)

Aluminium appears very promising for easy, low cost, short- and long-term storage

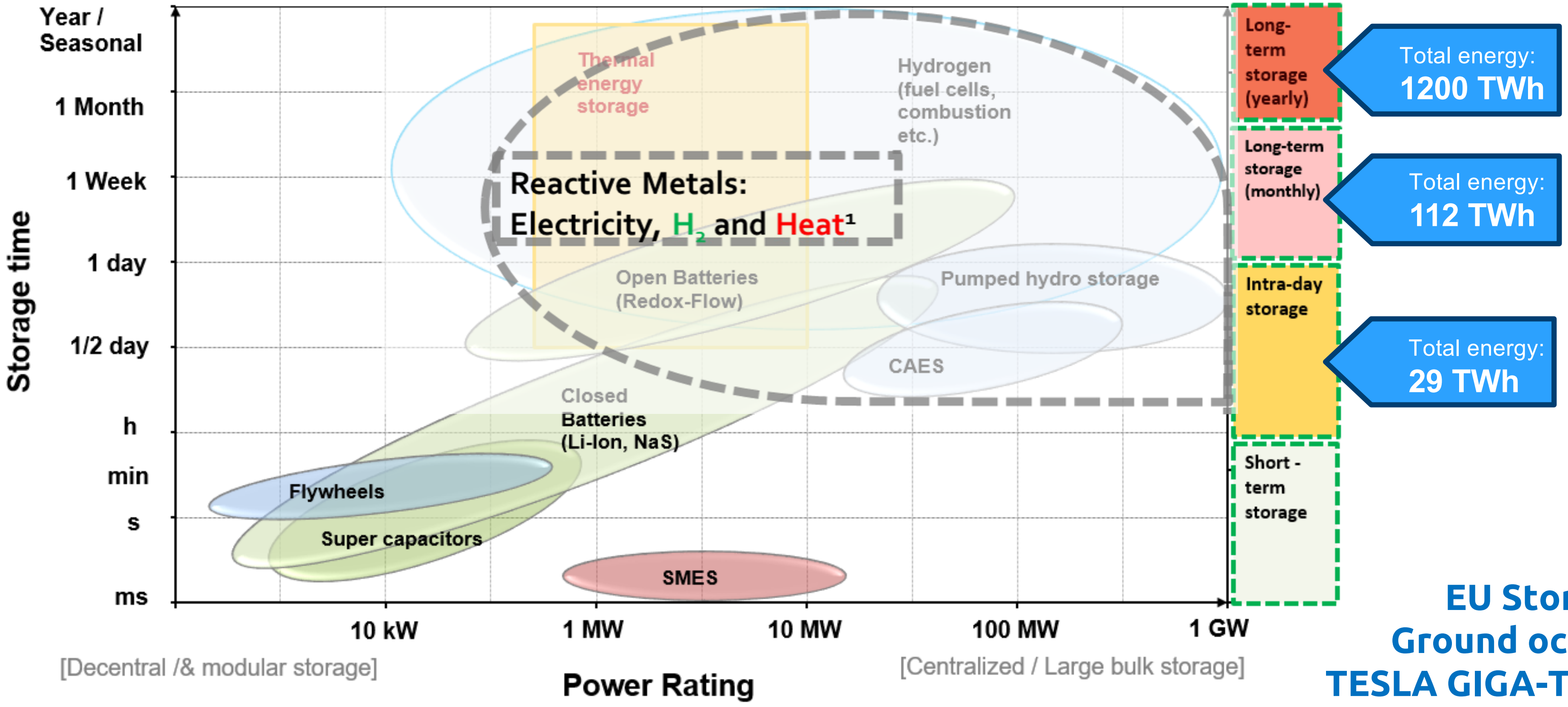
P. Julien, J. M. Bergthorson, *Sustainable Energy Fuels* (2017) 1, 615.

D. J. Durbin and C. Malardier-Jugroot, *Int. J. Hydrogen Energy* (2013) 38, 14595–14617.

Barelli, L.; et al.. *Power Energy technology*, 8 (9), Art. Nr.: 2000233. doi:10.1002/ente.202000233

Addressing the Energy Storage Demands: Aluminium

Aluminum as energy carrier and storage medium



about 6

less than 1

about 0.2

EU Storage needs: Ground occupation in TESLA GIGA-TEXAS units

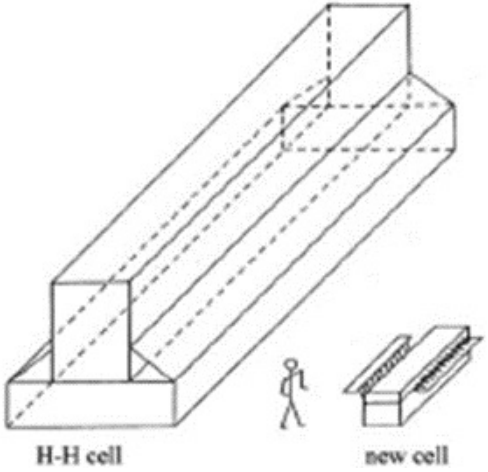
Barelli, L.; et al.. Reactive Metals as Energy Storage and Carrier Media: Use of Aluminum for Power Generation in Fuel Cell-Based Power Energy technology, 8 (9), Art. Nr.: 2000233. doi:10.1002/ente.202000233
Taylor, Peter; et al.l (2012). Pathways for Energy Storage in the UK. Centre for Low Carbon Futures, York.
Baumann, M.; et al. A review of multi-criteria decision making approaches for evaluating energy storage systems for grid applications. 2019. Renewable & sustainable energy reviews, 107, 516–534. doi:10.1016/j.rser.2019.02.016

Addressing the Energy Storage Demands: Aluminium

Hall-Heroult Process

- Zero CO_2 emission, only O_2
- No perfluorochemicals (PFCs) emitted

- 20 % less energy and flexible power
- 50 % less space, see figures
- 40 % less investments
- 15-30 % less operational costs



CO_2 & PFAs

O_2

Conventional Al-smelting

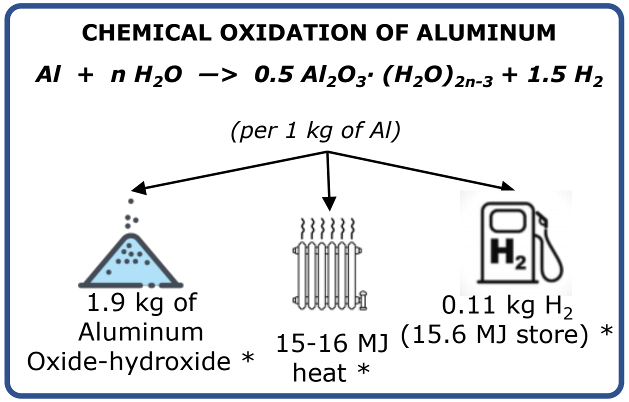
Inert anode Al-smelting

Courtesy of Jon Hjaltalin Magnusson, M.Sc.EE., CEO Arctus Aluminium Ltd., Reykjavik, Iceland // jhm@arctus.is

Addressing the Energy Storage Demands: Aluminium

THERMODYNAMIC CONVERSION

(wet combustion)



CHEMICAL OXIDATION OF ALUMINUM

$Al + n H_2O \rightarrow 0.5 Al_2O_3 \cdot (H_2O)_{2n-3} + 1.5 H_2$

(per 1 kg of Al)

1.9 kg of Aluminum Oxide-hydroxide *

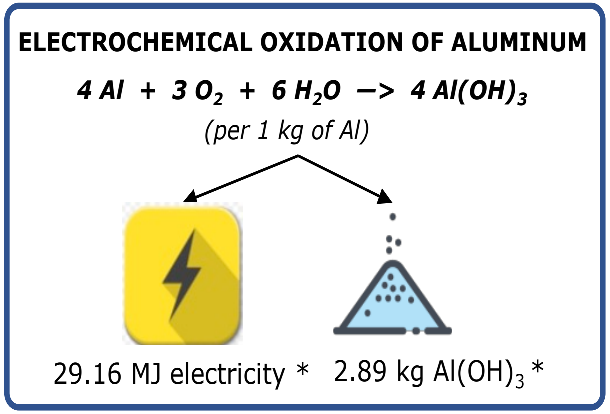
15-16 MJ heat *

0.11 kg H_2 (15.6 MJ store) *

- Stored energy is converted into H_2 and heat
- H_2 and heat are transformed into electricity via fuel cells and gas turbines
- RTE of 36%

ELECTROCHEMICAL CONVERSION

(primary batteries)



ELECTROCHEMICAL OXIDATION OF ALUMINUM

$4 Al + 3 O_2 + 6 H_2O \rightarrow 4 Al(OH)_3$

(per 1 kg of Al)

29.16 MJ electricity *

2.89 kg $Al(OH)_3$ *

- No thermal energy losses
- Direct electricity
- RTE up to 50%

E. I. Shkolnikov, A. Z. Zhuk, M. S. Vlaskin, Renewable Sustainable Energy Rev. 2011, 15, 4611. 3Y. Yavor, S. Goroshin, J. M. Bergthorson, D. L. Frost, R. Stowe, S. Ringuette, Int. J. Hydrogen Energy 2013, 38, 14992.

M. Baumann, L. Barelli, S. Passerini *Adv. Energy Mater.* **2020**, 10, 2001002

Addressing the Energy Storage Demands: Aluminium

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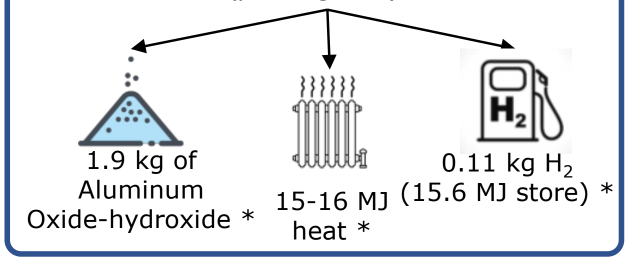
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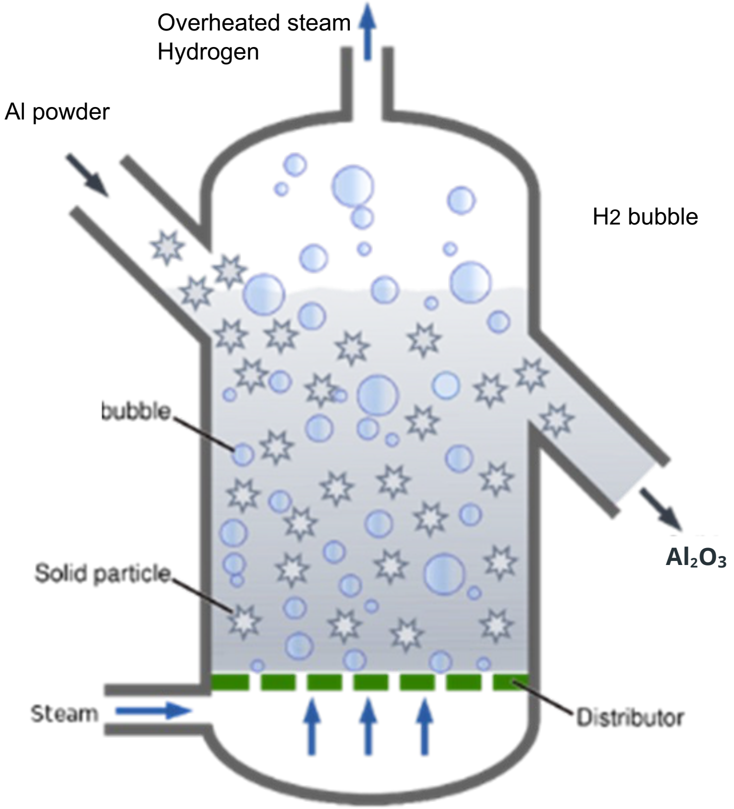


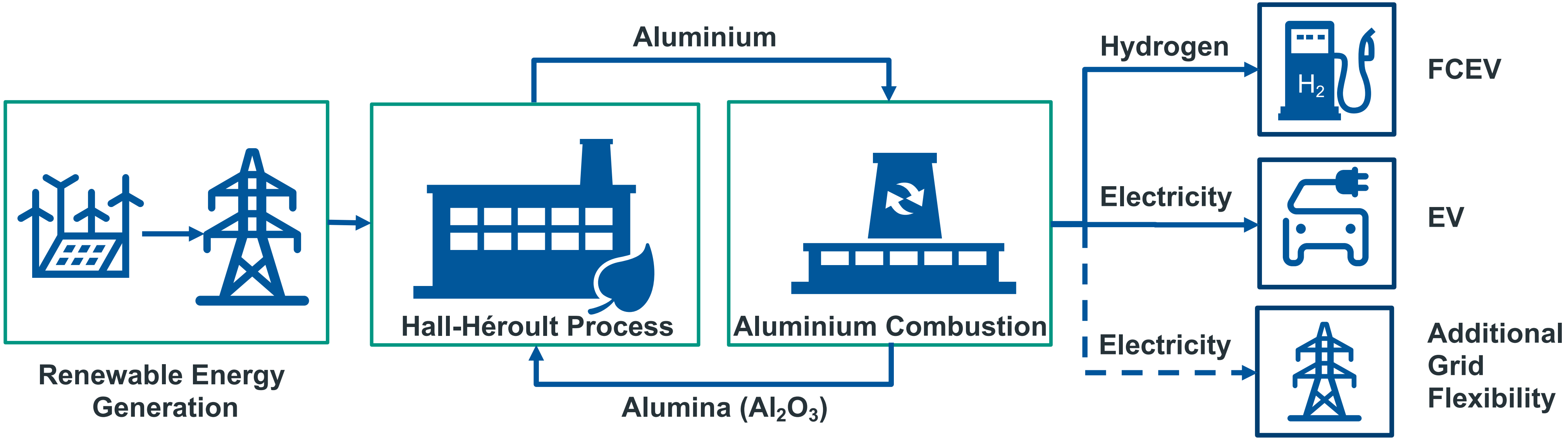
Fluidized Bed reactor – simple water combustion process

E. I. Shkolnikov, A. Z. Zhuk, M. S. Vlaskin, Renewable Sustainable Energy Rev. 2011, 15, 4611. 3Y.
Yavor, S. Goroshin, J. M. Bergthorson, D. L. Frost, R. Stowe, S. Ringuette, Int. J. Hydrogen Energy 2013, 38, 14992.

Addressing the Energy Storage Demands: Aluminium

Implementation Scenario – Business case: BEV and FCEV charging stations

$2Al(s)+3H_2O(g) \rightarrow Al_2O_3(s)+3H_2(g)$ -815.4 kJ/mol

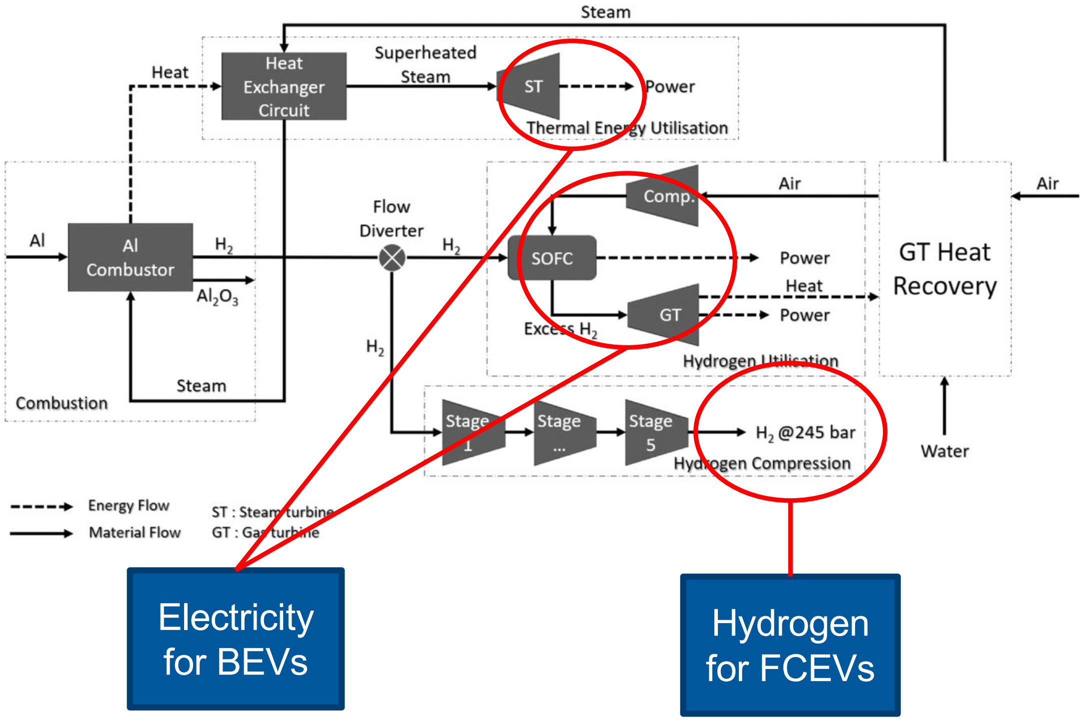


circular approach
recyclable energy carrier

1 kg of Al produces:
15.1 MJ heat
0.11 kg H_2
1.9 kg Al_2O_3 (to be recycled for Al production)

H. Ersoy et al., "Hybrid Energy Storage and Hydrogen Supply Based on Aluminum—a Multiservice Case for Electric Mobility and Energy Storage Services" Advanced Materials Technologies, Jan. 2022, doi: 10.1002/admt.202101400

Implementing Scenario: Decarbonisation @2050 - Aluminium in Power-to-X applications



Electricity for BEVs

Hydrogen for FCEVs

Technical features of the station

SOFC Partial Load	P_{el}	H_2	$\eta_{Power\text{-}to\text{-}X}$
100%	4 MW	-	35.6%
80%	3.1 MW	28 kg/h	38.8%
65%	2.6 MW	46.8 kg/h	40.7%

- Feeding Al stream: 0.275 kg/s
- CAPEX: 4200–6200 €/kW

International Energy Agency: *Net-zero by 2050 (https://www.iea.org/reports/net-zero-by-2050)*
Hydrogen Council: *Roadmap towards zero emissions: The complementary role of BEVs and FCEVs (https://hydrogencouncil.com/wp-content/uploads/2021/10/Transport-Study-Full-Report-Hydrogen-Council-1.pdf)*

H. Ersoy et al., "Hybrid Energy Storage and Hydrogen Supply Based on Aluminum—a Multiservice Case for Electric Mobility and Energy Storage Services" Adv. Mat. Tech. (2022) doi: 10.1002/admt.202101400

Addressing the Energy Storage Demands: Aluminium

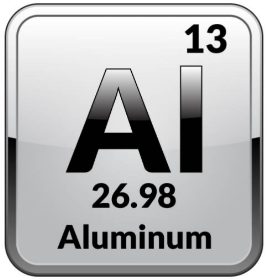
RTE, vol. energy density of various P-to-P technologies employing different energy carriers

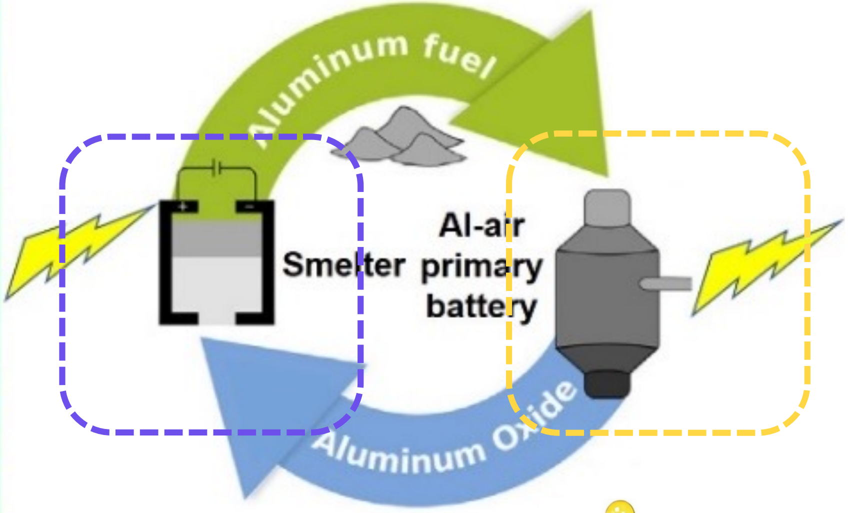
Energy Carrier	Conversion Technology	Round Trip Efficiency (RTE)	Energy Density [kWh/L]
Al	Aluminium Wet – Combustion (ST,GT, & SOFC)	35.6 %	23.5
H_2	PEM Electrolyzer – PEM Fuel Cell (PEMFC) Reversible – Solid Oxide Cell	30% (H_2@200 bar) 48% (H_2@70 bar)	0.53 0.2
Methanol / DME	Solid Oxide Electrolizer (SOE) / H_2 to methanol-DME / Solid Oxide Fuel Cell (SOFC)	36% (26.5%*)	5.5
Gasoline	SOE/ H_2 to gasoline/SOFC	27% (20%*)	8.8
LNG	SOE/TSA dehydration, H_2 and CO_2 membrane separation/SOFC	28% (23%*)	5.8

RTE values include the thermal (1750 kWh/tCO_2) ed electric (250 kWh/tCO_2) energy consumption for CO_2 trapping via low temperature absorption technology

H. Ersoy et al., "Hybrid Energy Storage and Hydrogen Supply Based on Aluminum—a Multiservice Case for Electric Mobility and Energy Storage Services" Advanced Materials Technologies, Jan. 2022, doi: 10.1002/admt.202101400

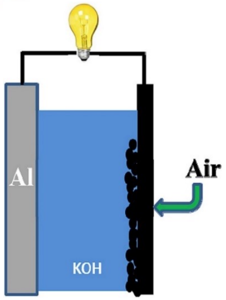
ALU-STORE Project: Aluminium as energy storage medium





Metal to power

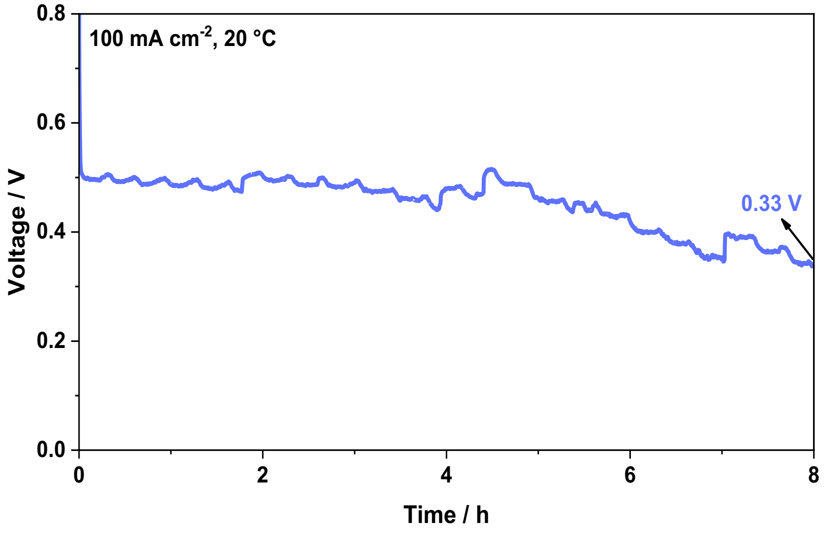
$$Al \xrightarrow{\text{Al−air batteries}} Al_2O_3 + energy$$



Anode: $4Al + 16OH^- \rightarrow 4Al(OH)_4^- + 12e^-$
Cathode: $3O_2 + 6H_2O + 12e^- \rightarrow 12OH^-$
Overall: $4Al + 4OH^- + 3O_2 + 6H_2O \rightarrow 4Al(OH)_4^-$

Al-air cells: State-of-the-art & Development

State-of-the-art: **Voltage and energy fading**

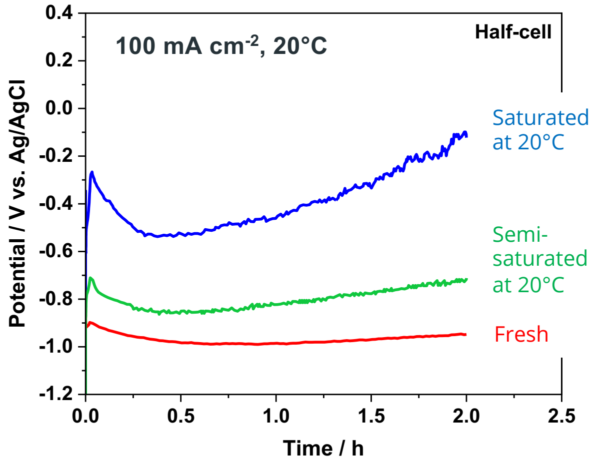


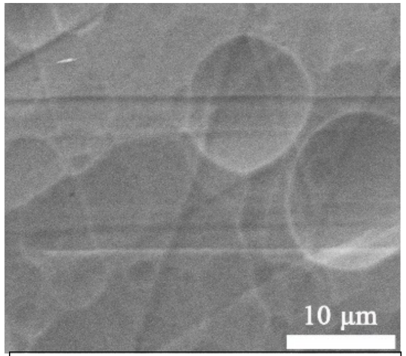
Previous literature: accumulation of $Al(OH)_3$ on the surface of Al anode

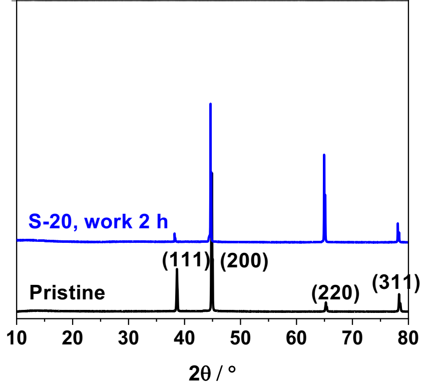
$$Al(OH)_4^- \rightarrow Al(OH)_3\downarrow + OH^-$$

C. Xu , S. Passerini et al. Journal of Power Sources 574 (2023) 233172

Development





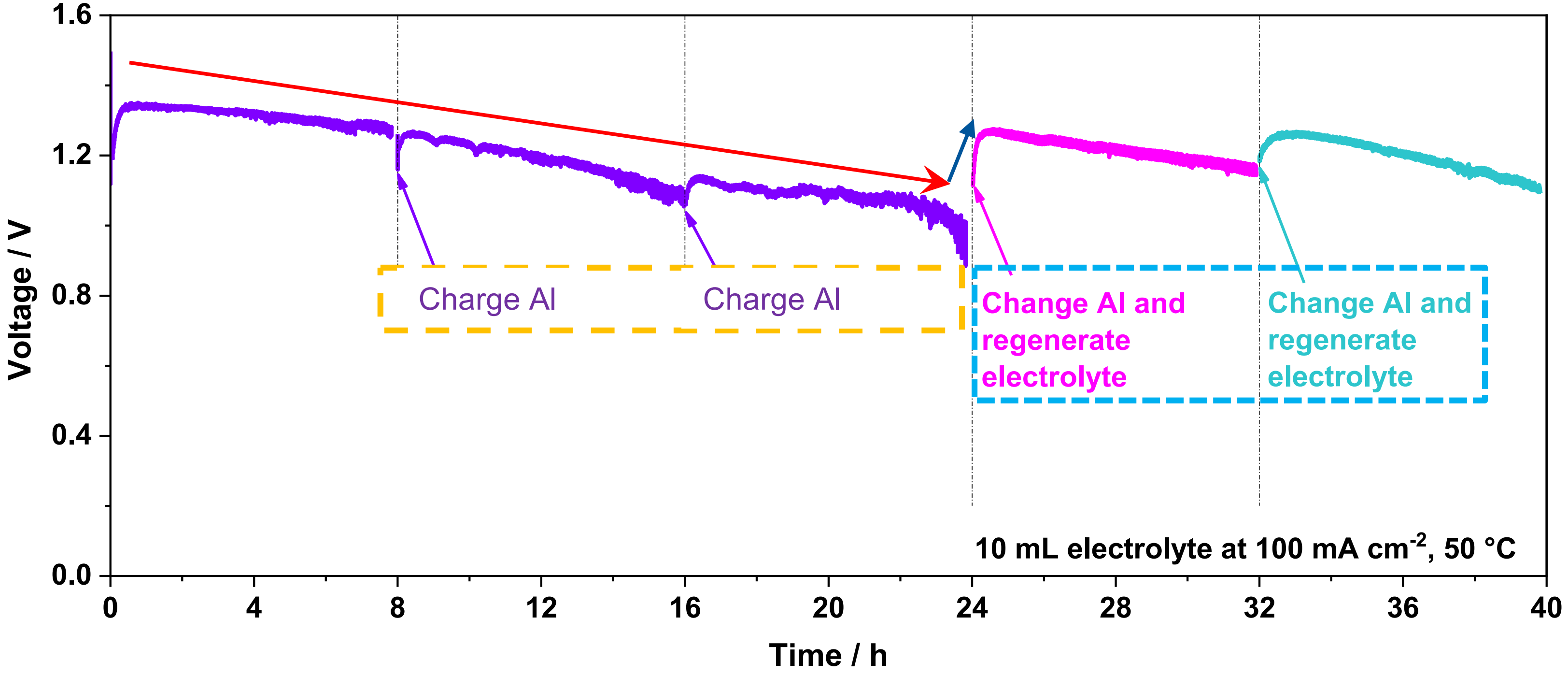


The voltage degradation is due to increasing $Al(OH)_4^-$ in the electrolyte, corresponding to decreasing OH^-

Need to adjust the electrolyte composition

Half cell: Al foil (3.4 cm^2) as working electrode; Ni foam (60 cm^2) as Counter electrode Ag/AgCl electrode as reference electrode; 40 mL (excess) electrolytes

Al-air cell: Ah-level Prototype cell and electrolyte regeneration

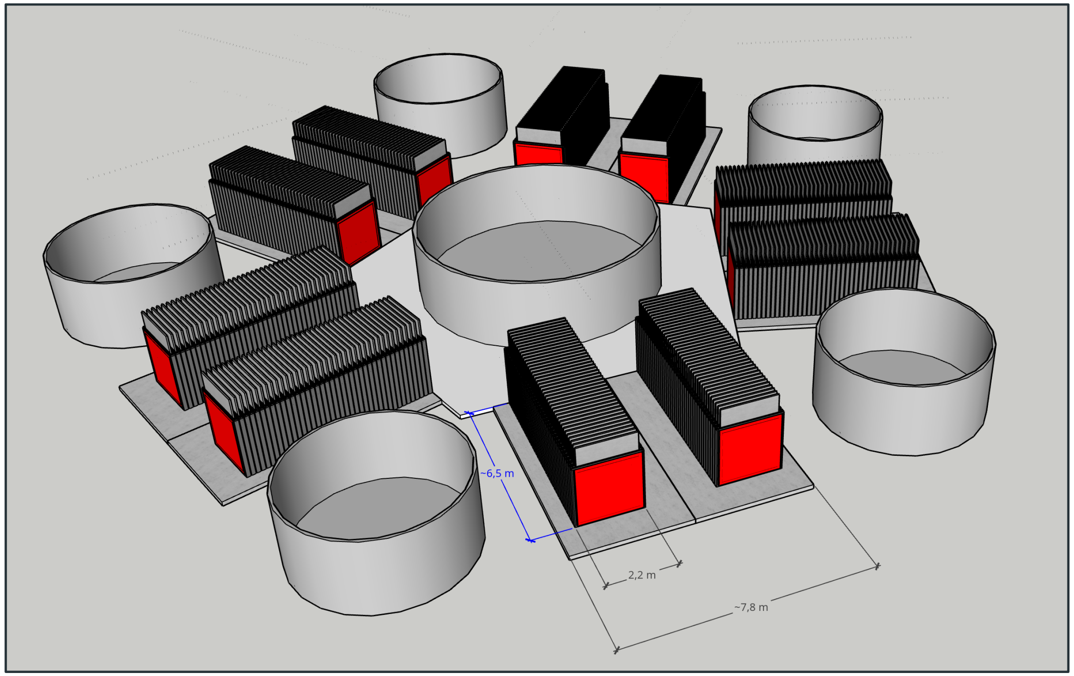


- **0-24 h**: Long-term discharge leads to **decreased voltage and specific energy**
- **@24 & 32 h**: The **voltage and specific energy are effectively recovered** by electrolyte‘s regeneration

Full cell: Al anode (1 cm^2) ; MnOx-based air cathode (4.5 cm^2)

C. Xu , S. Passerini et al. Journal of Power Sources 574 (2023) 233172

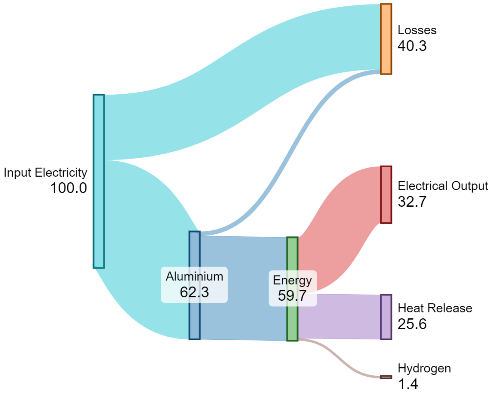
Al-air cell: Modeling of large-scale plant



Aluminium-air battery system with 400 cells and 1 MW power capacity.

System design aspects

System Parameters	Quantity	Unit
Design power	1	MW_e
Discharge duration	8	hours
Aluminium flow rate	0.2331	kg/kWh_e
Efficiency	~60	%
Heat rate	3.35	kWh/kg_{Al}
Number of Cells	400	cells
System lifetime	20	year
Annual operation days	360	days



Round-trip efficiency:
~33%

Might go up to: ~58
(with heat recovery)

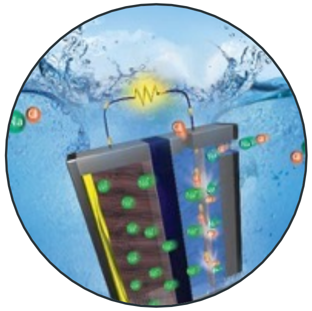
Hersoy H, , S. Passerini et al. unpublished results

Innovative Na batteries for long-term energy storage

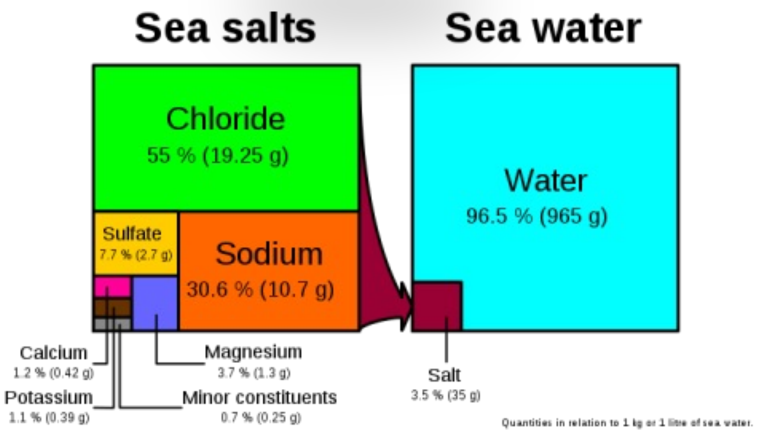
Seawater

Energy Production

"Seawater battery"



Energy Storage and Delivery



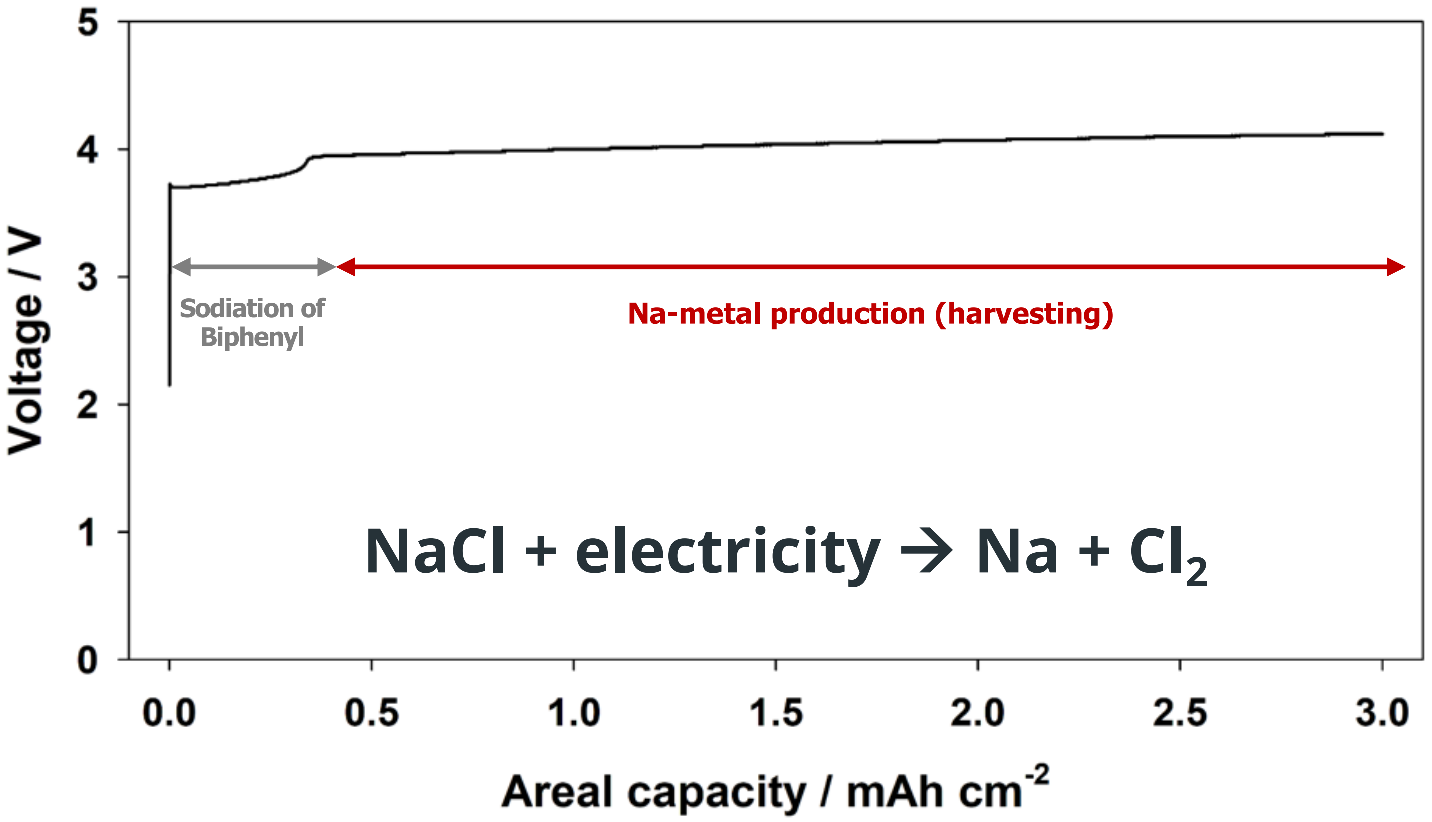
Mechanism:
Seawater batteries store energy as metallic Na through the electrolysis of NaCl

Sustainability:
Seawater is the most abundant and homogeneously distributed chemical on Earth

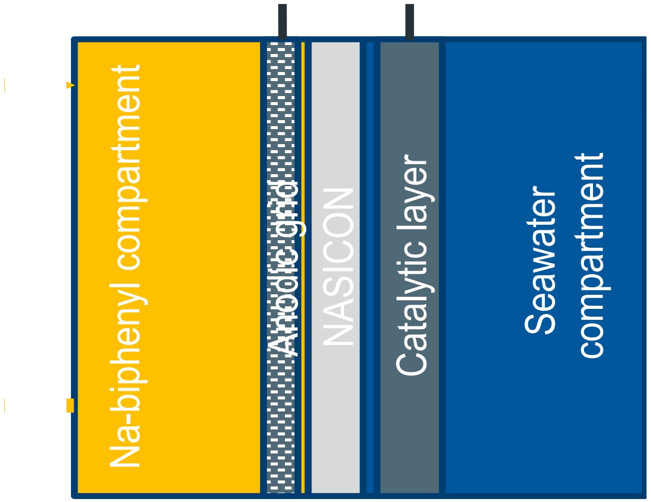
Long-term collaboration with
Prof. Youngsik Kim UNIST
Prof. YongIl Kim Gachon University

S. Passerini and coll, *J. Mater. Chem. A*, 2016, 4.19: 7202-7213.

Addressing the Energy Storage Demands: Sodium



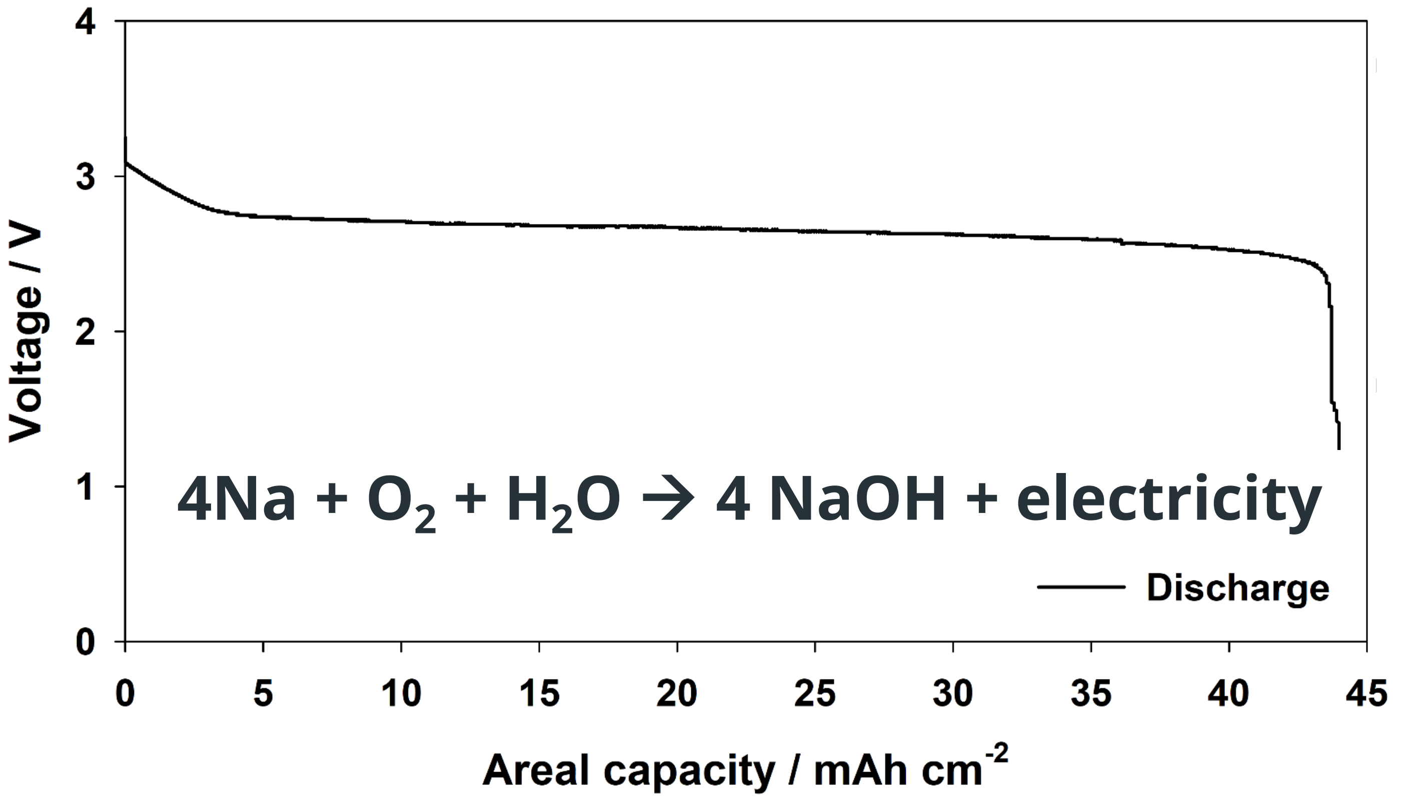
$NaCl$ + electricity → $Na + Cl_2$



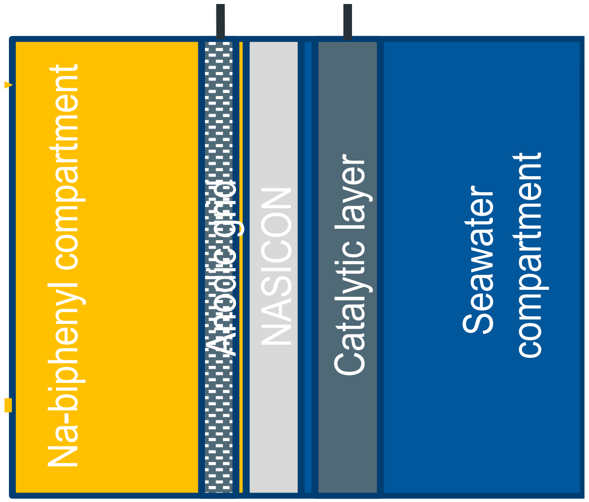
Sodium and Chlorine production and water desalinization

Y. Kim, S. Passerini et al., Adv. Funct. Mater. **2020**, 2001249; Y. Kim, G-T. Kim, A. Varzi and S. Passerini; KIT PCT WO 2022/048931 A1

Addressing the Energy Storage Demands: Sodium



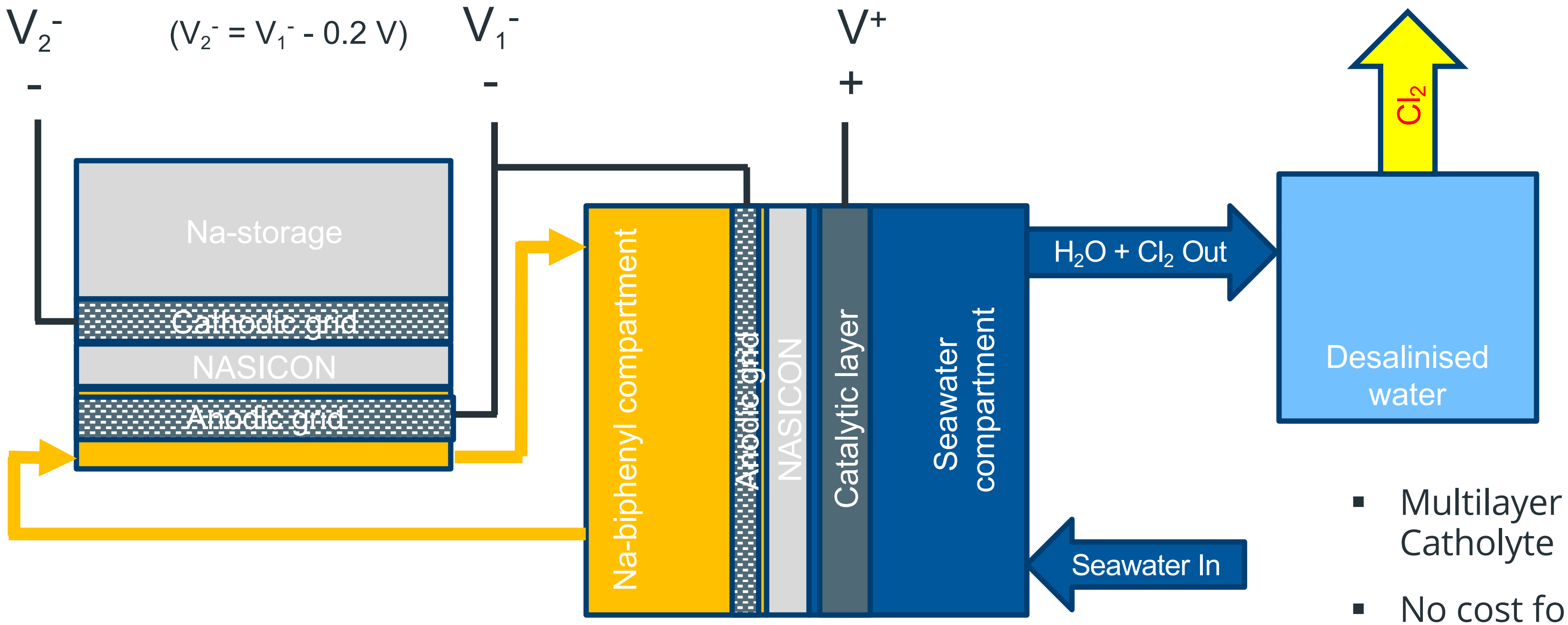
$$4Na + O_2 + H_2O \rightarrow 4\ NaOH + \text{electricity}$$



Power generation from Sodium and Seawater demonstrated
Applicable for marine transportation, on-shore and off-shore power generation

Y. Kim, S. Passerini et al., Adv. Funct. Mater. **2020**, 2001249; Y. Kim, G-T. Kim, A. Varzi and S. Passerini; KIT PCT WO 2022/048931 A1

Addressing the Energy Storage Demands : Sodium



NaBP (sol) → Na (m) + BP (sol)

$Na^+ + BP\ (sol) + 1e^- \rightarrow NaBP\ (sol)$

$Cl^- \rightarrow ½\ Cl_2$

Na-storage Unit

Na-extraction Unit

Cl_2-extraction Unit

- Multilayer electrolyte system: Catholyte | Solid electrolyte | Anolyte
- No cost for cathode using unlimited natural seawater (0.47 M NaCl)

The energy stored is proportional to the amount of Na stored

By-products: Chlorine, Desalinized water and CO_2 trapping

Y. Kim, S. Passerini et al., Adv. Funct. Mater. **2020**, 2001249; Y. Kim, G-T. Kim, A. Varzi and S. Passerini; KIT PCT WO 2022/048931 A1

Implementation Scenario – Business case: Sardinia

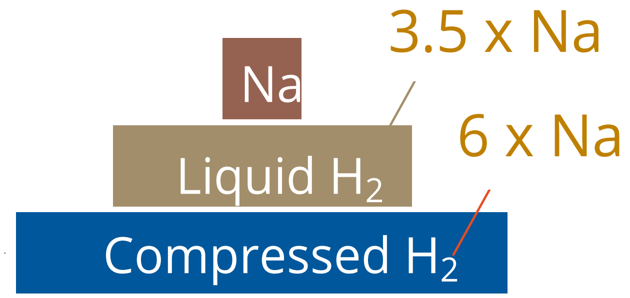
Energy characteristics:

- No natural gas network
- Old energy infrastructure
- Great Renewables potential

Primary energy use: 23.5 TWh/yr

Seasonal storage needs: 4.43 TWh

PV (69 km^2) + Seawater Battery


3.5 x Na
Na
6 x Na
Liquid H_2
Compressed H_2

High volumetric energy density
High energy efficiency (>70%)

Chlorine production

<u>131 mln di m^3</u>
(1.64 mln inhabitants)

Desalinised water production

<u>57,700 tons of CO_2</u>
36.2 g CO_2 per kWh of stored energy

CO_2 trapping

L. Barelli, S. Passerini and coll., Renewable and Sustainable Energy Reviews 187 (2023) 113701 DOI: 10.1016/j.rser.2023.113701

Summary

Al, Na and other abundant metal-based energy systems can help addressing several (and rather different) energy storage issues:

Sustainable Transportation (existing and fast-growing market)

Innovative approaches for marine transportation (Al conversion and Na-seawater batteries)

Delocalized power generation for the EV charging infrastructure via reactive metals (Al, Fe, Na, Ca, Mg, …)

Energy Storage (huge market perspectives)

Stationary storage (Na-seawater batteries)

Seasonal/annual electrochemical and hybrid storage via reactive metals (Al, Fe, Na, Ca, Mg,)

Addressing the Energy Storage Demands – Green Circles

TECHNISCHE UNIVERSITÄT DARMSTADT
KIT Karlsruher Institut für Technologie
MAX PLANCK INSTITUTE FOR SUSTAINABLE MATERIALS
DLR
JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ
UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386
h_da HOCHSCHULE DARMSTADT UNIVERSITY OF APPLIED SCIENCES

https://www.tu-darmstadt.de/clean-circles/about_cc/index.de.jsp

Acknowledgment

Federal Ministry of Education and Research

HELMHOLTZ ASSOCIATION

StoRIES

MINISTERO DELLA TRANSIZIONE ECOLOGICA

ENAM Electrochemistry and Nanotechnologies for Advanced Materials

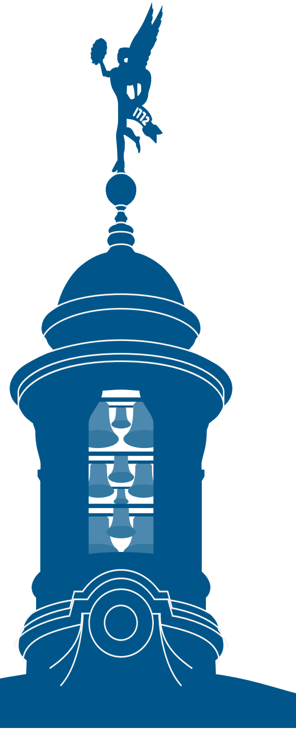
www.hiu-batteries.de

be displayed.

University of Perugia Prof. Linda Barelli

Universität
Münster

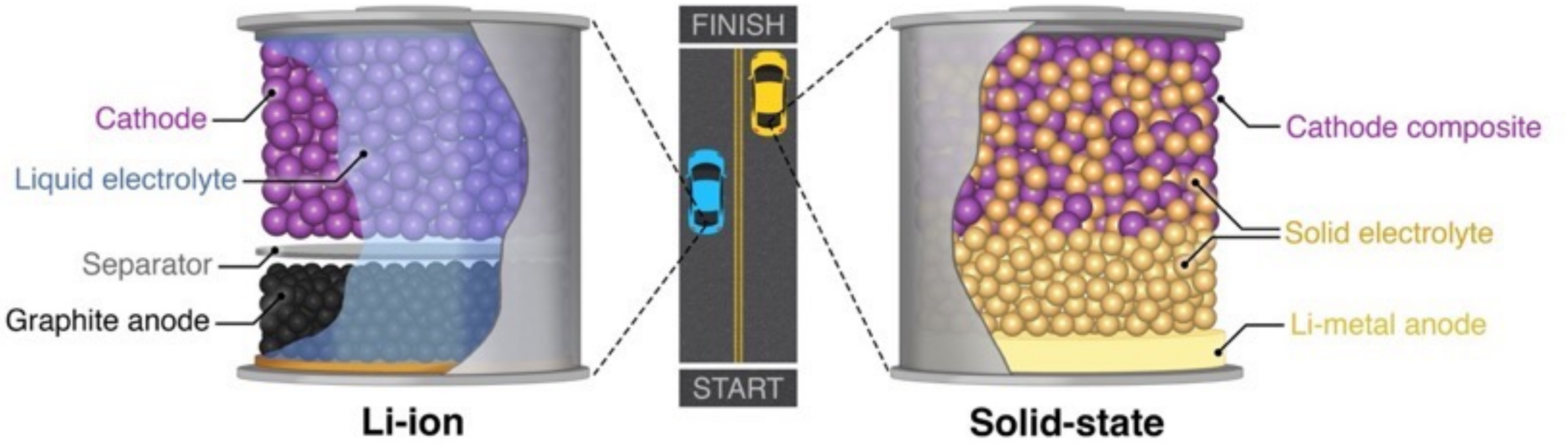
Towards realistic solid-state batteries: overcoming transport limitations in electrodes



wzeier@uni-muenster.de
w.zeier@fz-juelich.de

JÜLICH Forschungszentrum | HELMHOLTZ-INSTITUT MÜNSTER

Why is the world (seemingly) going solid?

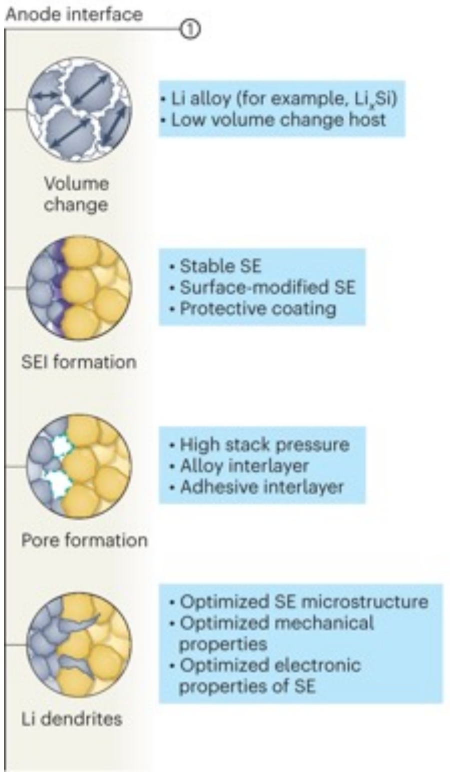


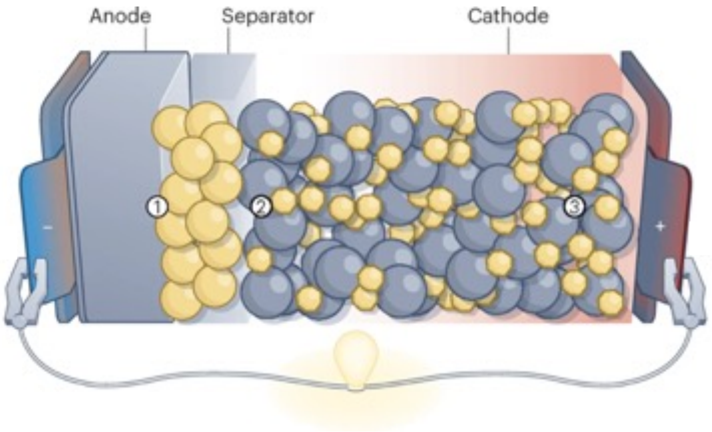
Projected higher safety = no liquid

Projected higher energy density = longer driving range

Projected higher power density = faster charging

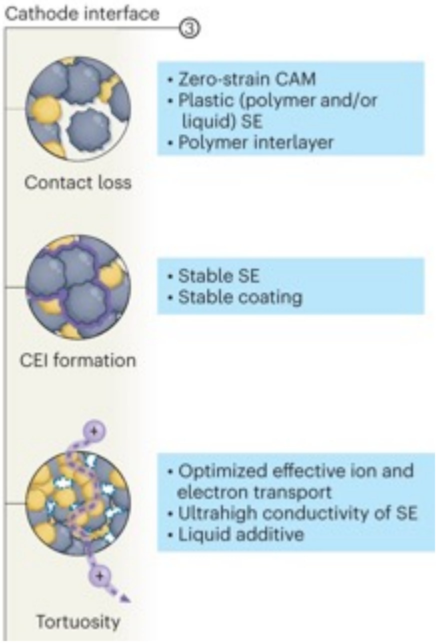
Diverse options come with a variety of challenges





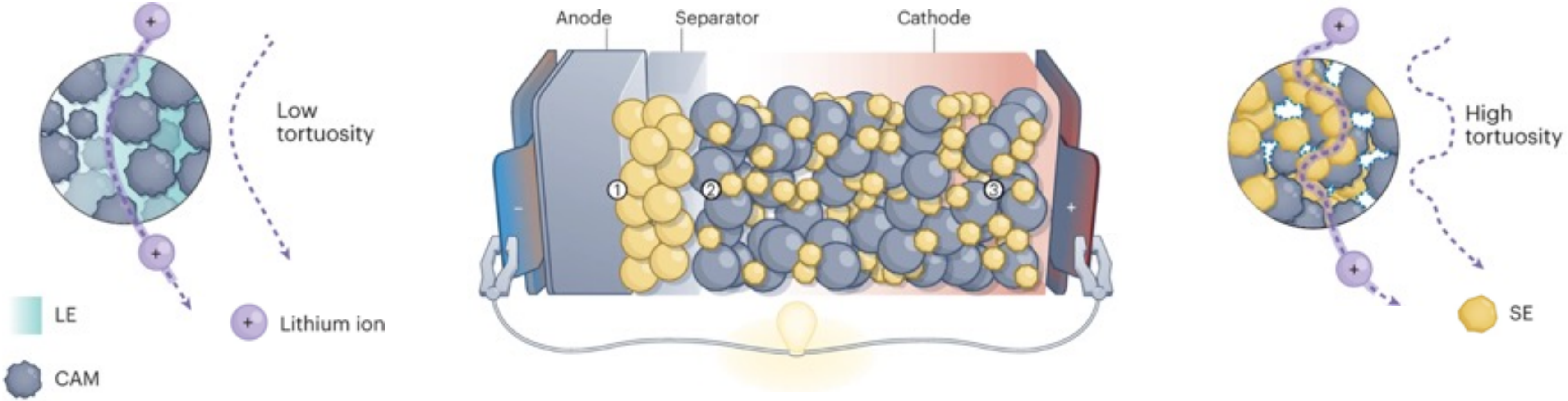
Variety interfacial challenges: interfaces, chemomechanics, and transport limitations…

…all as a function of all these different active materials and solid electrolytes



Janek, Zeier *Nature Energy* **2023**, *8*, 230

Optimizing transport in electrolytes and composites



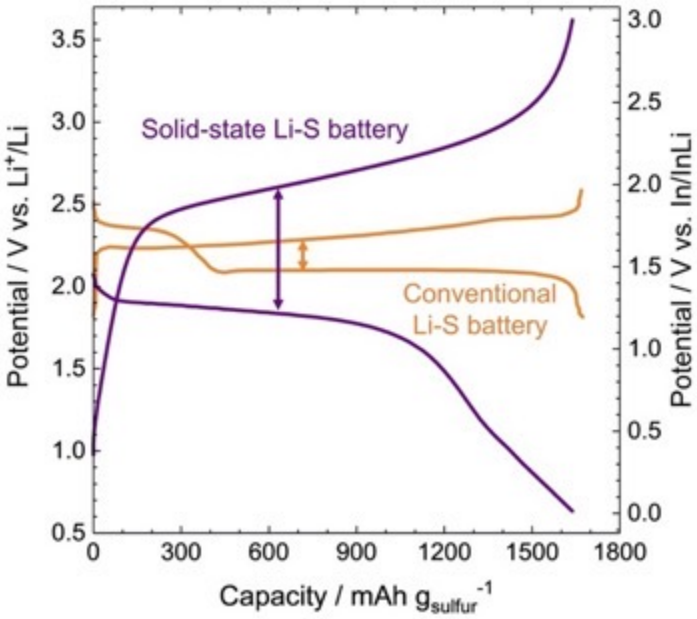
An electrochemical reaction needs both, ions and electrons in ample supply!

In other words, besides optimizing a solid state compounds property, we also need to optimize it in the application directly.

Problem: Depends on material, particle size, porosity, etc..

Janek, Zeier *Nature Energy* **2023**, *8*, 230

Solid-state batteries have local transport problems

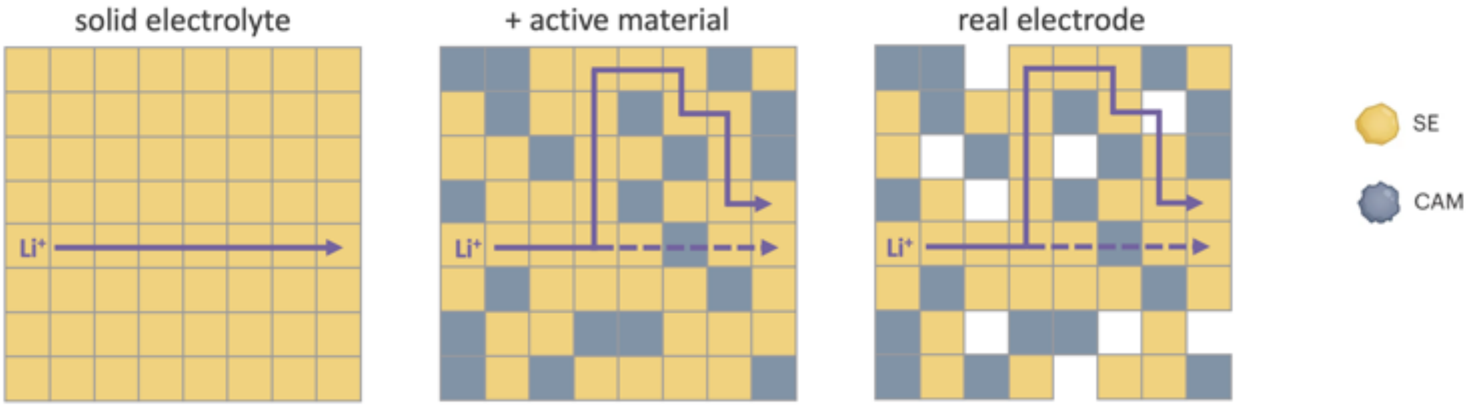


IR drop: large internal resistance, overpotential

Often **larger overpotentials in solid-state batteries**, especially at high loadings and high current densities

S. Ohno *et al. Adv. Funct. Mater.* **2021**, 2010620

Effective ionic transport decreases strongly in composites



We now have an effective transport in two (**three**) phases, no longer just one!

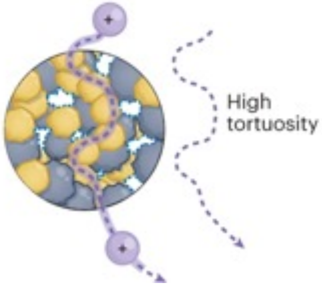
Volume fraction of SE

Effective ionic conductivity

$$\sigma_{\text{eff}} = \frac{\varepsilon}{\kappa} \cdot \sigma$$

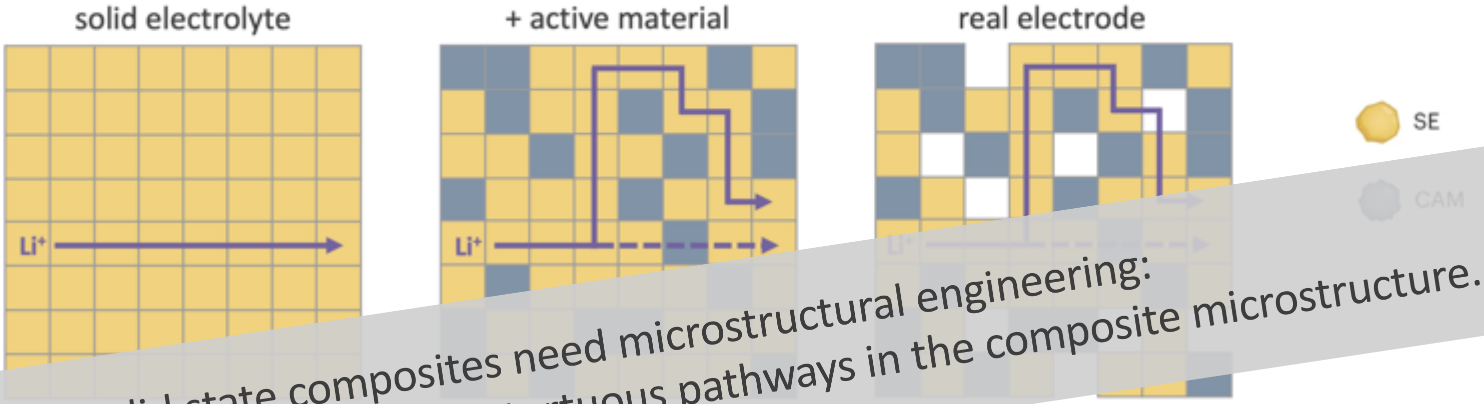
Ionic bulk conductivity

Tortuosity factor



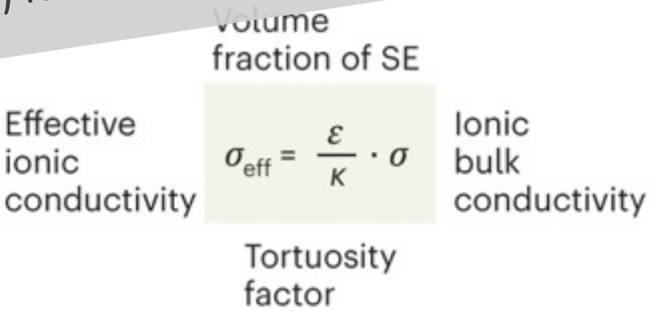
Janek, Zeier *Nature Energy* **2023**, *8*, 230

Effective ionic transport decreases strongly in composites

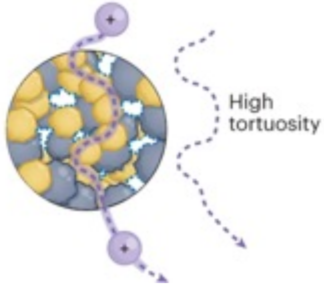


Solid state composites need microstructural engineering:
(1) faster ionic conductors and (2) less tortuous pathways in the composite microstructure.

We now have an effective transport in two (**three**) phases, no longer just one!



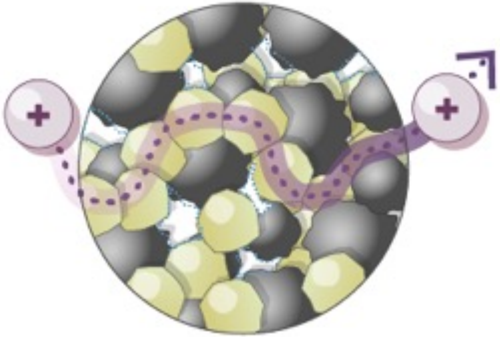
$$\sigma_{\mathrm{eff}} = \frac{\varepsilon}{\kappa} \cdot \sigma$$



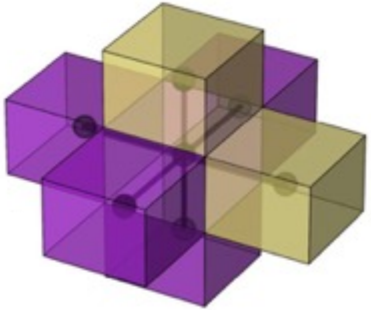
Janek, Zeier *Nature Energy* **2023**, *8*, 230

A short story on transport limitations in electrodes

Transport limitations in SSB

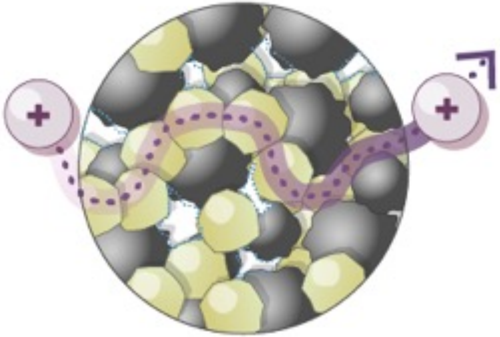


Streamline solid state composites

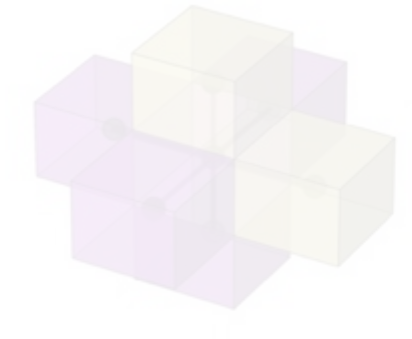


What else are these limitations affecting?

Transport limitations in SSB

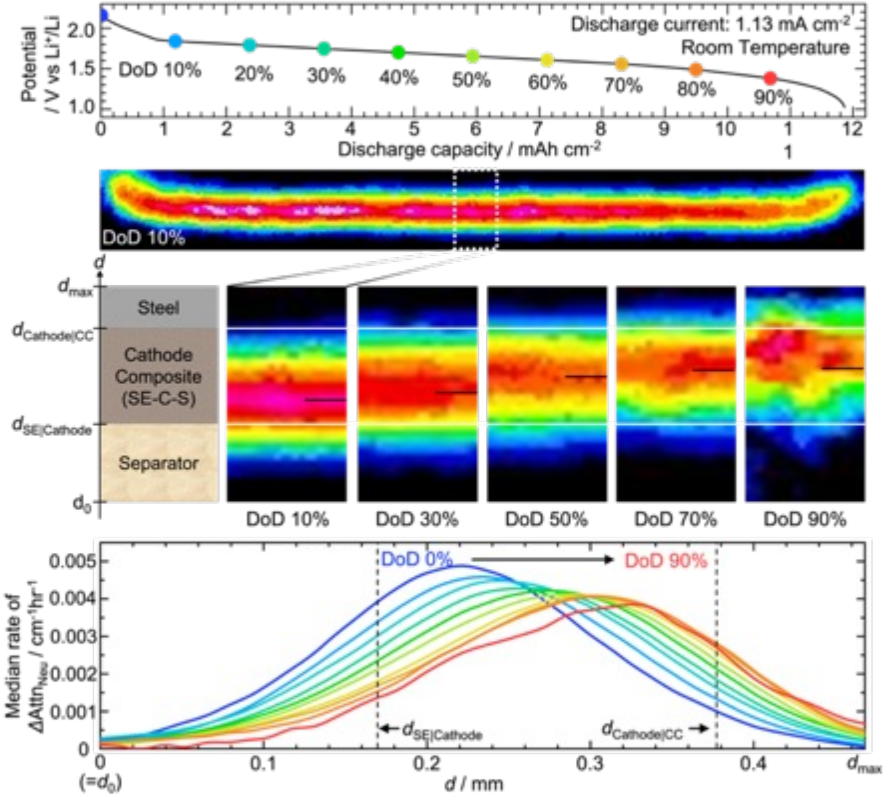


Streamline solid state composites

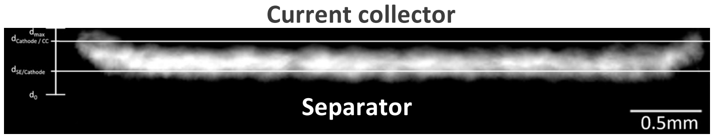


Influence of tortuosity and transport in cathode composites not understood, can we overcome them?

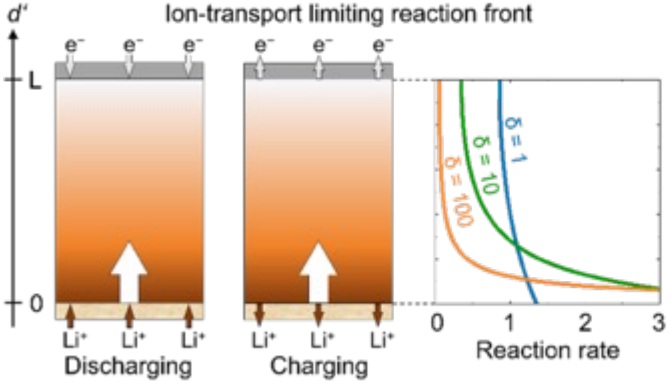
Inhomogeneous reaction front observable in SSB



Discharge means S converts to Li_2S

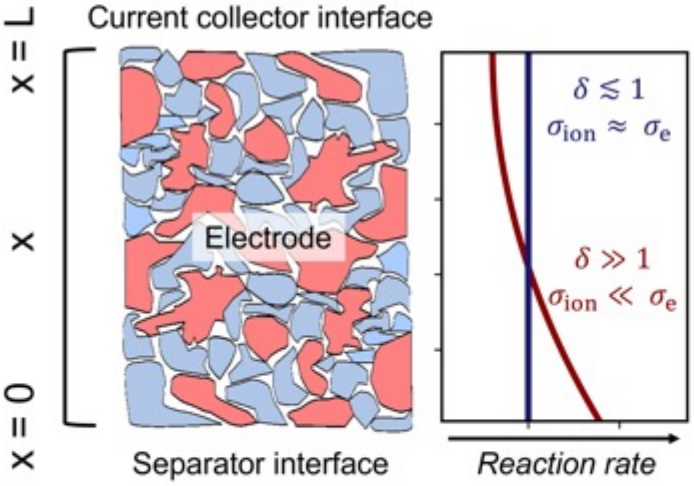


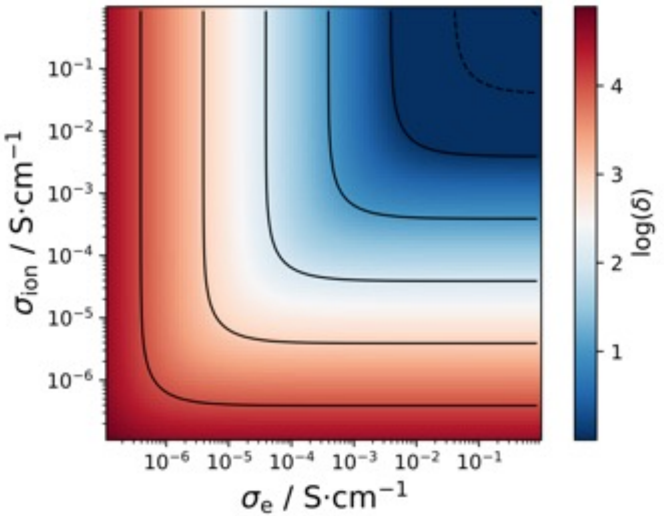
Reaction front starting from the separator visible due to transport imbalance!



R. Bradbury *et al.* *Adv. Energy Mater* **2023**, 2203426
Tomography performed in collaboration with Ingo Manke (HZB), Saneyuki Ohno (Tohoku Univ.)

δ −parameter: balancing of transport parameters





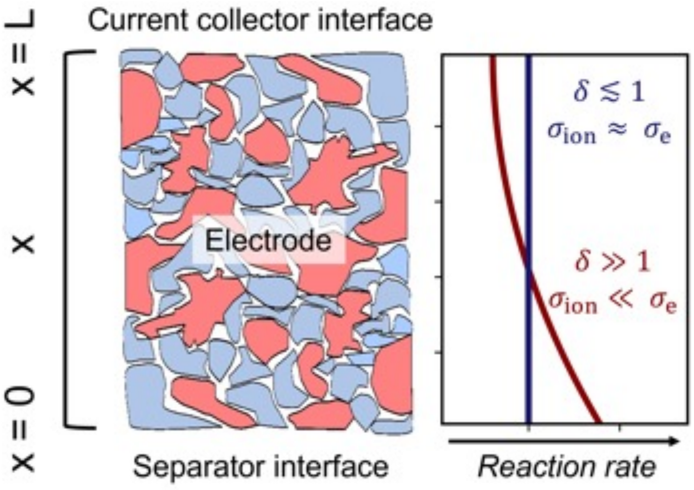
For homogenous transport, δ-parameter needs to be minimized:

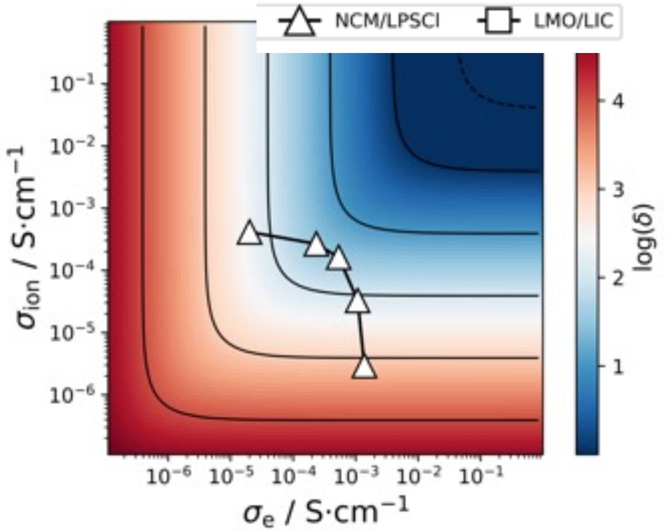
$$\delta = L \cdot I \cdot \frac{nF}{RT} \cdot \left(\frac{\sigma_{ion} + \sigma_e}{\sigma_{ion} \cdot \sigma_e}\right)$$

- Increasing thickness L and
- increasing current density (C-rate)

T. Bernges *et al. EES Batteries*, **2025**, doi:10.1039/d4eb00005f

What is this δ −parameter really?





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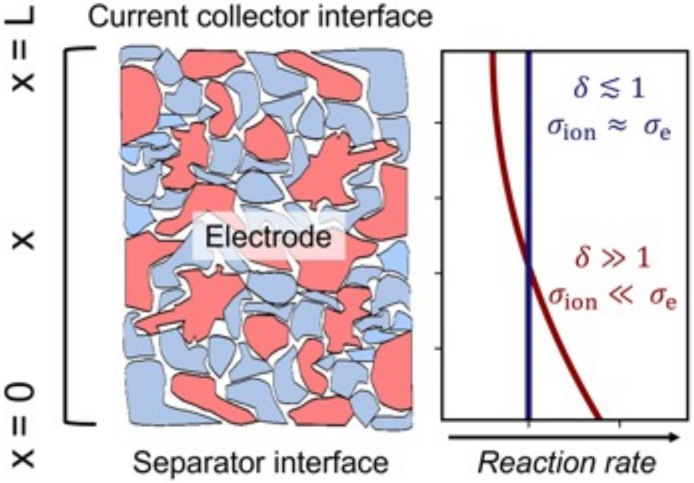

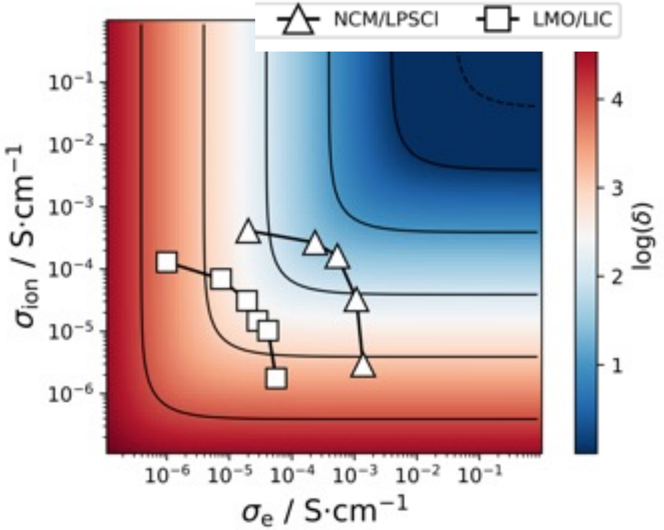

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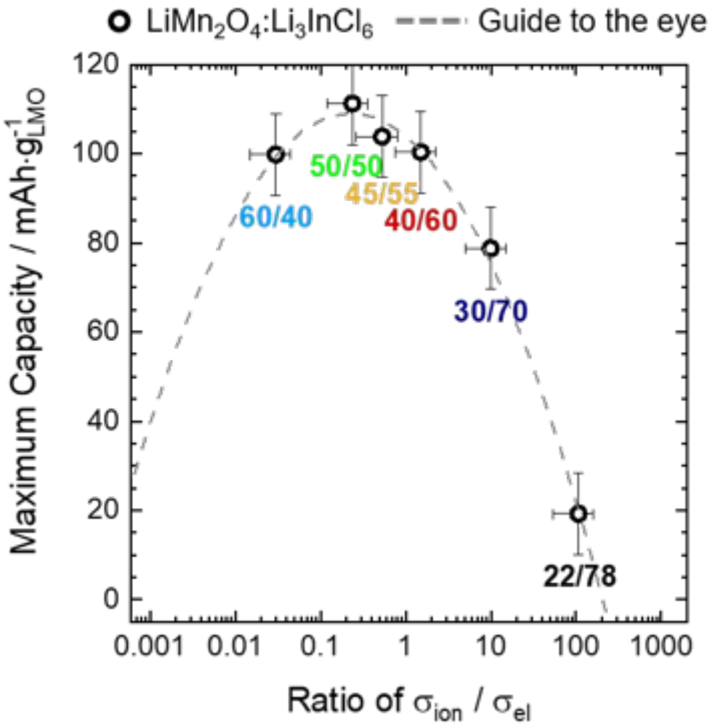
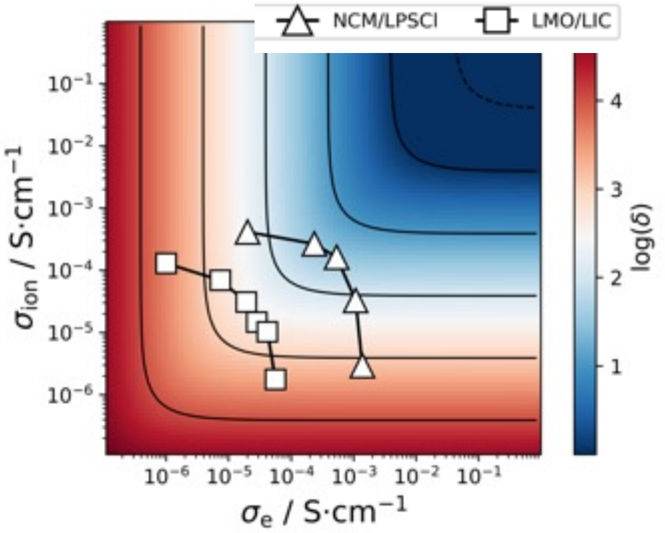
- Increasing thickness L and
- increasing current density (C-rate)

T. Bernges *et al. EES Batteries*, **2025**, doi:10.1039/d4eb00005f

For instance, taking $LiMn_2O_4$ / Li_3InCl_6 – balancing is important

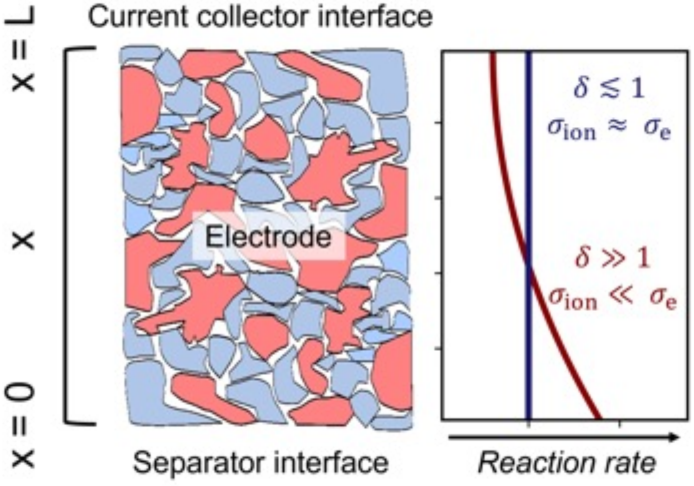
How much we energy we can store

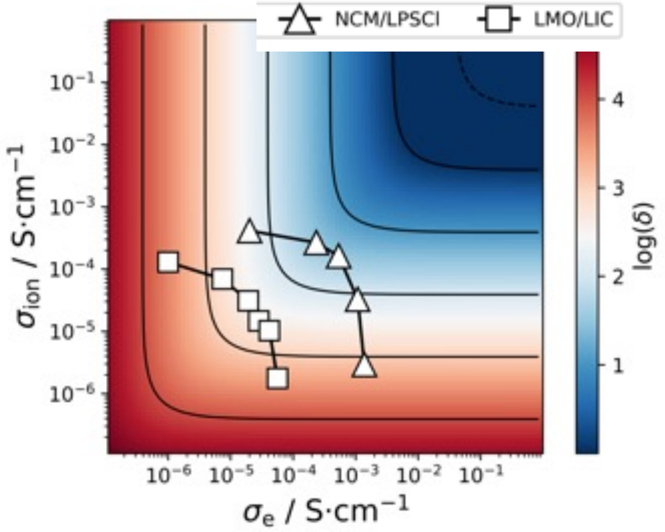




T.A. Hendriks *et al. Batteries & Supercaps* **2023**, e202200544
T. Bernges *et al. EES Batteries*, **2025**, doi:10.1039/d4eb00005f

What is this δ −parameter really?





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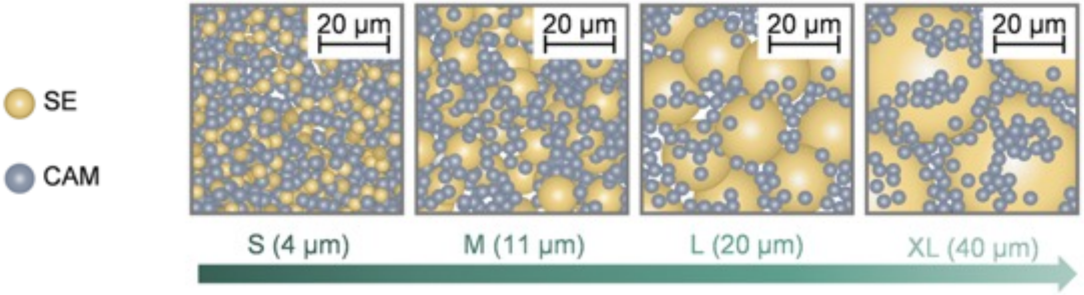
$$\delta = L \cdot I \cdot \frac{nF}{RT} \cdot \left(\frac{\sigma_{ion} + \sigma_e}{\sigma_{ion} \cdot \sigma_e}\right)$$

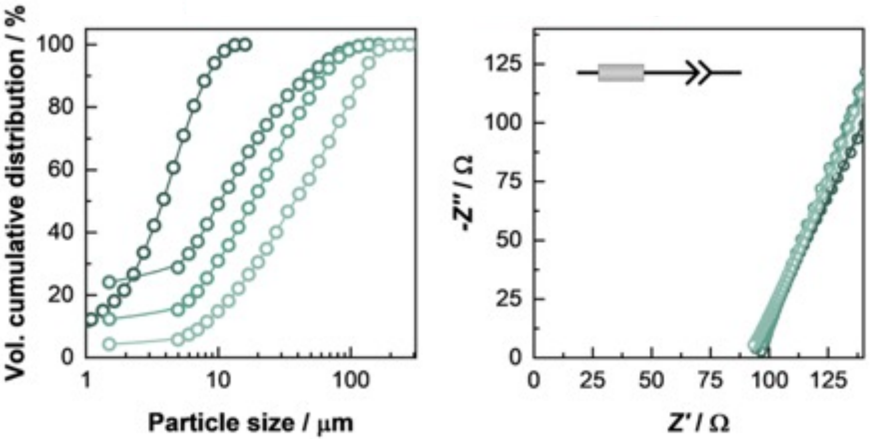
Quite some optimization, especially when changing compositions and microstructures…

T. Bernges *et al. EES Batteries*, **2025**, doi:10.1039/d4eb00005f

Option 1: Playing with the particle sizes of the SE



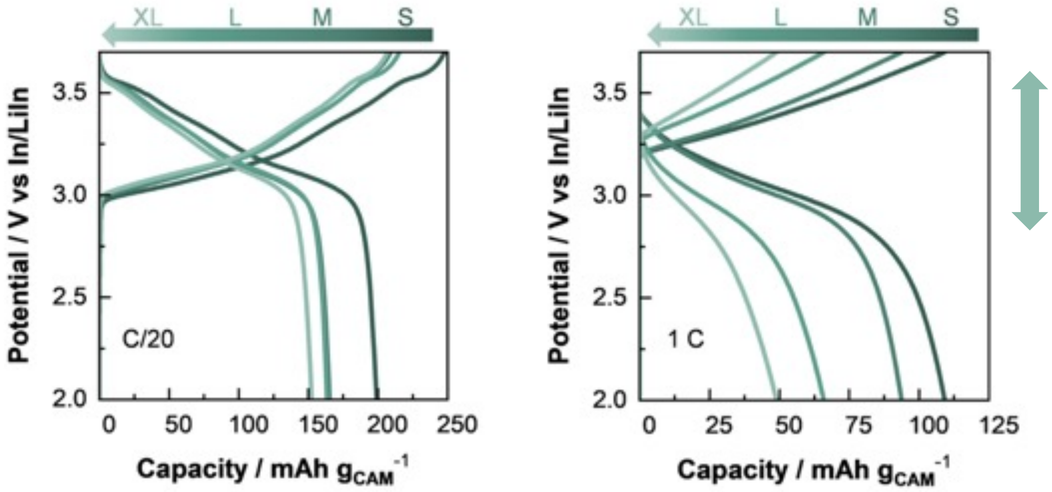
Li_6PS_5Cl SE can have different PSD...



... and the conductivity of the SE does not change.

E. Schlautmann *et al. Adv. Energy Mater.* **2023**, 2302309
In collaboration with AMG Lithium

How does it affect cycling: part 1



IR drop: large internal resistance, overpotential

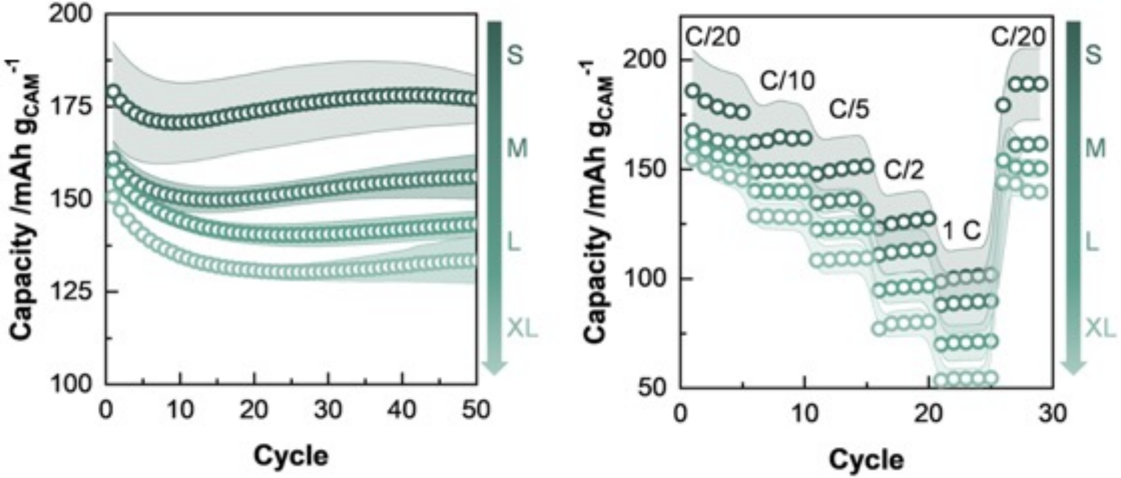
Higher overpotentials and lower capacity for larger SE particles.

Overpotential in the cells significantly affected at higher C-rates.

Clearly, resistance plays a role? But the conductivity of the SE did not change…

E. Schlautmann *et al.* *Adv. Energy Mater.* **2023**, 2302309

How does it affect cycling: part 2



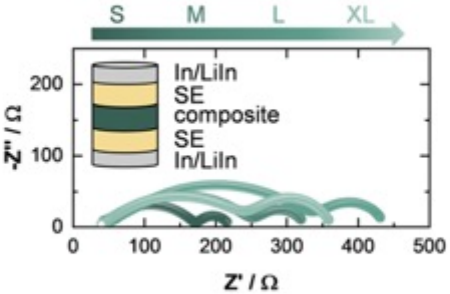
Lower capacity for larger SE particles. All triplicate cells.

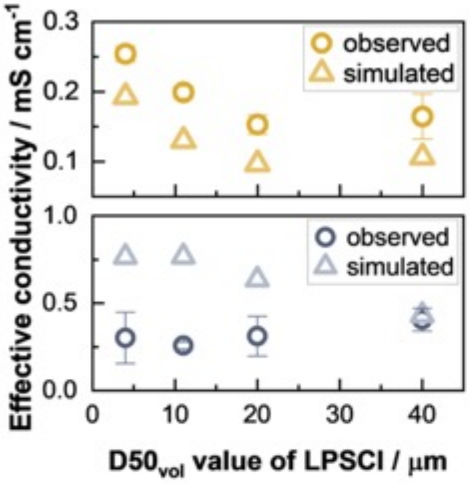
C-rate tests also show smaller SE particles are better.

Question: How does the transport change in these composites?

E. Schlautmann *et al. Adv. Energy Mater.* **2023**, 2302309

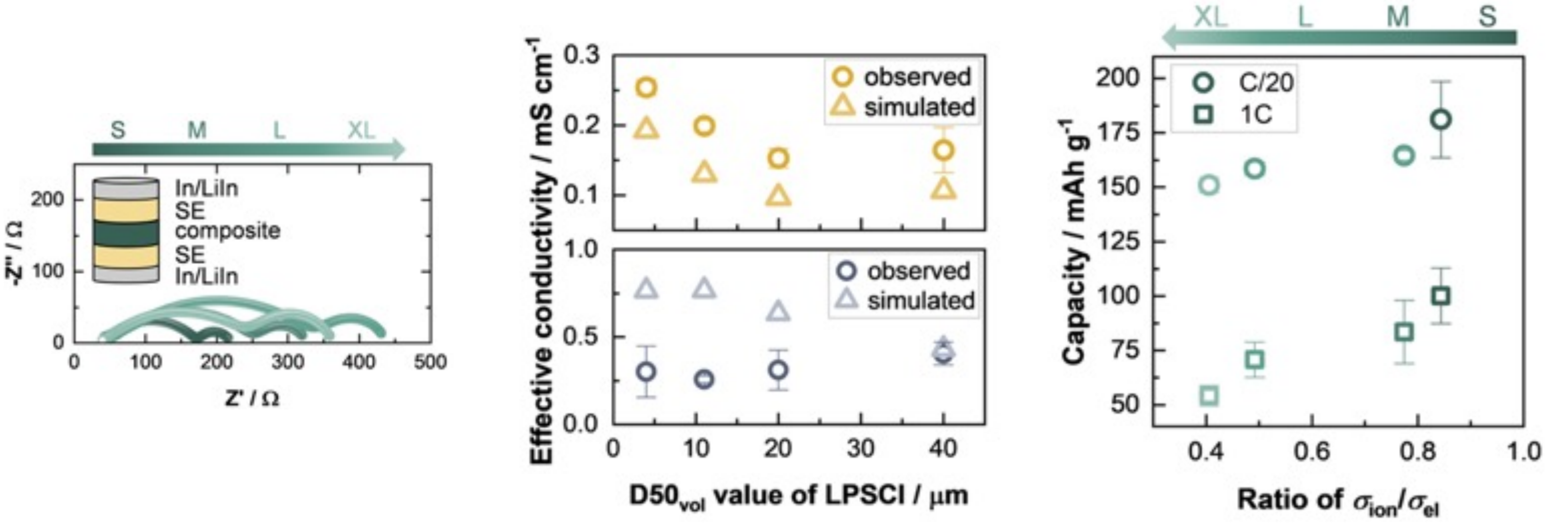
Ionic transport changes, electronic does not





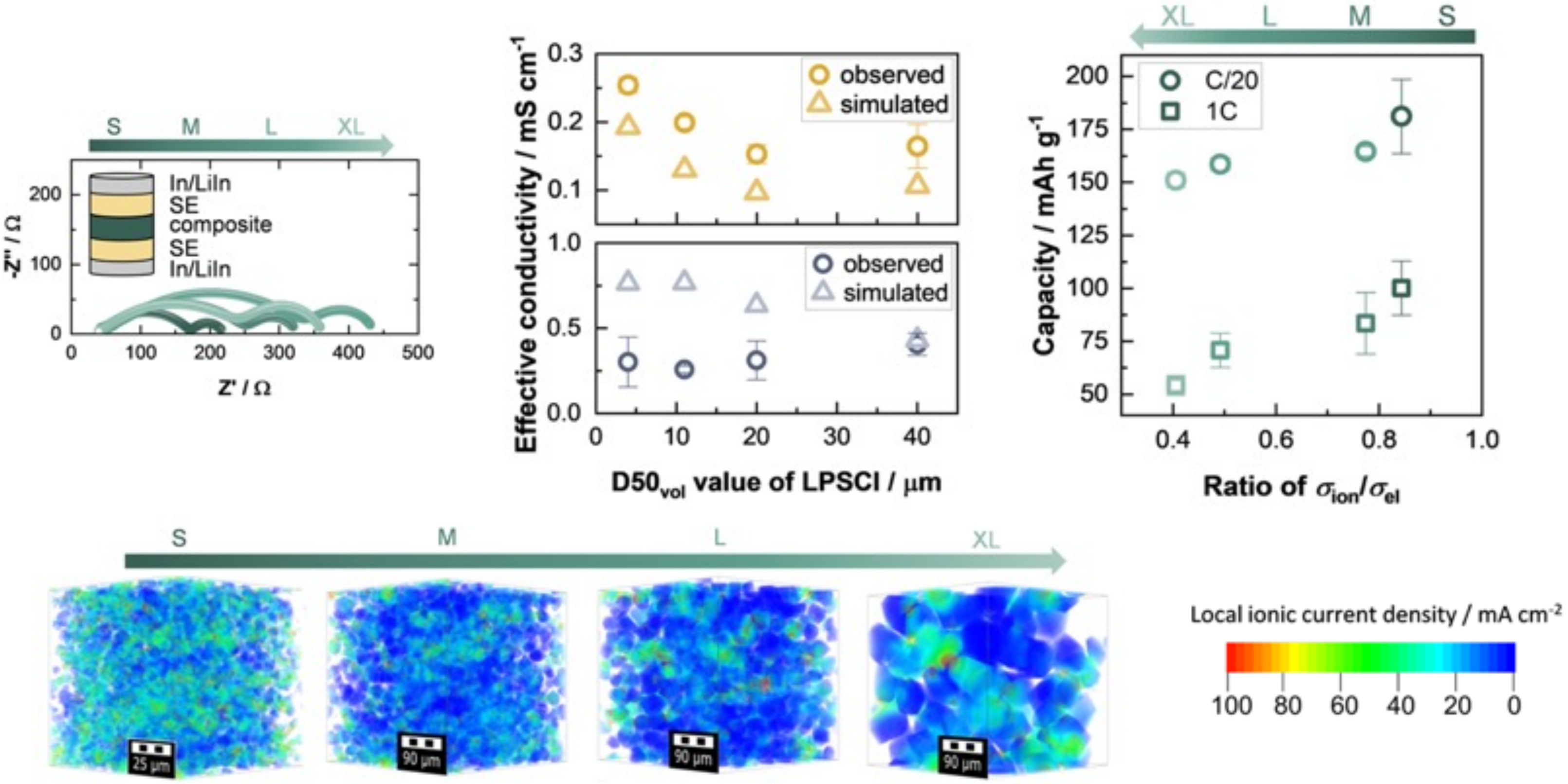
E. Schlautmann *et al. Adv. Energy Mater.* **2023**, 2302309

Capacity increases the closer both transport values are



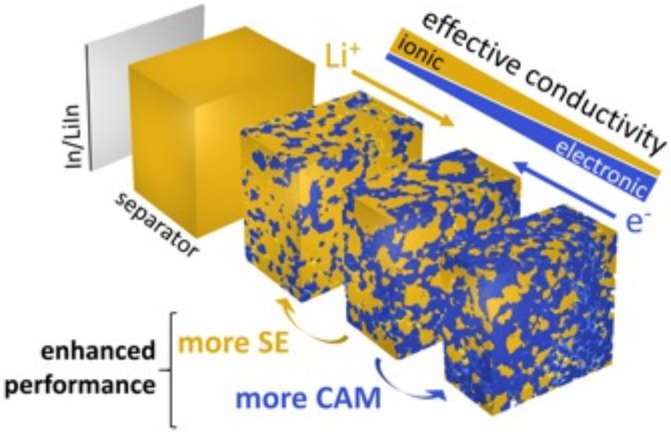
E. Schlautmann *et al. Adv. Energy Mater.* **2023**, 2302309

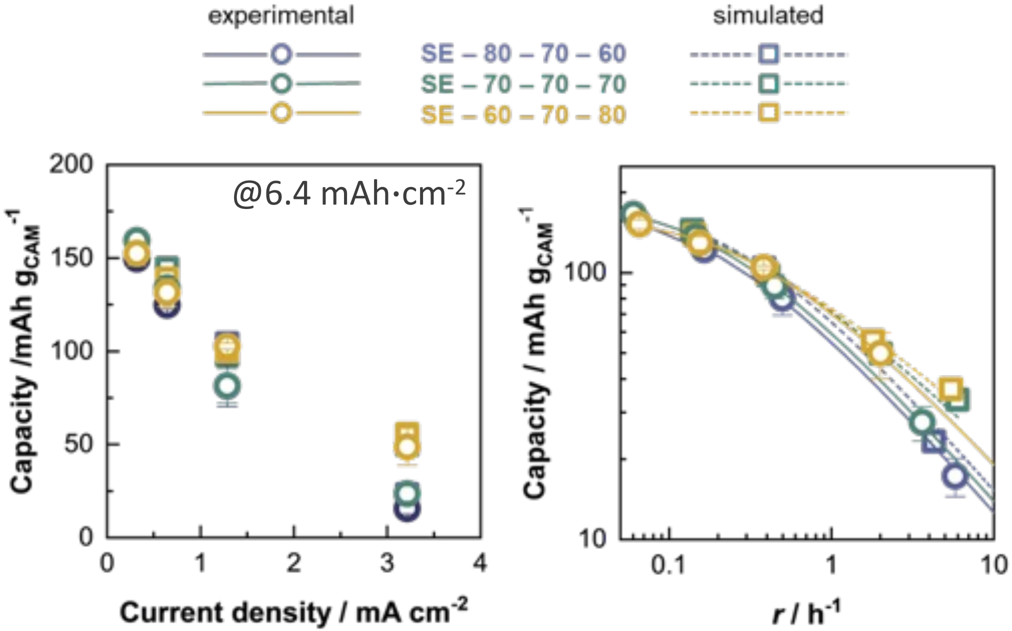
Small particles lead to higher and more uniform current



E. Schlautmann *et al. Adv. Energy Mater.* **2023**, 2302309
In collaboration with Anja Bielefeld (Univ. of Giessen)

Option 2: Gradient design of electrodes





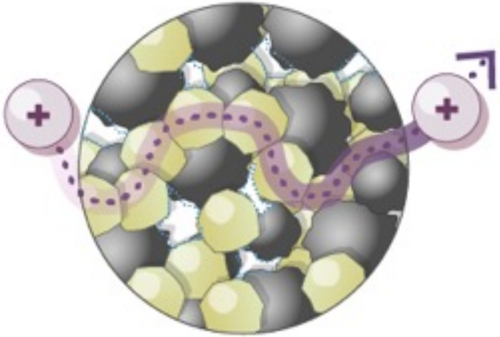
Measuring and understanding transport opens route for optimization!

E. Schlautmann *et al. unpublished*

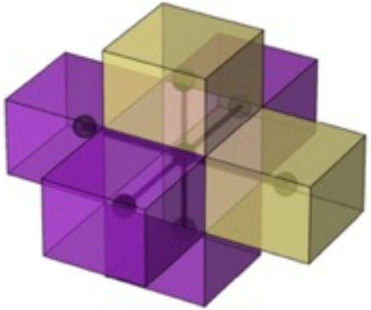
In collaboration with Arnulf Latz & Timo Danner (DLR)

Is it possible to streamline?

Transport limitations in SSB



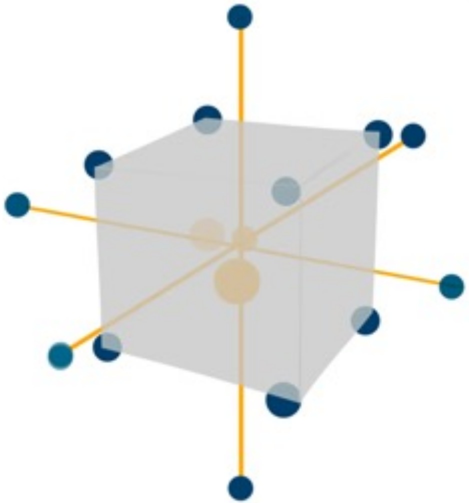
Streamline solid state composites



Measuring a property of a single system is one thing… but how can we streamline composite work?

Optimizing cells based on partial transport is tedious…

Huge parameter space

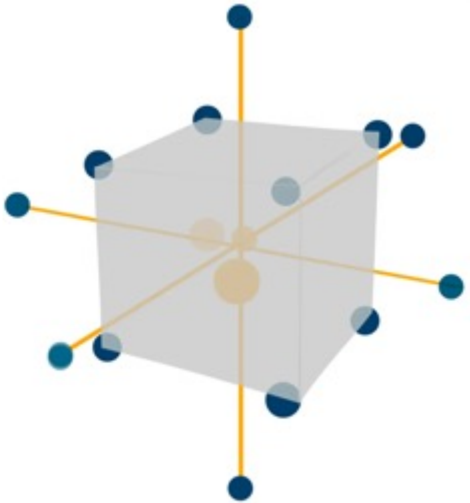


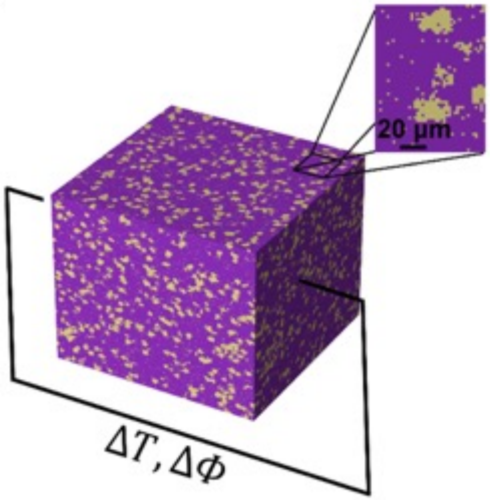
What if we could streamline this?

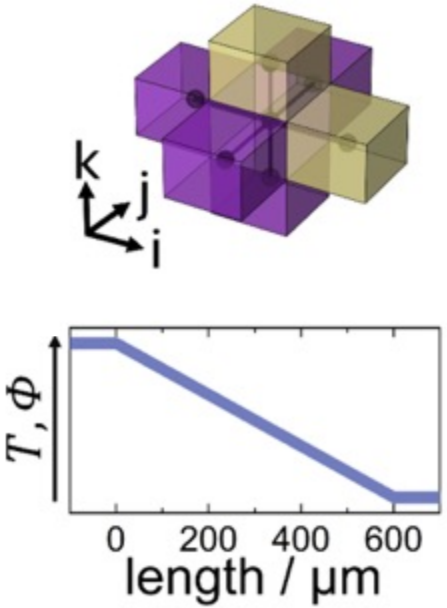
L. Ketter *et al. unpublished*

Optimizing cells based on partial transport is tedious…

Huge parameter space







What if we could streamline this? Resistor – network models help.

L. Ketter *et al. unpublished*

Optimizing cells based on partial transport is tedious…

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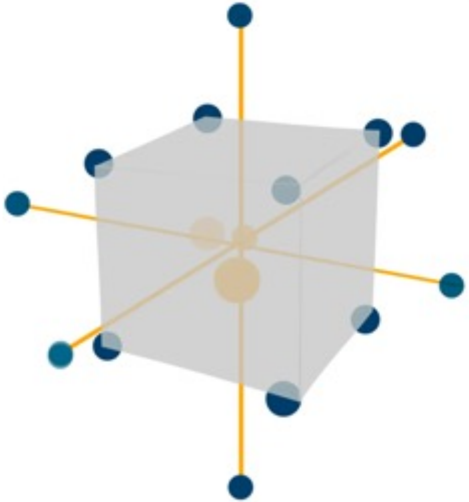
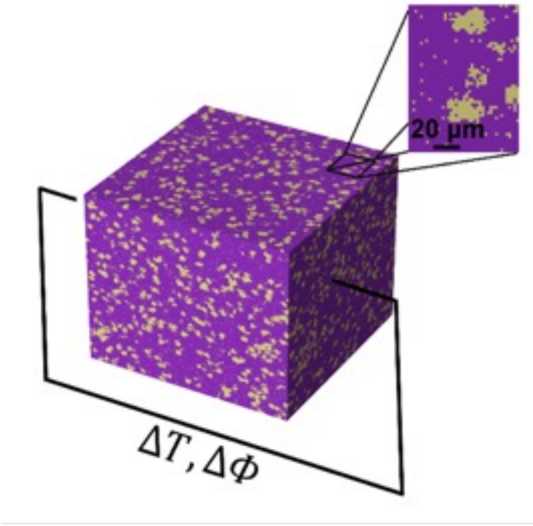
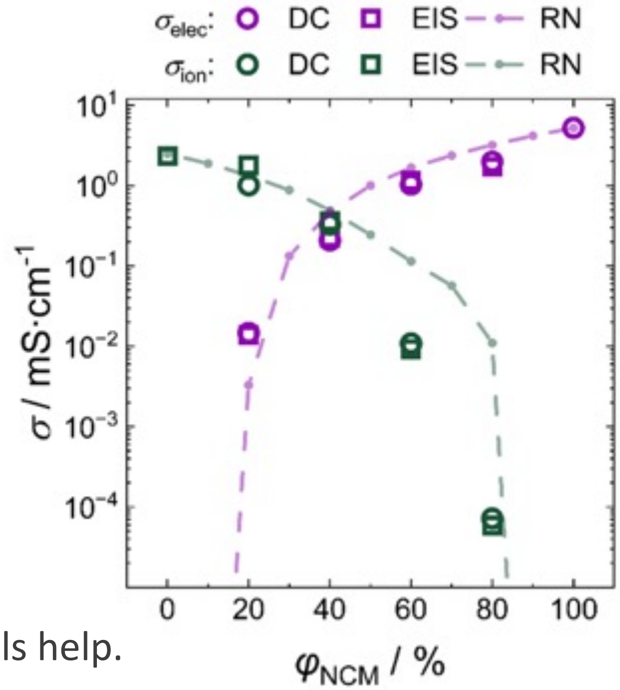




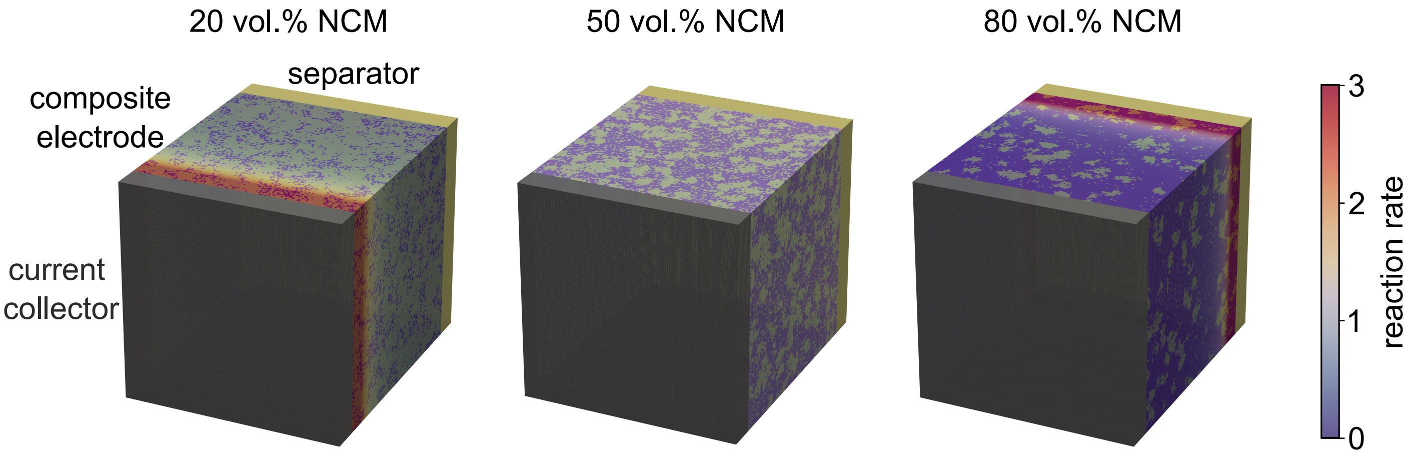


What if we could streamline this? Resistor – network models help.

Will not replace full continuum models for understanding, but faster starting point for experimentalists.

L. Ketter *et al. unpublished*

Resistor network model also captures thresholds

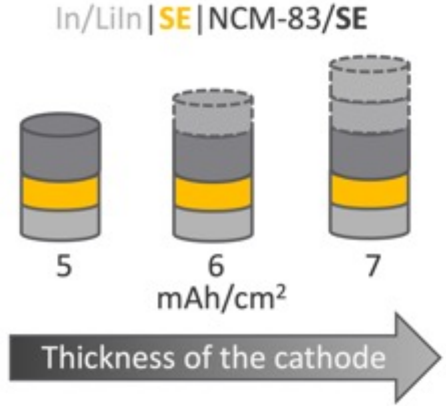


Resistor network model can be used to screen compositions and predict initial reaction rates using Newman model.

Minecraft science works!

L. Ketter *et al. unpublished*

Option 3: Faster solid electrolyte needed in thicker electrodes



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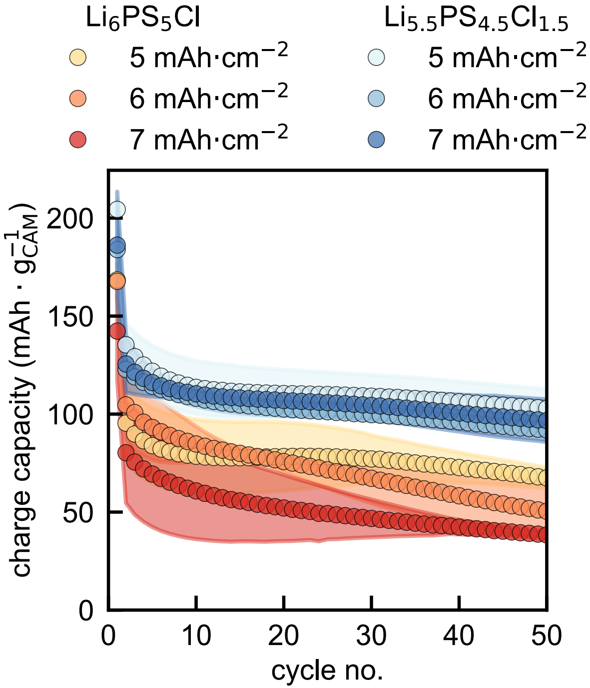
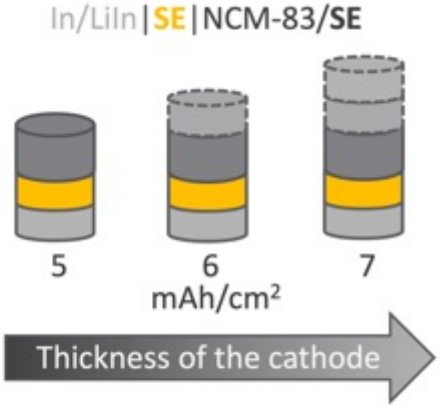


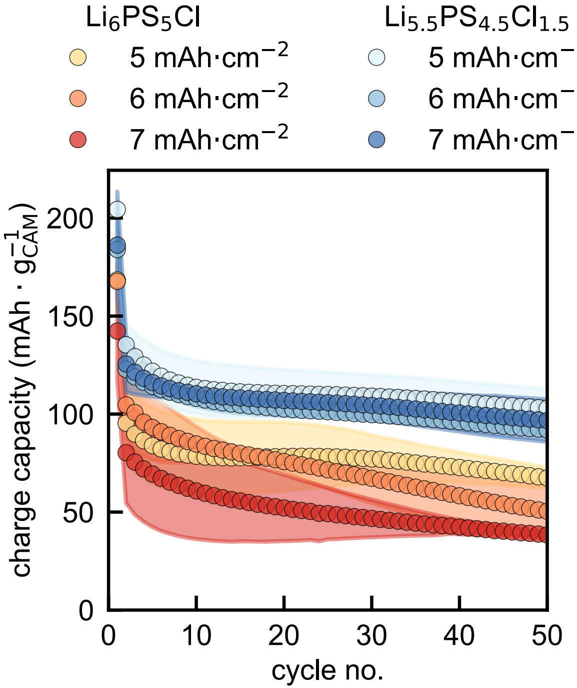
Less performance loss, if faster solid electrolyte is used in high loading SSB cells

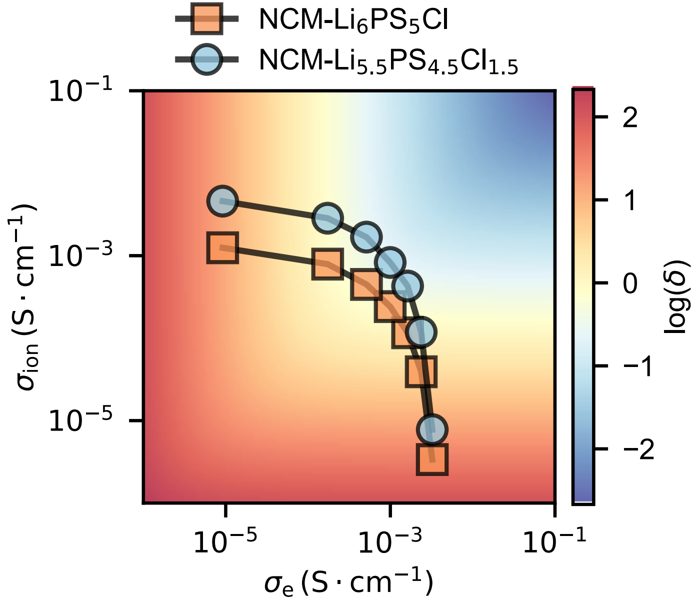
L. Ketter *et al. unpublished*

Option 3: Faster solid electrolyte needed in thicker electrodes



$$\delta = L \cdot I \cdot \frac{nF}{RT} \cdot \left(\frac{\sigma_{ion} + \sigma_e}{\sigma_{ion} \cdot \sigma_e}\right)$$





Less performance loss, if faster solid electrolyte is used in high loading SSB cells

L. Ketter *et al. unpublished*

Universität Münster

JÜLICH Forschungszentrum | HELMHOLTZ-INSTITUT MÜNSTER

Thank you for your attention

Solid state batteries are at the brink of commercialization.

Effective transport in composites and SSB needs to be measured and needs to be high.

Thick electrodes and more realistic loadings are a challenge for industry so far.

FEST BATT Cluster of Competence for Solid-state Batteries

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