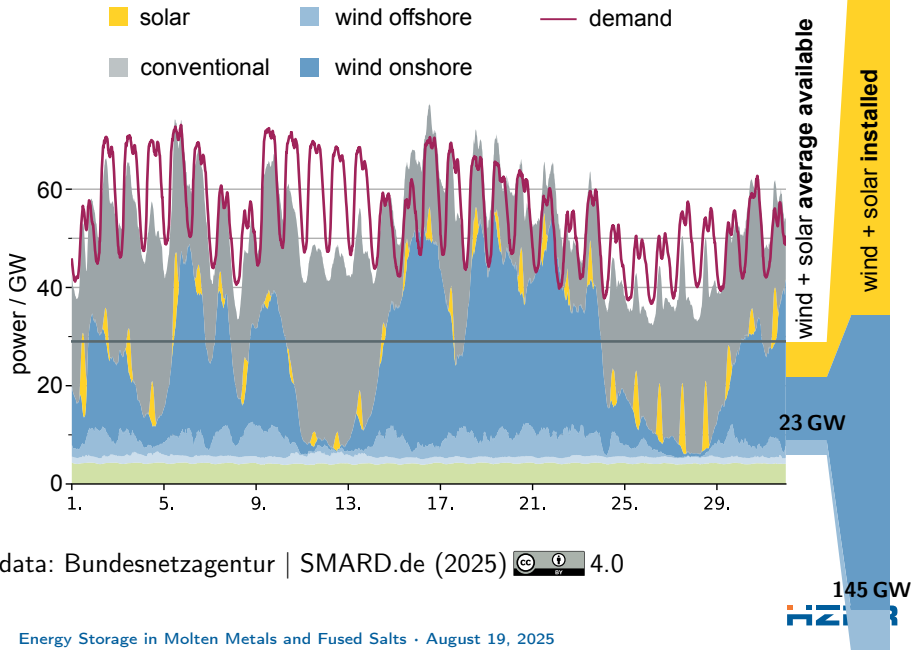


Energy Storage in Molten Metals and Fused Salts

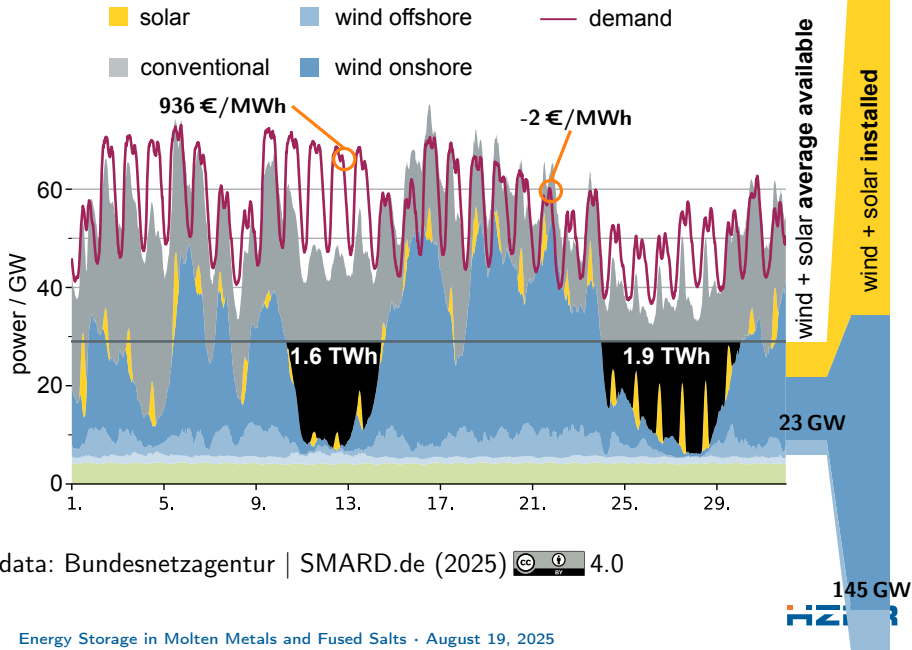
Tom Weier

August 19, 2025

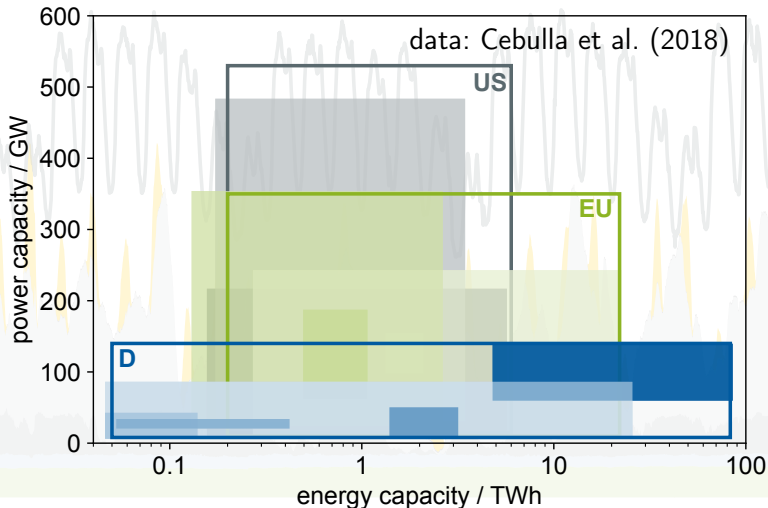
Electricity in Germany December 2024



Electricity in Germany December 2024

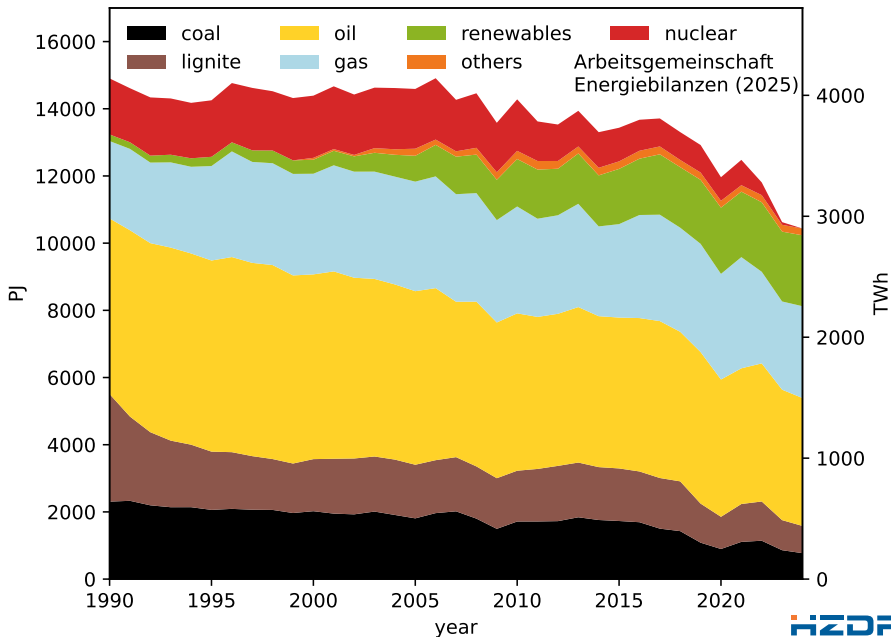


Storage demand for variable renewable energies

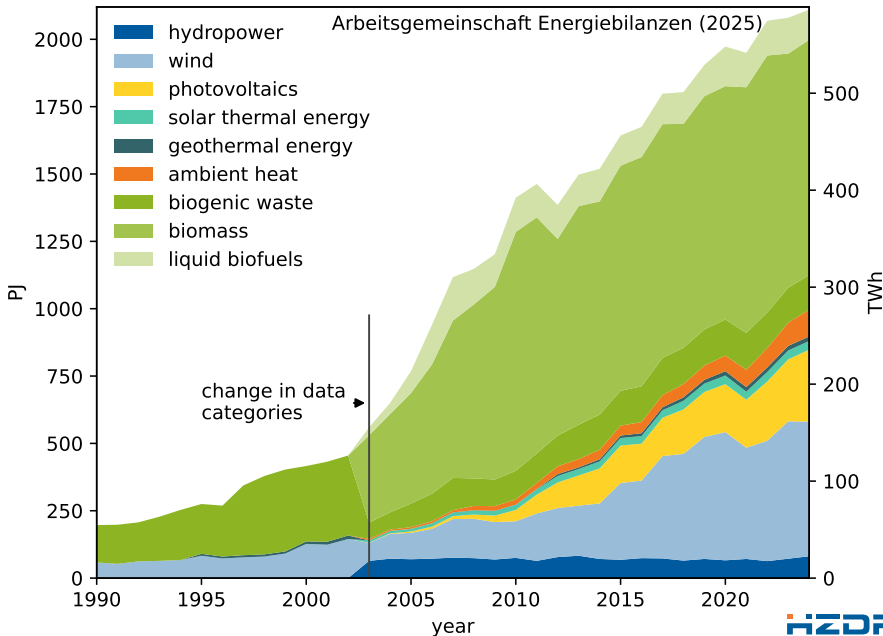


share of renewables $\geq 80\%$

Primary energy in Germany by sources



Renewable primary energy in Germany by sources



Norsk Hydro ASA Sunndal

Norsk Hydro, 2010



400 000 t Al/year, 15.3 GWh/day

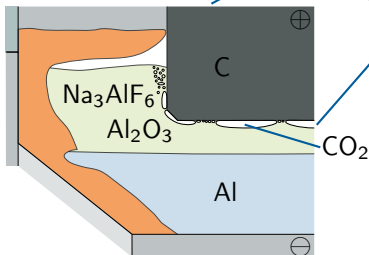
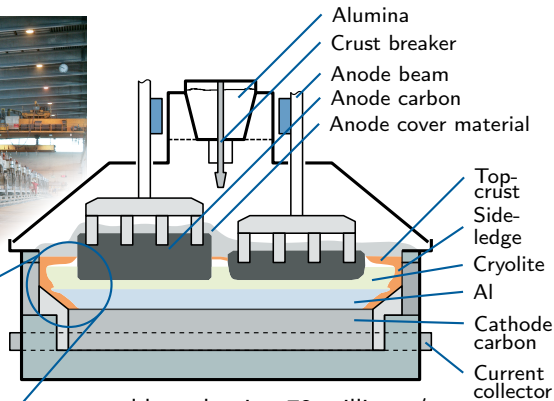
6 Energy Storage in Molten Metals and Fused Salts · August 19, 2025



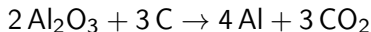
HZDR

Aluminium electrolysis

Norsk Hydro, 2010

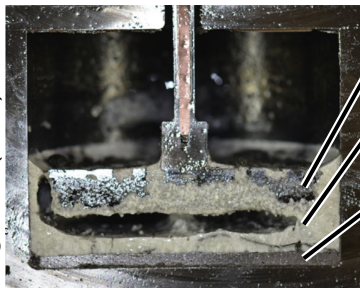


- world production 72 million t/year
- ➔ >3% world electricity production



- Cell:
 - $T_{\text{op}} = 960^\circ\text{C}$
 - 300 ... 600 kA
 - 9 ... 18 m length
 - 3 ... 5 m width

Liquid metal batteries

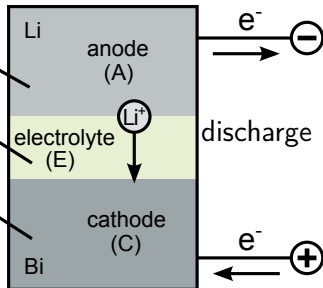


$$\rho^{(Li)} = 491 \text{ kg/m}^3$$

$$\rho^{(El)} = 1648 \text{ kg/m}^3$$

$$\rho^{(Bi)} = 9840 \text{ kg/m}^3$$

@ 450°C



Pros:

- simple construction
- cheap active materials
- high current density
- good cycle life
- scalability

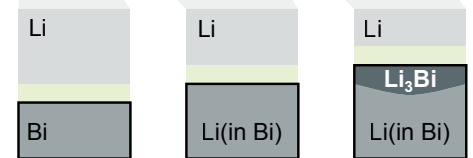
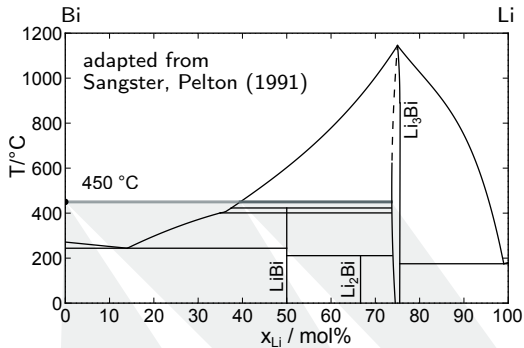
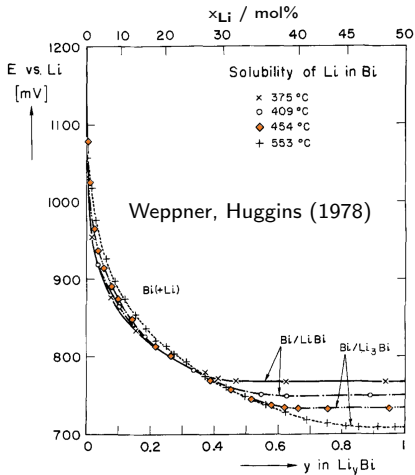
Cons:

- low cell voltage
- high temperature
- aggressive media
- complex fluid dynamics

Liquid metal batteries Li-Bi

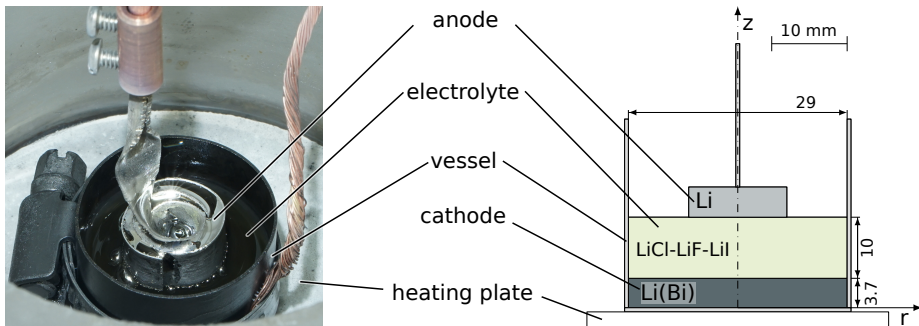
$$E_{OC} = -\frac{RT}{zF} \ln a_{Li(Bi)}$$

$$a_{Li(Bi)} = \gamma_{Li} x_{Li}$$



$$\dot{m}_{Li} = \frac{jM_{Li}}{z_e F}$$

Cycling with intermediate relaxation phases



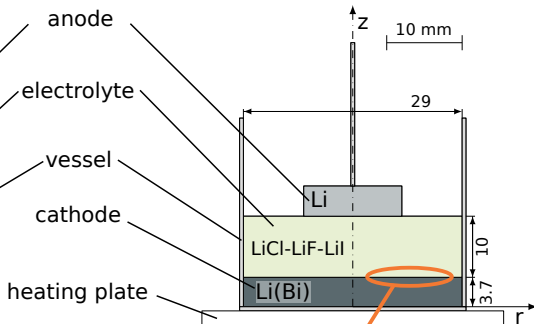
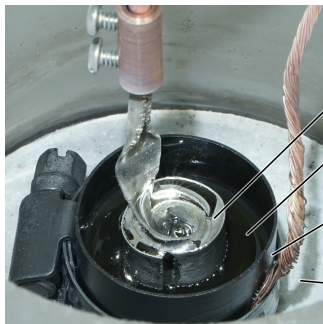
$$T_{\text{op}} = 460\text{ }^{\circ}\text{C}$$

$$A_A = 1\text{ cm}^2$$

$$\text{LiCl-LiF-LiI: } 29.1\text{-}11.7\text{-}59.2, T_m = 341\text{ }^{\circ}\text{C}$$

$$E = E_{\text{OC}} \pm (IR_E + \eta_{a,A} + \eta_{a,C} + \eta_{c,A} + \eta_{c,C})$$

Cycling with intermediate relaxation phases



$$T_{\text{op}} = 460^{\circ}\text{C}$$

$$A_A = 1\text{ cm}^2$$

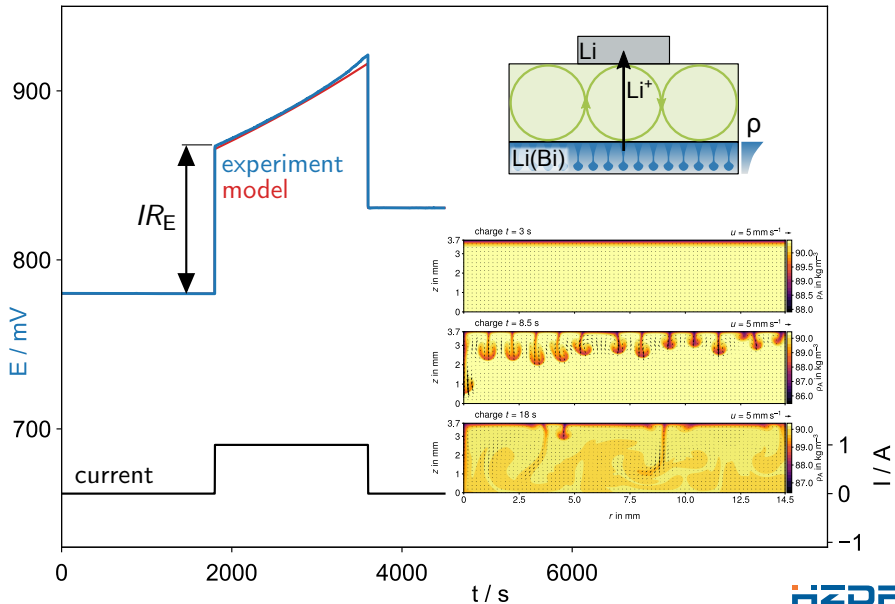
$$\text{LiCl-LiF-LiI: } 29.1\text{-}11.7\text{-}59.2, T_m = 341^{\circ}\text{C}$$

$$E = E_{\text{OC}} \pm (IR_E + \cancel{\eta_{a,A}} + \cancel{\eta_{a,C}} + \cancel{\eta_{c,A}} + \eta_{c,C})$$

$$\underbrace{-\frac{RT}{z_e F} \ln a_{\text{Li(Bi)}}}_{\text{at the electrolyte|Li(Bi) interface}}$$

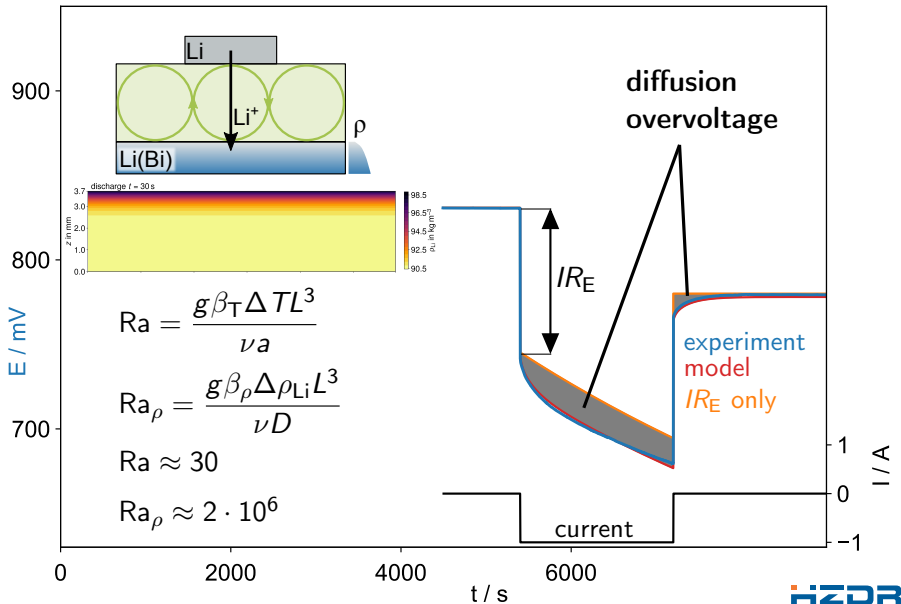
Charge

Personnetaz et al. (2019) Electrochem. Comm.
Kelley, Weier (2018) Appl. Mech. Rev.

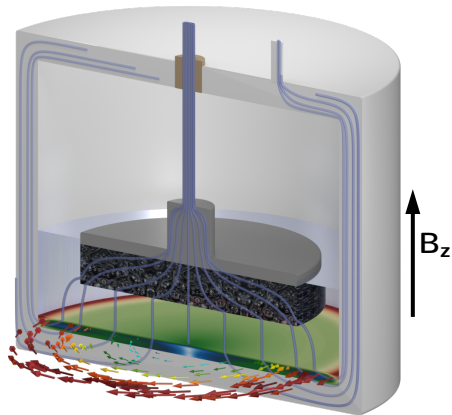
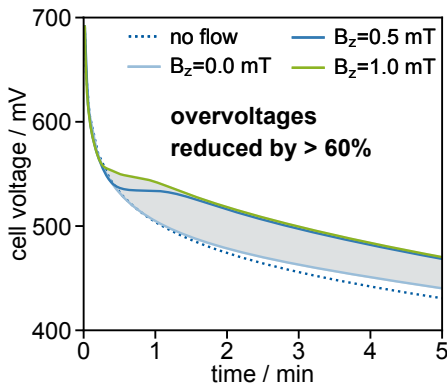


Discharge

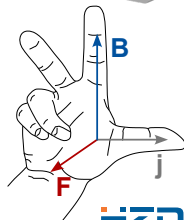
Personnetaz et al. (2019) Electrochem. Comm.
Kelley, Weier (2018) Appl. Mech. Rev.



Mixing by swirling flows



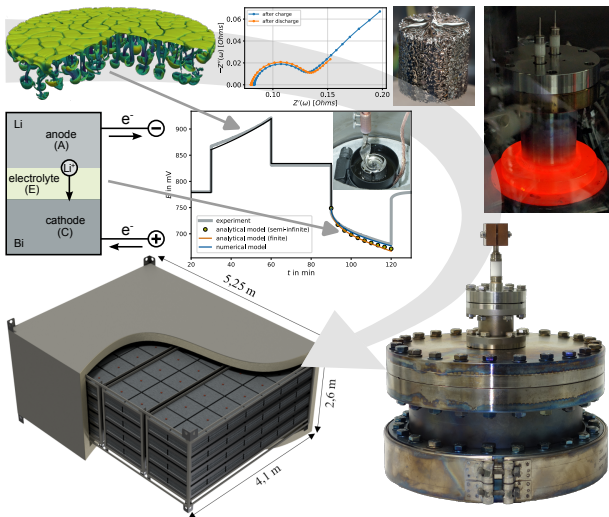
- 100 Ah cell of Ning et al. (2015) modeled (Li||Bi)
- current density 1 A/cm^2 , fully charged ($x_{\text{Li}}=0.02$)



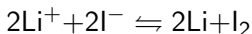
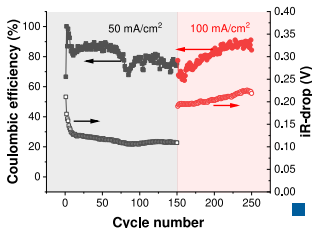
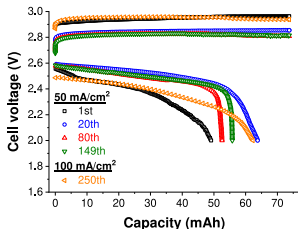
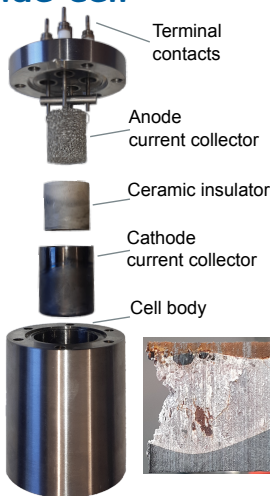
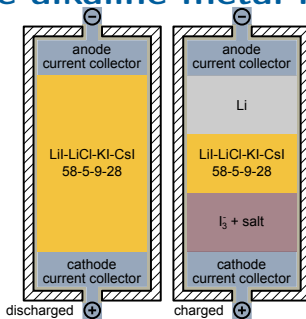
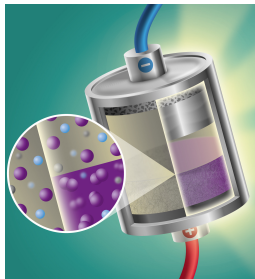
Weber et al. (2020) J. Power Sources Adv.

Modelling & scale-up

- modeling of momentum, heat and mass transfer
- ion transport in molten salts
- density effects
- electrochemical kinetics (Butler-Volmer, Tafel)
- fast spectral-element codes for special cases (Semtex, SFEMaNS)
- realistic geometries with OpenFOAM
- database containing thermophysical properties of liquid metals and molten salts
- open source



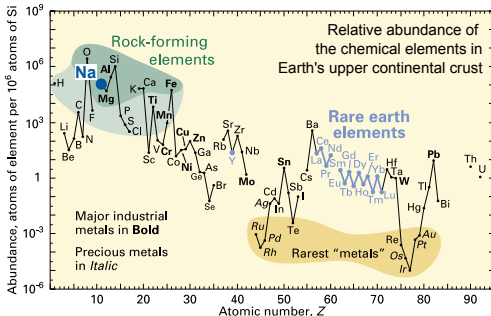
Membrane-free alkaline metal-iodide cell



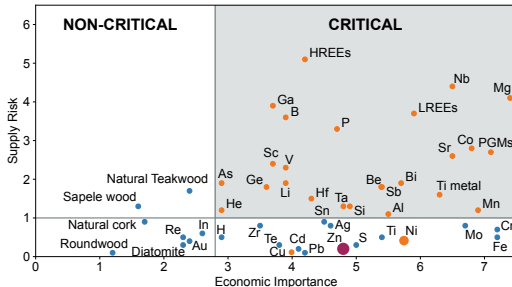
- $T_{\text{op}} \sim 240^\circ\text{C}$
- $\text{OCV} \sim 2.7\text{ V}$

- $\sim 478\text{ Wh/kg}$ theoretical capacity
- assembled in discharged state

Raw materials criticality assessment



- Haxel et al. (2002, adapted)
- Na sixth most abundant element in Earth's crust
 - Zechstein Sea 250 Mio years ago → gigantic rock salt formations
 - e.g. in Saxony-Anhalt



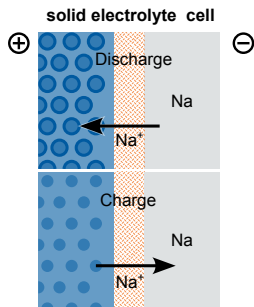
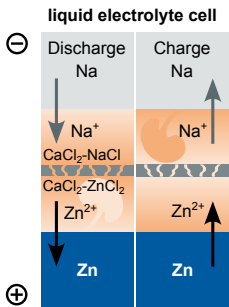
- EU strategic raw materials criticality assessment (Grohol, Veeh, 2023)
- few materials left out
- critical material if supply risk > 1 and economic importance > 2.8

Horizon 2020 Project SOLSTICE - Concept

“Sodium-Zinc molten salt batteries for low-cost stationary storage”

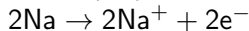
two Na||Zn-based systems:

- 1 liquid electrodes, liquid electrolyte:
 $T_{\text{op}} = 600\text{ }^{\circ}\text{C}$, scalable on cell level
- 2 liquid electrodes, solid electrolyte:
 $T_{\text{op}} = 300\text{ }^{\circ}\text{C}$, similar to Na|NiCl₂

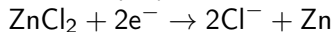


Discharge

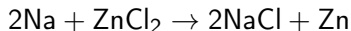
anode (Na):



cathode (Zn):

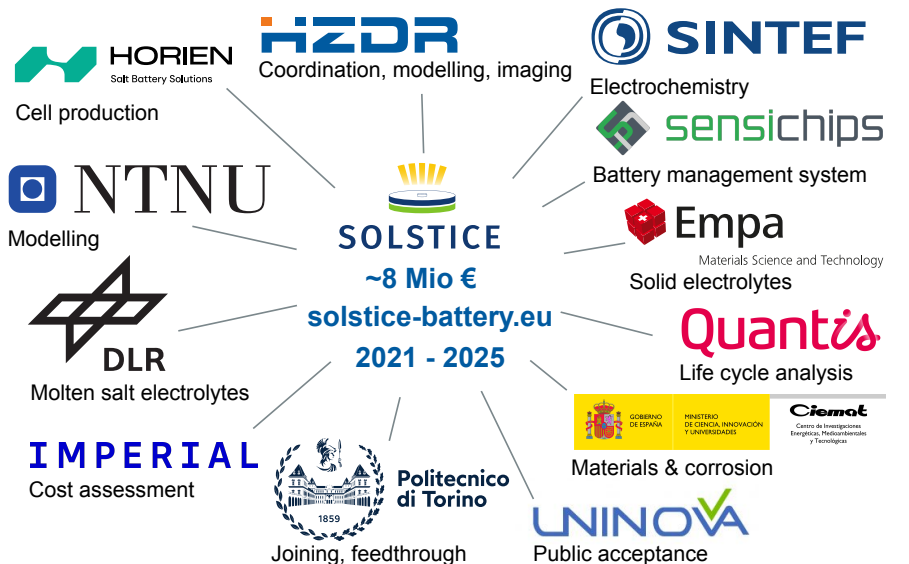


sum reaction:

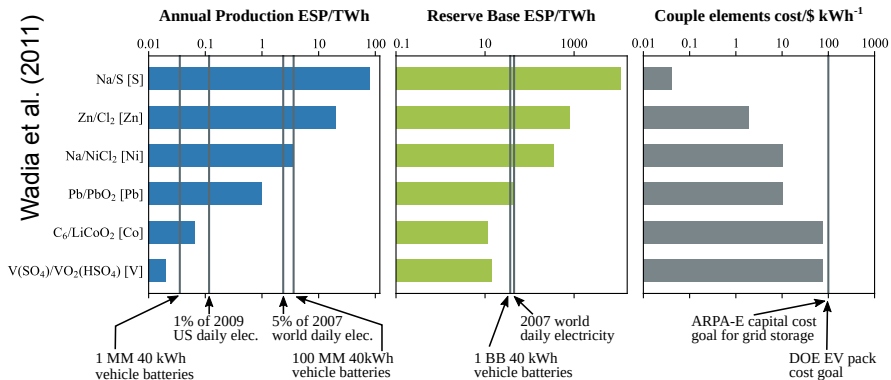


- 1.95 V (standard conditions)
- 570 Wh/kg theoretical capacity
- ~4 €/kWh (active materials)
- conversion vs. alloying
- alleviates cathode material challenges

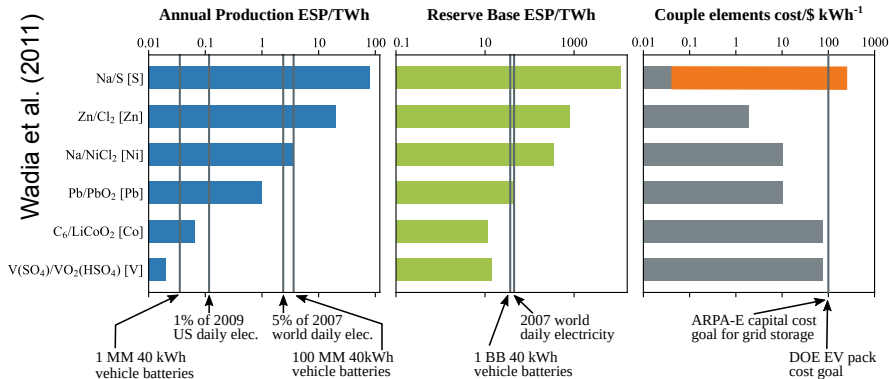
Horizon 2020 Project SOLSTICE - Consortium



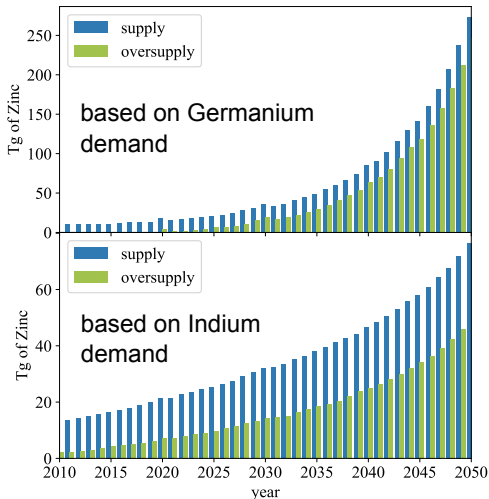
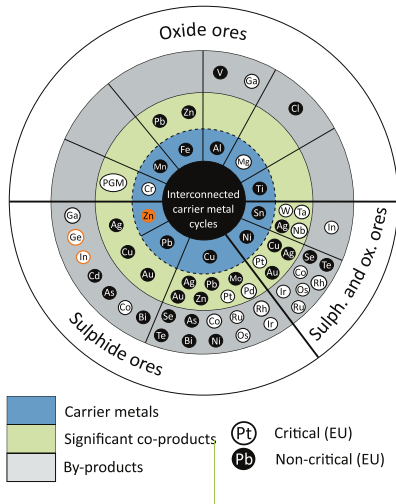
Energy Storage Potential



Energy Storage Potential



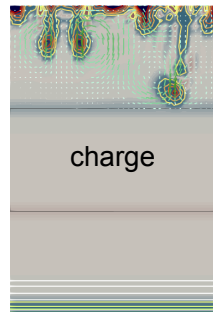
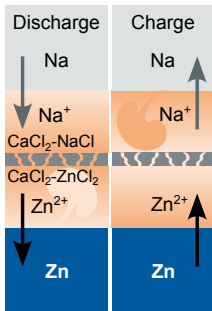
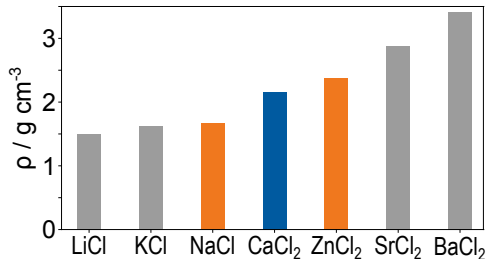
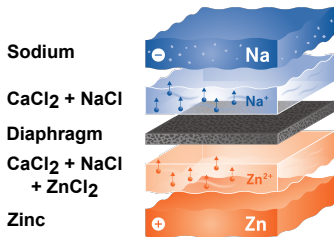
Solar cell materials and their hosts^{*}



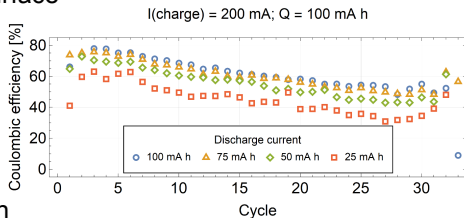
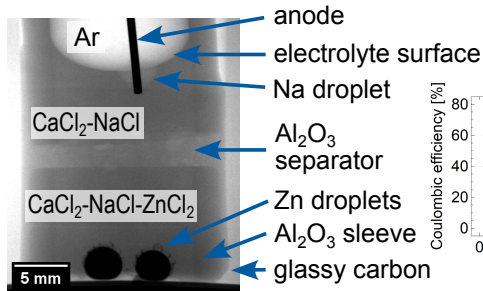
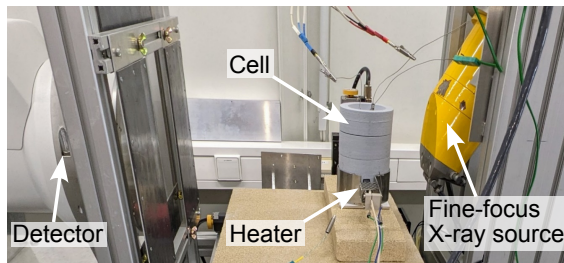
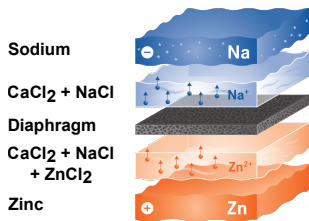
adapted from Frenzel et al. (2017) and Elshkaki and Graedel (2015)

★ a footnote

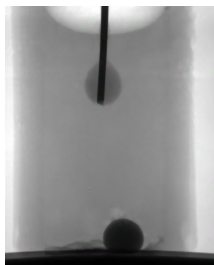
Na-ZnCl₂ liquid-electrolyte cell



Na-ZnCl₂ liquid-electrolyte - X-ray radiography



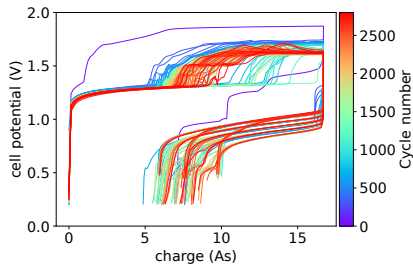
Na-ZnCl₂ liquid-electrolyte - X-ray radiography



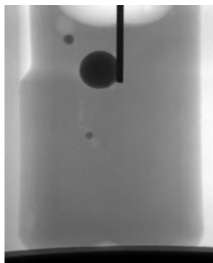
t_0



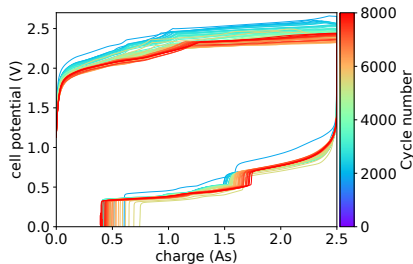
$t_0 + \Delta t$



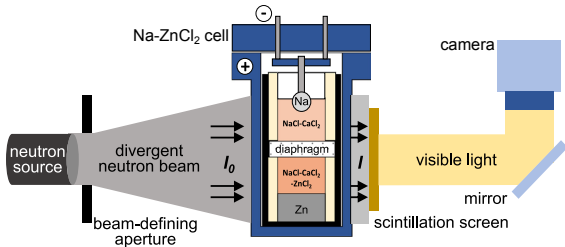
undivided cell



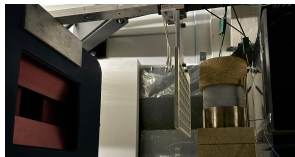
undivided cell with Al_2O_3 -powder (reversed polarity)



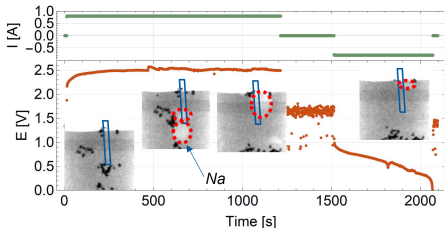
Na-ZnCl₂ liquid-electrolyte - n-beam radiography



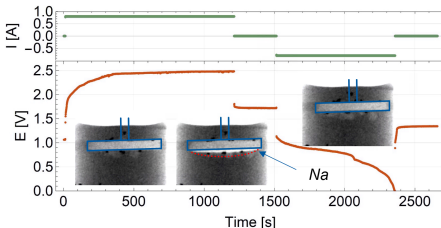
PSI NEUTRA



needle current collector



disc current collector



Na-ZnCl₂ liquid-electrolyte - hurdles



corrosion



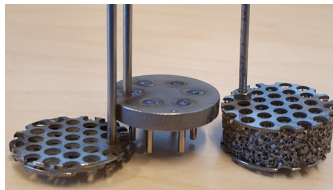
sealing



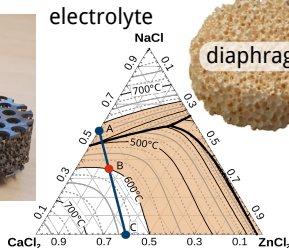
Ca
co-deposition



wetting



current collector



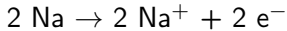
diaphragm

The cell interior is a harsh environment at high temperature.

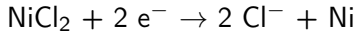
Solid-electrolyte cell - ZEBRA as a role model

Na|NiCl₂ battery (Zero Emission Battery Research Activities)

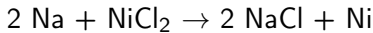
anode (Na):



cathode (NiCl₂):



sum reaction:

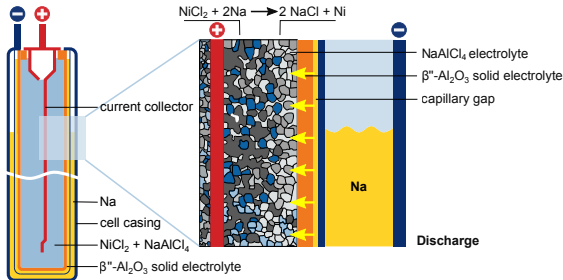


2.58 V cell voltage

790 Wh/kg theoretical specific energy



FZSoNick (2023)

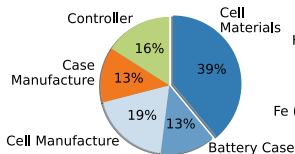


Daimler AG (2009)

Na-ZnCl₂ solid electrolyte cell

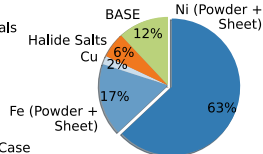
ZEBRA (Na-NiCl₂):

cost fractions components

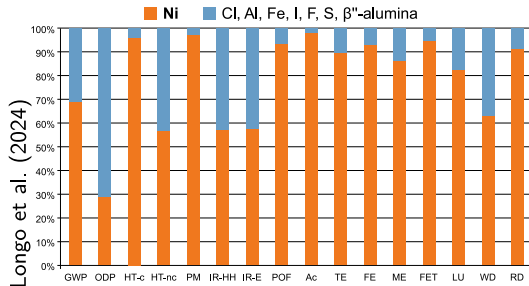


Lu et al. (2013)

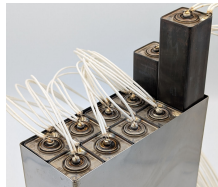
cost fractions materials



→ ~20% cost reduction



Longo et al. (2024)



18 cm



14 cm



10 cm



5 cm (from bottom)

FZSoNick (2023)

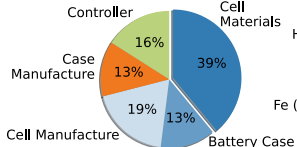


Ageing: disintegration of granules, materials segregation, and coarsening of Zn particles

Na-ZnCl₂ solid electrolyte cell

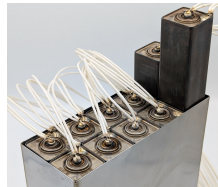
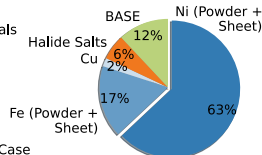
ZEBRA (Na-NiCl₂):

cost fractions components

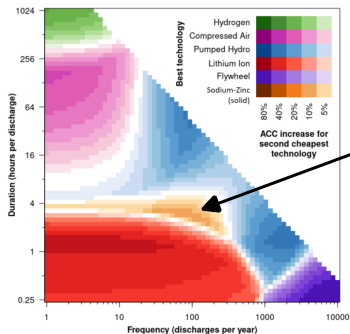


Lu et al. (2013)

cost fractions materials



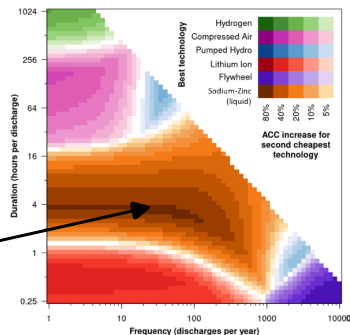
Johnson et al. (2025)



Na-ZnCl₂

solid electrolyte

liquid electrolyte



Recycling

materials separated at the macro-scale

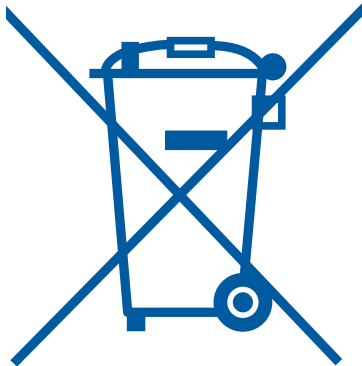
→ great bonus for recycling

Na-ZnCl₂ liquid-electrolyte cell

- full discharge: $\text{Zn} + \text{NaCl}$
- thick layers $\mathcal{O}(\text{cm})$
- large cells

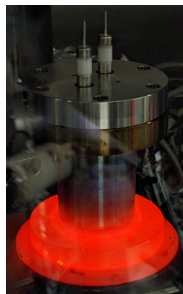
Na-ZnCl₂ solid-electrolyte cell

- established recycling procedure for ZEBRA
- already “Zero Impact Battery”
- excellent recyclability features will not suffer from changing cathode chemistry



Conclusions

- LMBs have a completely liquid interior → fluid dynamics
- important aspect: scale-up on the cell level
- composition gradients determine convection in the cathode
- mixing during discharge to mitigate concentration polarization, swirl helps
- Na-ZnCl₂ alleviates the cathode material challenges + increases cell voltage
- solid electrolyte cells with Zn-based cathodes
- liquid electrolyte cells:
 - lower TRL
 - many challenges, interesting phenomena
 - larger cost reduction potential on the long run



Thank you for your interest!

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 963599.

