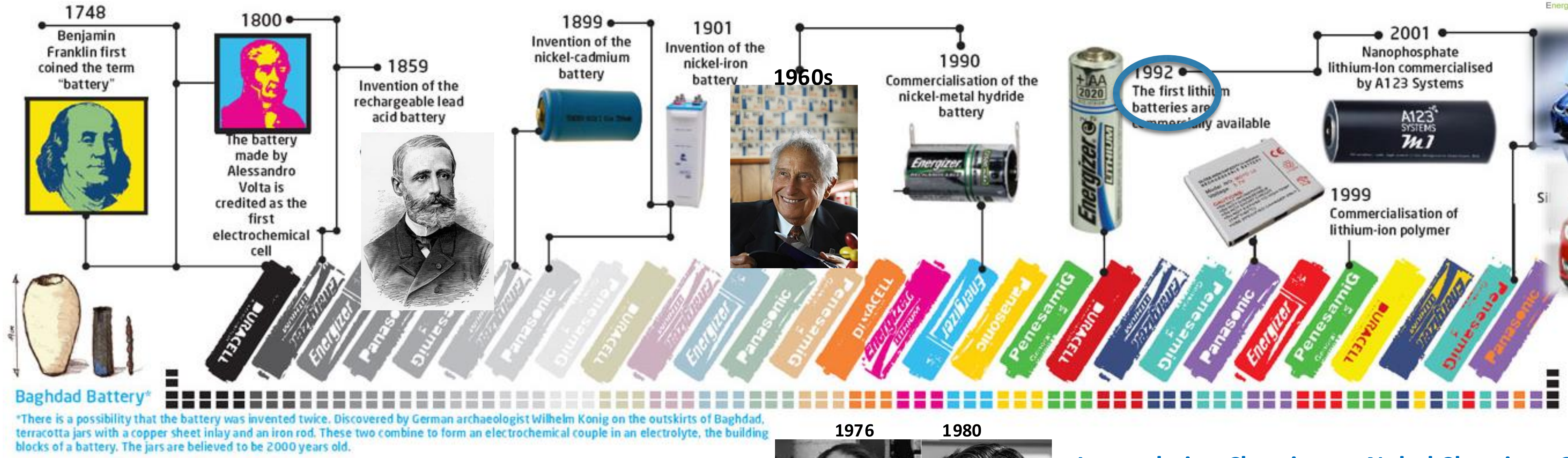
The Global Race for A Better Battery

Y. Shirley Meng
The University of Chicago
Argonne Collaborative Center for Energy Storage Science
Energy Storage Research Alliance

University of Maryland, College Park
Oct. 23, 2025

A Brief History of Battery and Industrialization

Laboratory for Energy Storage and Conversion



2010

1976 1980

Intercalation Chemistry – Nobel Chemistry 2019 !

IoT
mWh

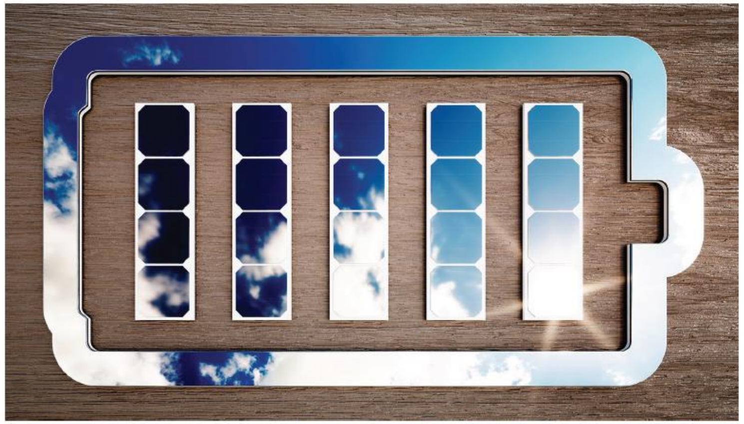
Robots
Wh

Drones
kWh

Aviation / SemiTruck
MWh

1Whr is a large energy unit = 3600 W.s (J)

Energy Storage for Renewables
GWh

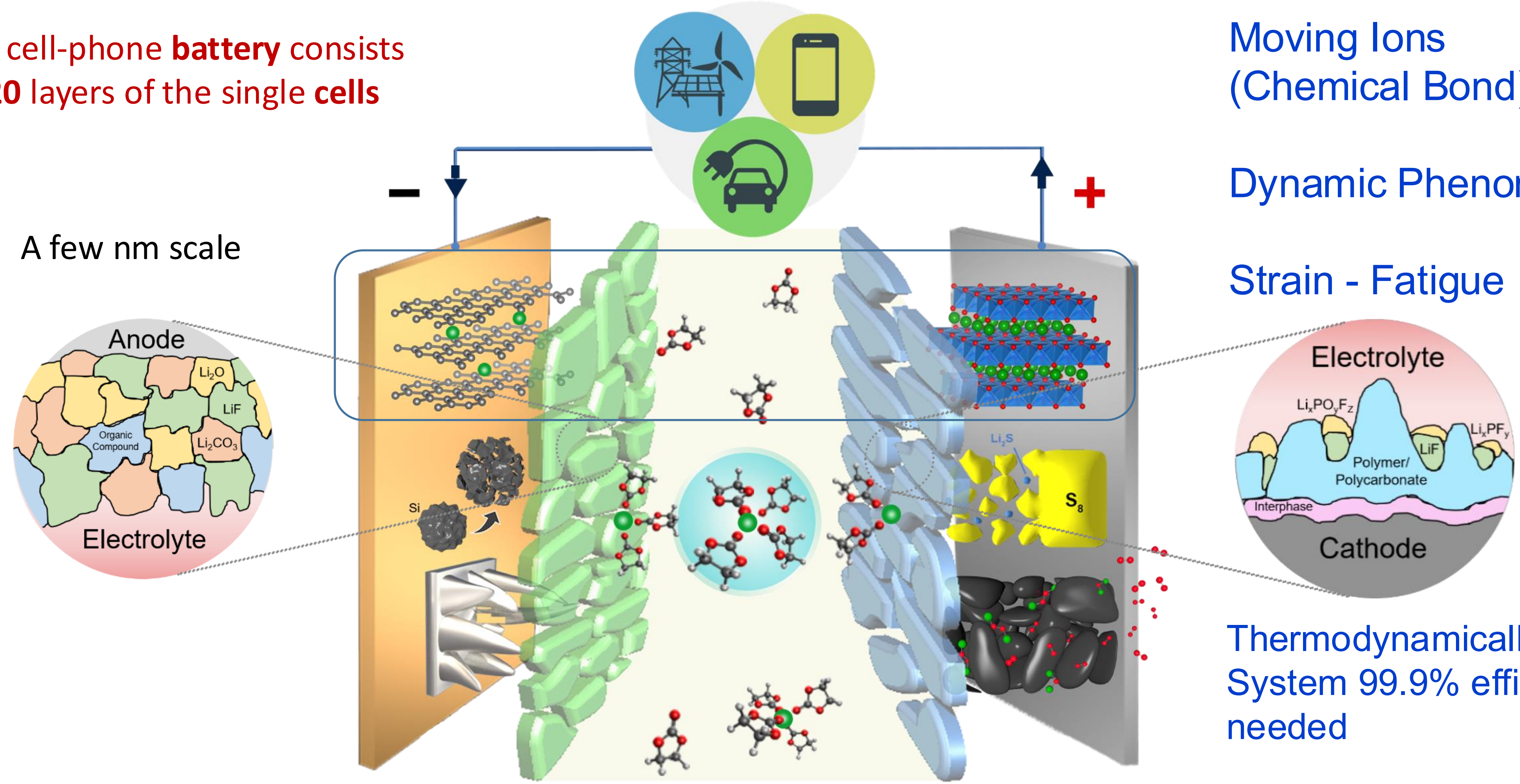


Rechargeable Battery - A Complex Engineering System

Kang Xu, Venkat Srinivasan and Y. Shirley Meng, Science 2023

One cell-phone **battery** consists **10-20** layers of the single **cells**

A few nm scale



Moving Ions (Chemical Bond)

Dynamic Phenomena

Strain - Fatigue

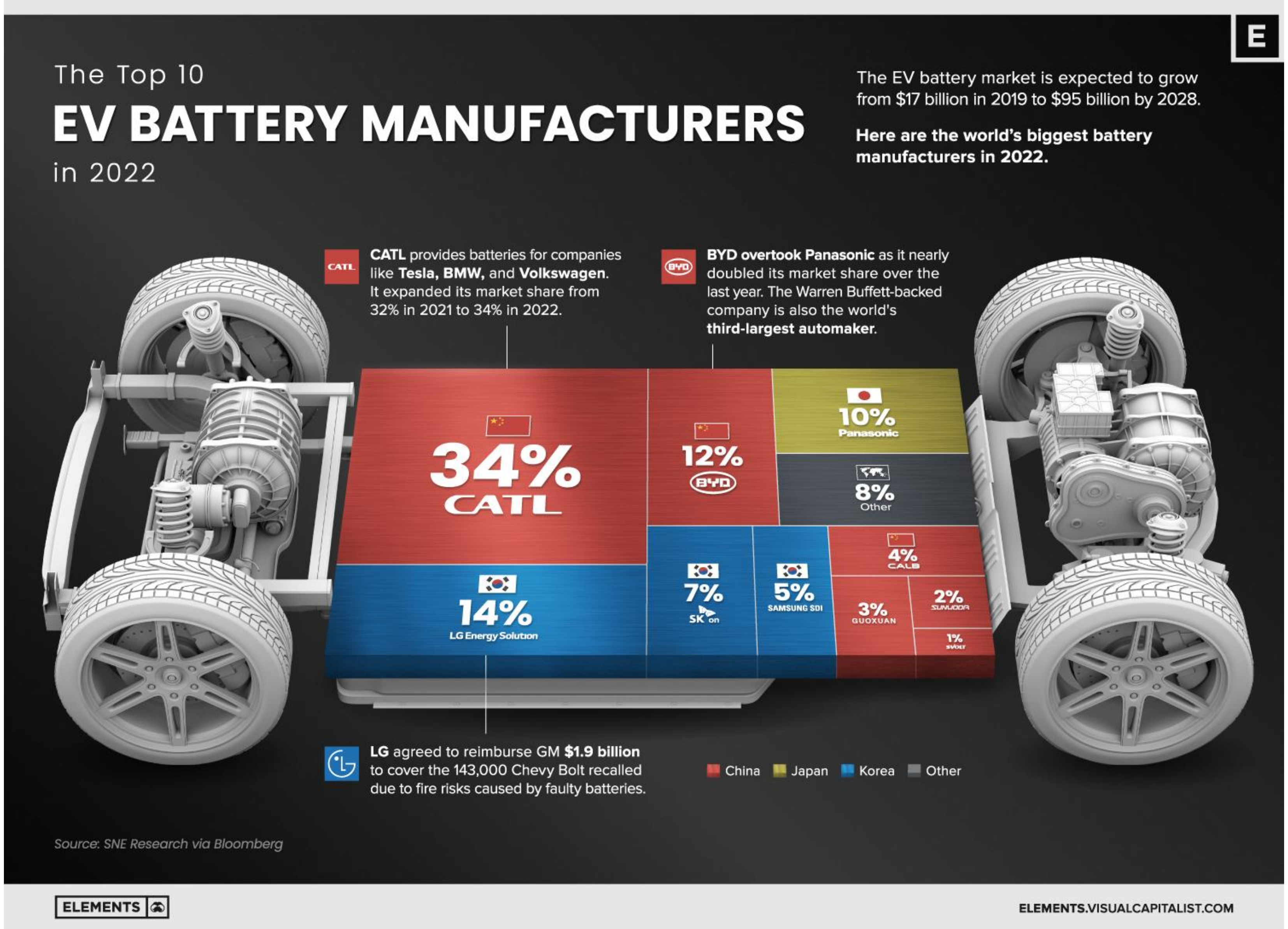
Thermodynamically Closed System 99.9% efficiency needed

SEI – Life and Safety Differentiators

THE UNIVERSITY OF CHICAGO PRITZKER SCHOOL OF MOLECULAR ENGINEERING

Argonne NATIONAL LABORATORY

World Production of LIB >1TWh/Year 2024 (Today)



In 1998, Academician Chen Liquan, built the first production line using a complete set of Chinese equipment.

In 1999, South Korea entered the lithium-ion battery market, and LG Chem completed South Korea's first battery product.

In 2000, BYD won an order from Motorola

In 2001, China entered WTO

In 2004, CATL became an iPod supplier. China's lithium battery industry emerged. China's annual output of lithium-ion batteries is 800 million units, accounting for 38% of the global share, second only to Japan.

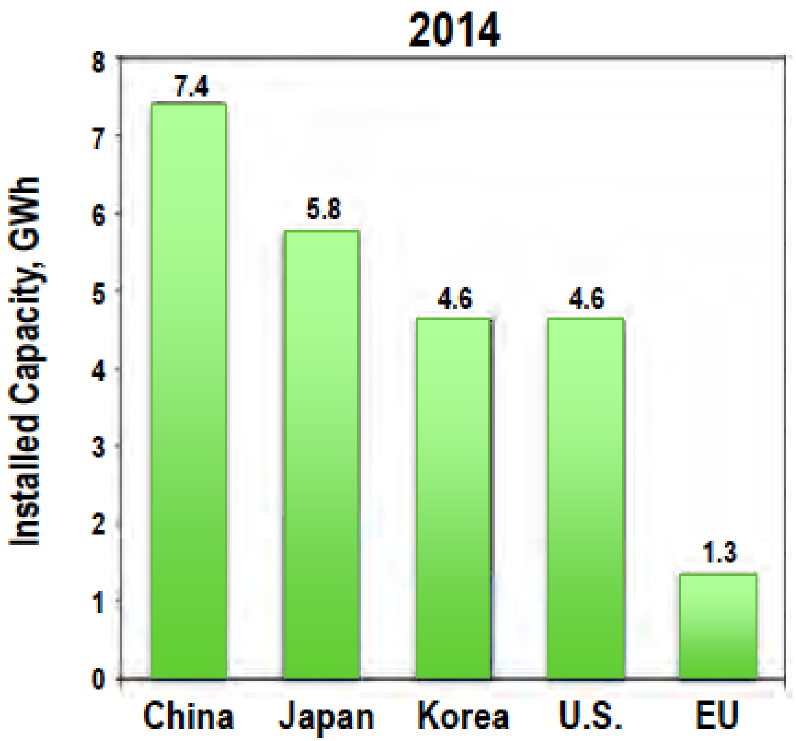
Start in 2002 "Electric Vehicle Key Project"
- 863 National High-Tech Development Plan
- Spent **880 million yuan** for EV research in five years

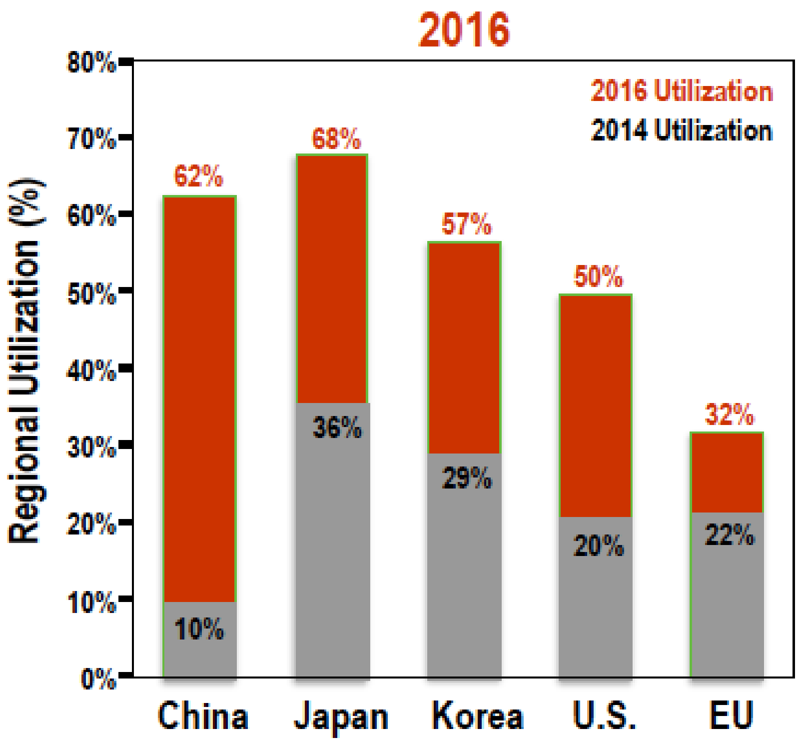
Start in 2013 China Central government subsidies

- 60,000 yuan for passenger electric cars (>250 km)
- 300,000 yuan for electric buses
- Exemption from vehicle purchase tax
- Local subsidies: up to 60% of EV retail price
- Non-subsidy measures: license-plate restrictions

2014 We All Started from The Same Spot! (Past)

Regional Automotive LIB Cell Capacity and Utilization





- Automotive lithium-ion battery demand growing but short of global manufacturing capacity.
- Utilization of U.S. plants increased from 20% in 2014 to ~50% in 2016.
- Forecasted compound annual growth rates in lithium-ion demand: 22%–41% (through 2020).

A Vision for the Future (World View)

ONLY 2% done with what we need , that is 200-300TWh batteries !

- 8.5 Billion People by 2030 – More than half in developing countries

each person has about 10kWh battery – we will need 85TWh battery

- 6 Billion Smartphones/Smart Tablets – All connected via 5G

This is a small market now – but people with real 5G need fast charging/fast discharging

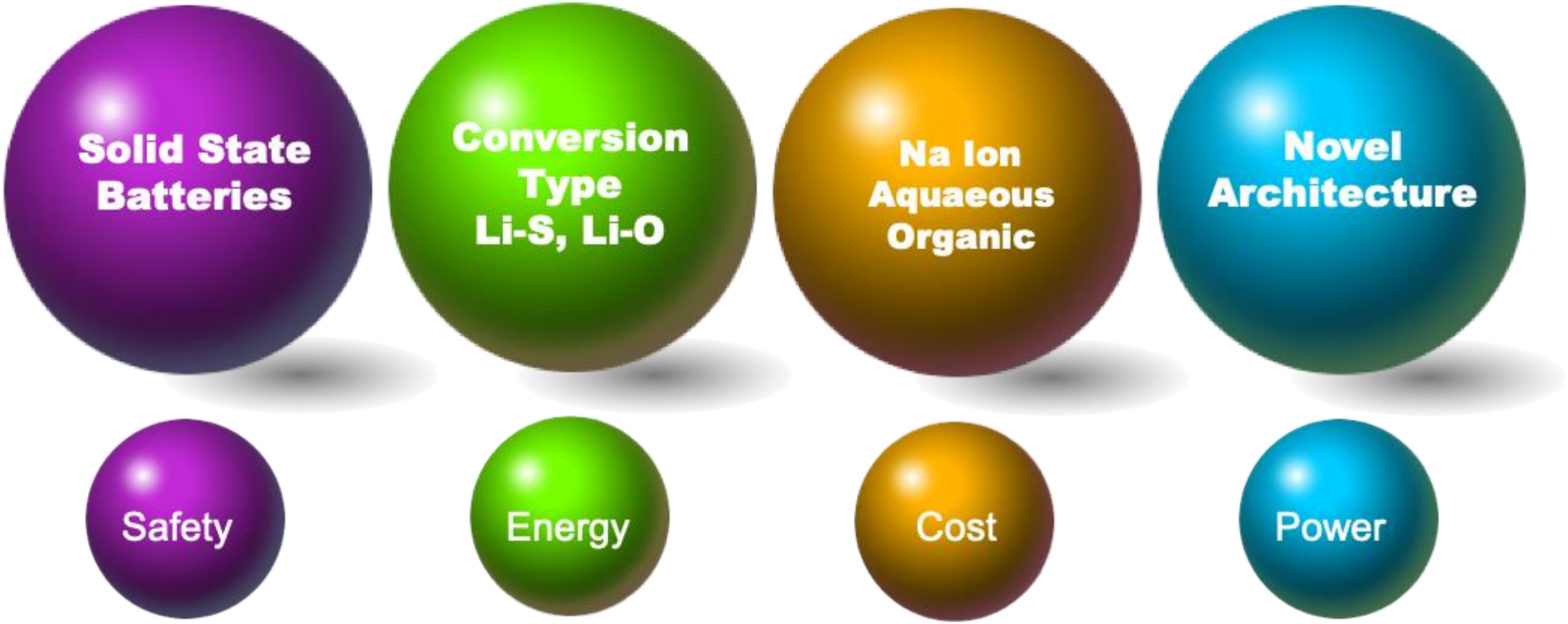
- 1 Billion Cars to be Electrified – Possibly Electric Planes

We predict that total number of cars will reduce, cars will be better utilized and we will have electric heavy duty trucks and possible V2G enabled – 100TWh

- Grid of the Future

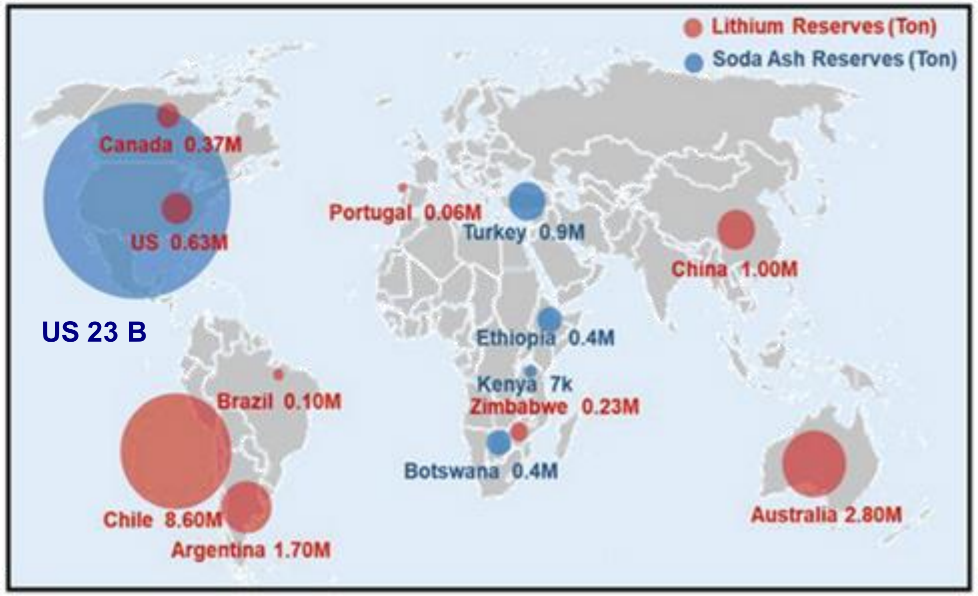
Long duration needs can be fulfilled by technologies other than batteries (H2+Hydro+Thermal) – 100TWh

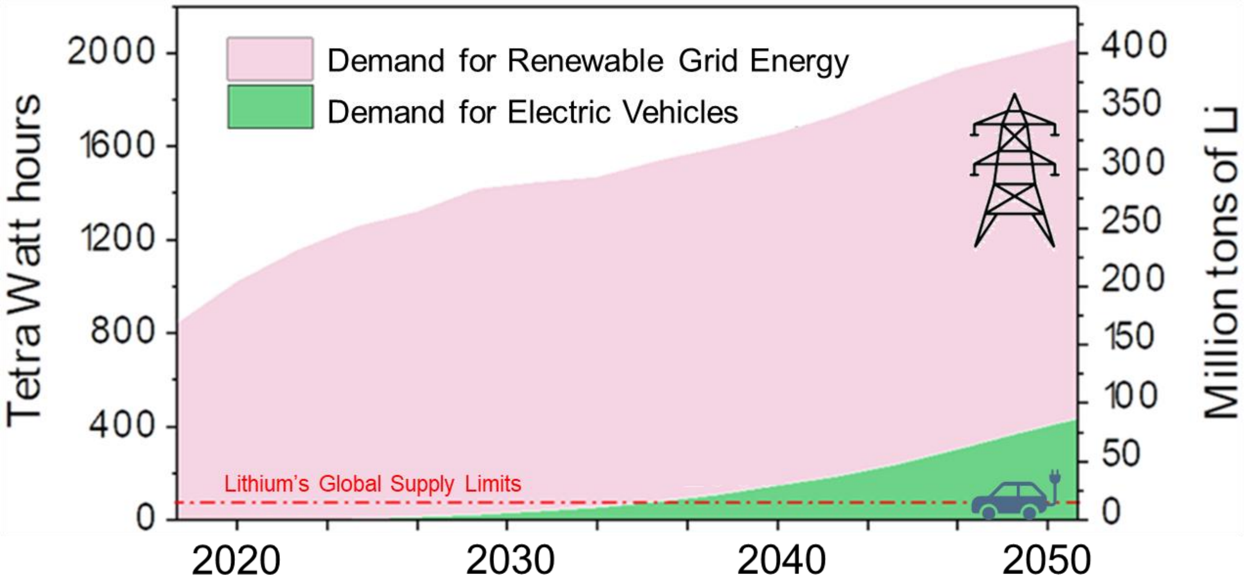
Next Decade of Energy Storage and Battery Technology



High energy batteries that never catch fire	Batteries last more than 30 years	Batteries can be 100% recycled (supply chain)	Batteries that can be charged full in 5 minutes

Na vs Li Materials Sustainability





US Energy Storage : Scale

1) **Electrical Grid**
   - Per capita - 12000 kWh / year
   - 400 tera-watt hours if just 10% storage
     → 60 million tons of Li Needed

2) **Vehicles**
   - 17 million / year, if all EVs
   - 0.85 tera-watt hours
     → 0.13 million tons of Li Needed

Abundant Sodium in the U.S. is needed to accelerate energy transition

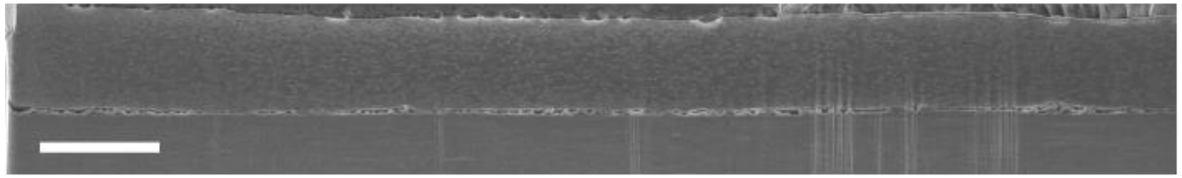
Na battery will reduce the demand for Li, Cu, Co and possibly Ni

Na battery can be shipped more safely

Na battery can allow more customer choices

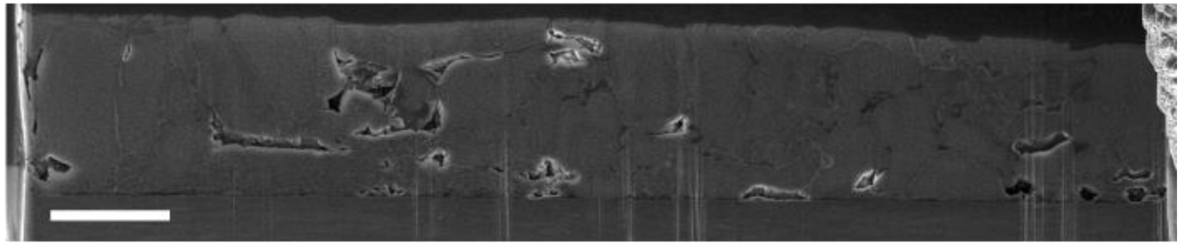
Analysis of Na Metal Deposition and Stripping

(a) 1 M $NaPF_6$ in DME



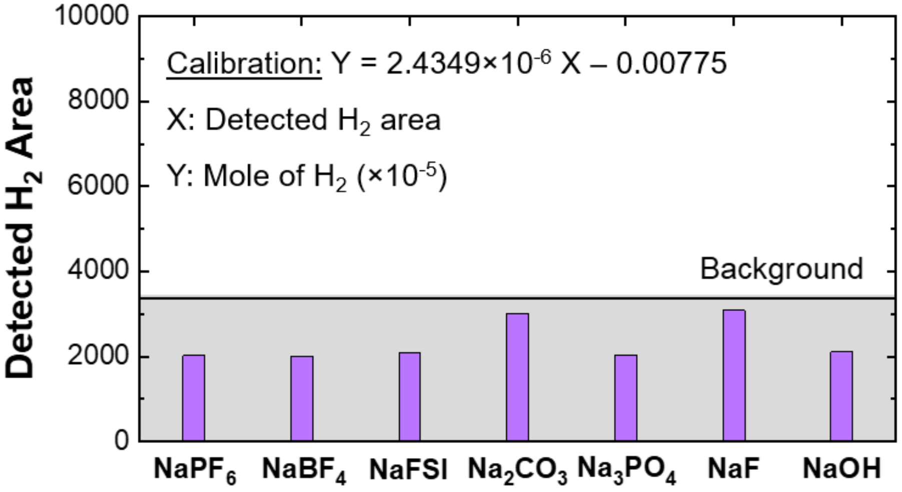
180 kPa

(b) 1 M $NaPF_6$ in EC:DMC (1:1)



250 kPa

The sodium was plated at 0.5 mA/cm2 for 1 mAh/cm^2 on Al foil. The images are acquired under 5kV voltage and 0.2 nA current using a TLD detector. The scale bars are 10 μm.



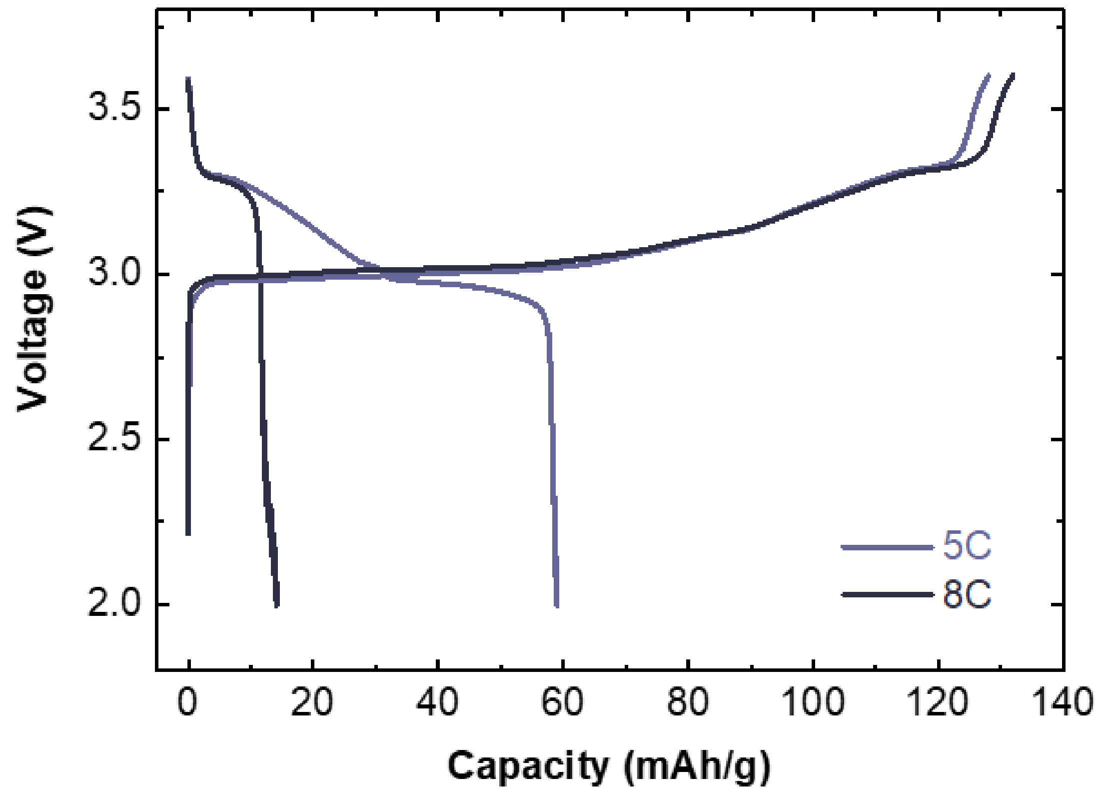
Standard	Detected H_2 Area
$NaPF_6$	2025
$NaBF_4$	2004
NaFSI	2100
Na_2CO_3	3013
Na_3PO_4	2037
NaF	3127
NaOH	2115

The controlled TGC experiment on standard commercial powders showed no hydrogen generation. This test was performed using ethanol as the solvent.

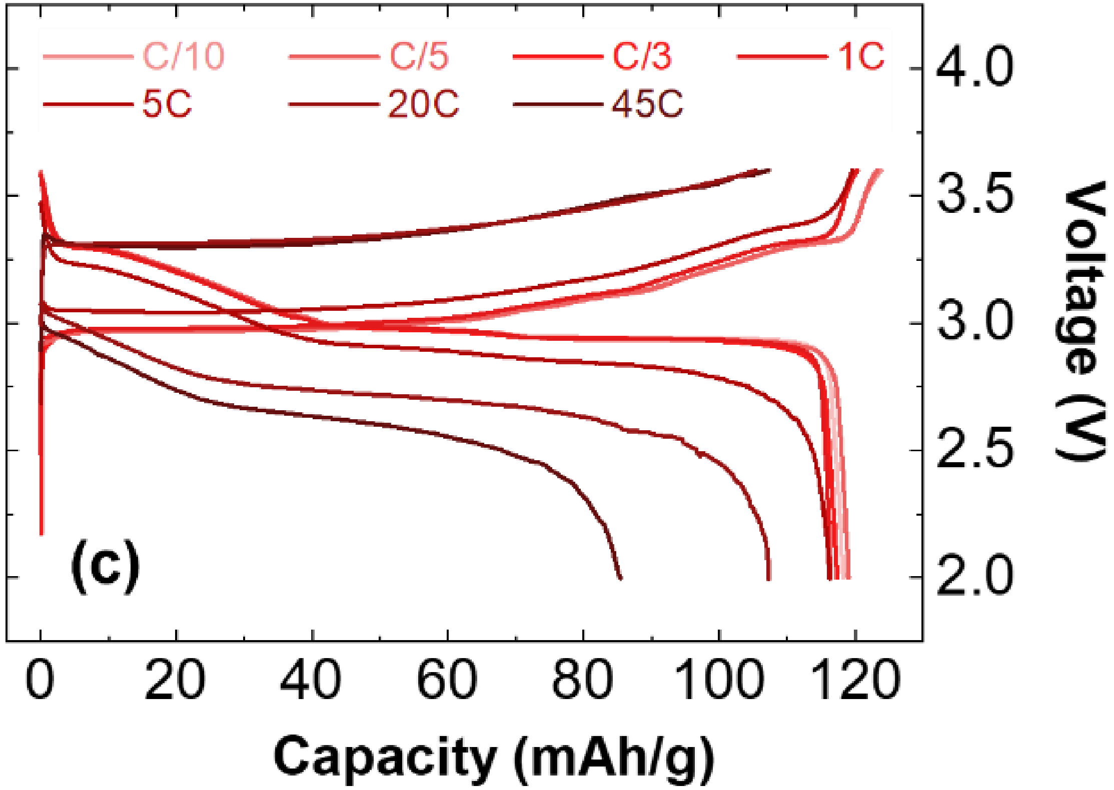
Power of Sodium Battery

1C = 1 hour charging/ 20C = 3 min charging!

Na Metal as anode, $NaCrO_2$ as the cathode. The cells have controlled 100% excess of sodium inventory.

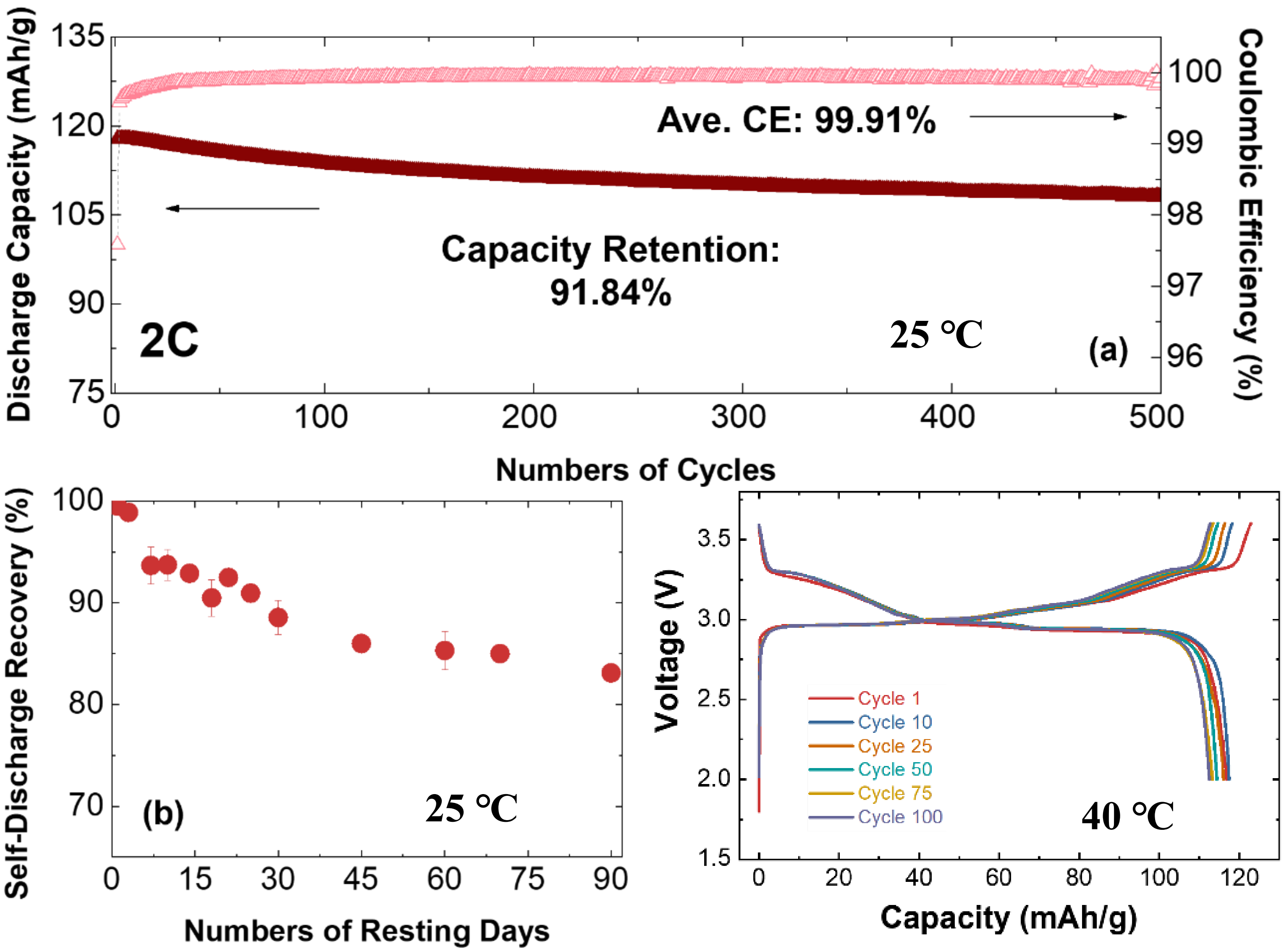


1M $NaPF_6$ in EC:DMC (1:1)



1M $NaPF_6$ in DME

B. Sayahpour, … M. Zhang and Y.S. Meng, “ Quantitative analysis of sodium metal deposition and interphase in Na metal batteries “, *Energy & Environmental Science,* January 2024



Dr. Baharak Sayahpour (ASML)

We made the anode, electrolyte, cathode

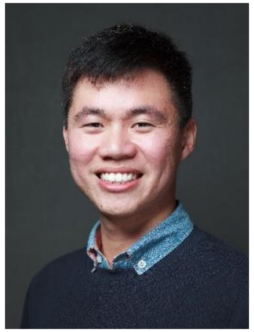
Active work since my CAREER award in 2010

National Science Foundation

THE UNIVERSITY OF CHICAGO
PRITZKER SCHOOL OF MOLECULAR ENGINEERING

UNIGRID

UNIGRID’s Value: Energy & Safety

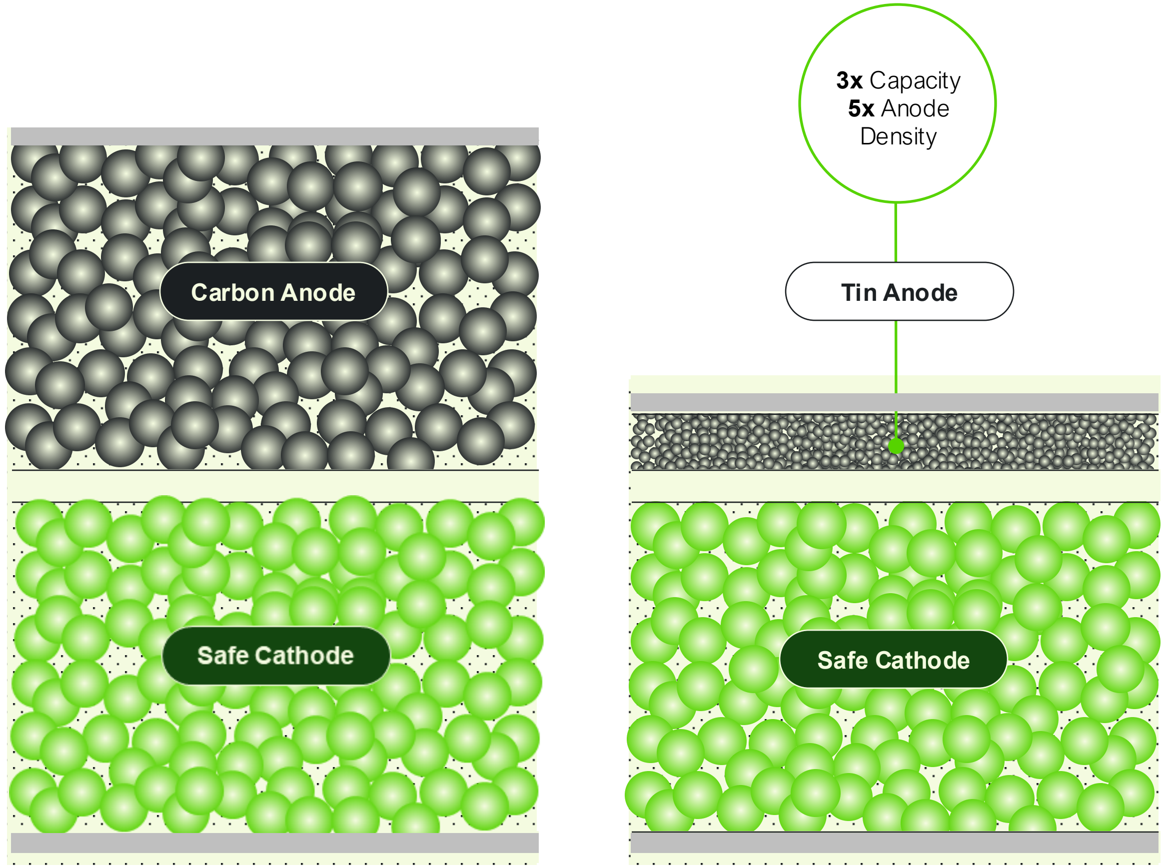


Dr. Darren Tan

Sodium Ion Battery Landscape	Key IP	Cathode	Anode	Wh/kg	Wh/L	Cycles	Market
UNIGRID	**Anode**	**Any**	**Alloy**	**180 Wh/kg**	**450 Wh/L**	**>3000**	**EV / ESS**
FARADION	Cathode	Layered Oxide	Carbon	160 Wh/kg	200 to 300 Wh/L	>3000	EV / ESS
CATL	Cathode	Layered Oxide / PBAs	Carbon	160 Wh/kg		–	EV / ESS
Natron Energy	Cathode	Symmetric Prussian Blue Analogues	–	20 Wh/kg	18 Wh/L	>50000	Backup Power
中科海钠 HiNa BATTERY	Cathode	Layered Oxide	Carbon	145 Wh/kg	180 to 300 Wh/L	>4500	EV
容百科技 RONBAY TECHNOLOGY	Cathode	Prussian Blue Analogues	Carbon	–		–	EV / ESS
ZOOLNASM 众钠能源	Cathode	Poly-anionic	Carbon	–		–	EV / ESS
钠创 NATRIUM	Cathode	Layered Oxide & Poly-anionic	Carbon	145 Wh/kg		>5000	EV / ESS
EVE	Cathode	Layered Oxide	Carbon	145 Wh/kg		>5000	EV / ESS
Tiamat Energy	Cathode	Poly-anionic	Carbon	110 Wh/kg		>5000	EV / ESS
LiFUN	Cathode	Layered Oxide / PBAs	Carbon	140 Wh/kg		>4000	EV / ESS
Nippon Electric Glass	Separator	Layered Oxide	Carbon	–	–	–	ESS
amte power	Cathode	–	Carbon	140 Wh/kg	180 to 300 Wh/L	>1000	ESS
SVOLT	Cathode	–	Carbon	160 Wh/kg		>2000	EV / ESS

UNIGRID

Anode - Energy Innovation



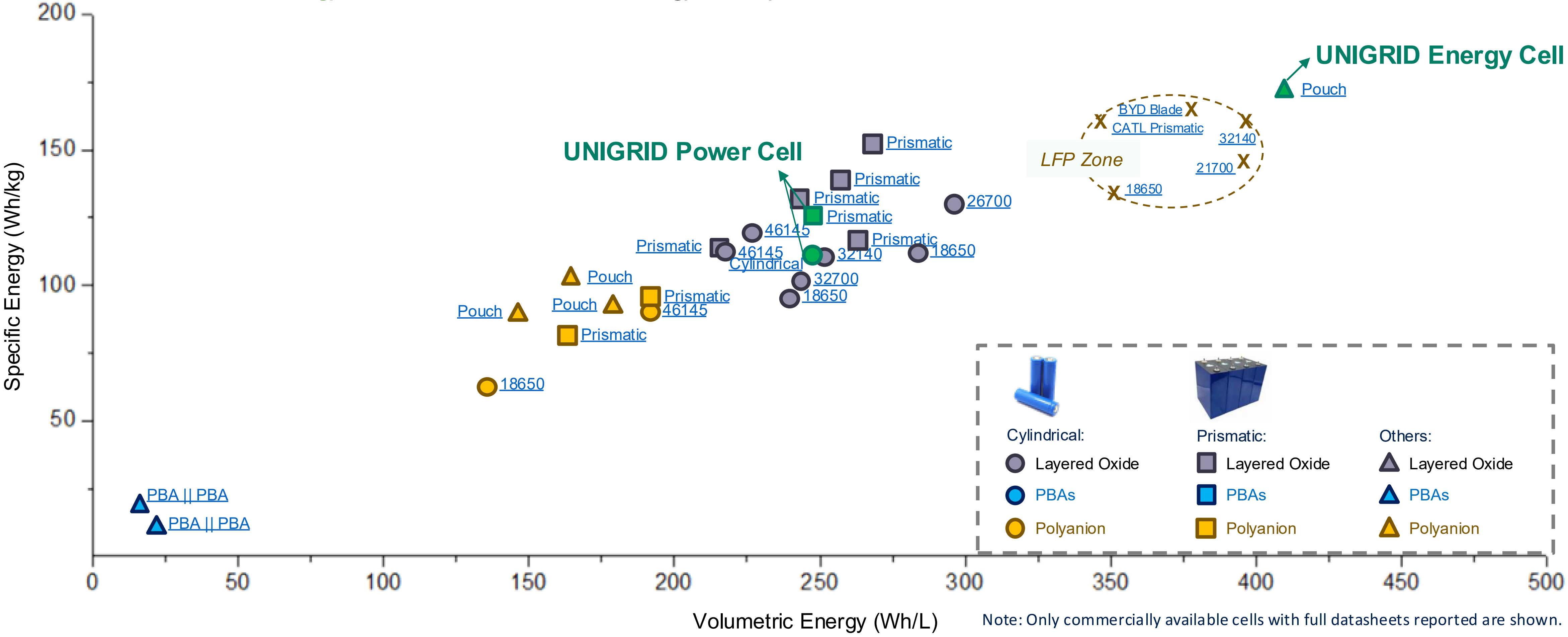
UNIGRID
Power Cell

UNIGRID
Energy Cell

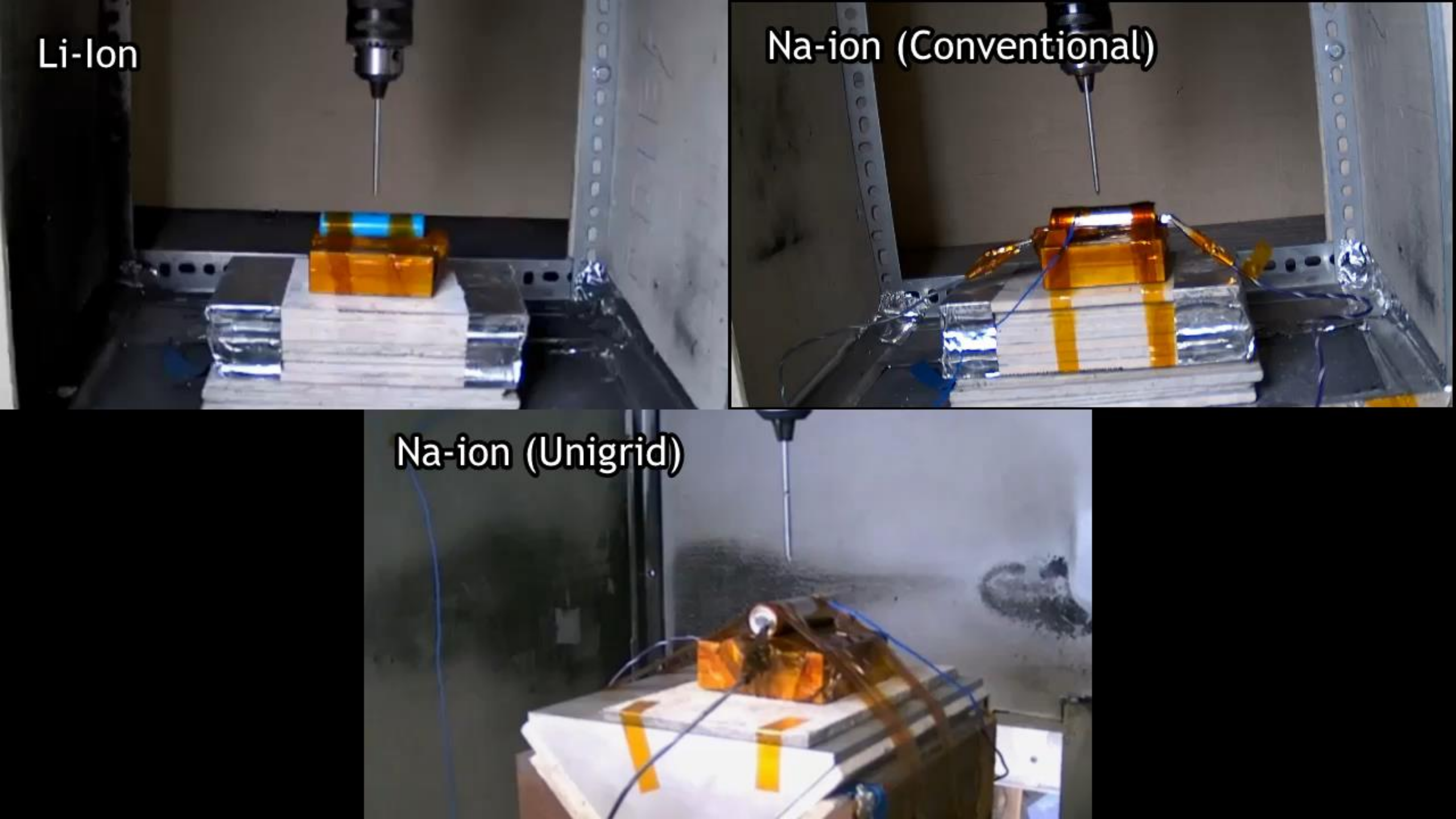
UNIGRID

Sodium-ion - Reported Energy Densities

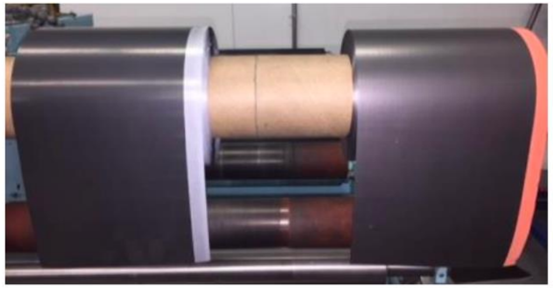
- UNIGRID Energy Cell sets record in Na-ion energy density, as the **Na-cell that exceeds LFP**



Note: Only commercially available cells with full datasheets reported are shown.


Li-Ion
Na-ion (Conventional)
Na-ion (Unigrid)

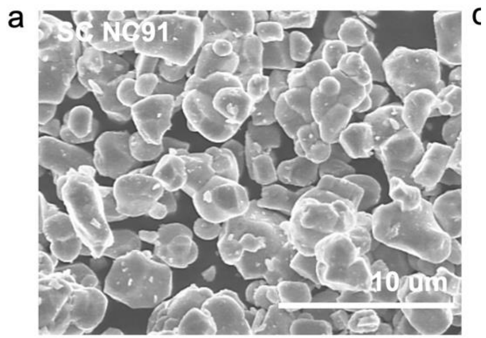
The Race is NOT Over Yet for Lithium Batteries



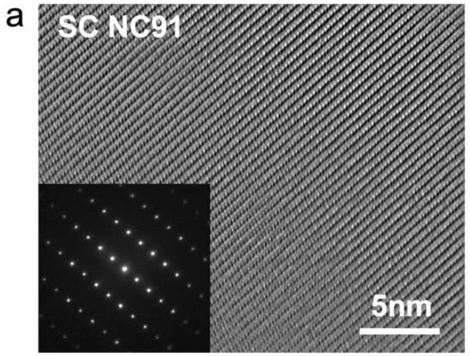
Maxwell Technologies 2017

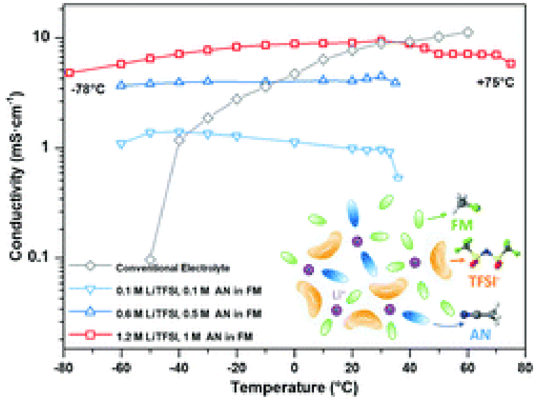
Tesla Acquisition 2019

All Dry 4680 in Cybertruck 2024



Better Cost Performance Ratio



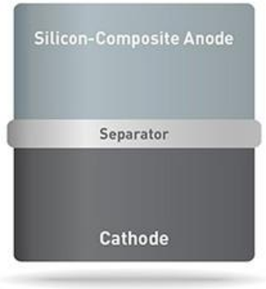


-60 to +60 C

Wider operation temperatures

Gen 0
Li-Metal
100-200 Wh/kg
200-300 Wh/L
Dangerous

Gen 1
Li-ion
200-250 Wh/kg
600 Wh/L
Safe



Gen 2
Li-ion
250-300 Wh/kg
700 Wh/L
Safe

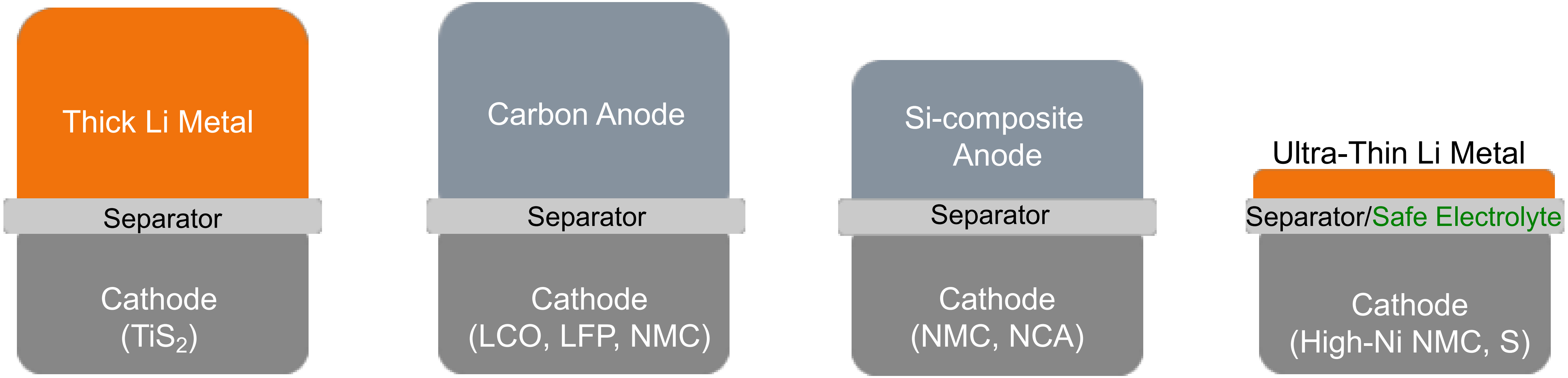
Gen 3
Li-Metal
400-500 Wh/kg
1200 Wh/L
Safest

Dry Battery Electrode (DBE) Processing	Single Crystal NMC/NCA	Electrolyte Genome	Anode-Free

Li Metal Batteries and Battery500 Consortium

BATTERY500 CONSORTIUM

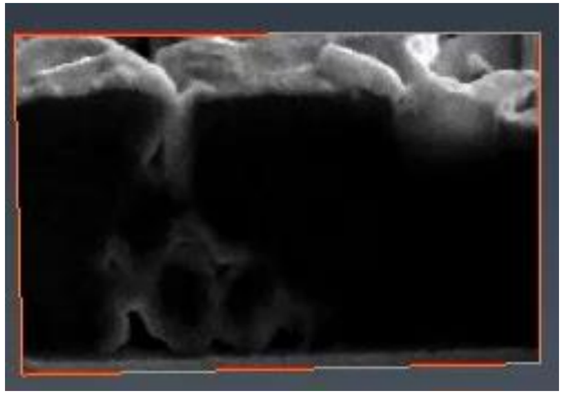
This will ENABLE 500MILES per charge of EVs

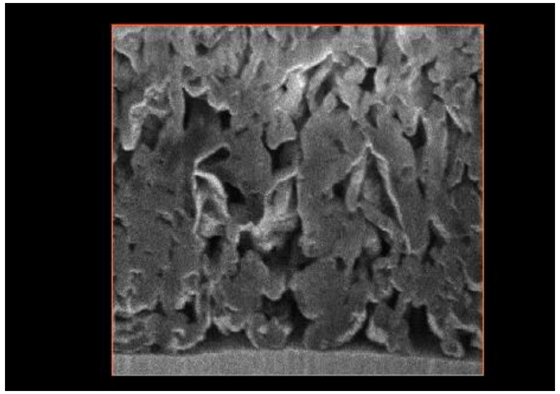


Gen 0	Gen 1	Gen 2	Gen 3
Li-Metal	**Li-ion**	**Li-ion**	**Li-Metal**
100-200 Wh/kg	200-250 Wh/kg	250-300 Wh/kg	400-500 Wh/kg
200-300 Wh/L	600 Wh/L	700 Wh/L	1200 Wh/L
Dangerous	Safe	Safe	Safe

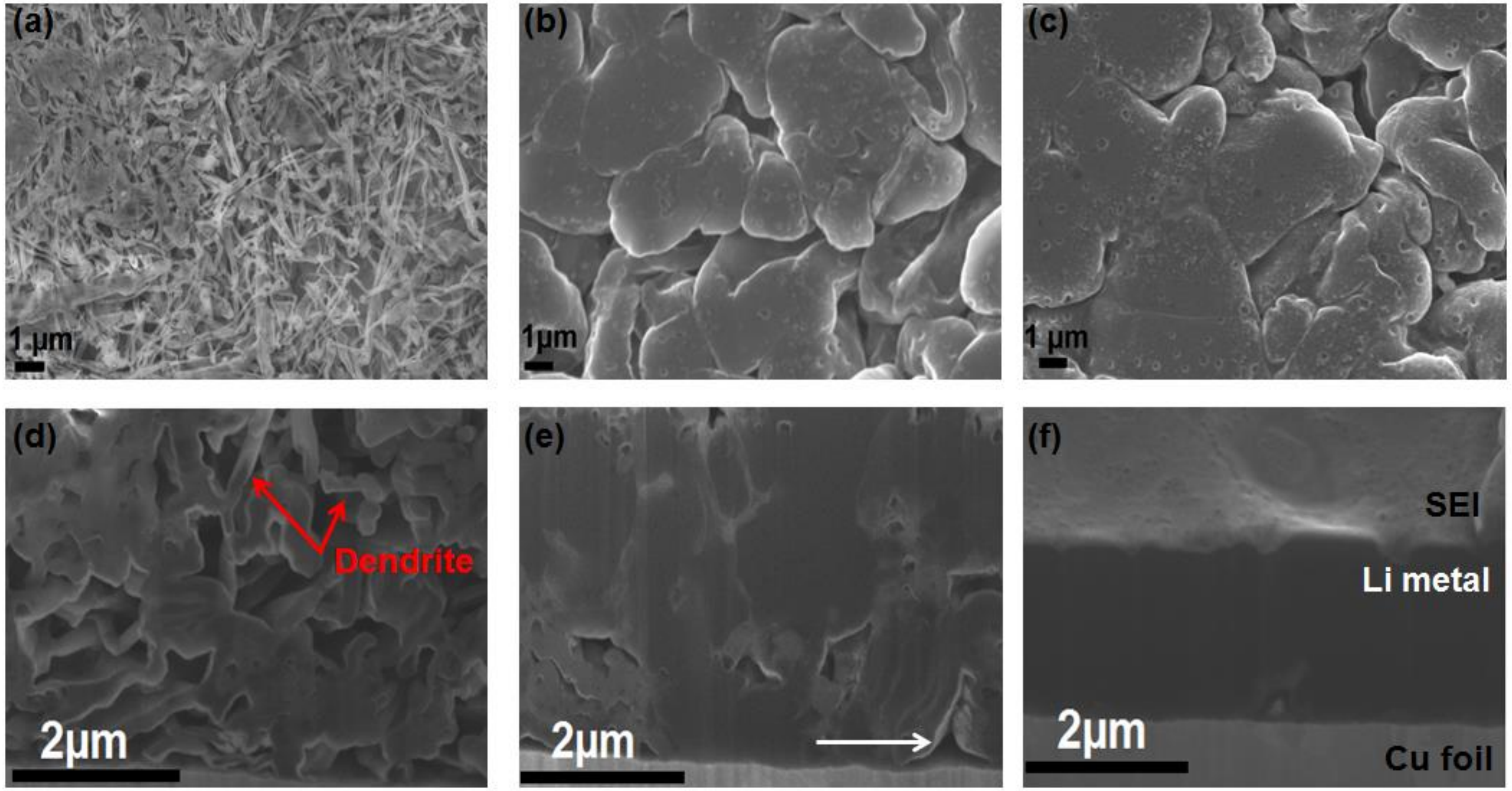
Electrolyte! Electrolyte! Electrolyte!

J. Alvarado , …Y.S. Meng, et al, Energy & Env. Sciences, 2019





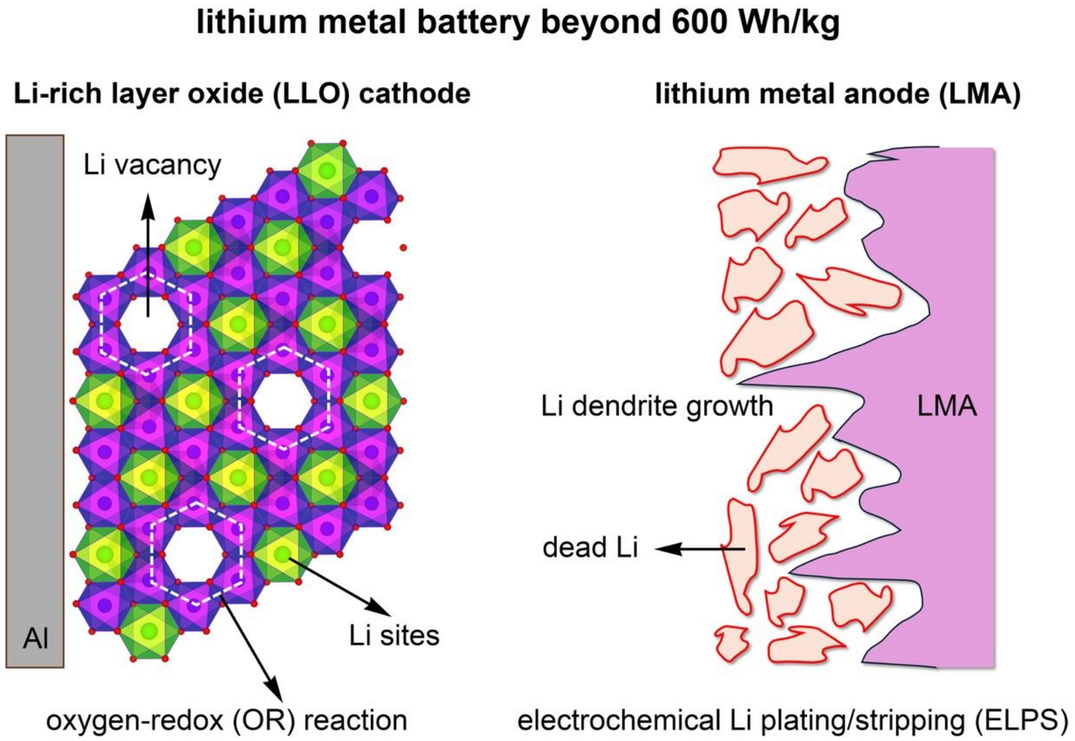
Gen II | **New Salts** | **New Electrolyte**

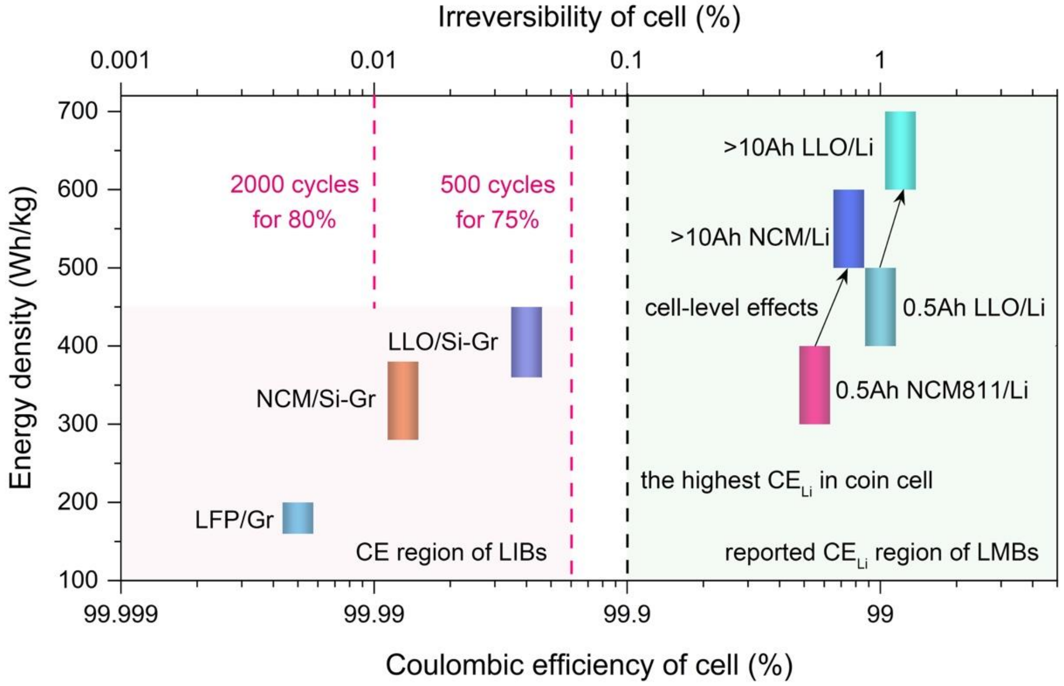


Breakthroughs in Electrolytes - Concentrated, Locally Coordinated, Non-carbonate

Columbic Efficiency increases from 98% to 99.6%

- Li-rich layer oxide cathode is the promising layer oxide cathode for lithium metal battery beyond 600Wh kg^{-1}
- the huge Coulombic efficiency gap between current lithium metal anode and the target

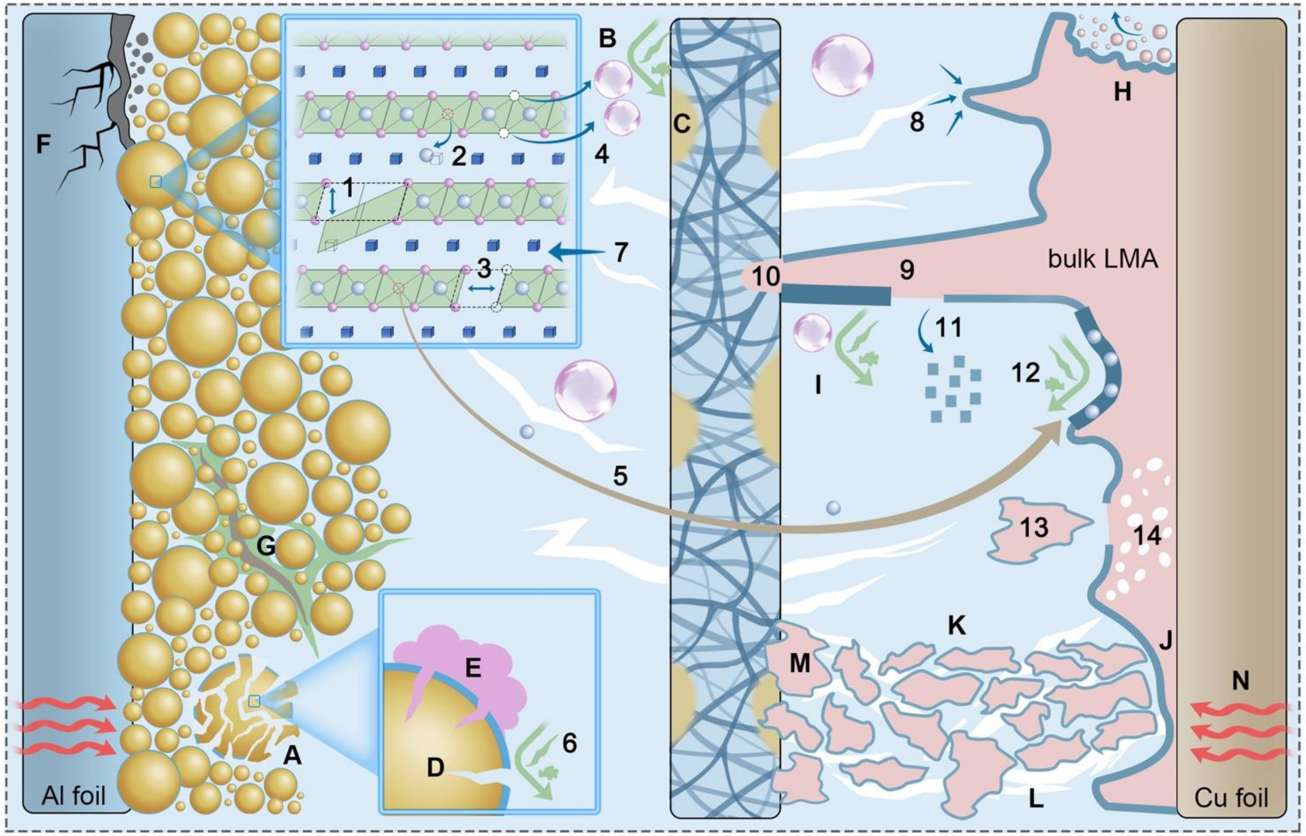




How can we achieve the Coulombic efficiency of Li > 99.90%?

What happens to the ~0.5% loss for Li during electrochemical plating/stripping?

◆ illustrations of material-level degradation and corresponding cell-level impacts in lithium metal battery



cathode | anode | electrolyte | separator

material-level degradation (1-14)

1: collapse of TM-oxygen polyhedra
2: surface TM ions migration to Li sites
3: distortion of TM-oxygen polyhedra
4: instability of lattice oxygen
5: TM ions dissolution and migration to anode
6: electrolyte oxidation at cathode surface
7: increasing Li^{+} transfer resistance
8: local ion depletion and charge accumulation
9: Li dendrite growth
10: penetration and rupture of SEI
11: SEI dissolution and decomposition
12: electrolyte reduction at metallic Li
13: root-preferred stripping to form dead Li
14: multi-sites cavitation on bulk LMA

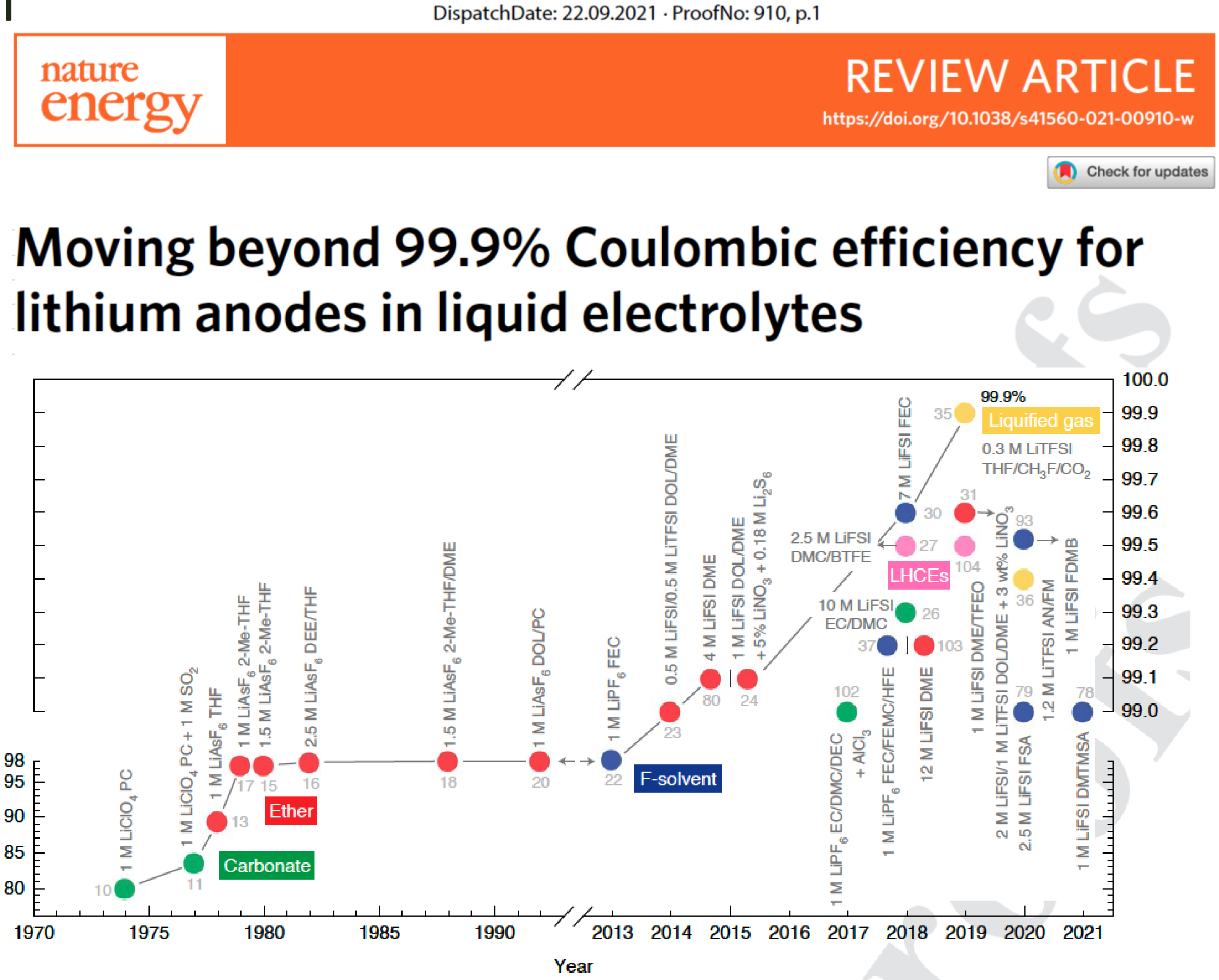
cell-level degradation (A-N)

A: cathode particle pulverization
B: oxygen-induced electrolyte decomposition
C: byproducts blocking seperator porosity
D: surface-localized cracking of cathode
E: cathode interficial byproducts
F: localized foil corrosion and cracking
G: electrode without conductive contact
H: galvanic corrosion of LMA
I : chemical corrosion of LMA
J: exhuastion of active Li in bulk LMA
K: accumulation of porous dead Li layer
L: localized insufficient electrolyte wettability
M: dead Li blocking seperator surface
N: uneven Joule heat distribution

the active Li loss in lithium metal anode plays key role in determining the lifespan of battery

BUT the active Li loss is masked by typical battery capacity fade

Possible to Invent More Electrolytes to Enable Metal Anodes


DispatchDate: 22.09.2021 · ProofNo: 910, p.1

nature energy

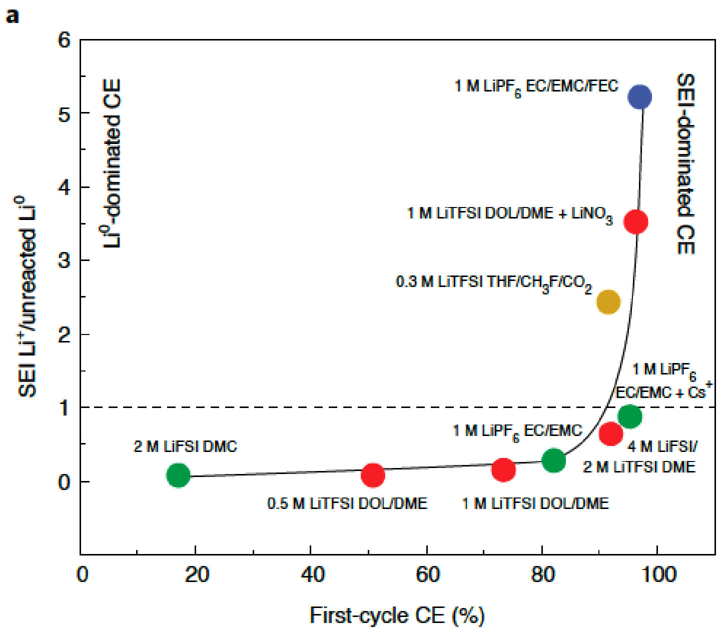
REVIEW ARTICLE

https://doi.org/10.1038/s41560-021-00910-w

Check for updates

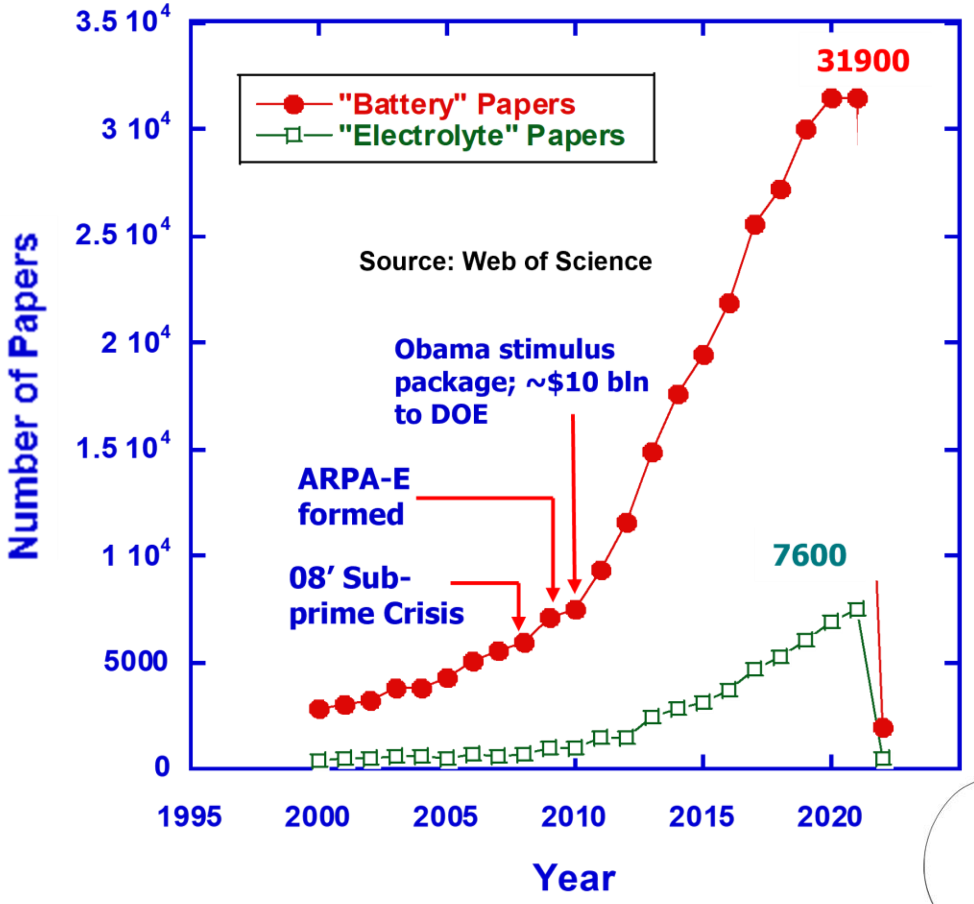
Moving beyond 99.9% Coulombic efficiency for lithium anodes in liquid electrolytes

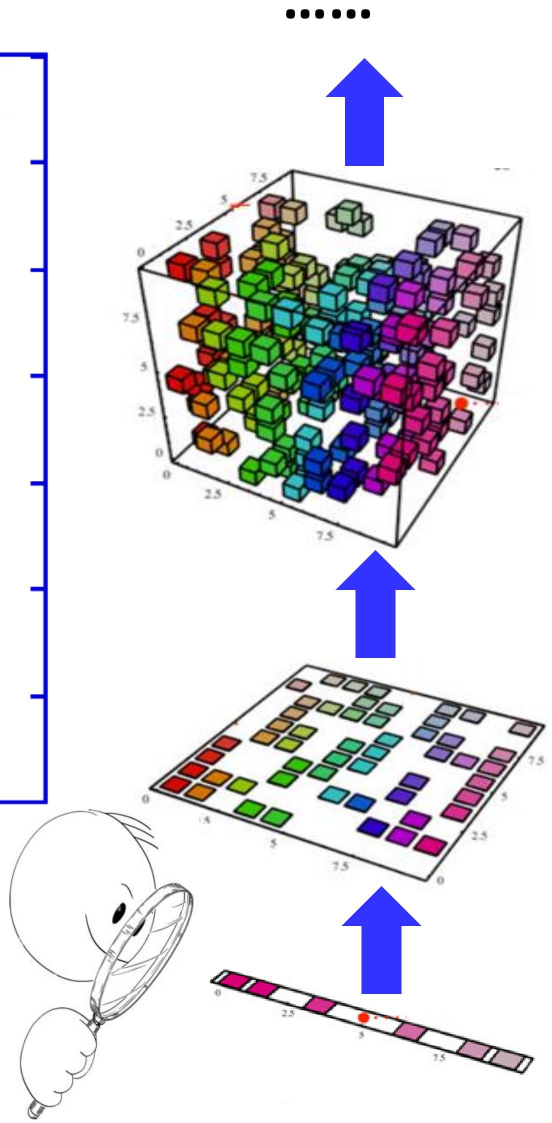
Collaboration with
Prof. Betar Gallant and Yang Shao-Horn



Electrolyte Literature – A New Barrier for New Discovery?

- **Battery research has been "hot" since 2010**
- **In 2021, around 650 battery papers published per week**
    - ~150 papers on "battery electrolyte"
- **Not a single individual can follow the literature**
- **Let alone understanding in-depth, or identifying patterns/relations underneath the text**





Courtesy of Dr. Kang Xu

SES Beyond Li-ion™

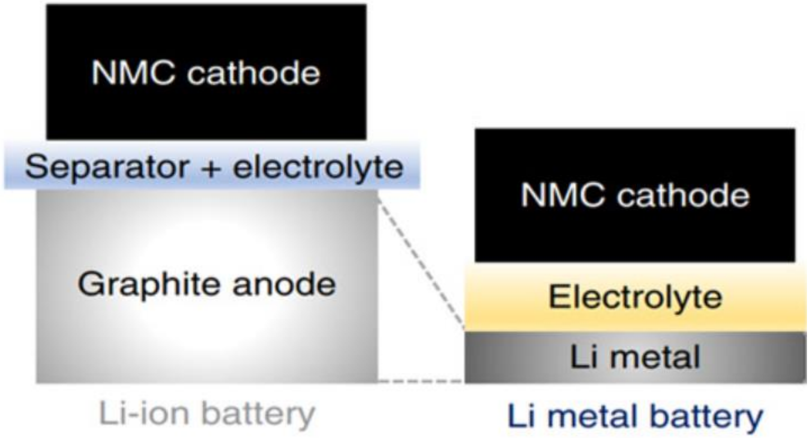
Make Contact
with the Molecular
Universe.

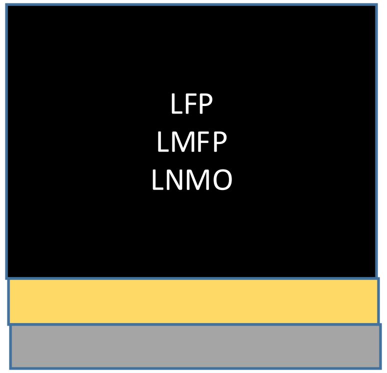
SES

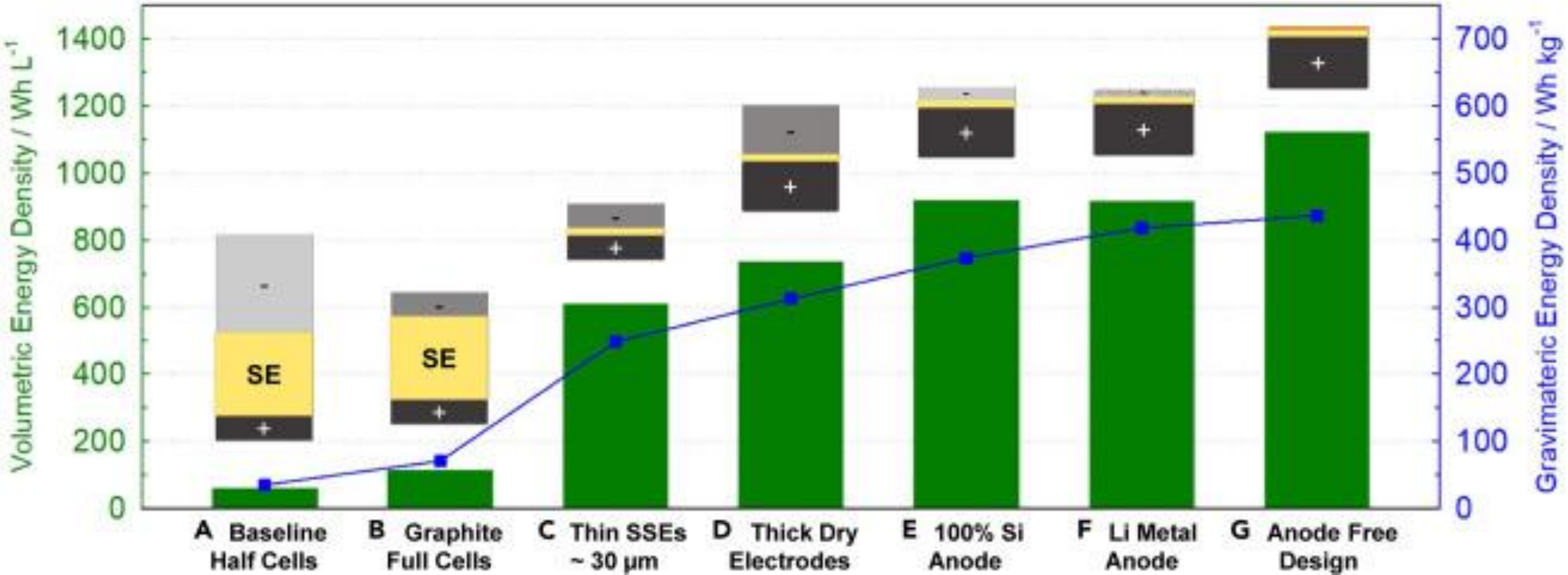
All Solid-State Batteries – Platform Technology

High-Energy-Density** and **Safe Batteries

*with **Solid-State Electrolyte***







Energy Density > 500Wh/kg
Conversion type Cathodes
Metal Anodes
Ultra Thin Separator

Safety
Particularly for Oxides Sulfides ?
Polymers X

Fluorine - Free Chemistry

Stackable Design

Dry Processing

Ultralong Cycle Life

Wider Operation Temperature

Enable Conversion Chemistry

Sodium Anode-Free Solid-State Batteries

Can achieve 3 goals simultaneously…

1. Maximize energy density

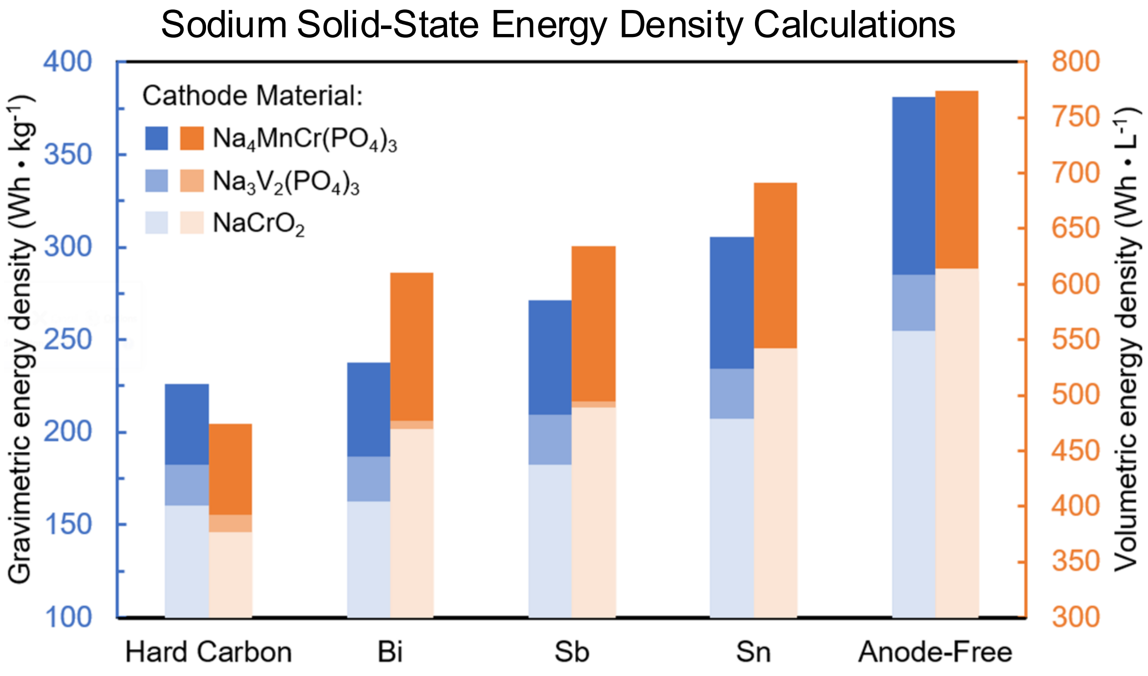
- Lowest reduction potential → highest cell voltage
- Smaller and lighter cells

2. Minimize cost

- No anode material cost, lower processing cost
- Sodium cheaper than Lithium

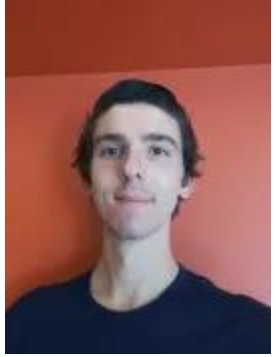
3. Improved safety

- No flammable organic liquid electrolytes
- No large amounts of sodium metal foils



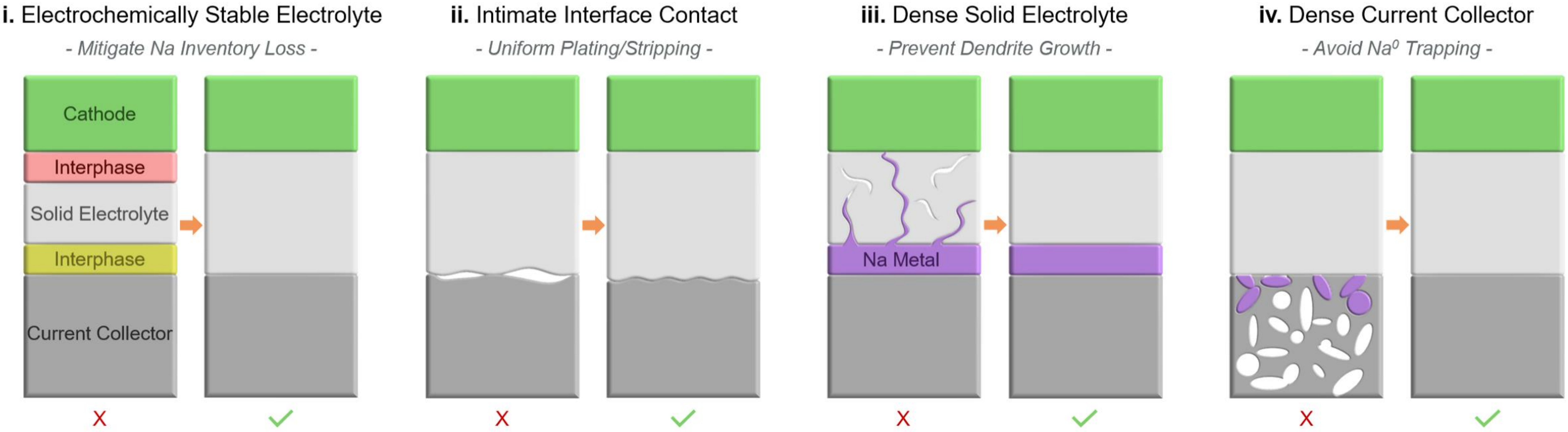
Critical Design Factors

G. Deysher, J.A.S. Oh, … Y.S. Meng, “ An Anode-Free Sodium All-Solid-State Battery “, 2024, Nature Energy



Dr. Grayson Deysher

- 4 fundamental criteria for enabling anode-free solid-state batteries



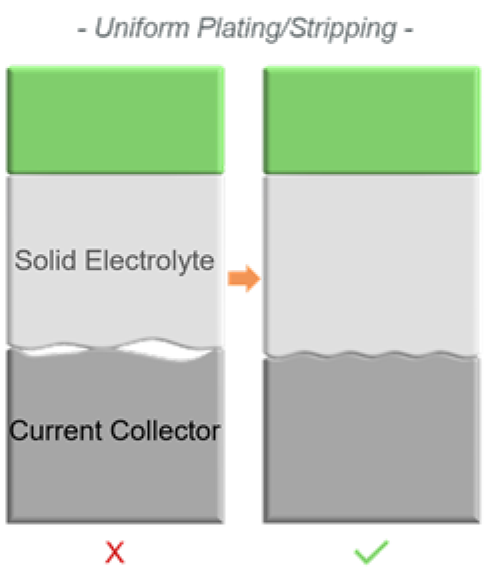
- Must design a cell from the ground up
  - Material selection and cell architecture

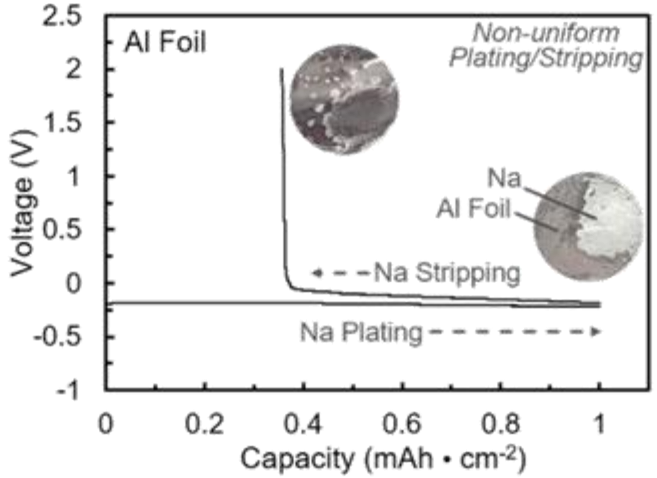
Intimate Interface Contact

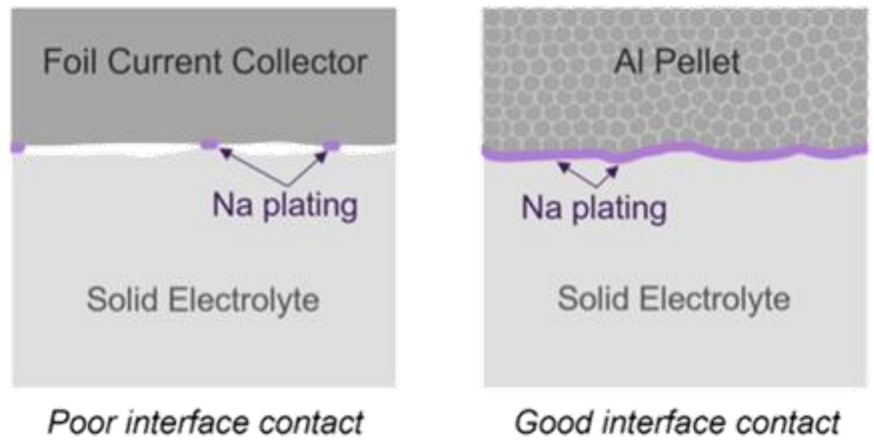
G. Deysher, J.A.S. Oh, … Y.S. Meng, "[An Anode-Free Sodium All-Solid-State Battery](#) ", 2024, Nature Energy

Patent Pending

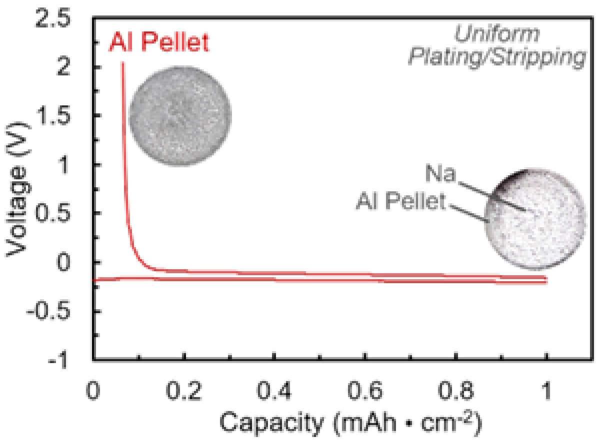
ii. Intimate Interface Contact



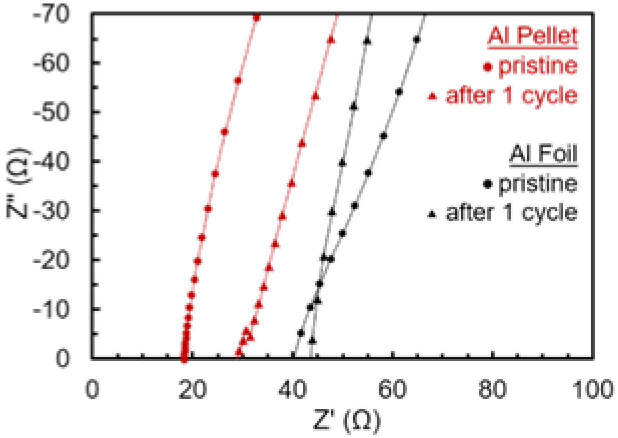


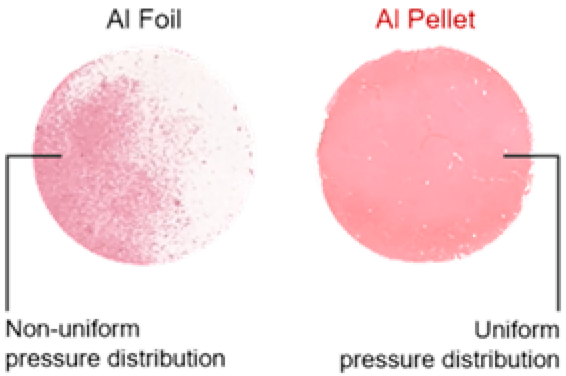


- Pelletized Al can achieve intimate contact with the NBH electrolyte



Al Pellet = Lower interface resistance

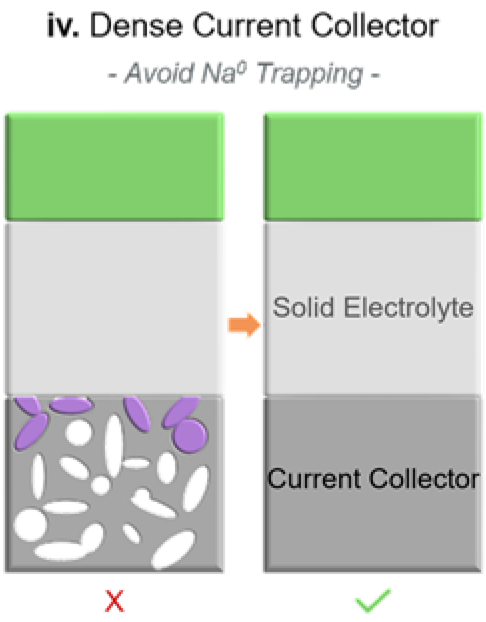


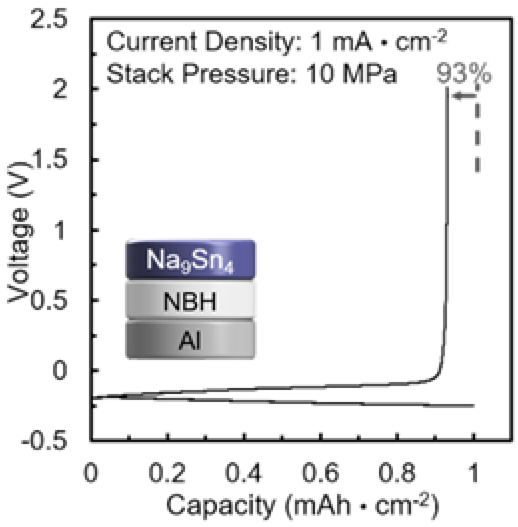


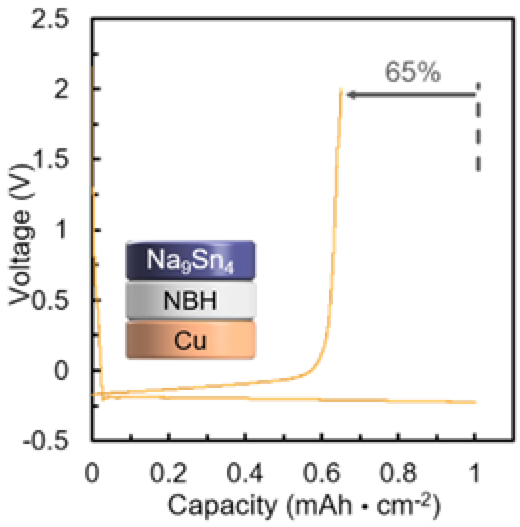
Designed Dense Current Collector

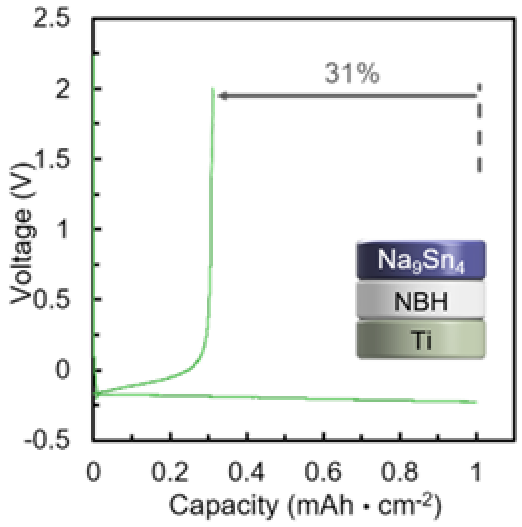
G. Deysher, J.A.S. Oh, … Y.S. Meng, " An Anode-Free Sodium All-Solid-State Battery ", 2024, Nature Energy

Patent Pending

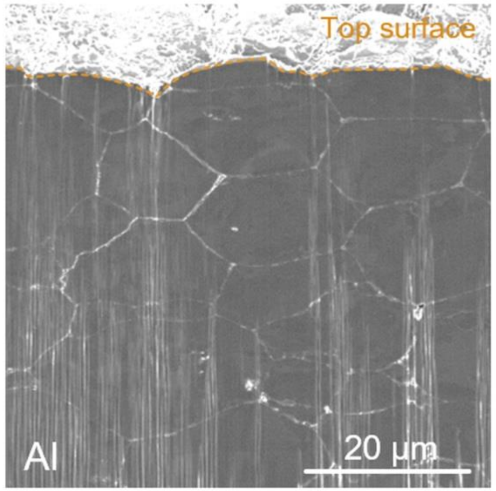


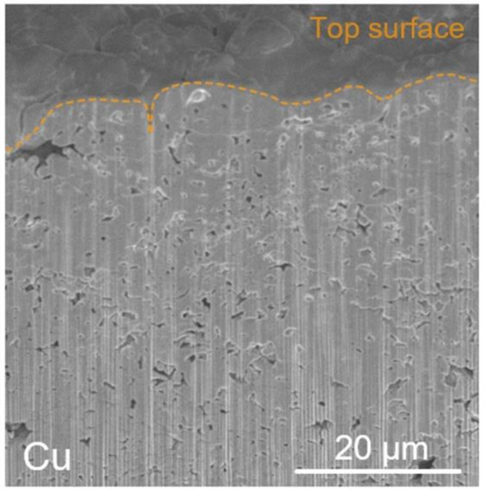


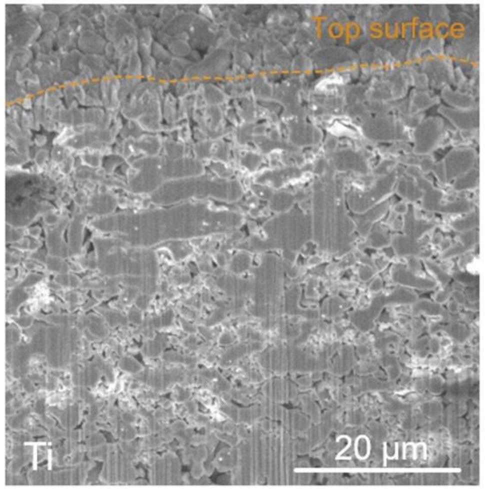




- Soft Al can be easily densified during cell fabrication
  - Unlike Cu and Ti



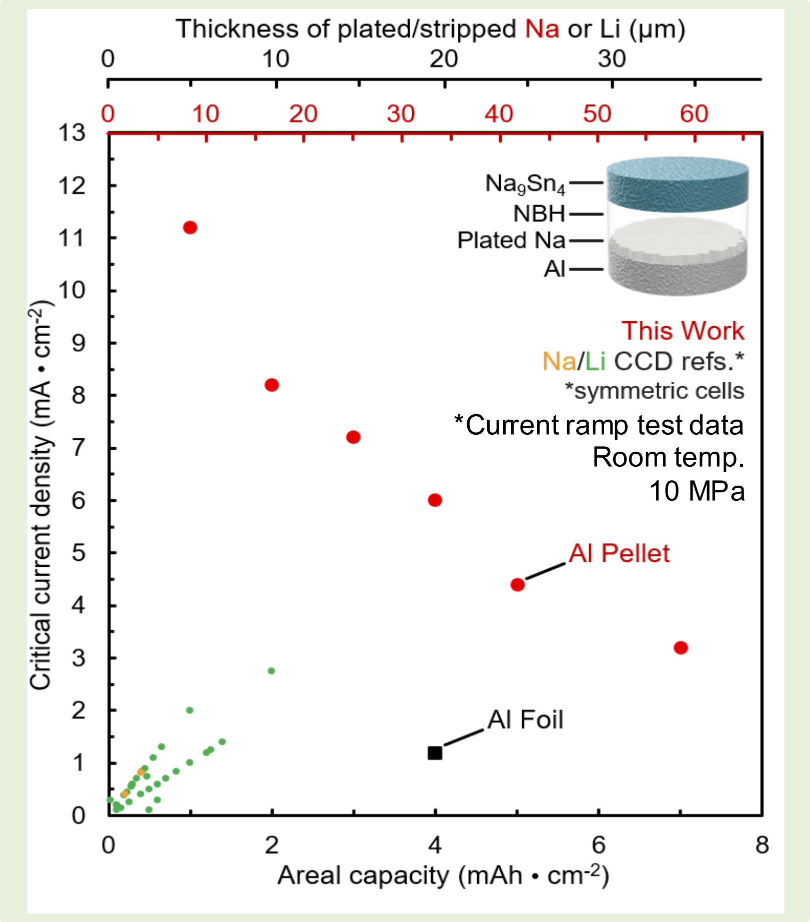




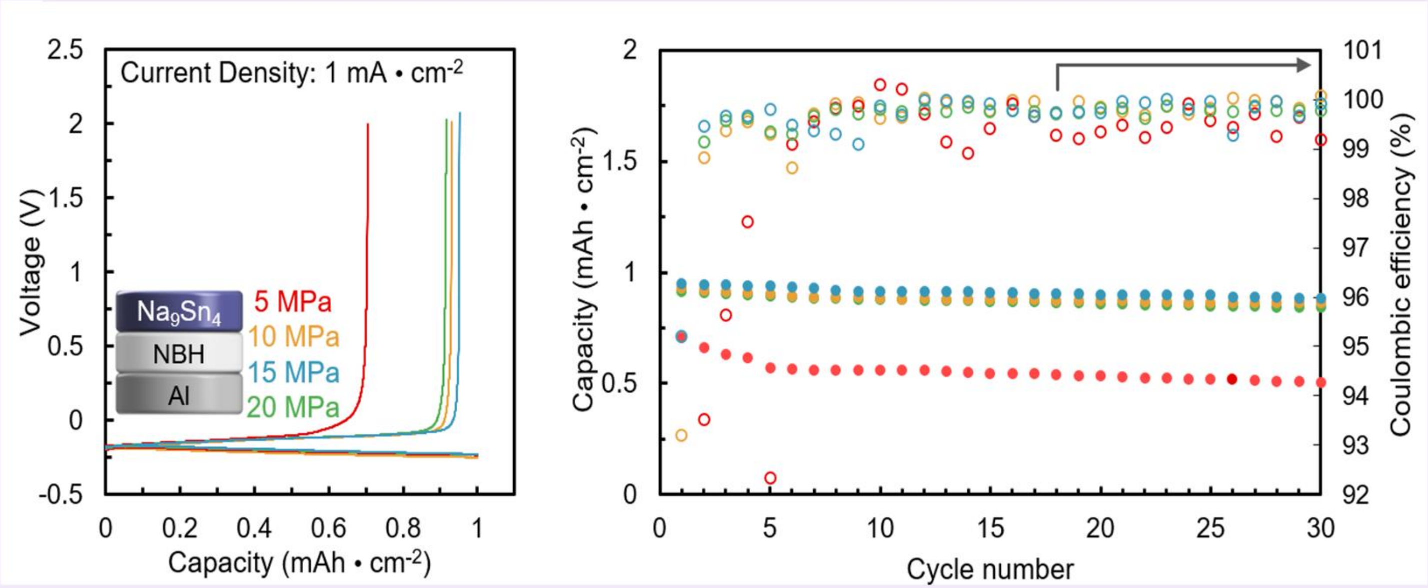
G. Deysher, J.A.S. Oh, … Y.S. Meng, " An Anode-Free Sodium All-Solid-State Battery ", 2024, Nature Energy

Current Density

Patent Pending



Cell Stack Pressure

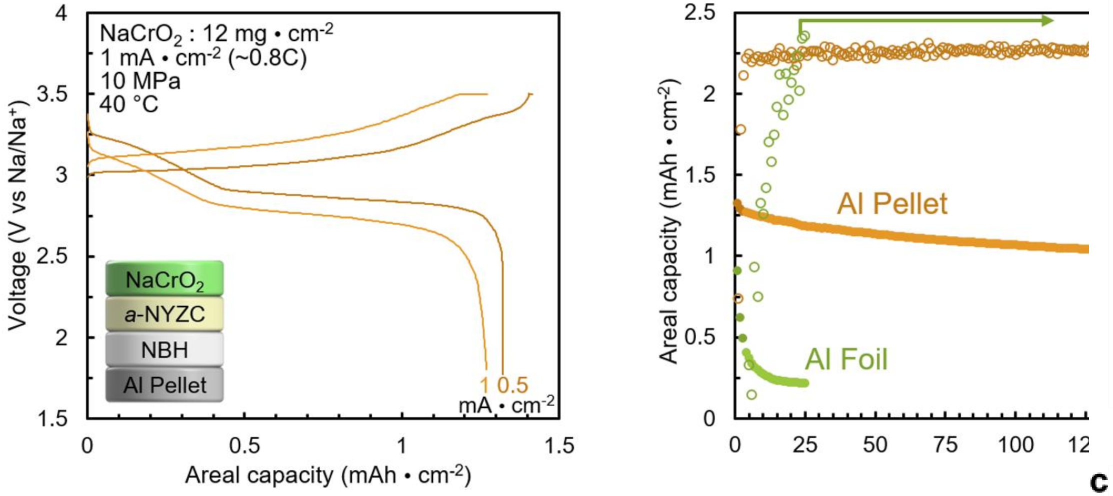


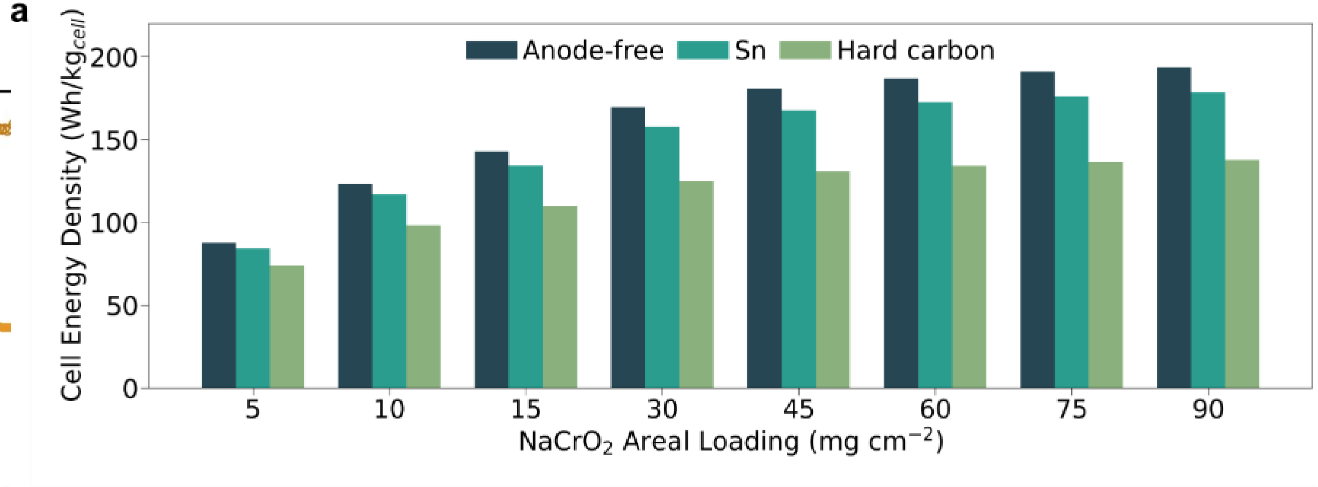
- High critical current density
  - Pathway to fast charging
- Low pressure cyclability
  - Pathway to practical commercial cells

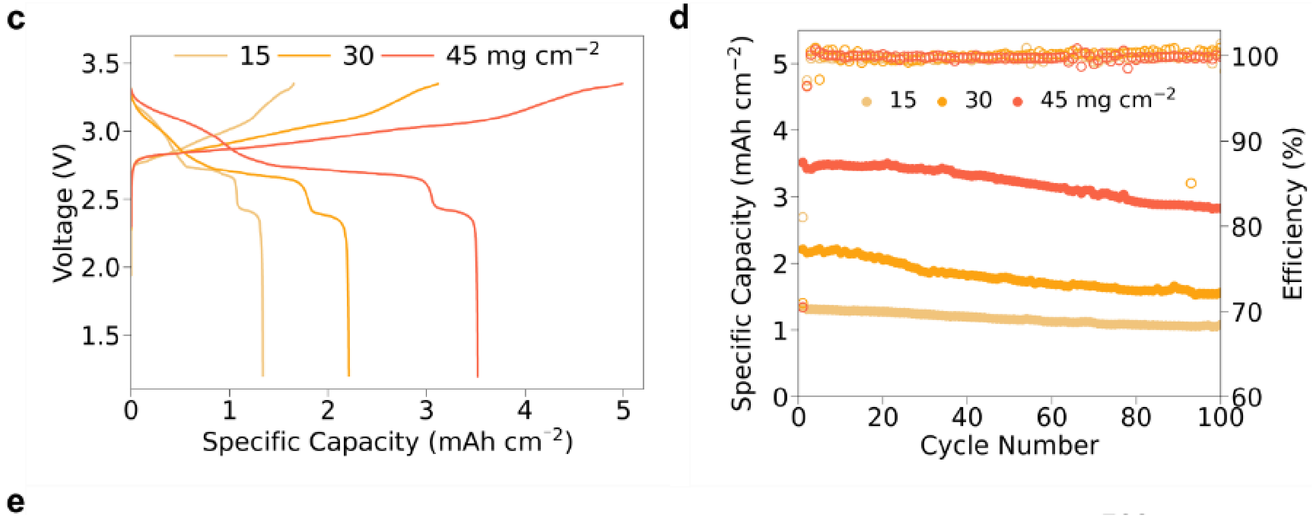
Sodium All Solid-State Full Cell

G. Deysher, J.A.S. Oh, … Y.S. Meng, "An Anode-Free Sodium All-Solid-State Battery", 2024, Nature Energy   Patent Pending

- Enable full-cell cycling ($NaCrO_2$ cathode)







Thick Battery Cathode enabled by novel superionic Na conductor

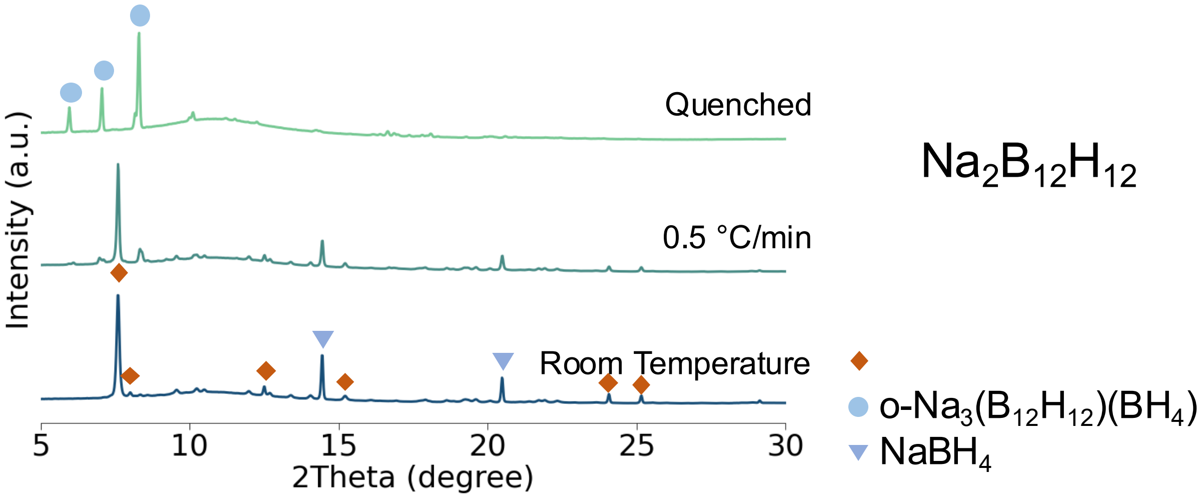
Dr. J.A.S. Oh Patent Pending and To be Submitted

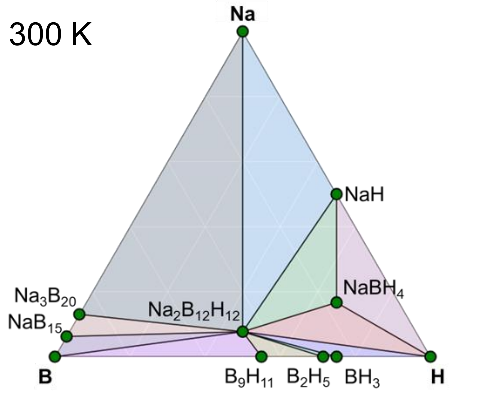
Materials Discovery – Metastable o-NBH

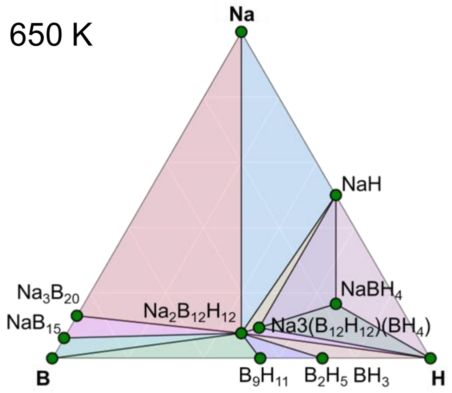
Patent Pending

Dr. Sam Oh

- ➢ $Na_2B_{12}H_{12}$ reacted with $NaBH_4$
  - ➢ Both are poor Na^+ conductors on their own







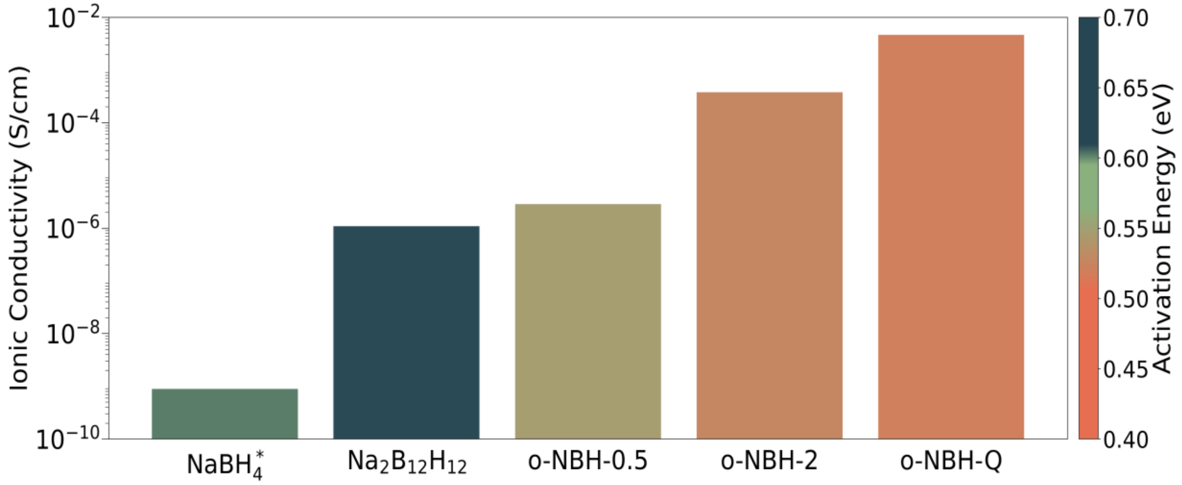
- ➢ Different cooling rate exhibits different crystal structure at room temperature
  - ➢ o-NBH stabilized with quenching
  - ➢ $Na_2B_{12}H_{12}$ and $NaBH_4$ patterns when cooled slowly
  - ➢ Metastable nature of o-NBH stabilized by rapid cooling

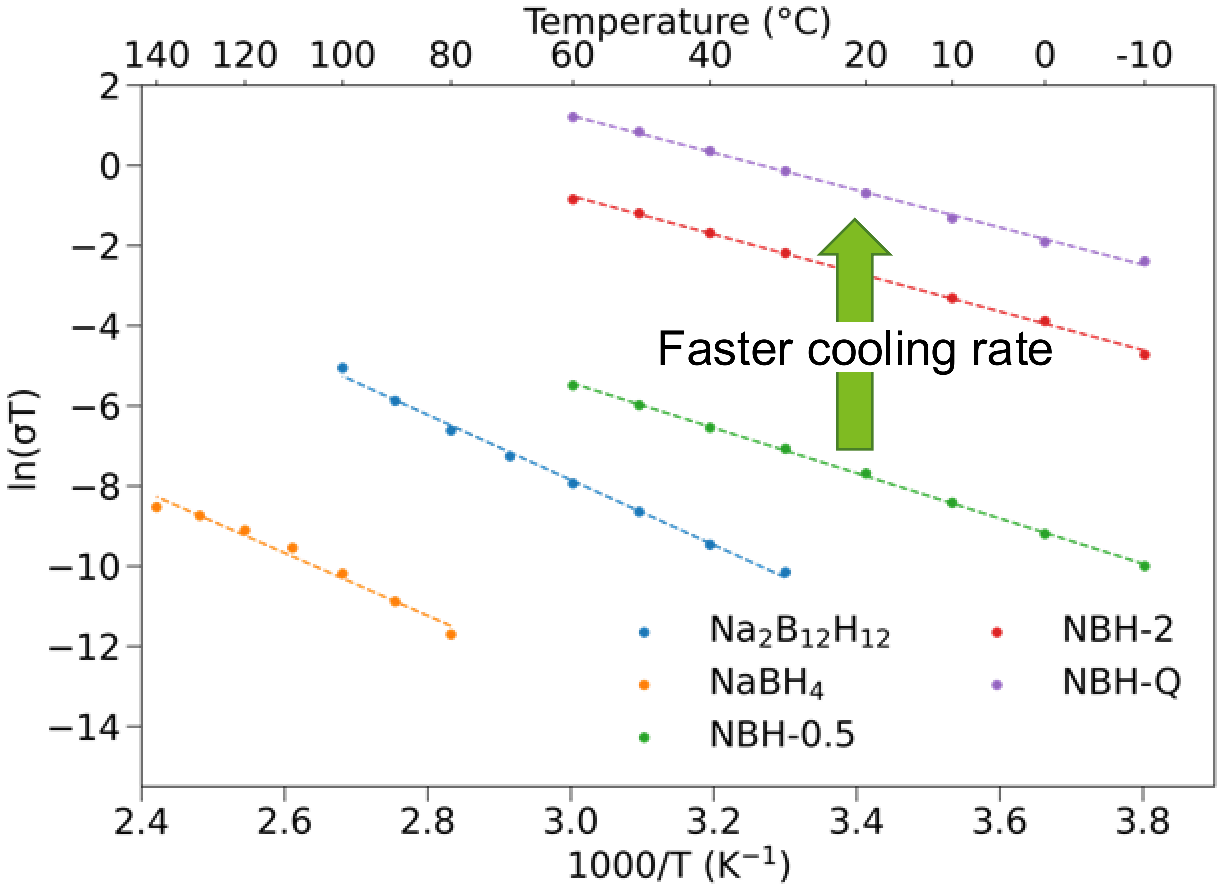
Oh, J.A.S., Yu, Z., Griffith, K. J., Ong, S. P., Meng, Y.S., et al. 2025. *Joule*

Activation Energy

Activation energy estimated by EIS measure at different temperature

- Ionic conductivity – temperature follows the Arrhenius relationship
  - $\sigma_T = \sigma_T \, exp^{-E_a/kT}$
- Faster cooling rate maximizes ionic conductivity
  - Quenched





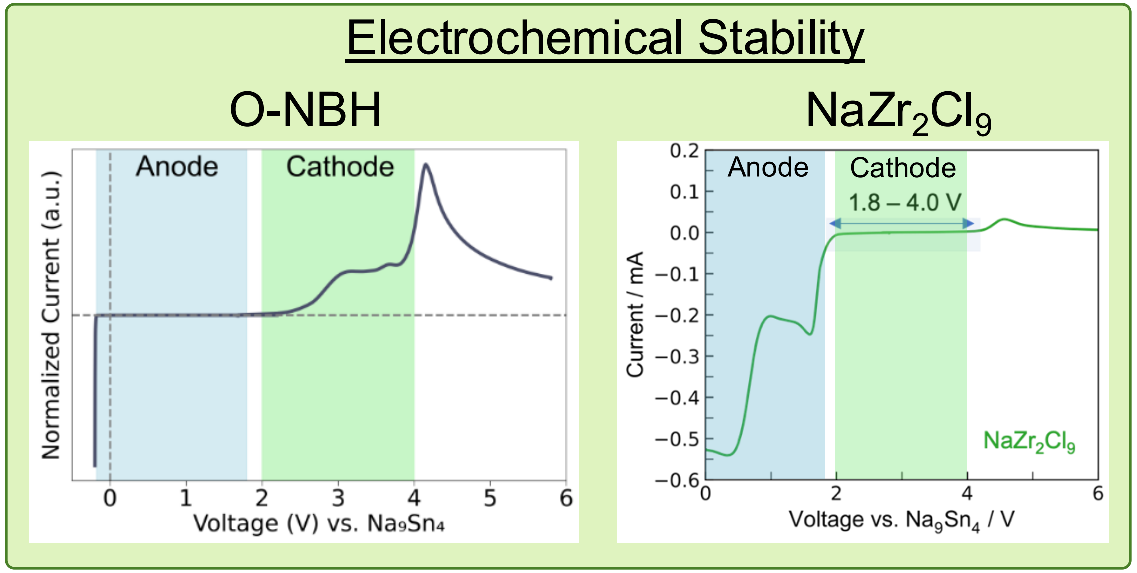
Oh, J.A.S., Yu, Z., Griffith, K. J., Ong, S. P., Meng, Y.S., et al. 2025. *Joule*

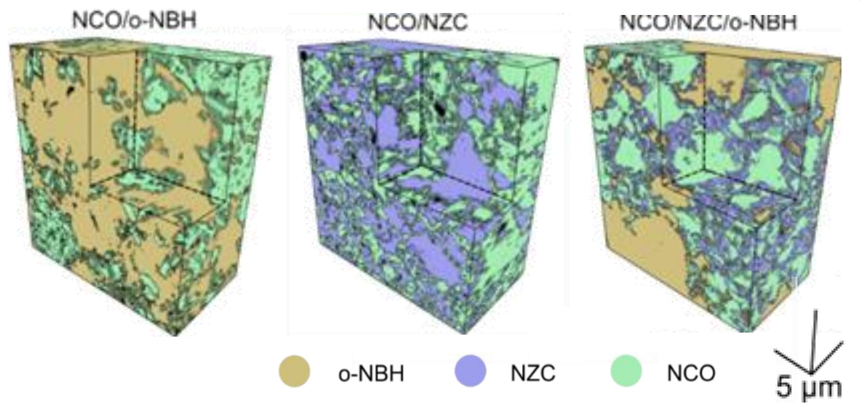
Cathode Composite Electrochemical Performance

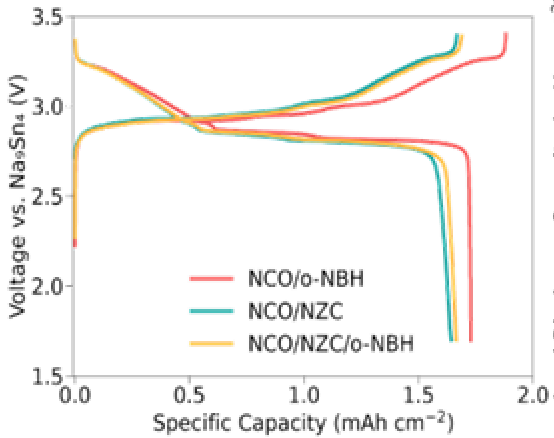
- o-NBH is not stable at cathode potentials
  - Oxidizes around 2.5 V

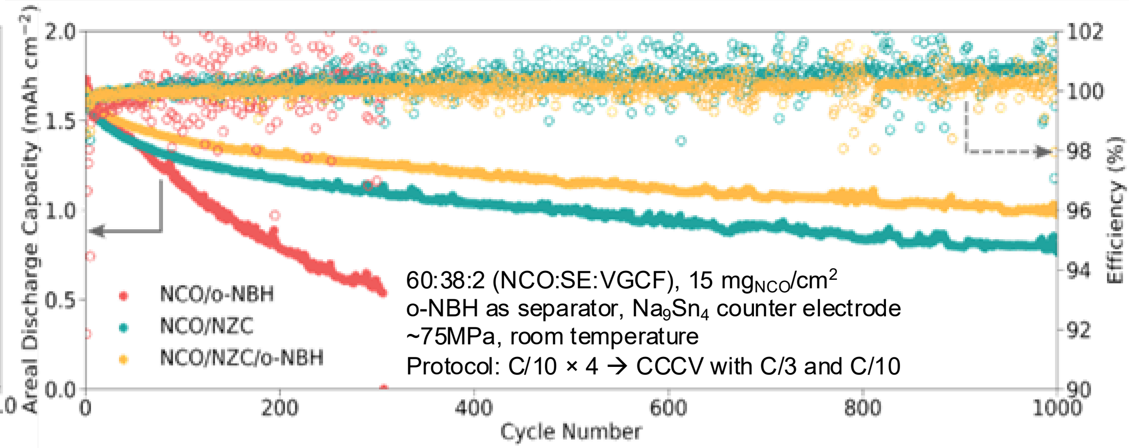
New cathode design strategy →

- Coat $NaCrO_2$ cathode with stable $NaZr_2Cl_9$
  - Stable cathode-electrolyte interface
- Mix in o-NBH for fast Na^+ conduction









Oh, J.A.S., Yu, Z., Griffith, K. J., Ong, S. P., Meng, Y.S., et al. 2025. *Joule*

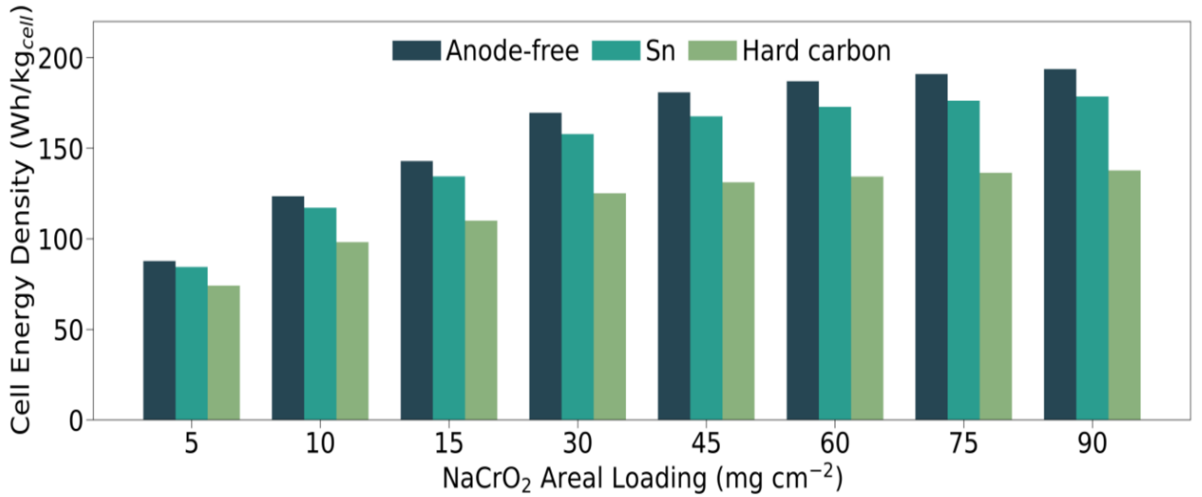
High Loading Full Cell Cycling

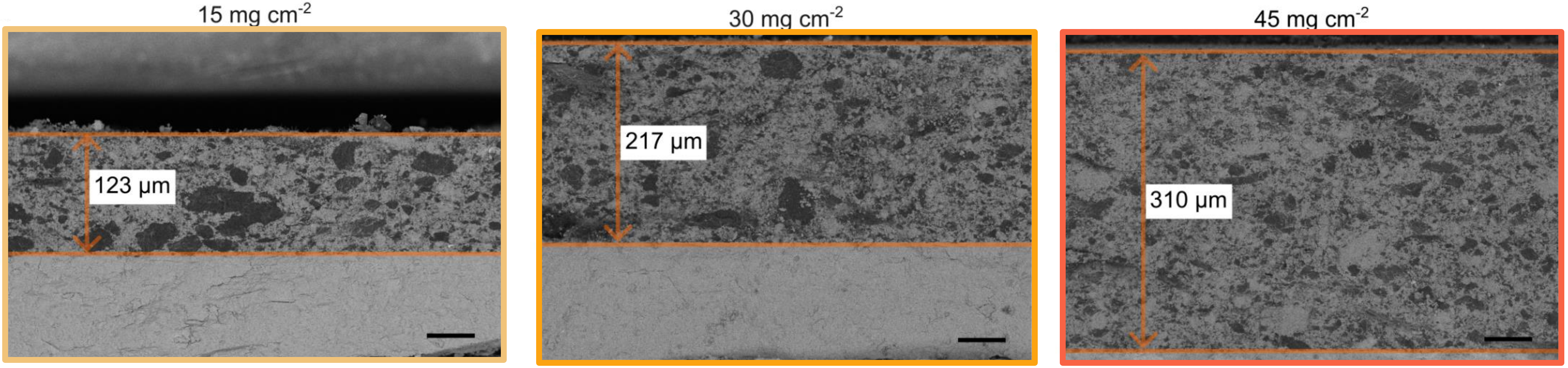
Energy density increases with higher cathode loading

- Plateaus after ~45 mg/cm^2 $NaCrO_2$

Cathode composites fabricated up to ~300 µm thick

- Theoretical capacity = **5.4 mAh/cm^2**





Oh, J.A.S., Yu, Z., Griffith, K. J., Ong, S. P., Meng, Y.S., et al. 2025. *Joule*

Conclusions and Outlook

All-solid-state batteries are in good progression:

- Realize high-capacity anode (Si) with excellent capacity retention
- Prelithiation works best with minimum structural loss cathode
- Morphological control is critical
- Proof-of-concept pouch cell operating at **5 MPa** and exposed to dry-room condition

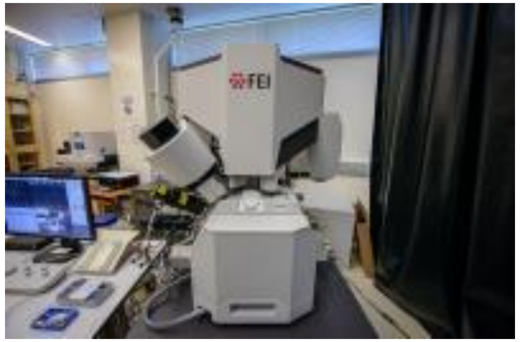
Sodium solid-state batteries are promising complementary to lithium counterpart:

- Research efforts in sodium batteries still lagging
- Li_6PS_5Cl analogue is found in sodium
- *Amorphous* SSE path new research direction to super- ionic conductivity!

Collaborators and Funding

Sustainable Power and Energy Center

sdni
San Diego Nanotechnology Infrastructure



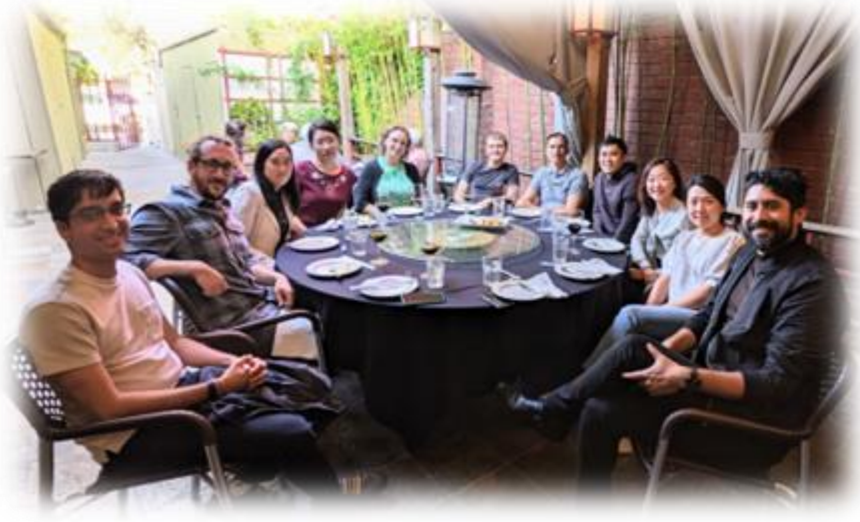
UC IRVINE MATERIALS RESEARCH INSTITUTE

U.S. DEPARTMENT OF ENERGY | Office of Science
NECCES

(John Vetrano, Jane Zhu and Craig Henderson)

BATTERY 500 CONSORTIUM

Vehicle Technology Office
(Tien Duong and David Howell)



Alumni of LESC

LGES Frontier Research Laboratory (2021 – present)
Various Industrial Partners including
(LG Energy Solution / ThermoFisher Scientific / Shell / UL /Nissan /Cummins/ SES/ Supernal /GM / Applied Materials/Tesla/BMW)

Na Batteries Since 2010

NSF

National Science Foundation
DMR program (Na Batteries)

Global Race for Solid State Battery – West vs. East