CHANGING WHAT'S POSSIBLE

Prospects for Safer Batteries for Transportation

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Ninth Triennial International Aircraft Fire and Cabin Safety Research Conference
October 28-31, 2019
Atlantic City, New Jersey

Drivers for next generation batteries

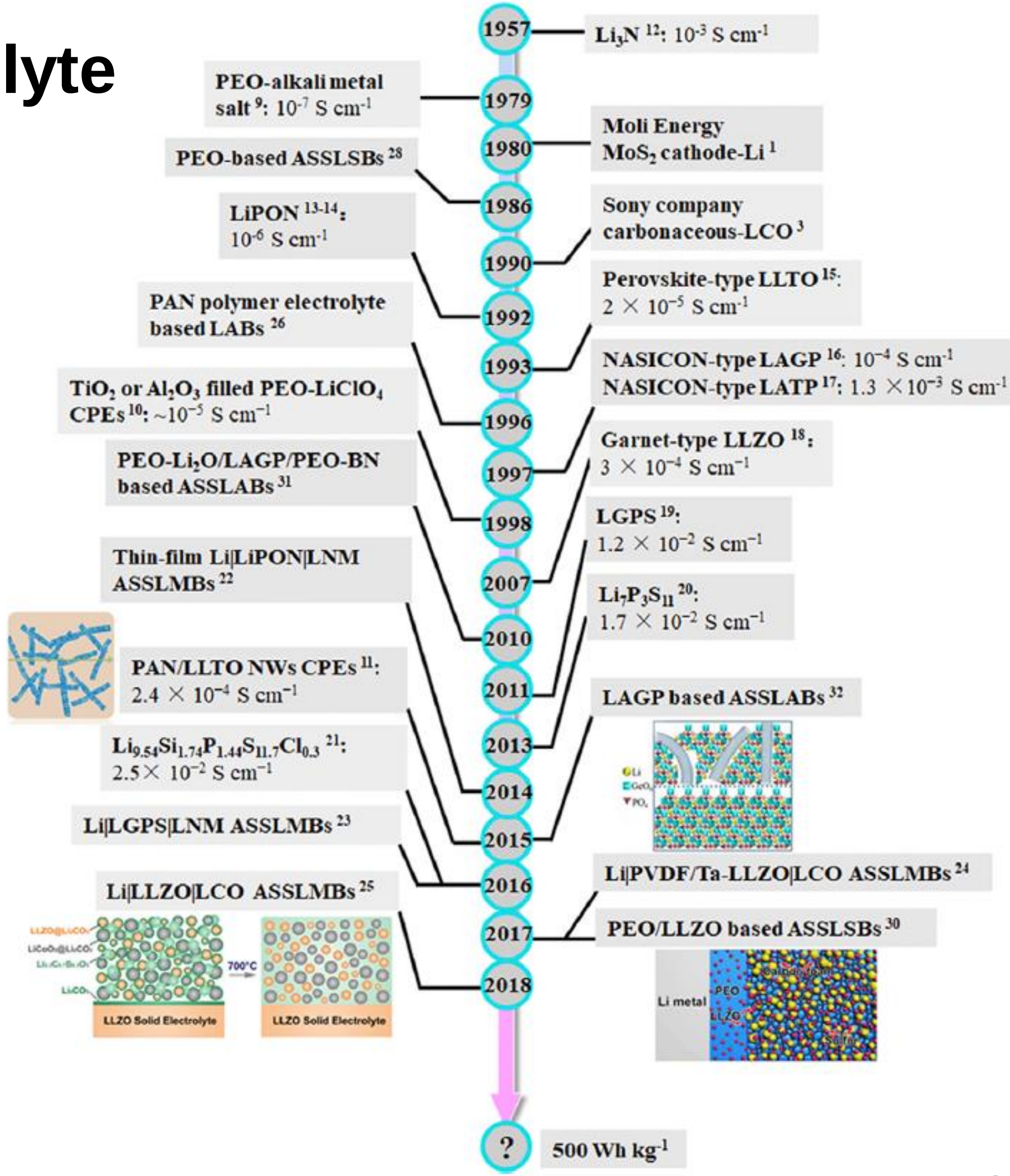
- **Safety**

First utility scale battery fire in US (Surprise, AZ)
At least 21 fires have already occurred at utility battery projects in South *Korea* (BloombergNEF)

Tesla burns in crash, killing driver and 'keeps catching fire' at tow yard; February 24, 2019, Davies, Florida

- **Energy density- quest for 500 Wh/kg**
  - Not possible without Li metal anode and conversion cathode or liquid fuel

Solid state electrolyte chronological development



Chem 5, 1–33, April 11, 2019

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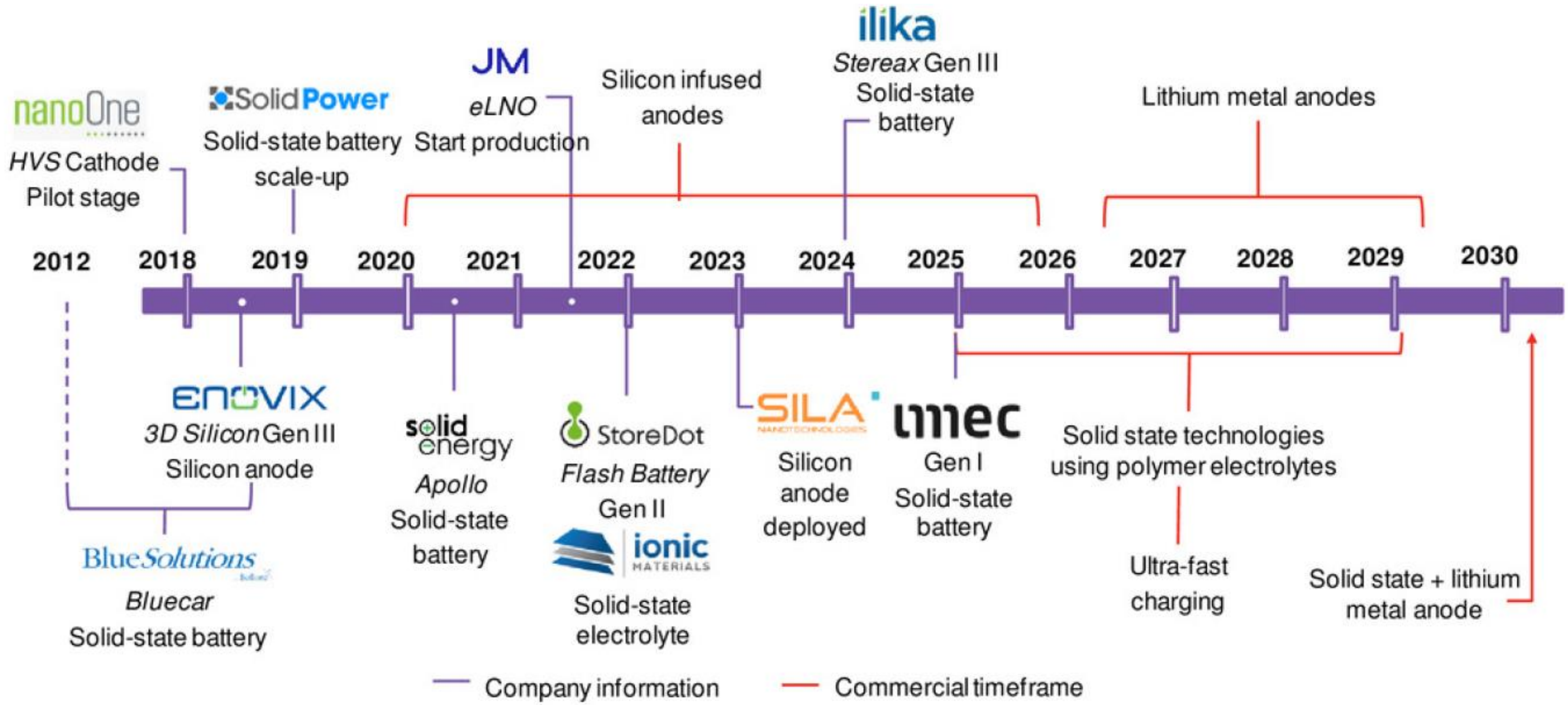
BNEF Technology Timeframe



Source: Bloomberg NEF and company interviews

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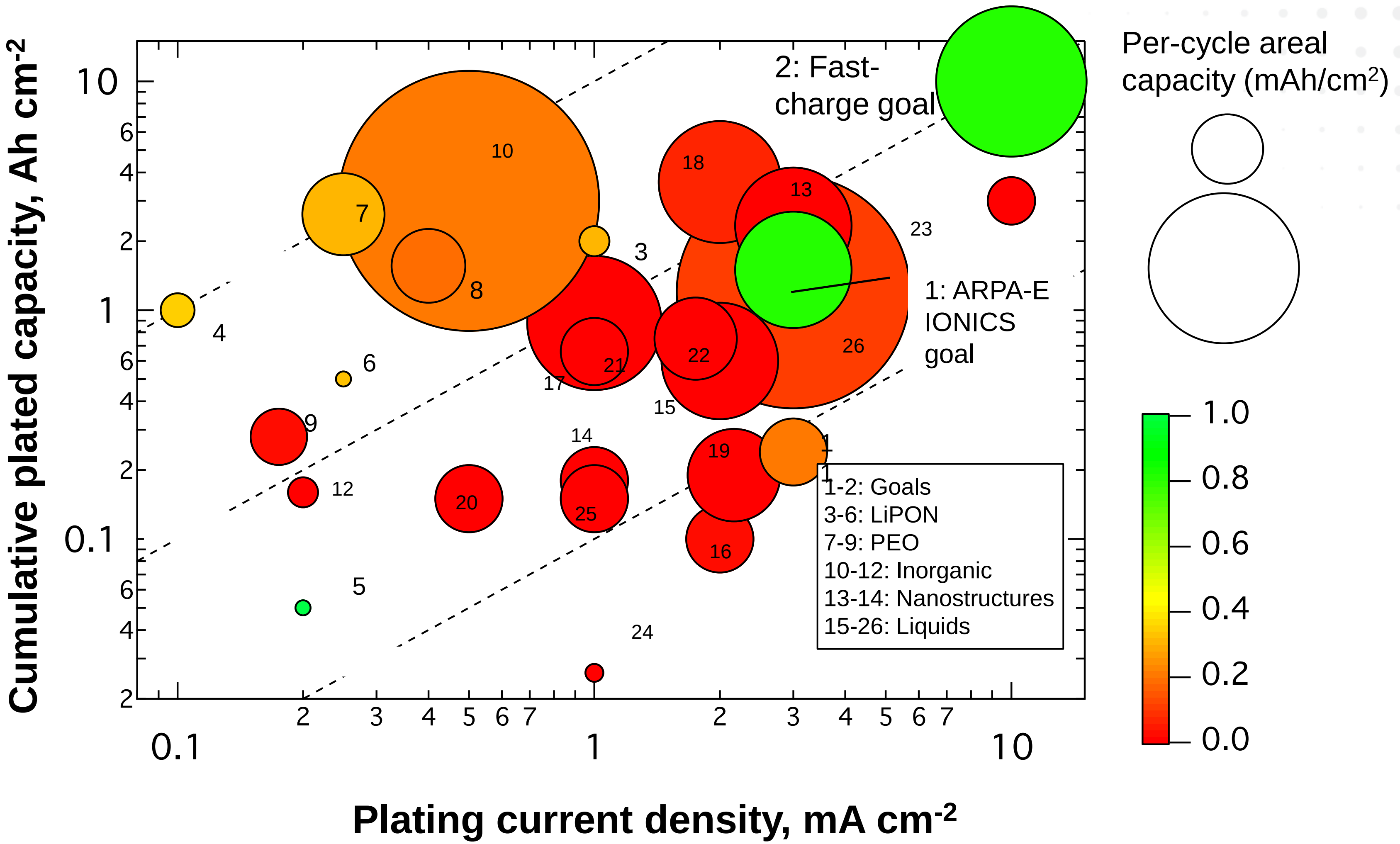
Main lithium cycling issues in solid state battery

- Dendrite formation/battery shorts
- Li segregation/non-uniformity
- Soft shorts/defects
- Mossy lithium plating/loss of Li
- Anode (and cathode) volume change
- Plating on other conducting surface
- High ASR/thick membrane
- Interfacial resistance growth/chemical reactions
- Solid catholyte/high resistance

Four key metrics to evaluate lithium cycling



P. Albertus, S. Babinec, S. Litzelman & A. Newman
Nature Energy, **3** (2018) 16–21

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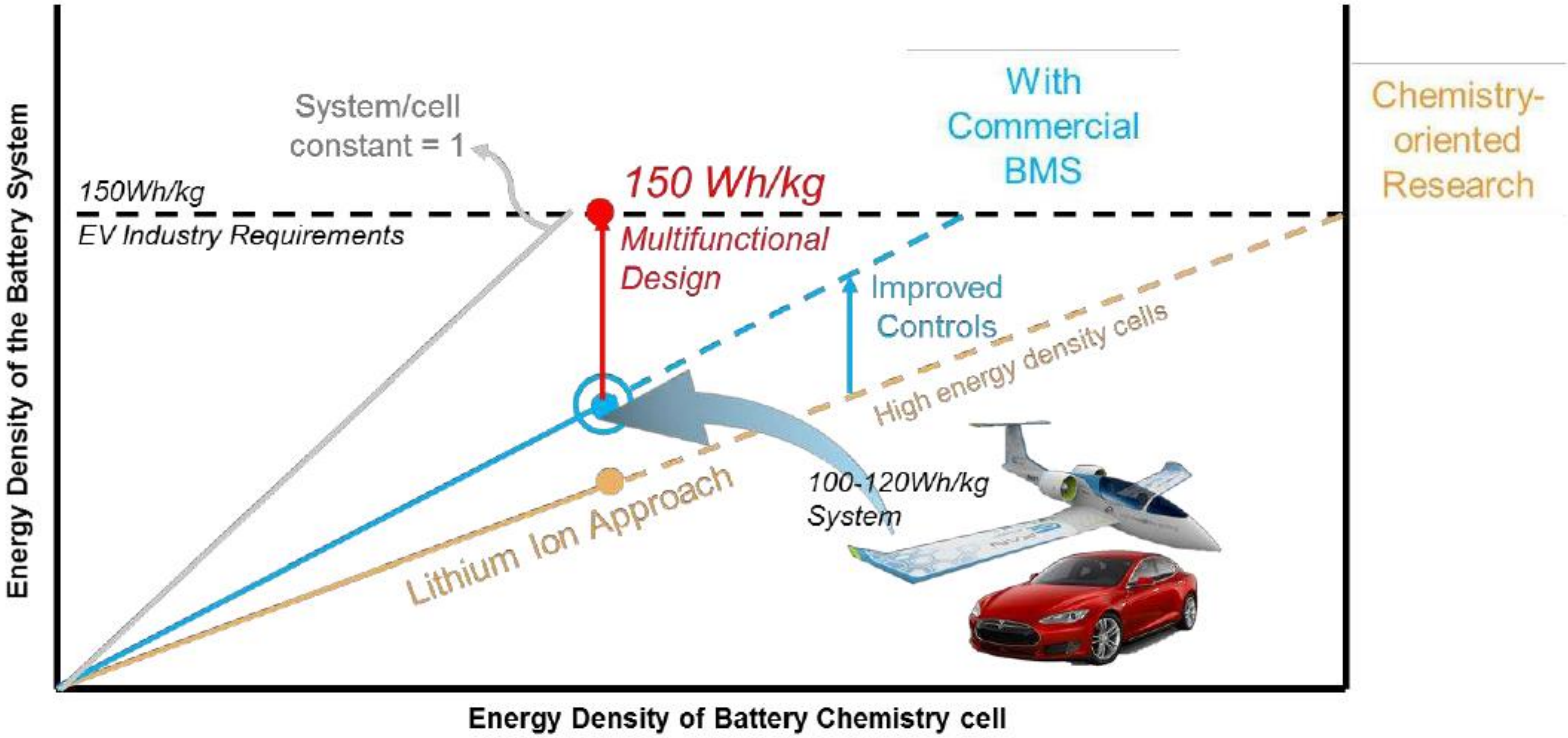
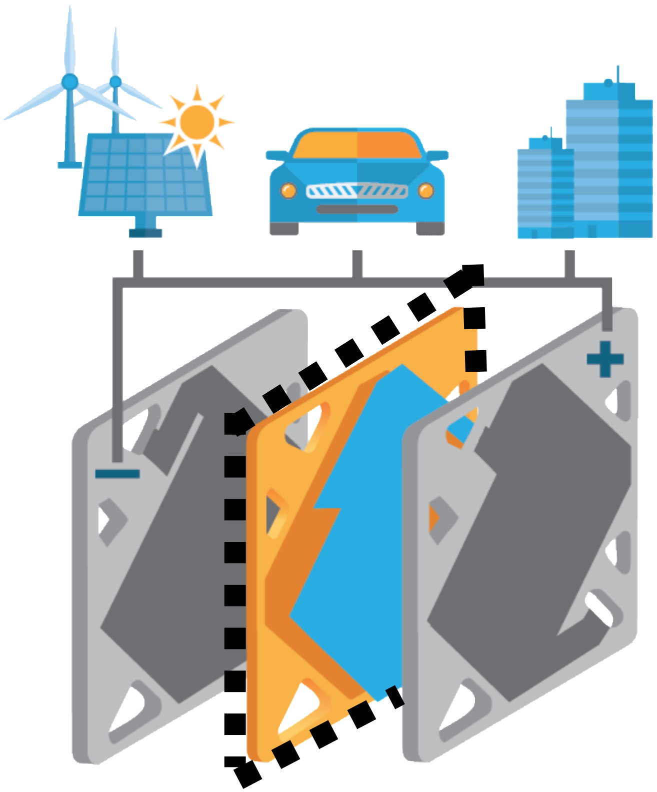
RANGE program goal: more robust battery



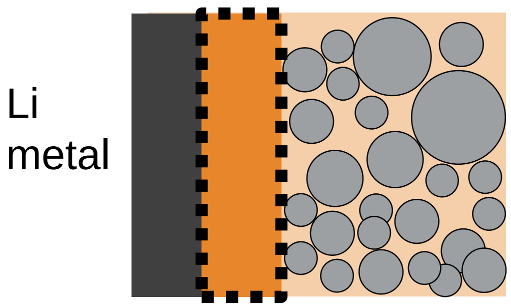
IONICS: Integration and Optimization of Novel Ion-Conducting Solids



IONICS program mission

Create *solid separators* for electrochemical cells using solid ion conductors to enable transformational performance and cost improvements in electrochemical cells.

Block dendrites



Category 1: Li^+ conductors to enable the cycling of Li metal

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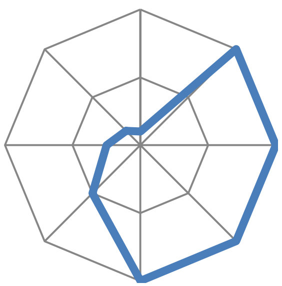
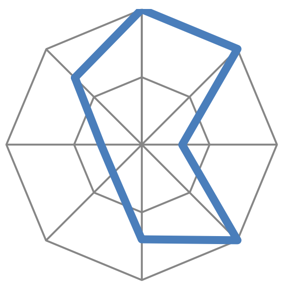
IONICS program goal: overcome property tradeoffs to create transformational components

Current status: tradeoffs among properties of ion conductors prevent electrochemical cell improvements

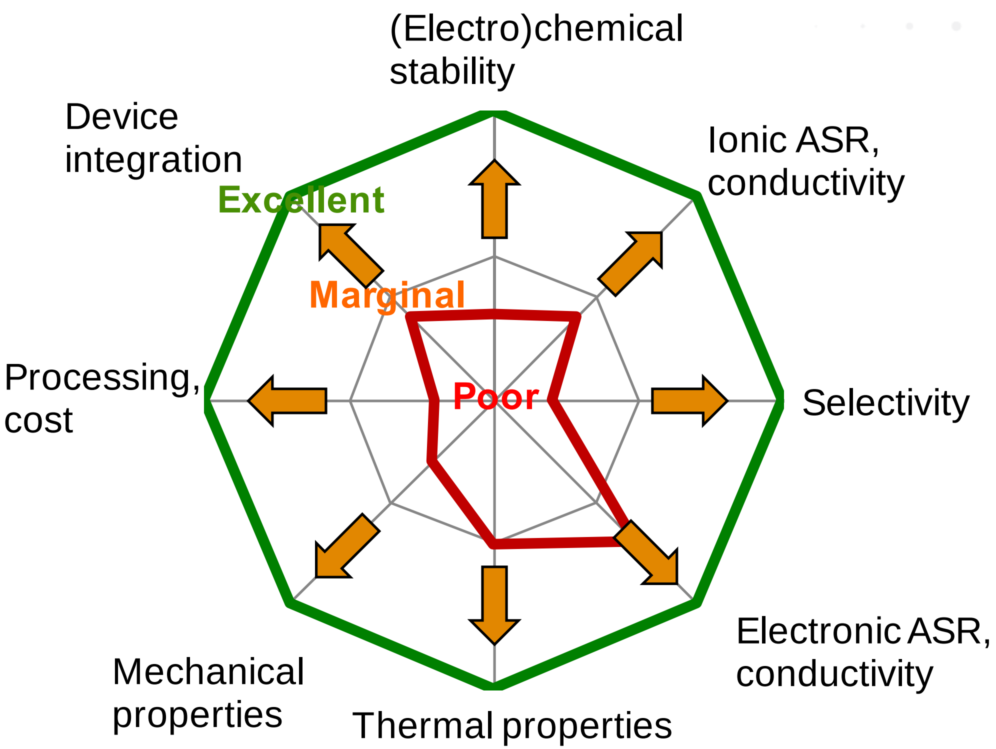


LiPON



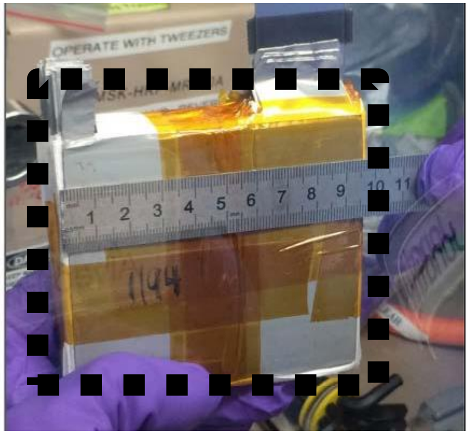
LGPS

IONICS program: *from the beginning* seek to overcome *fundamental property tradeoffs*



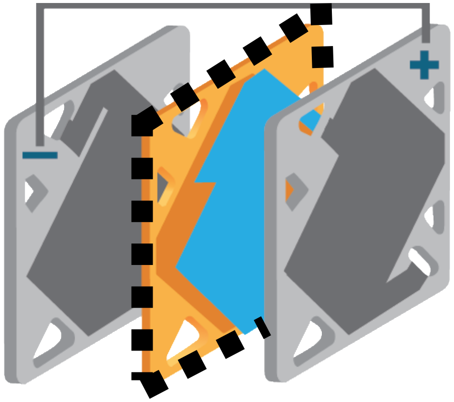
IONICS is focused on the separator component

Typical ARPA-E program



Device metrics:
W/kg, Wh/kg, \$/kW, \$/kWh, durability, mA/cm^2 at a given V, etc.

IONICS program



Component metrics in the device context:
Selectivity, stability, separator and interfacial ASR, dendrite resistance, \$/m^2.

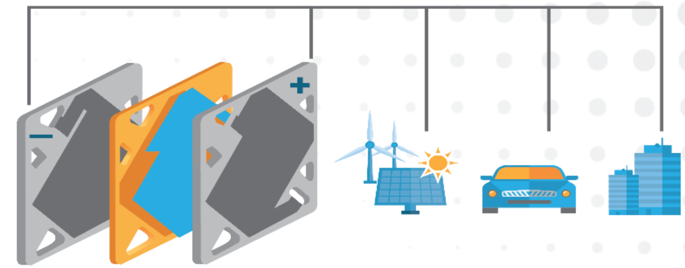
IONICS Plus program

Device metrics:
W/kg, Wh/kg, \$/kW, \$/kWh, durability, mA/cm^2 at a given V, etc.

Success in the separator development allowed for building full batteries

IONICS

16 Project Teams • 3 Technology Areas



Category 1: Li^+ conductors to enable the cycling of Li metal

POLY PLUS
24M
OAK RIDGE National Laboratory
ionic MATERIALS
UC San Diego

OPEN, RANGE

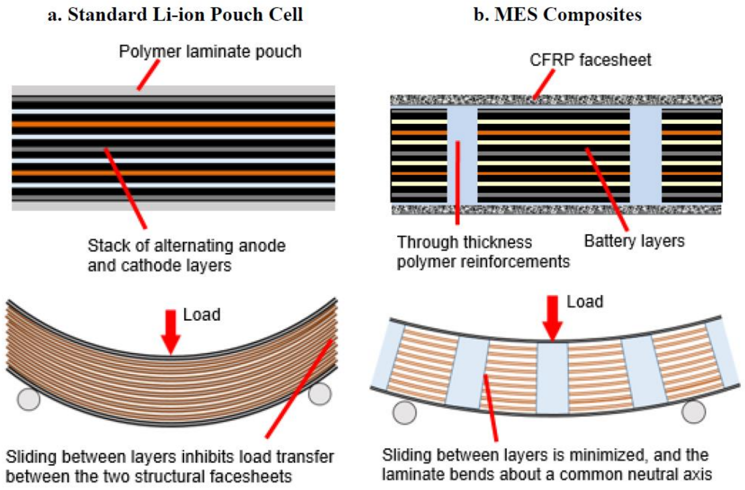
Battery related projects

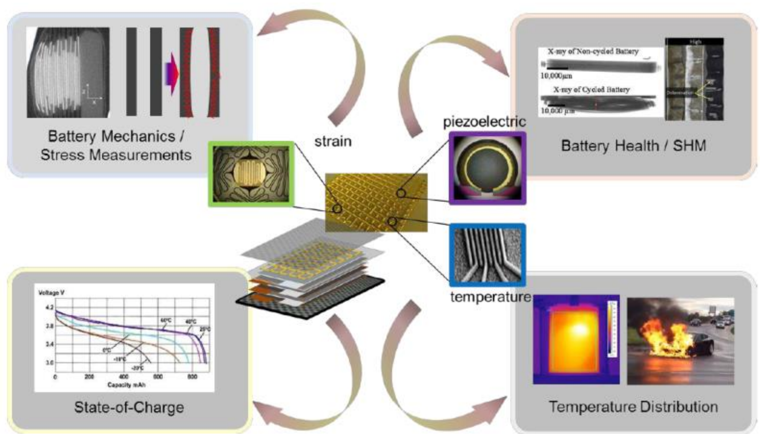
SILA NANOTECHNOLOGIES
UNIVERSITY OF MARYLAND
UNIVERSITY OF MARYLAND
ionic MATERIALS
M UNIVERSITY OF MICHIGAN
Stanford University

Stanford University
PI: Fu Kuo Chang

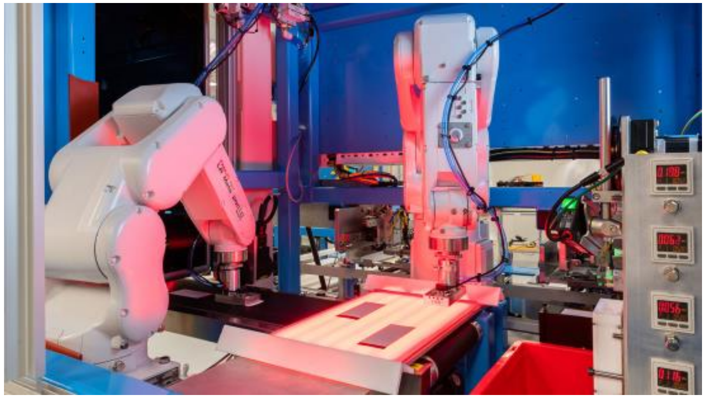
Solid Power
PI: Doug Campbell

Load – Bearing Battery





Pilot Line



The company is working closely with Ford, BMW and others toward meeting industry performance, scale, and cost goals.

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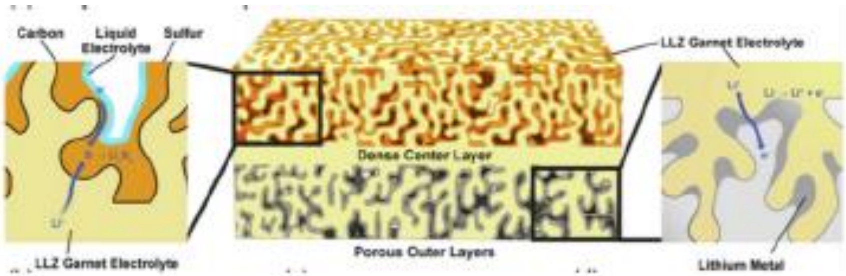
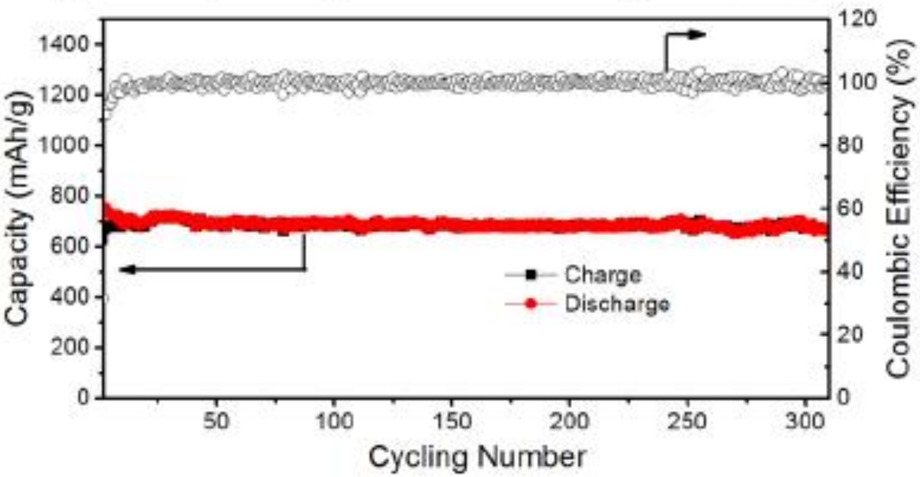
University of Maryland
PI: Wachsman

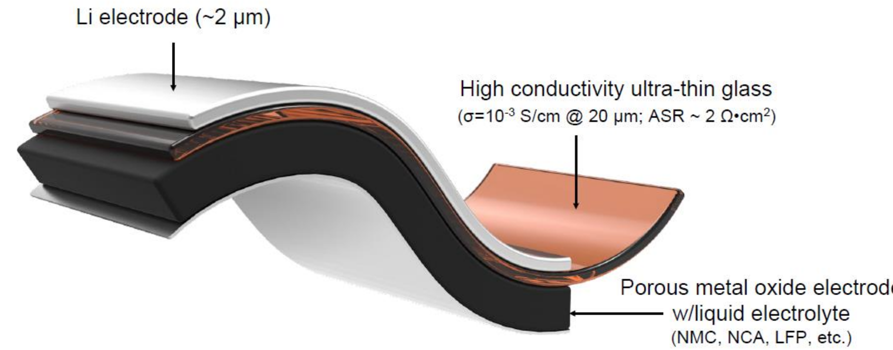
Polyplus Battery Company
PI: Visco

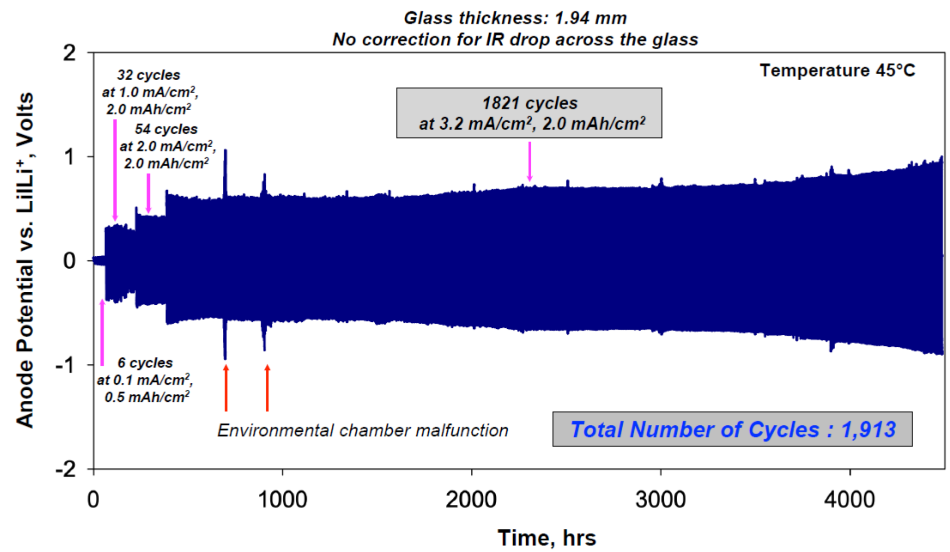
Li – S Battery





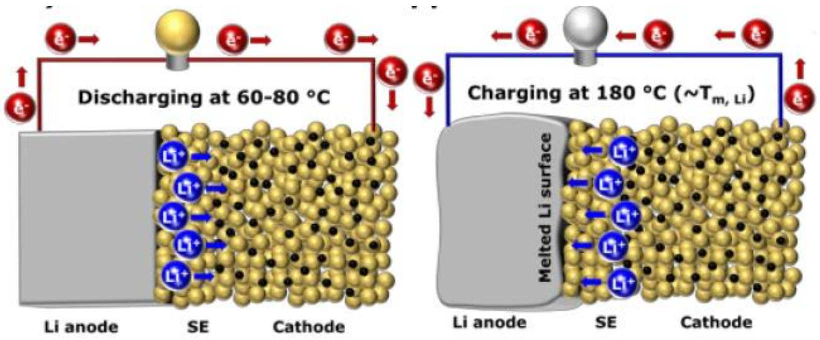
- ~ 300 Wh/kg
- ~ 99% coulombic efficiency
- 300 cycles with no fade (excess lithium)
- Challenge is high density of LLZO electrolyte

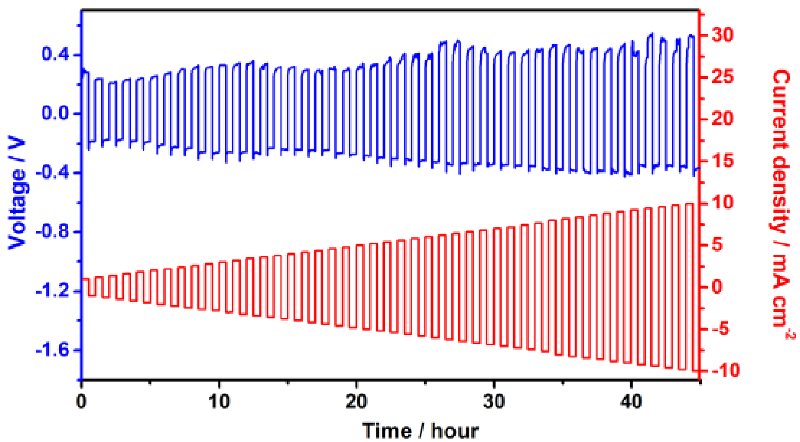




- Sulfide glass thickness 1.94 mm

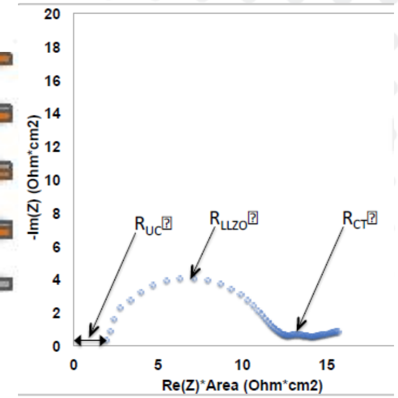
Univ. Calif. San Diego
PI: Liu

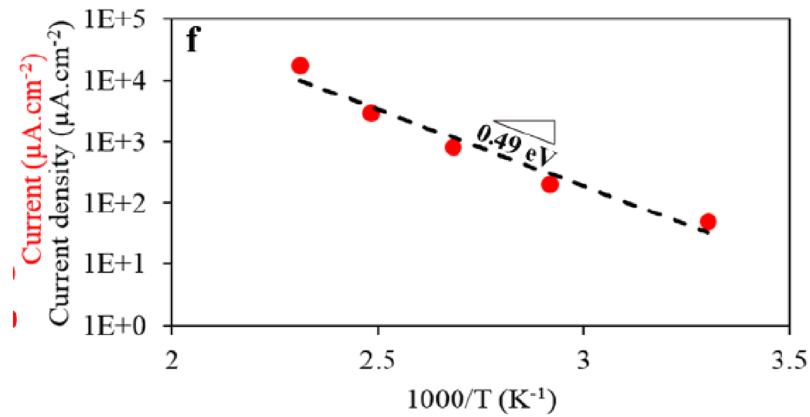




- Robust 80 micron electrolyte enables 10 mA/cm^2

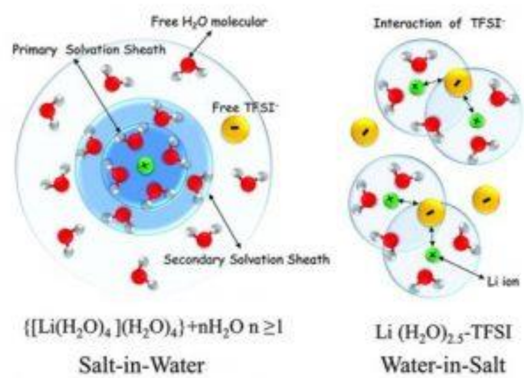
University of Michigan
PI: Sakamoto

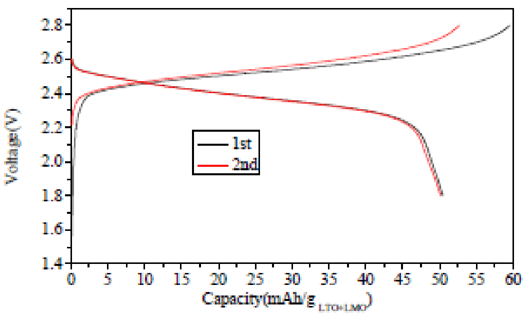


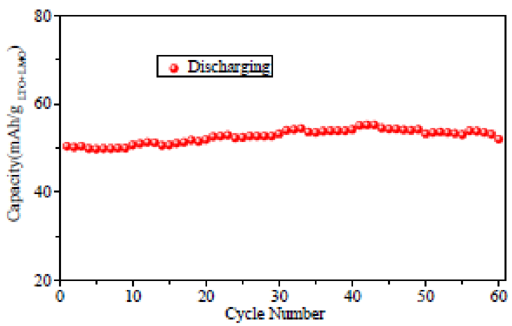


- Critical current density increases with temperature
- Tile structure addresses challenge with brittle ceramics during processing
- Engineered surfaces enable < 15 Ω.cm2 ASR produced with a scaleable process

University of Maryland
PI: Wang

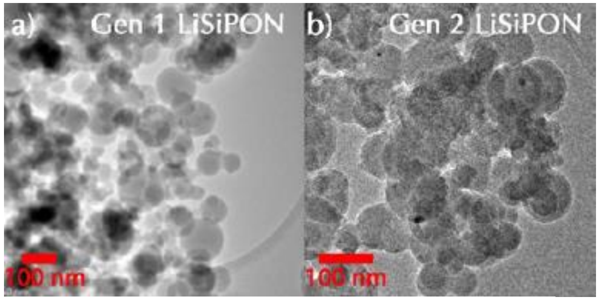


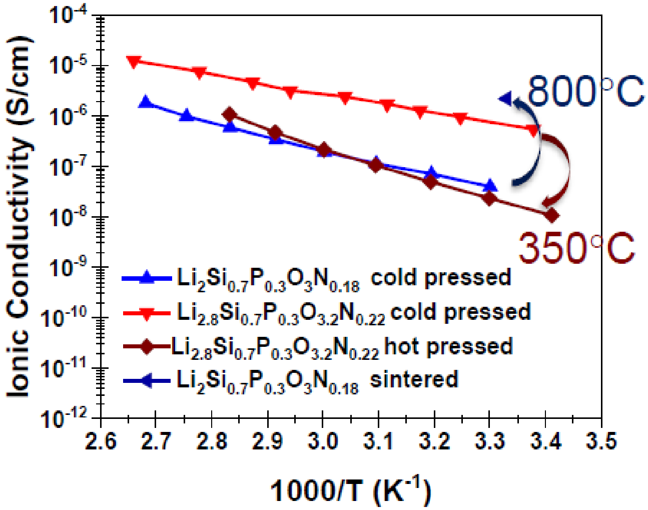




- LMO/LTO Capacity ratio: 1.14
- Electrolyte: 9.5M LITFSI-X-H_2O
- Areal capacity: 0.5 mAh/cm^2
- Rate: 0.5 C

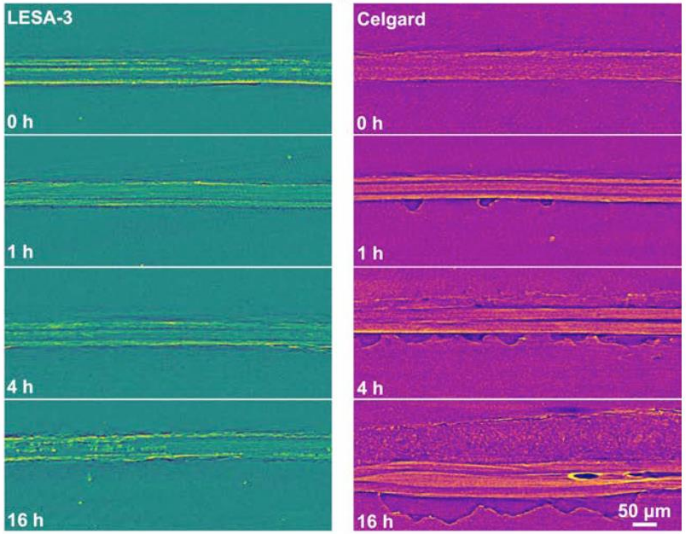
Oak Ridge Nat. Lab.
PI: Dudney

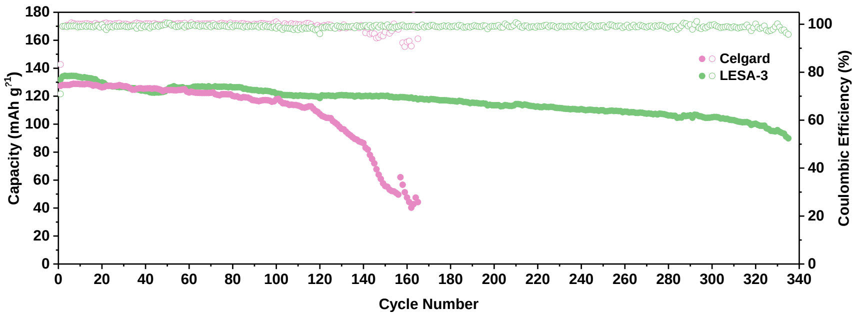




- Higher processing temperature improves ionic conductivity
- Large scale sputtering is a viable option.
- Powders of oxynitride glass provide alternative processing.
- Will a dense, sintered glass membrane effectively resist Li filaments and dendrites?

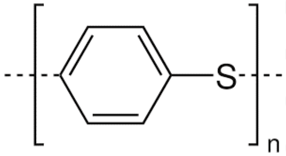
24 M
PI: Chang

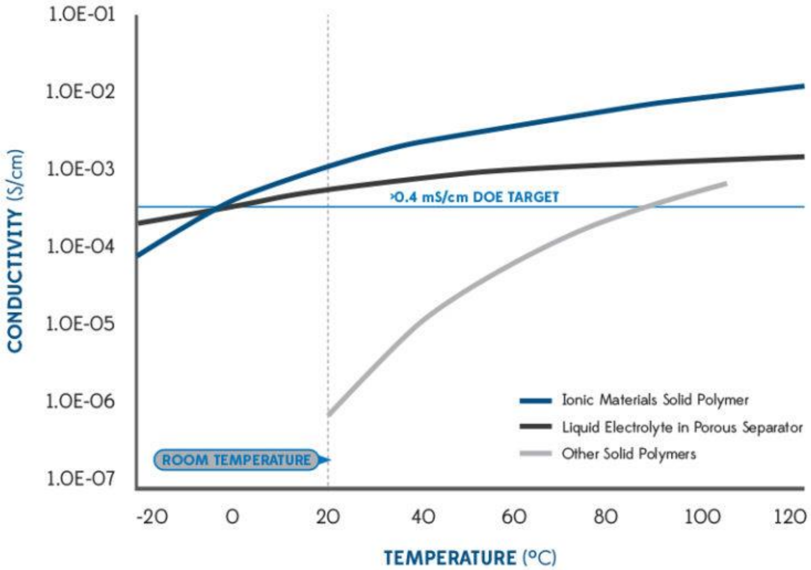




- Composites operating in newly-identified region of stability have been successfully synthesized, applied to separators, and interfaced with lithium metal.

Ionic Materials
PI: Zimmerman

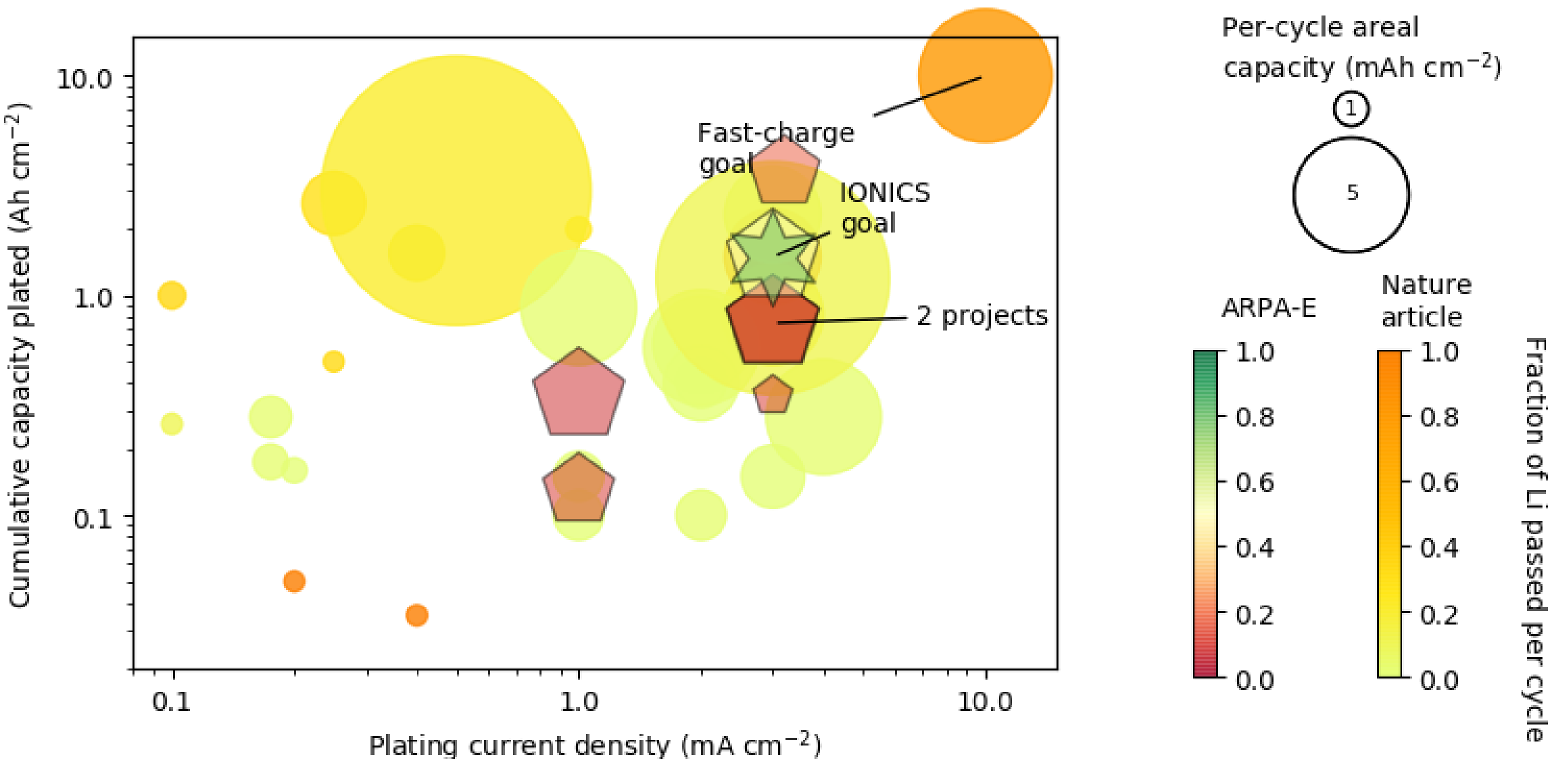
Variants of 



- Up to 1.3 mS/cm at room temperature
- Lithium transference number of 0.7
- High voltage capability (5 volts)

Four key metrics to evaluate lithium cycling

Current status



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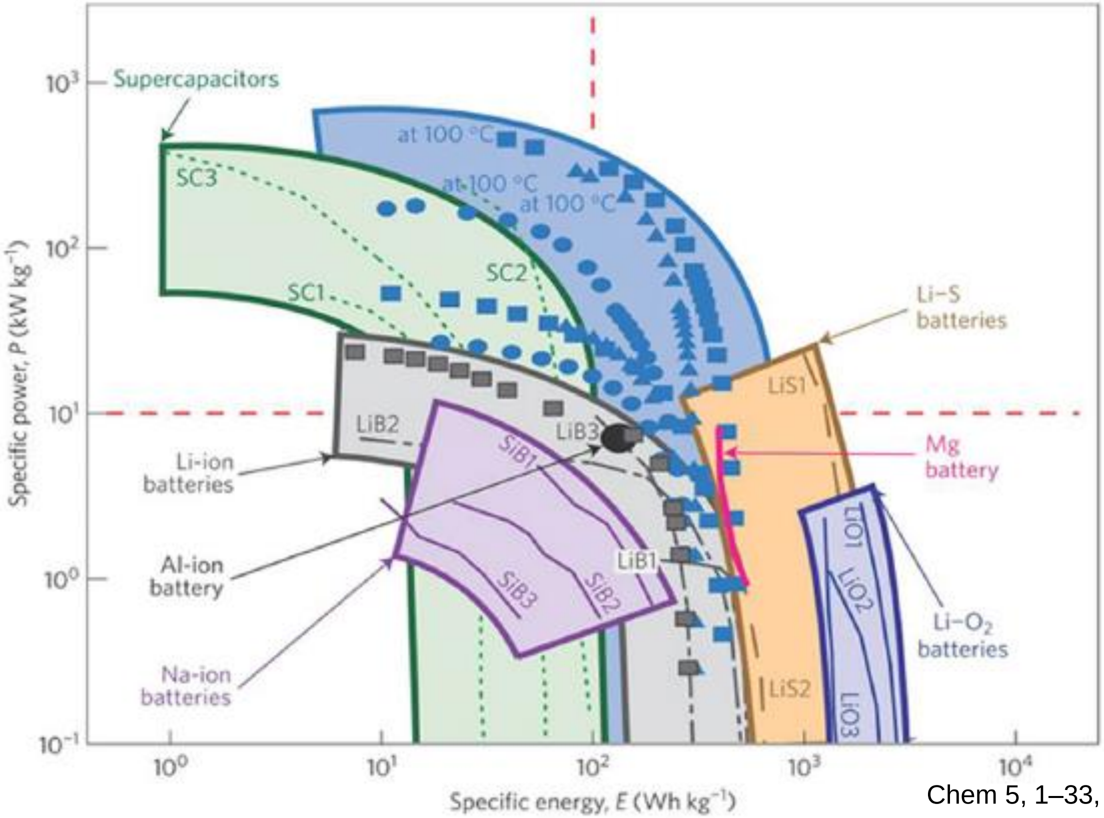
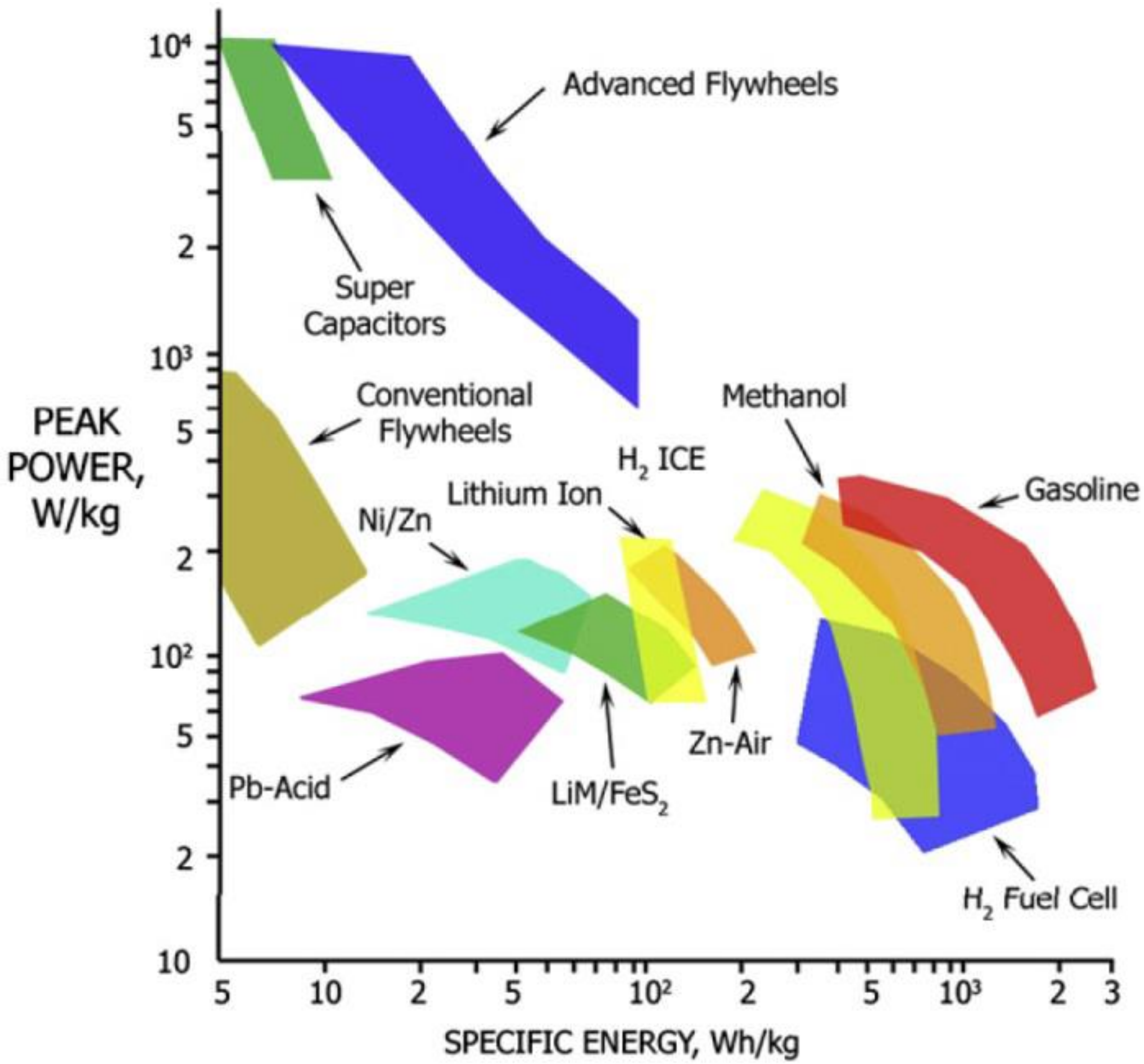
Engineering Trade: Power & Energy



Chem 5, 1–33, April 11, 2019

- Solid-State batteries could provide both power and energy that exceeds lithium ion.
- Performance is at 100C but lower temperatures are possible with improved ionic conductivity.

Energy Storage Beyond Batteries



- Heavy duty and long haul transportation require energy density provided by fuel cells – will still need battery hybridization for power.
- Future ICE vehicles could be powered by non-carbon fuels, e.g. H_2 or NH_3

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Conclusions

- The Advanced Research Project Agency - Energy (ARPA-E) has been funding battery projects that address the need for low cost energy storage for transportation since its inception a decade ago.
- More recent programs are RANGE and IONICS.
- Progress has been made with various battery chemistries and cell designs, including aqueous batteries and solid state electrolytes.
- Developing load bearing batteries that require less safe guards allows for lower energy density, while still achieving the vehicle's targeted range.