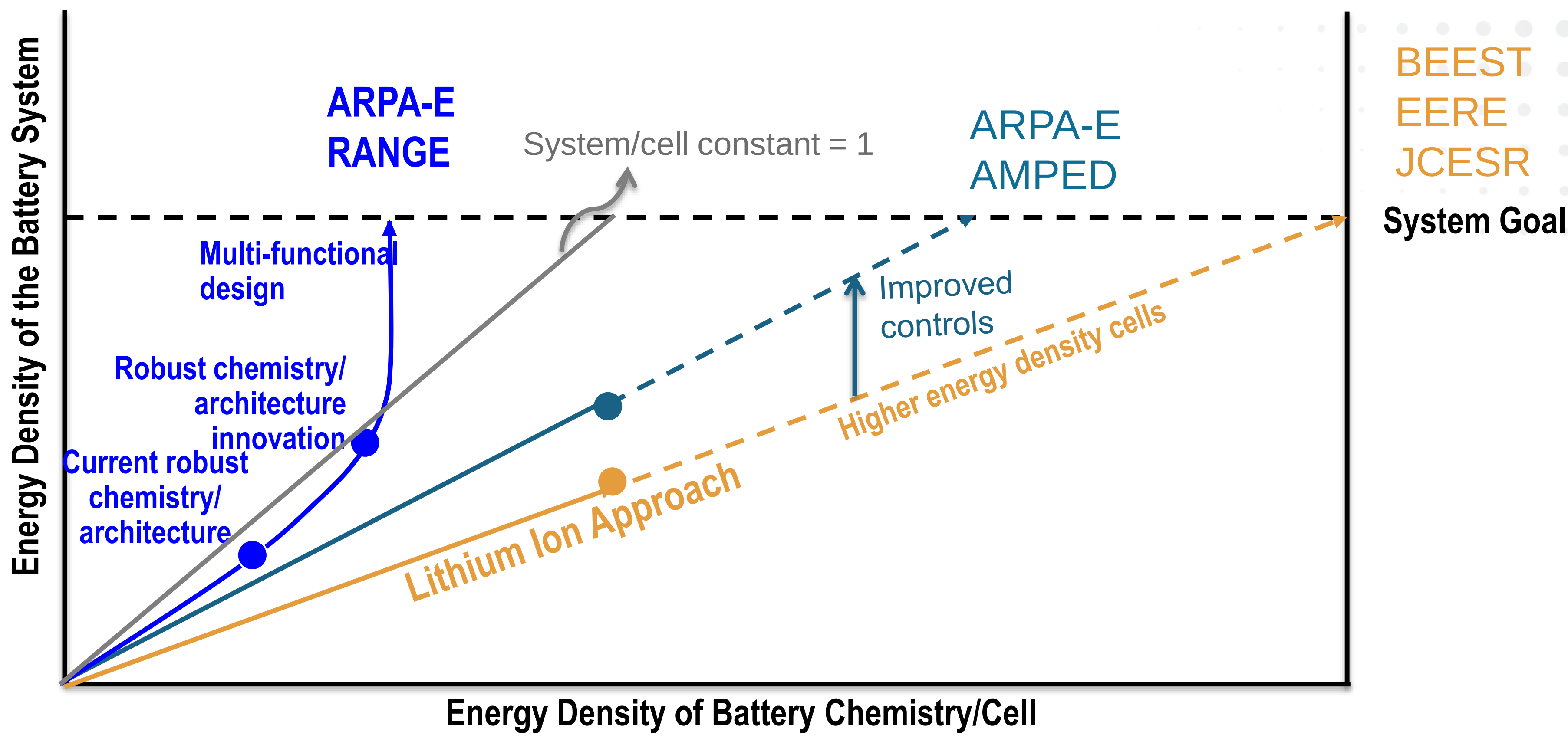
CHANGING WHAT'S POSSIBLE

RANGE concepts beyond the RANGE program

Paul Albertus
ARPA-E Program Director

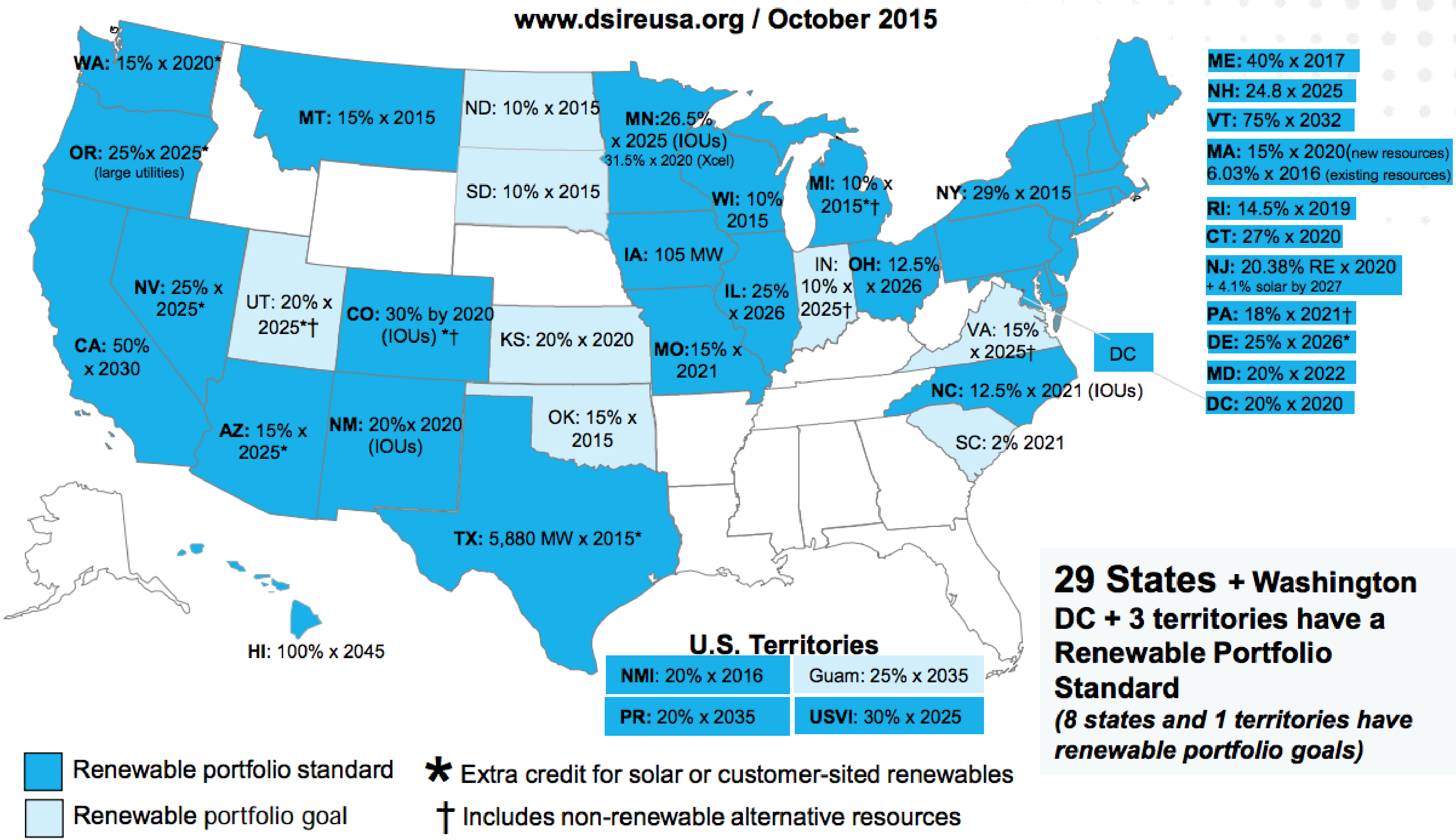
March 30, 2016

RANGE concepts apply beyond EV batteries



RANGE concepts are also applicable to **grid energy storage**, where system-level safety, robustness, and energy density are critical.

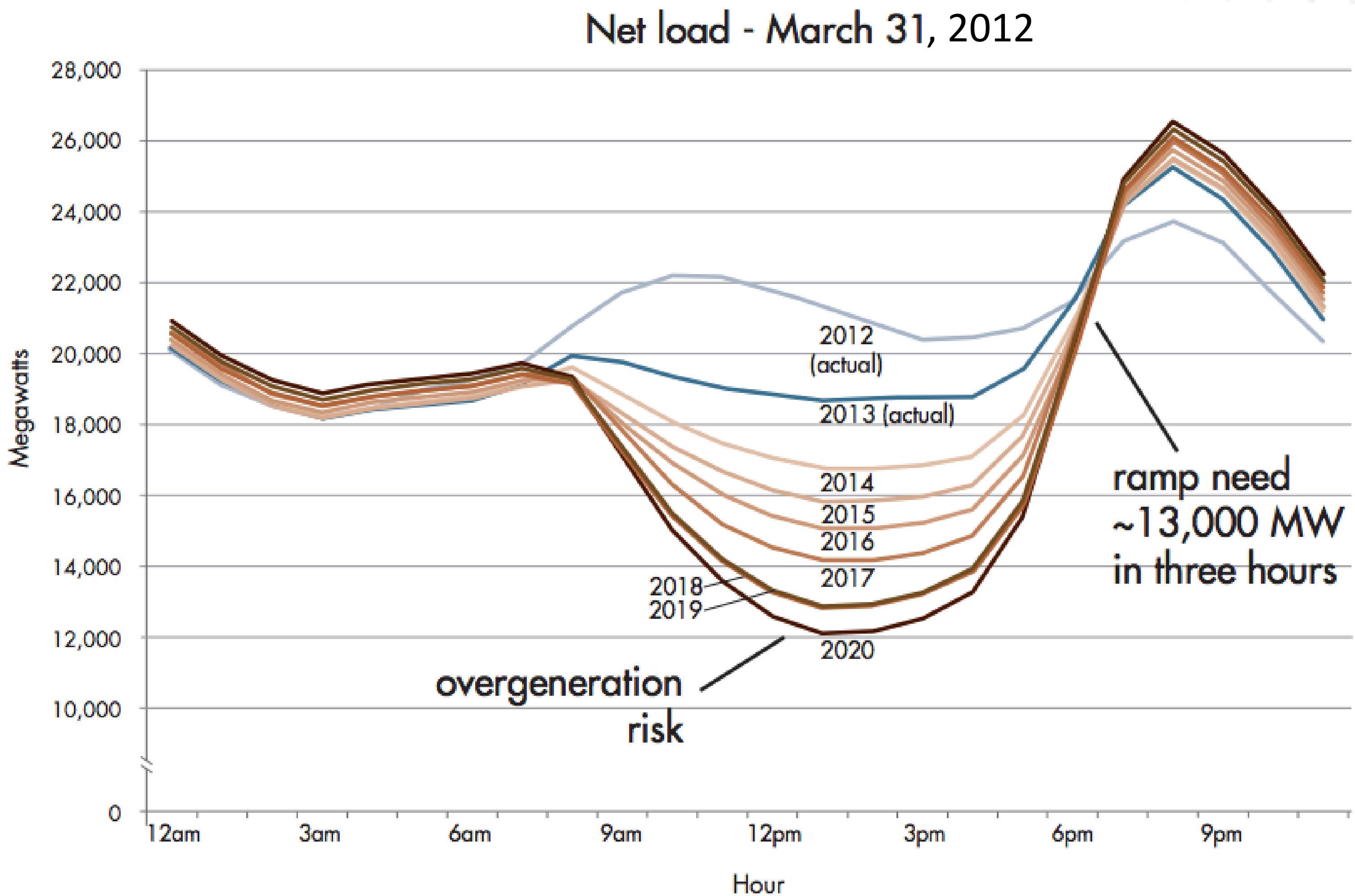
Policy is driving renewables penetration



29 States + Washington DC + 3 territories have a Renewable Portfolio Standard

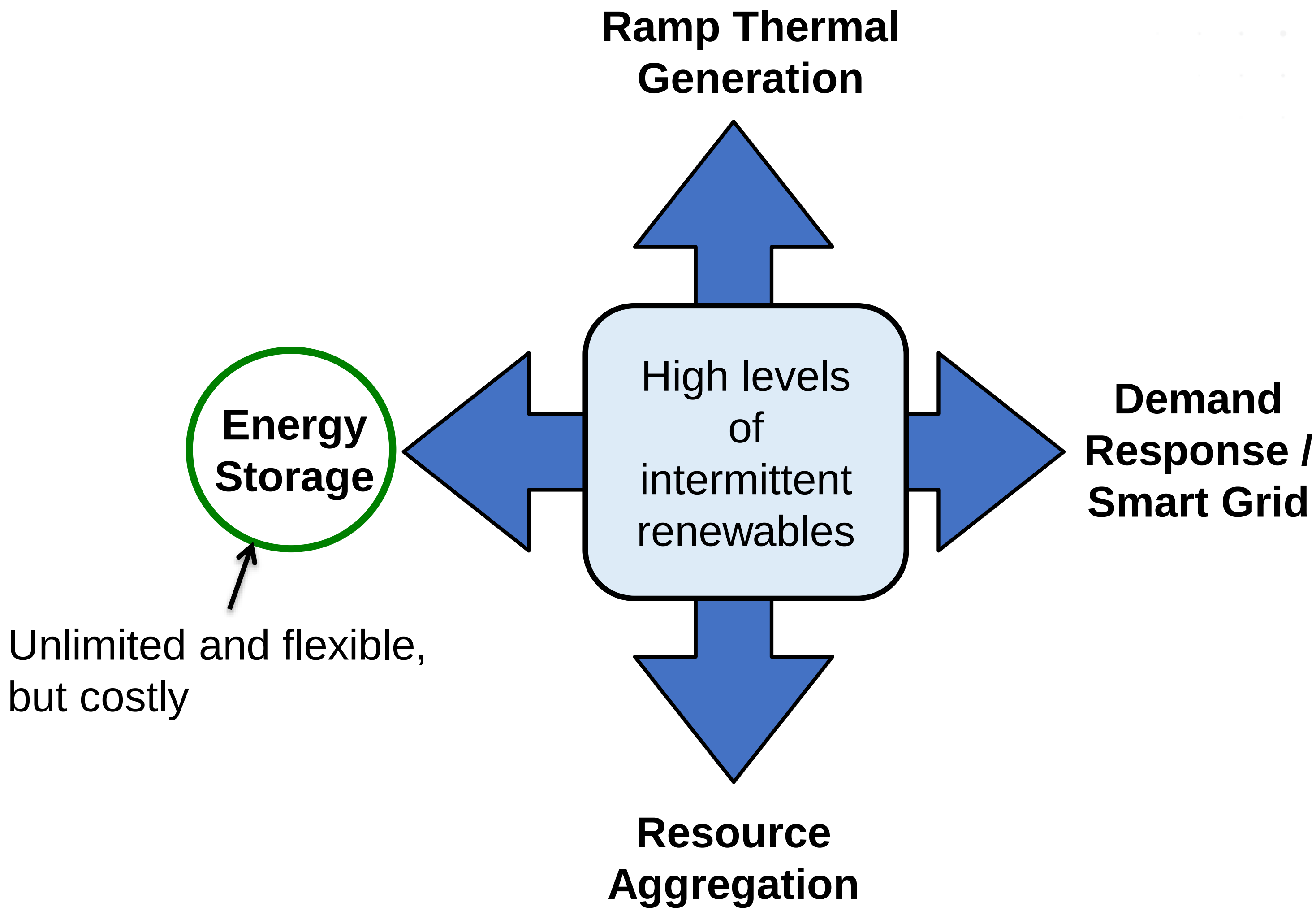
(8 states and 1 territories have renewable portfolio goals)

Renewables drive variability and ramping

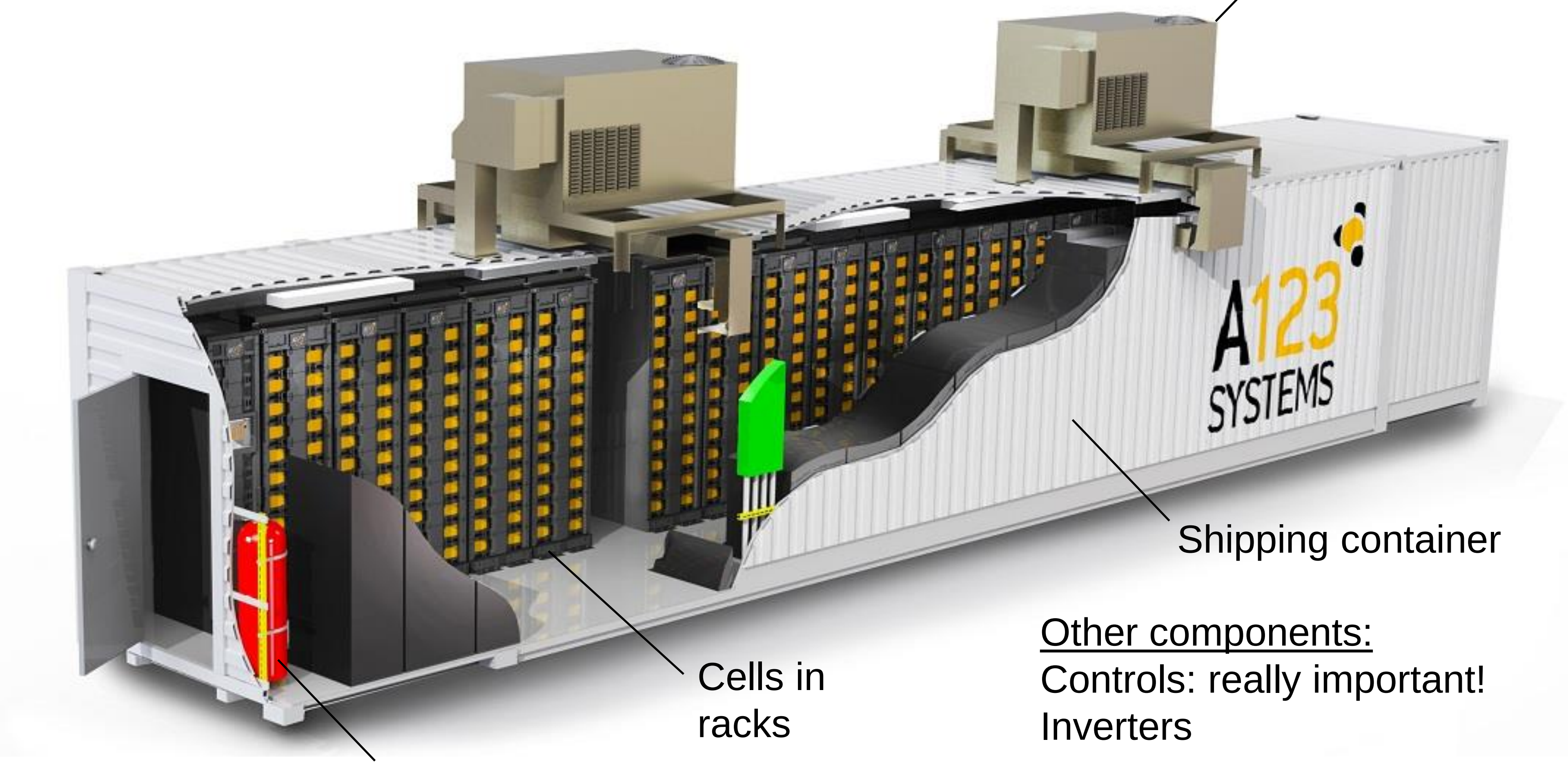


https://www.caiso.com/Documents/FlexibleResourcesHelpRenewables_FastFacts.pdf

Storage has a role in integrating renewables



The incumbent grid-storage system

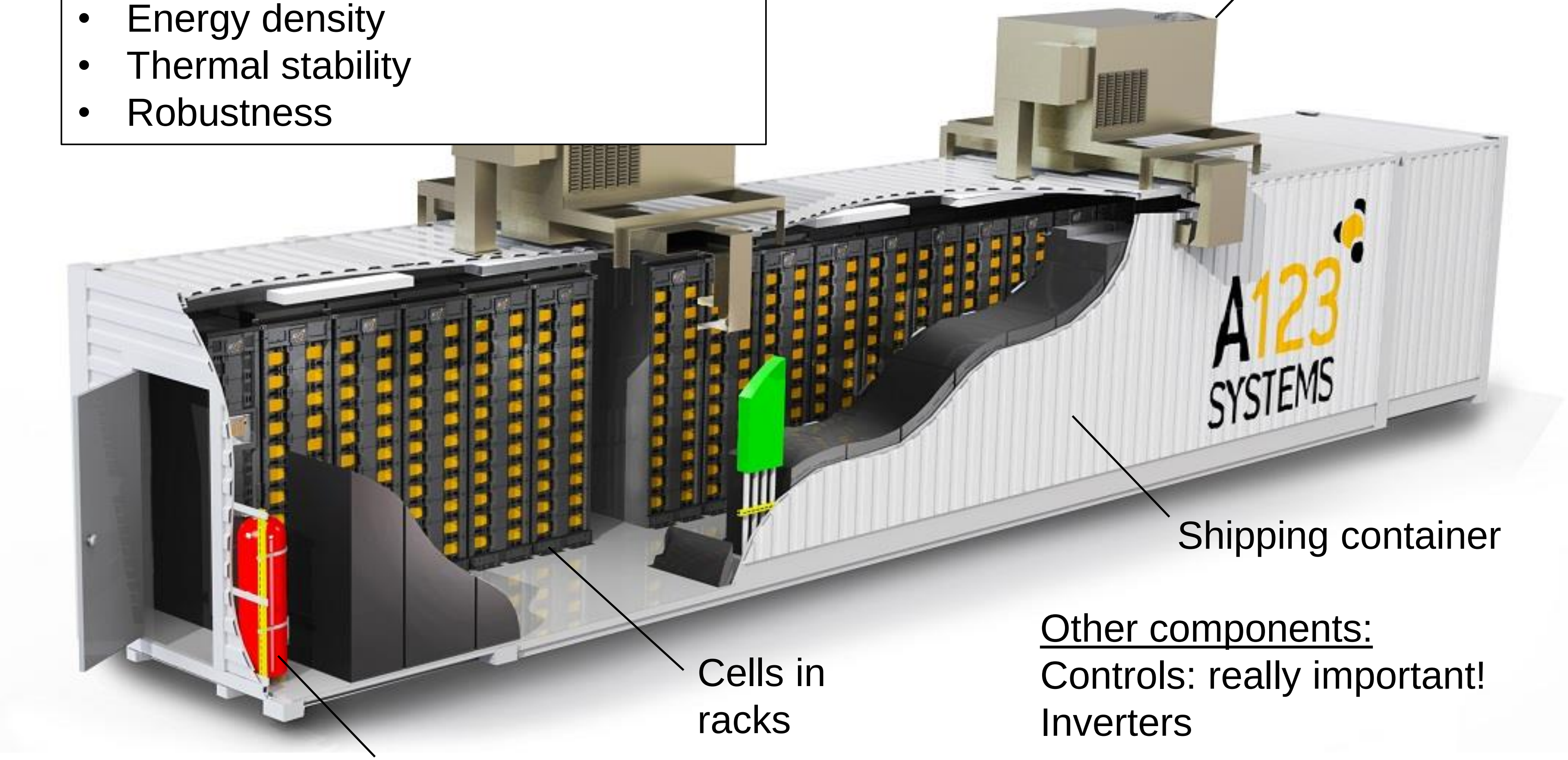


Other components:
Controls: really important!
Inverters

The incumbent grid-storage system

Clear system implications of *cell-level:*

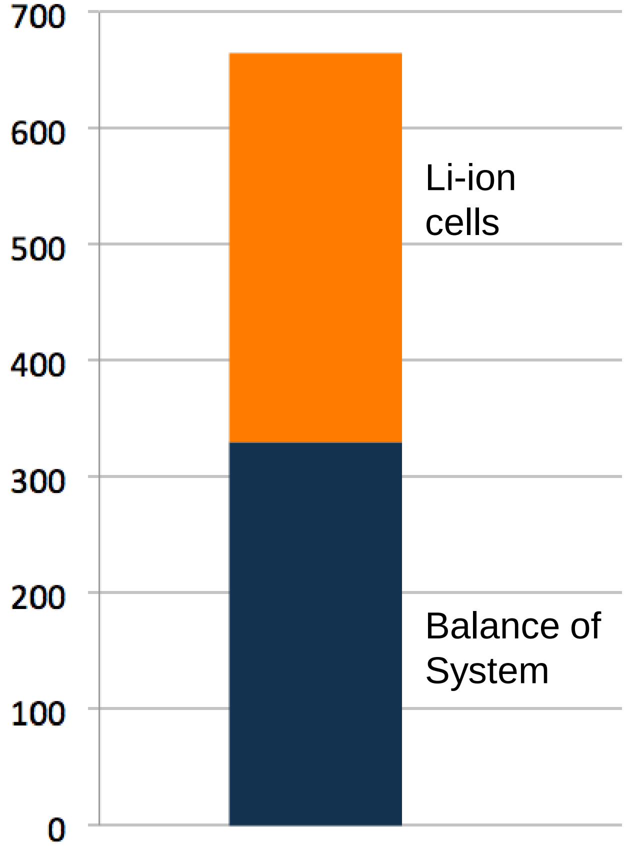
- Energy density
- Thermal stability
- Robustness



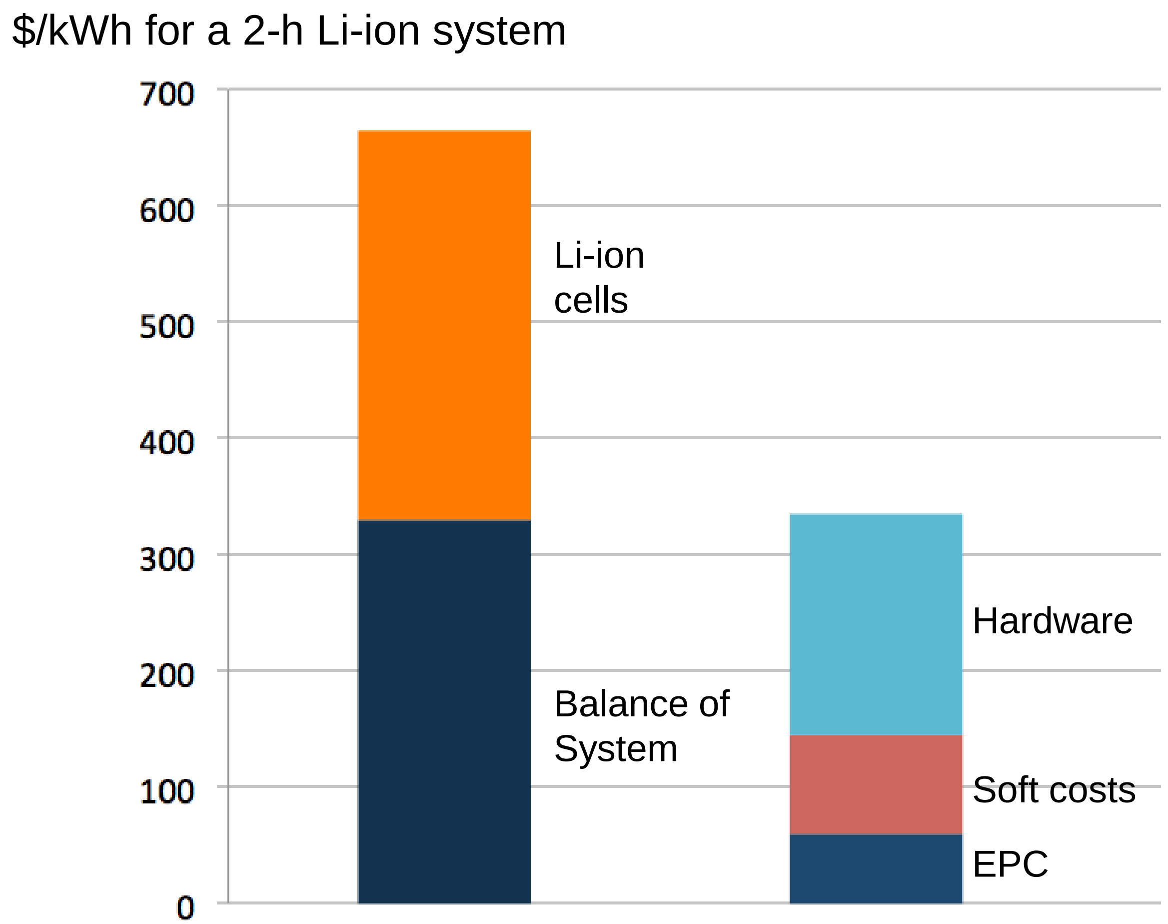
<u>Other components:</u>
Controls: really important!
Inverters

RANGE concepts can lower grid storage costs

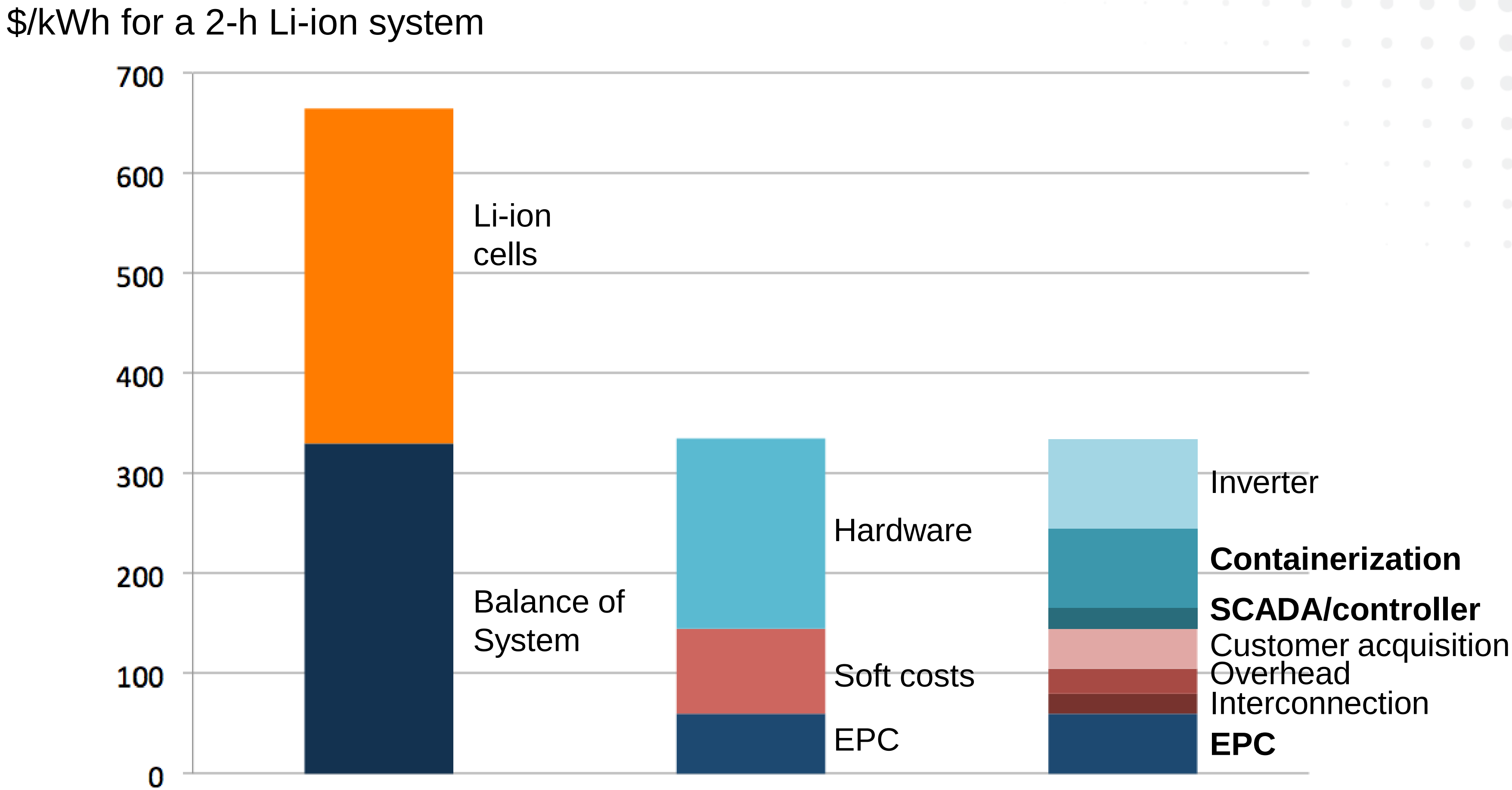
$/kWh for a 2-h Li-ion system



RANGE concepts can lower grid storage costs

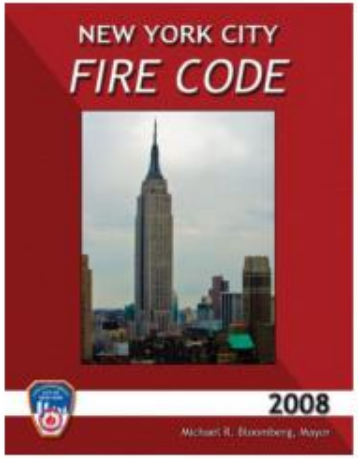


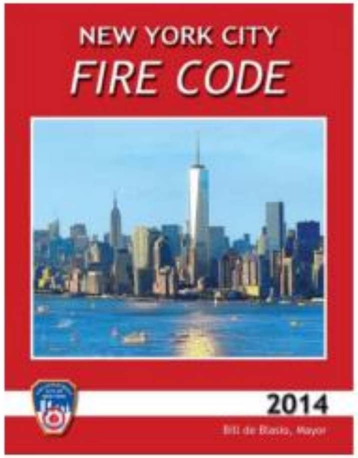
RANGE concepts can lower grid storage costs



Today, more than ~15% of a total installed grid storage system could be addressed by RANGE concepts.

RANGE concepts can expand markets addressed





2008 NYC Fire Code – Sections 608 & 609

- Flooded lead acid > 50 gallons
- Valve-regulated lead acid > 50 gallons

2014 NYC Fire Code – Section 608

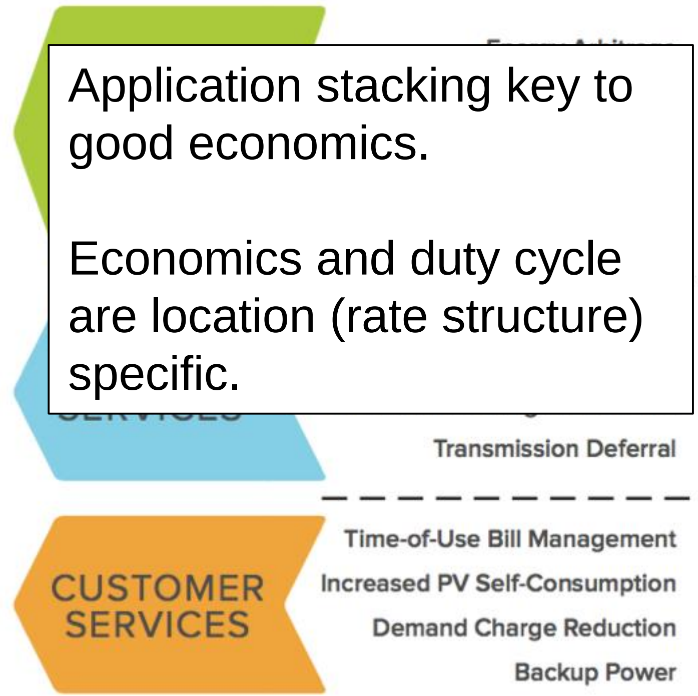
- Flooded lead acid > 50 gallons
- Valve-regulated lead acid > 50 gallons
- Flooded nickel cadmium > 50 gallons
- Lithium-ion > 1000 pounds
- Lithium metal polymer > 1000 pounds

Transportation and grid targets differ

	Transportation	Grid
Performance	see below	see below
Cycle life	1,000 (for full EVs)	5,000 (~1 cycle/day, 15 years)
System cost	125 $/kWh (for full EVs)	150 $/kWh

Transportation – Performance

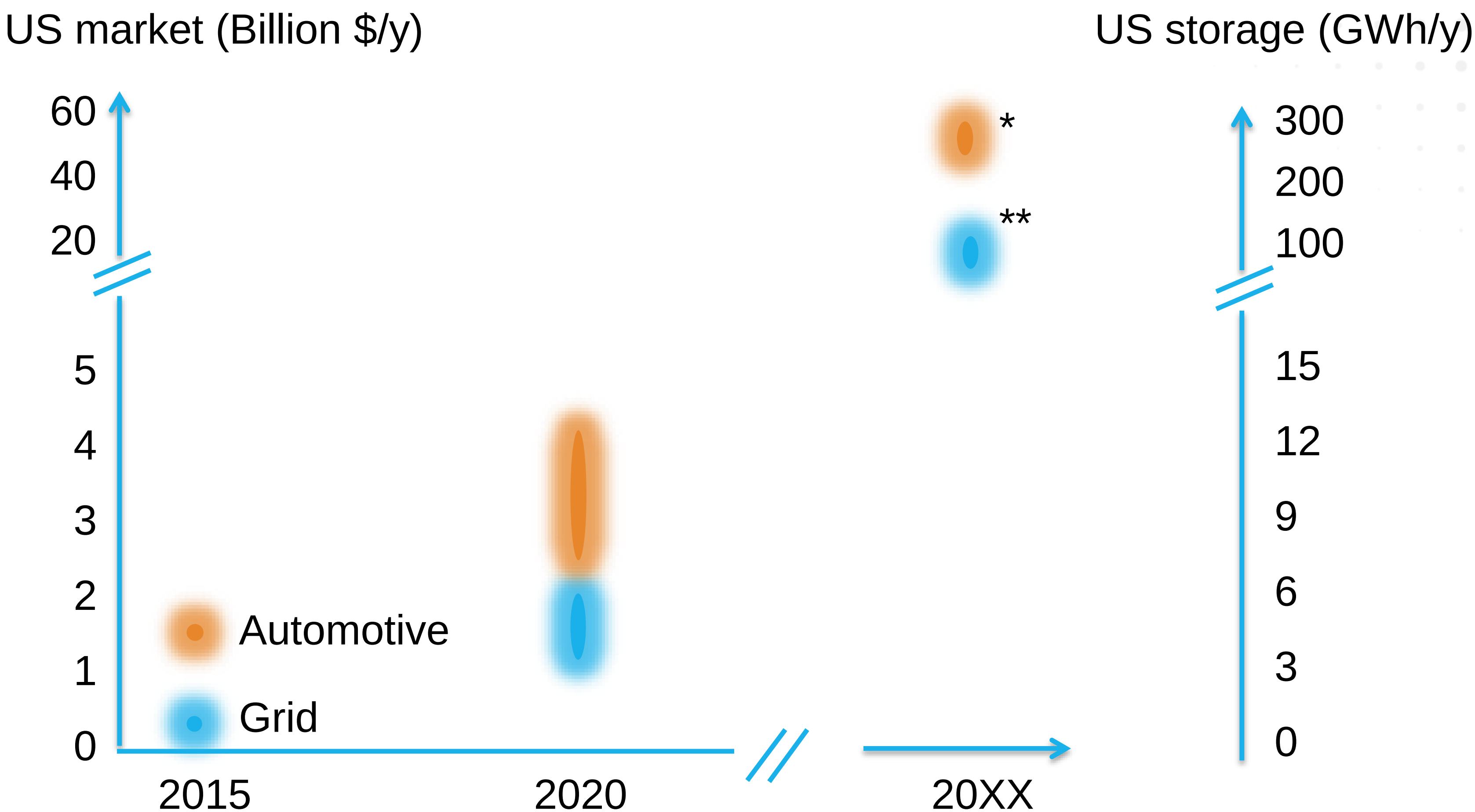
Grid – Performance



Application stacking key to good economics.

Economics and duty cycle are location (rate structure) specific.

Grid storage has significant growth potential



* Assumes 5M vehicles/y with 60 kWh battery pack, 200 $/kWh.
**Assumes total grid storage of 1600 GWh (4h of US average power), 15y life, 200 $/kWh.

Vehicle batteries should be grid resources

- To use vehicle batteries for grid services, need:
  - Robust vehicle batteries with >5,000 cycles
  - Smart controls and smart use cases
- Second life: safe, robust batteries reduce qualification costs.

What you can do: ARPA-E CHARGES program

1. Economic Valuation
2. Test Protocols
3. Battery Testing
4. Microgrid Testing
5. Commercial Deployment Pathway

2015 — 2019

UCSD Center for Energy Research	**DNV GL**
Bill Torre, Byron Washom: Module and microgrid testing	DNV GL: Economic modeling, test protocols, battery testing
Graham Elliot: Economic modeling	GroupNIRE: Microgrid testing
Shirley Meng: Battery chemistry	NYBEST, NAATBatt, NYSERDA, ConEd: Advisory board
SDG&E, SoCalEdison, NRG: Advisory board	

What you can do: talk with grid performers

ESS INC
ENERGY STORAGE SYSTEMS

24m

PRIMUS POWER™

FLUIDICENERGY™

VIONX™ ENERGY

VE RI TAS
HARVARD

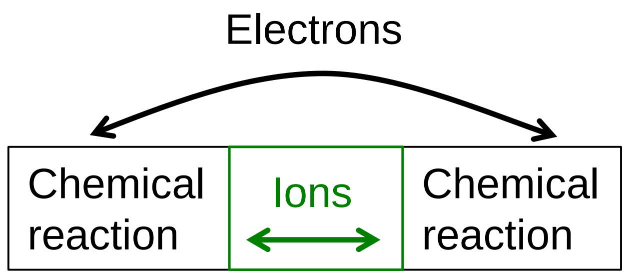
Coming next from ARPA-E: Integration and Optimization of Novel Ion-Conducting Solids (IONICS)

Please note:

- The IONICS FOA was issued on February 26 and is in the quiet period
- In the event of any inconsistency between this presentation and the IONICS FOA, the latter will control.
- Amendments to the FOA, if any, are published on eXCHANGE.

The electrochemical cell and the program focus

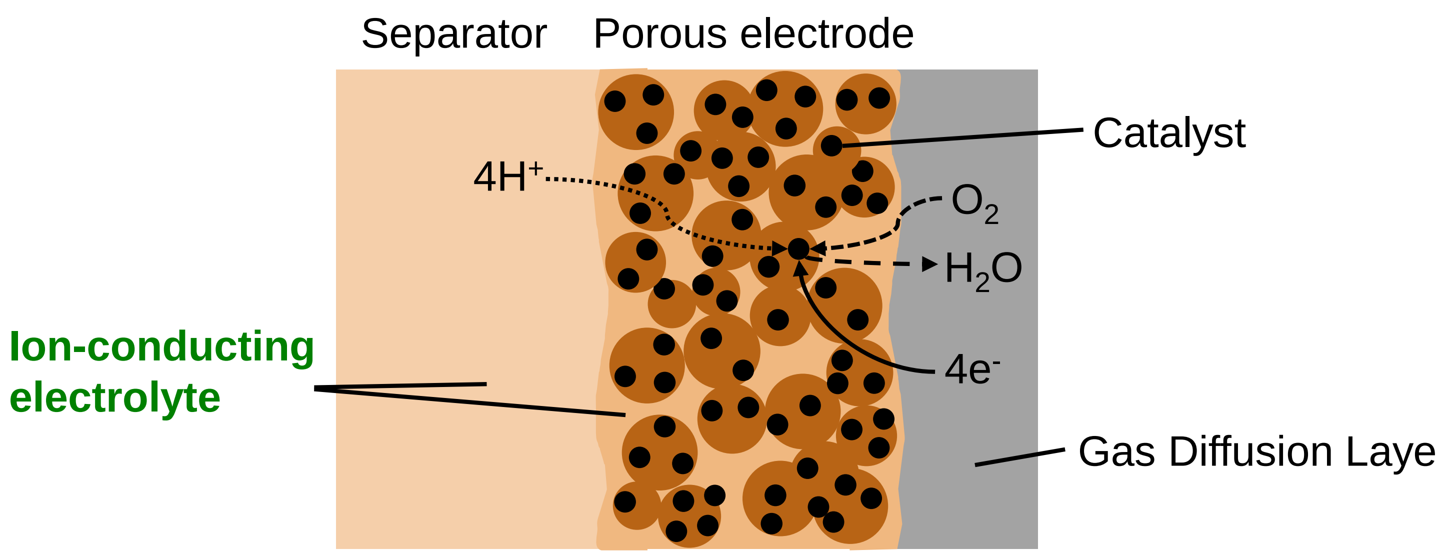
Electrochemical cell: schematic



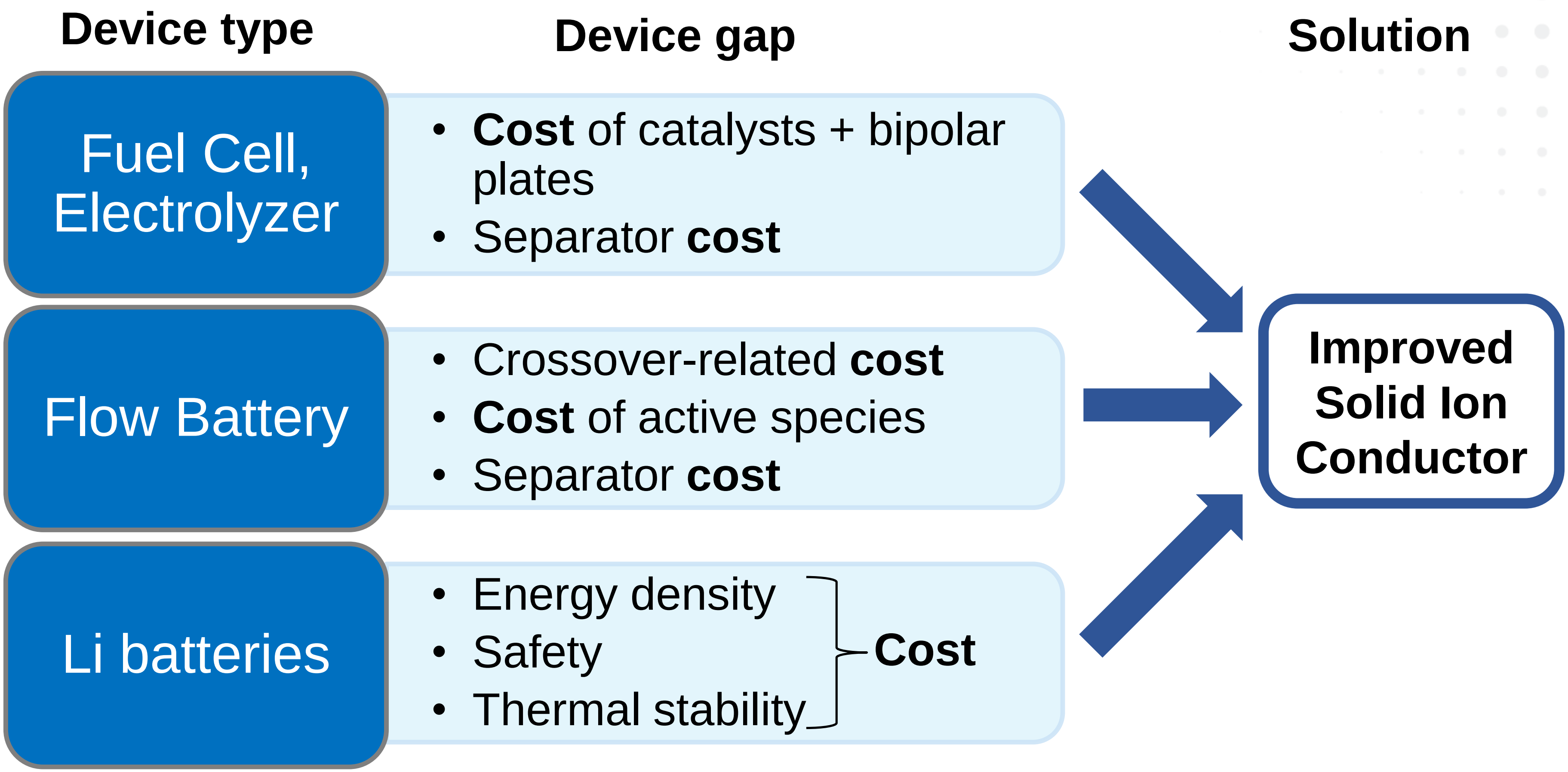
Electrochemical cell: benefits

- Link chemical reactions with electron flow.
- High energy efficiency (90% RTE DC-DC possible)
- Scalable (milli-Watts to Mega-Watts)

Program focus: Ion-conducting electrolyte

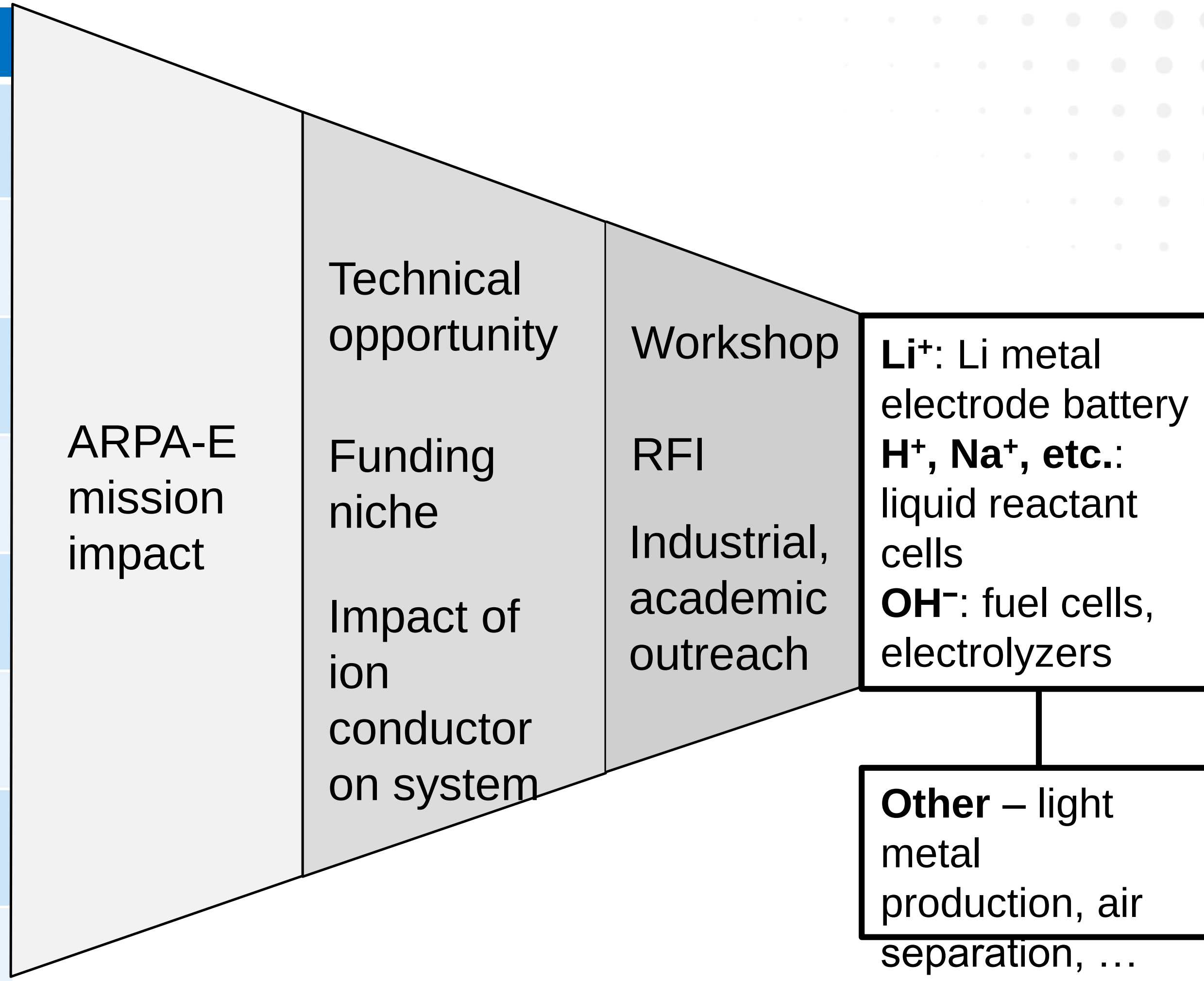


Problem: device gaps are limiting success

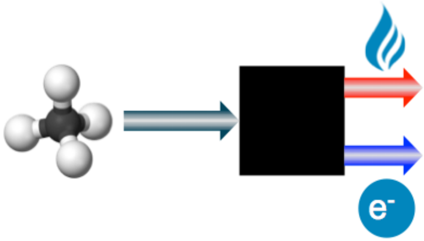


We have defined categories from a broad space

Ion	Use
Li^+	Metal electrode, flow, and molten salt cells
OH^-	Stationary fuel cells, electrolyzers
H^+	Flow cells and stationary fuel cells
Mg^{2+}, Al^{3+}	Light metal production
O^{2-}, e^-	Air separation, Syn gas
H^+, e^-	Stationary fuel cells, electrosynthesis
Na^+	Metal electrode, AMTEC, Flow cells
…	…



Program impacts span applications

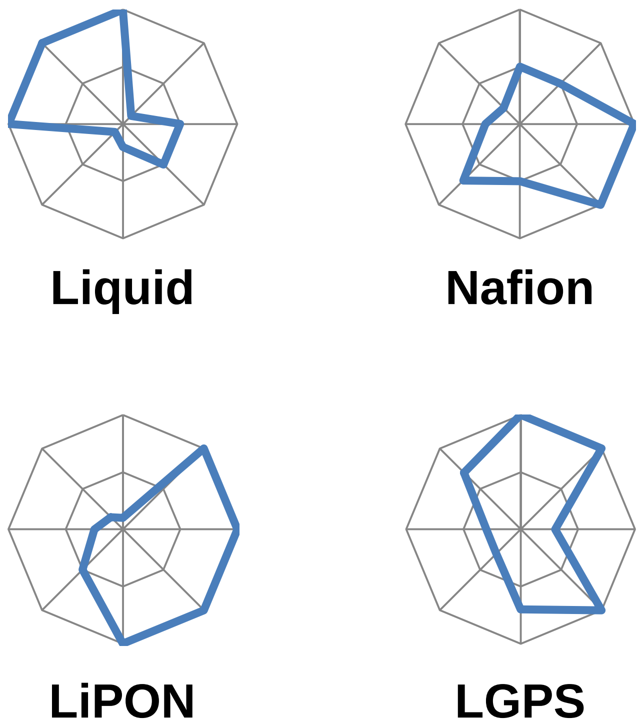


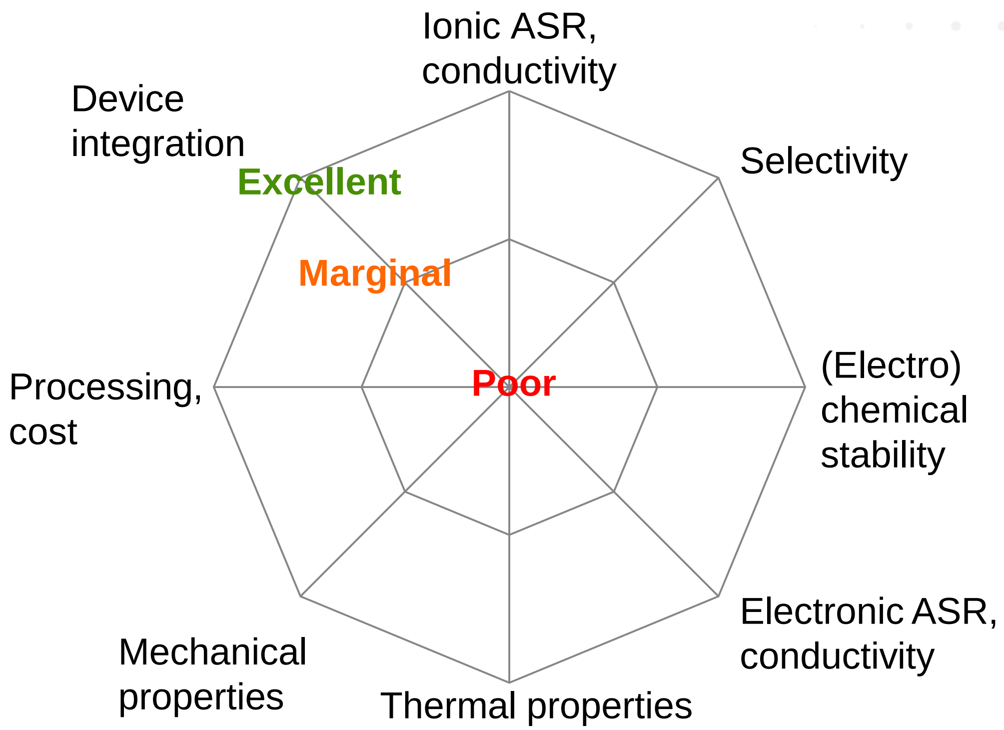
Category	Application	Device Impact	Application Impact	US energy Impact
AEM	**CHP**	↓15% system cost	↑50% CHP adoption[1,2]	Energy ↓1% GHG ↓0.6%
	Vehicle Fuel Cells	↓25% system cost	↑10% FCV adoption	Oil ↓7% GHG ↓1%
Flow Cell	**Grid Energy Storage**	<$100/kWh system cost	Enable >30% renewable penetration	GHG ↓
Lithium	**Electric Vehicles**	<$125/kWh battery packs	↑10% EV adoption	Energy ↓1% Oil ↓3% GHG ↓1%

[1]White House 2020 goal
[2]Combined Heat and Power: A Clean Energy Solution, U.S. DOE and EPA (2012)

The problem: having it all, and at the same time

Current reality: tradeoffs among properties of ion conductors severely limit electrochemical cell improvements





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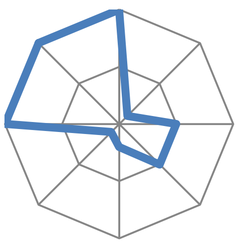
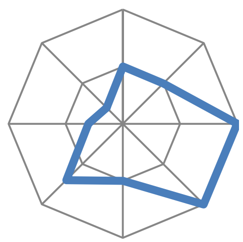
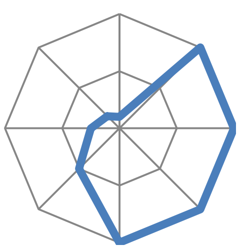


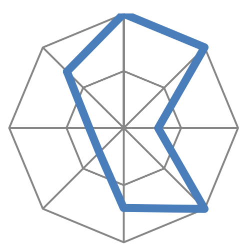
Liquid



Nafion

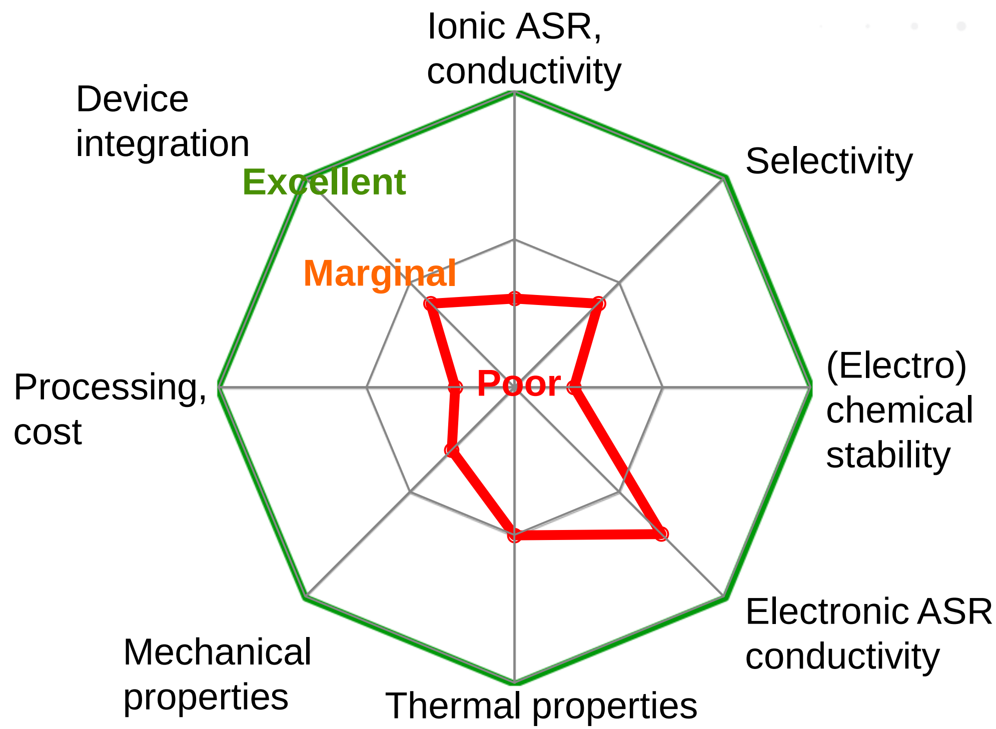


LiPON



LGPS

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



Red: generic SOA. Green: desired.

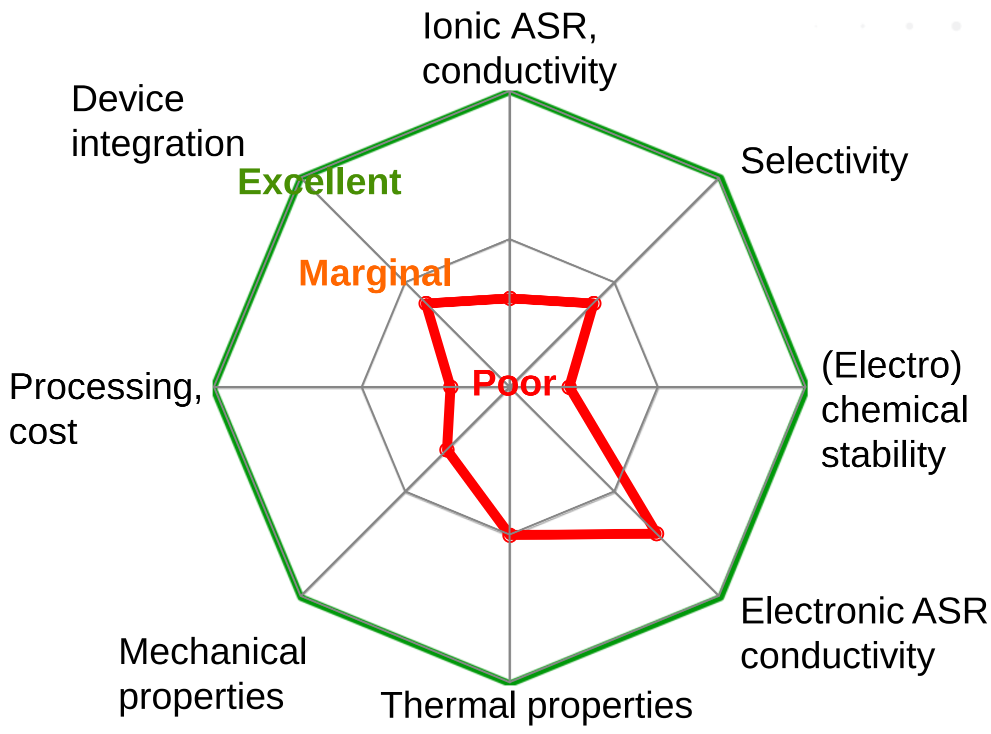
The problem: having it all, and at the same time

Liquids are SOA, but have fatal flaws

Solids need improvement, no fatal flaws

	Liquids	Solids
Ionic conductivity		
Selectivity		
Chemical stability		
Thermal stability		
Mechanical properties		
Processing/Cost		
Device integration		

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



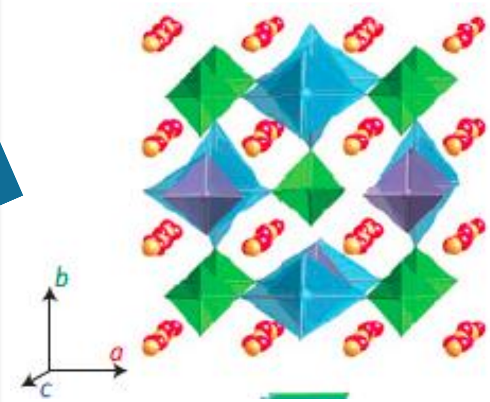
Red: generic SOA. Green: desired.

Example: paradigm of much of today's research


LETTERS
PUBLISHED ONLINE: 31 JULY 2011 | DOI: 10.1038/NMAT3066
nature materials

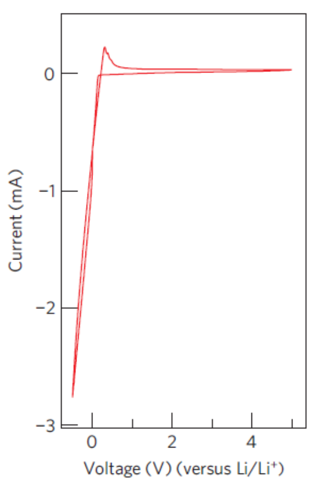
A lithium superionic conductor

Noriaki Kamaya[1], Kenji Homma[1], Yuichiro Yamakawa[1], Masaaki ...
Masao Yonemura[2], Takashi Kamiyama[2], Yuki Kato[3], Shigenori Ha... ...amoto[3]
and Akio Mitsui[4]



But…

"Chemical Stability"



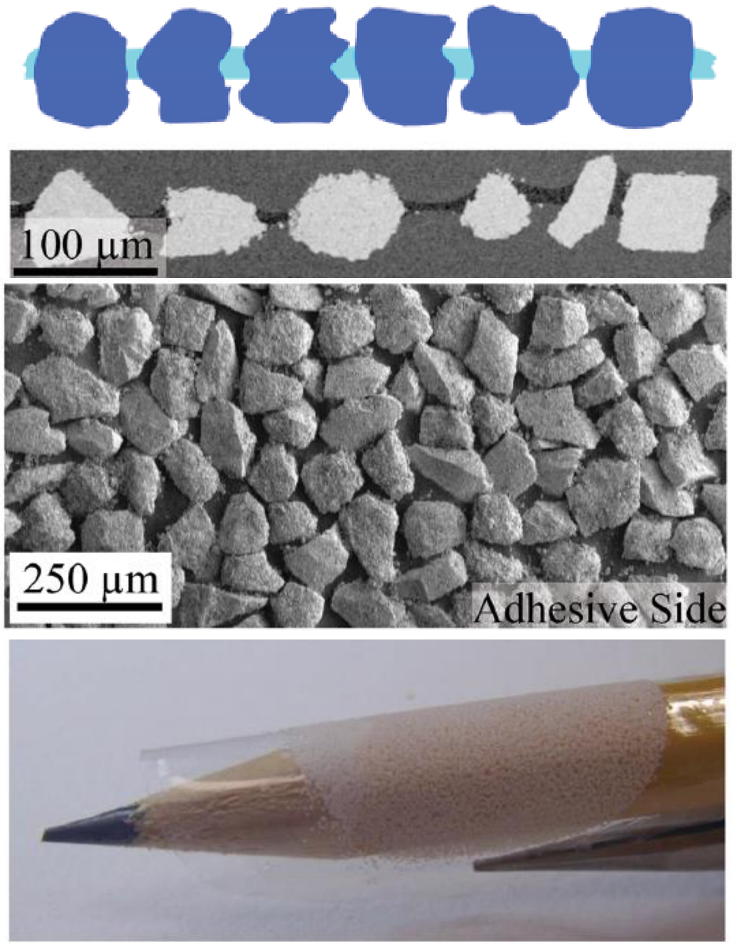
Material is not truly stable across a wide potential window

Other open questions:

- Mechanical properties
- Thermal stability
- Processing
- Device integration

Overcoming tradeoffs: Li^+ conductor

Li^+-conducting composite membrane



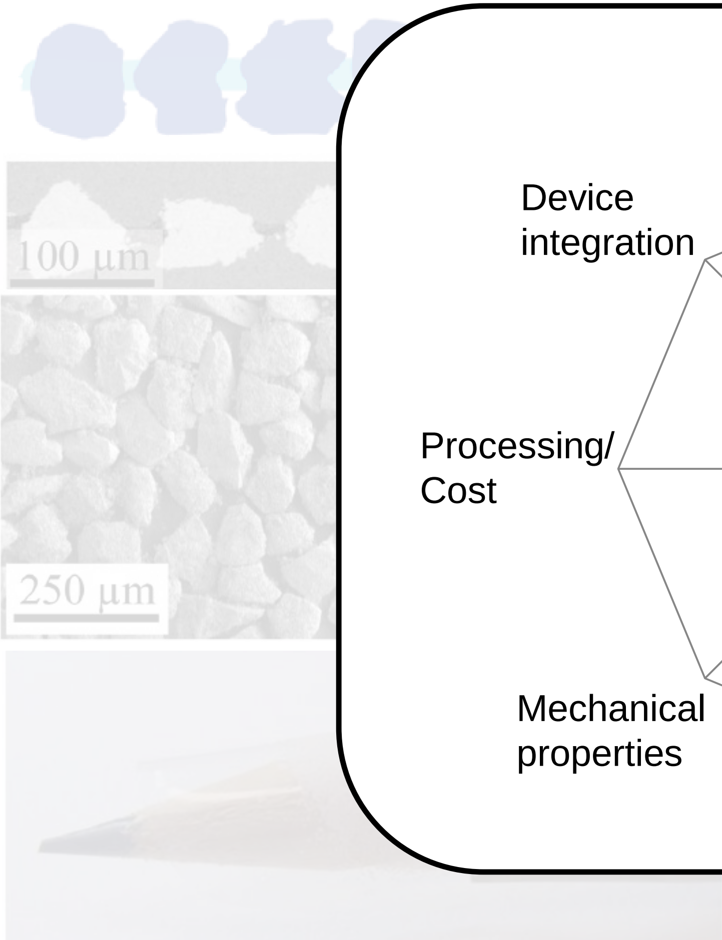
- Highlights of the Aetukuri* paper:
  - Membrane suitable for **roll-to-roll processing**.
  - Polymer chosen for **chemical and thermal stability** in typical battery electrolytes.
  - **Eliminate processing** solid ceramic particles into a dense membrane.
  - **Measurement of Li dendrite formation** carried out.

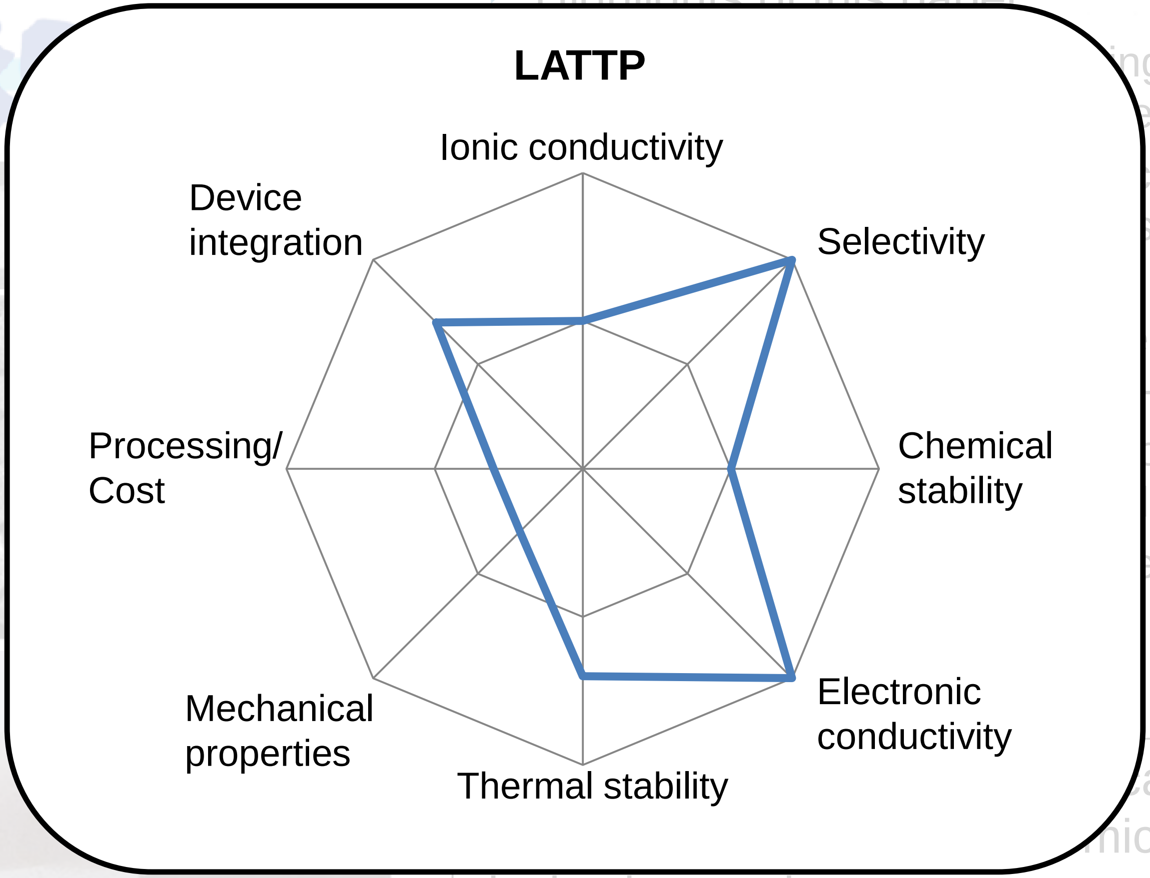
*Aetukuri et al., Advanced Energy Materials, 2015.

Ceramic: $Li_{1.6}Al_{0.5}Ti_{0.95}Ta_{0.5}(PO_4)_3$
Polymer: poly olefin

Overcoming tradeoffs: Li^+ conductor

Li^+-conducting composite membrane



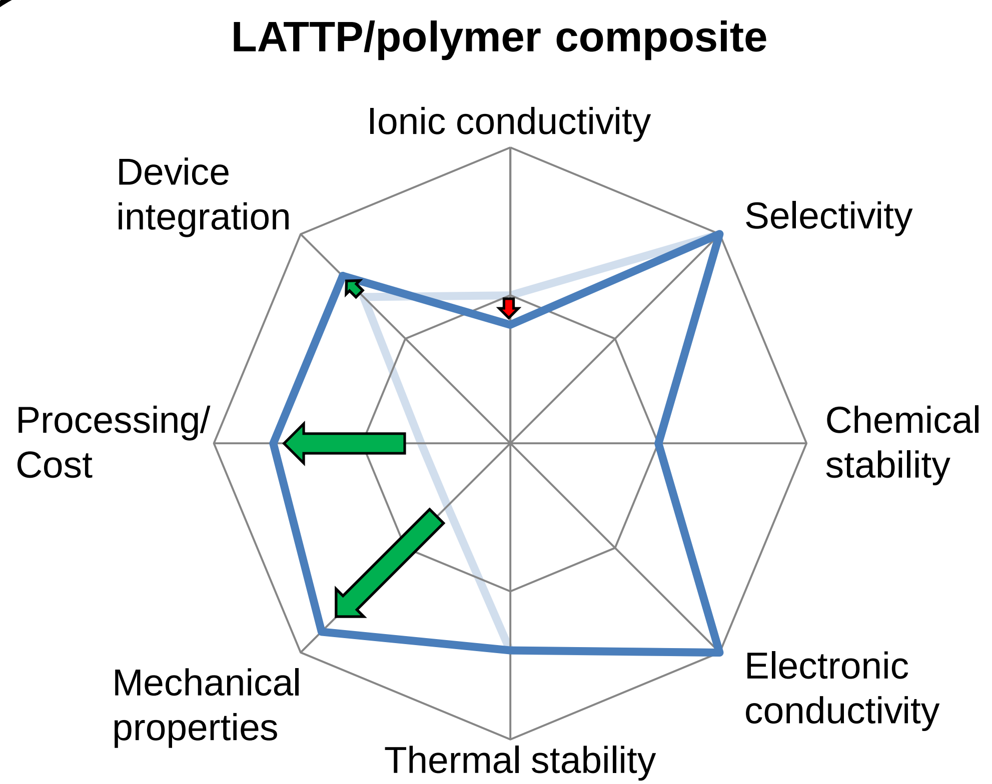


Aetukuri et al., Advanced Energy Materials, 2015.

Ceramic: $Li_{1.6}Al_{0.5}Ti_{0.95}Ta_{0.5}(PO_4)_3$
Polymer: poly olefin

Overcoming tradeoffs: Li$^+$ conductor

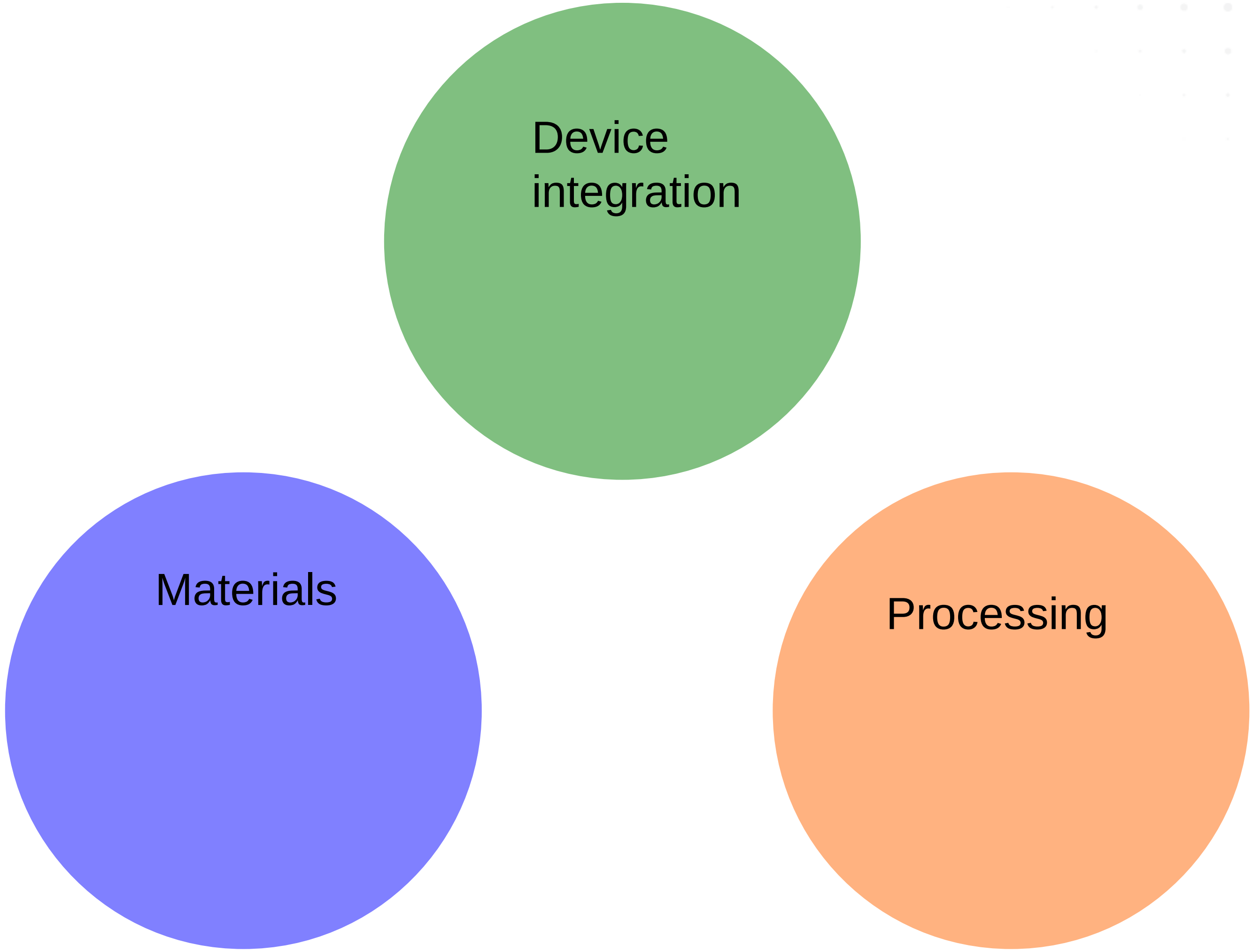
Li$^+$-conducting composite membrane



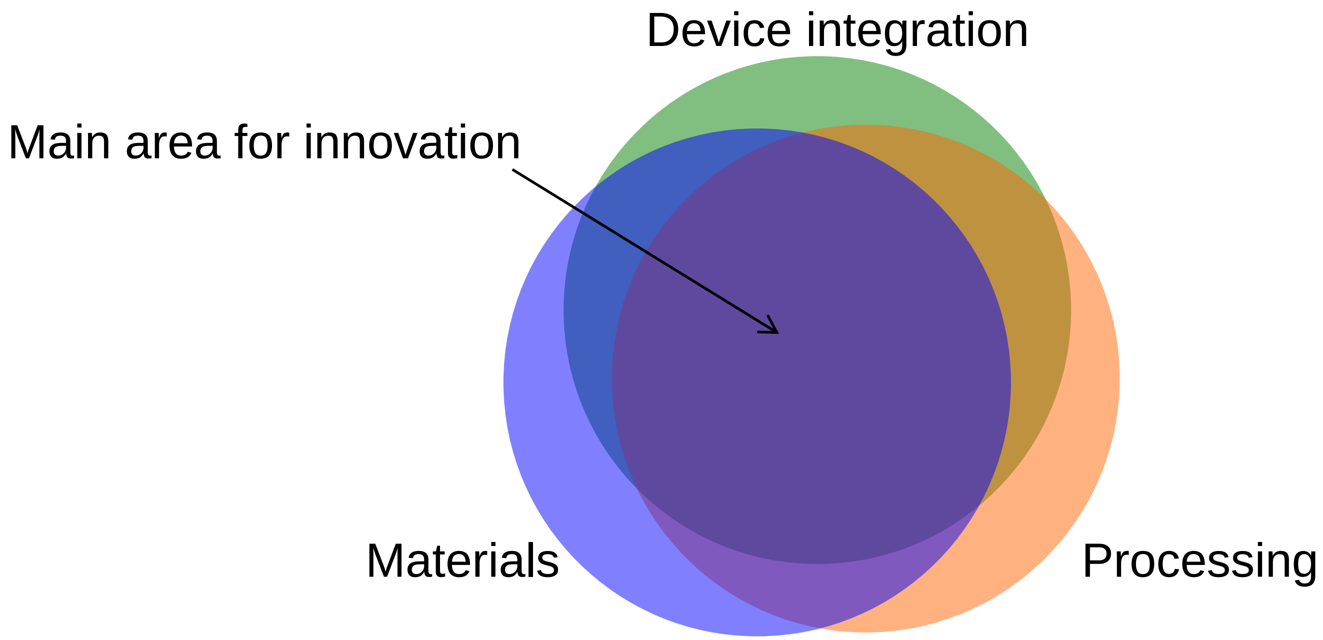
Aetukuri et al., Advanced Energy Materials, 2015.

Ceramic: $Li_{1.6}Al_{0.5}Ti_{0.95}Ta_{0.5}(PO_4)_3$
Polymer: poly olefin

Where will the innovation happen?



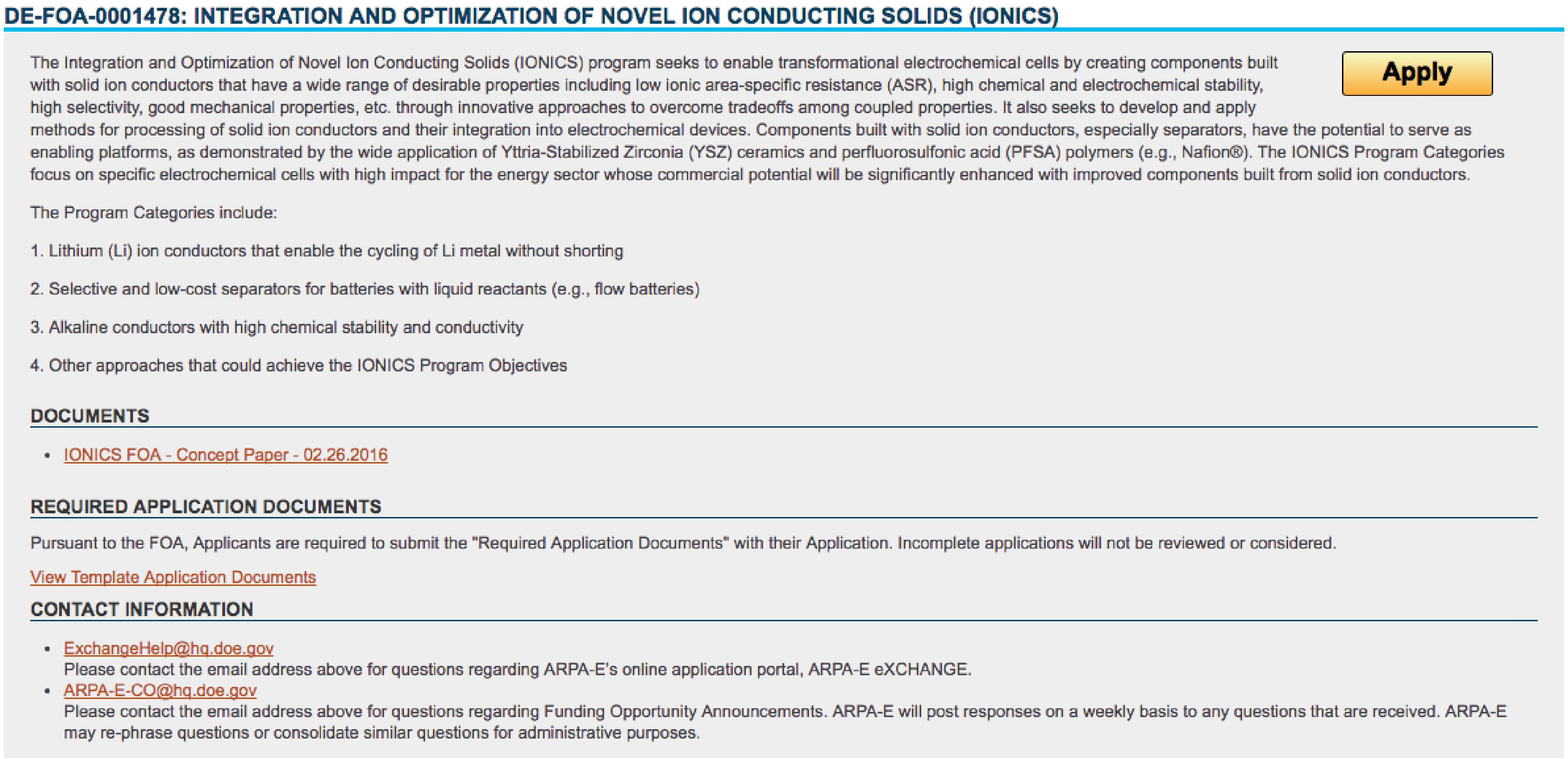
Innovation primarily at the intersections



Foundational science and engineering

- solid state ionics
- inorganic chemistry
- solid state chemistry
- polymer-polymer compos.
- functional glasses
- polymer-ceramic compos.
- mechanical properties
- thin film deposition
- organic chemistry
- photoelectrochemistry
- analytical mat. sci.
- process engineering

IONICS FOA details



- **Concept papers due next Monday, March 28.**

Extra slides

Category 1 motivation and opportunities

- Li-ion batteries are being scaled up, but face limits because of (1) energy density, (2) thermal stability, and (3) safety
- Potential solution: replace negative electrode with Li metal and liquid electrolyte with a solid
- Only LiPON has shown long-term cycling of Li metal at 25°C, but low conductivity requires thin-film cells that don't scale
- Literature suggests that ~2x shear modulus of Li metal is sufficient to block dendrites
- Also recent progress in ceramic/polymer composites
- The minimum requirement for Category 1 is to cycle Li metal at 25°C and conditions defined in Section 1.D; applicants may also propose fabricating porous electrodes using Li^+ conducting solid materials

**IONICS FOA Sect. I.D (Technical Categories of Interest), pg. 12-13*

Category 1 potential areas of (& not of) interest

Examples of technical approaches of interest include, but are not limited to:

- Composites of existing Li^+ conducting materials, especially polymer/ceramic composites with a high potential to achieve both a full set of desired properties and an ability to use existing roll-to-roll processing lines
- Low-cost, continuous, scalable processing techniques for inorganic solid ion conductors. As one example, a process is under development to make thin (down to 20 microns), flexible, polycrystalline, ceramic layers
- New materials that offer significantly improved properties compared with existing materials. As one example, a dry Li^+-conducting polymer that achieves a conductivity exceeding 5E-4 S/cm at 25°C and other desired properties would be a significant advance
- The use of self-forming mechanisms to create passivating interfacial layers, or even the active materials or the separator itself, as a way to reduce processing steps
- Supported films, which allow ion conductor thickness significantly less than 20 microns.

Area specifically not of interest:

- Liquid-based approaches to achieving technical metrics

**IONICS FOA Sect. I.D (Technical Categories of Interest), pg. 13 and III.C.3. (Areas Specifically Not of Interest), pg. 39.*

Category 1 metrics

**IONICS FOA Sect. I.E (Technical Performance Targets), pg.20-21.*

ID	Metric	Value
1.1	Separator that enables the cycling of Li metal without shorting at 25°C	Modulus, surface, and microstructural properties that prevent Li metal shorting
1.2	Thermal properties	Suitable for cell operation from −20 to 70°C
1.3	Component area over which property values are achieved to within ≥90% uniformity	≥30 cm^2
1.4	Cost	≤$10/$m^2$
1.5	Ionic ASR at 25°C	≤5 Ohm-cm^2
1.6	Capacity of Li metal moved per cycle	≥3 mAh/cm^2
1.7	Current density	≥3 mA/cm^2
1.8	Number of cycles without Li metal shorting, or ≥20% degradation of other performance metrics	≥500
1.9	Electrochemical stability	0-4.5 V *vs.* Li/Li^+ is desired; sufficient to meet metric 1.14 is required
1.10	Thickness	≤20 µm
1.11	Depth of discharge of the Li electrode (*i.e.,* fraction of the Li metal present that is cycled)	≥80%
1.12	Electronic ASR at 25°C	≥1E5 Ohm-cm^2
1.13	Mechanical properties for handling and operation	Suitable for handling components with an area at least that defined in metric 1.3, and for operation
1.14	Device Integration	Suitable for integration into a cell that achieves ≥1000 Wh/L and ≥400 Wh/kg for the cell repeat unit (current collectors, electrodes, and separator)

Please see IONICS FOA Sect. I.E (Technical Performance Targets), pg. 21 for footnotes elaborating on these metrics

Category 1 metrics: electrodes (optional)

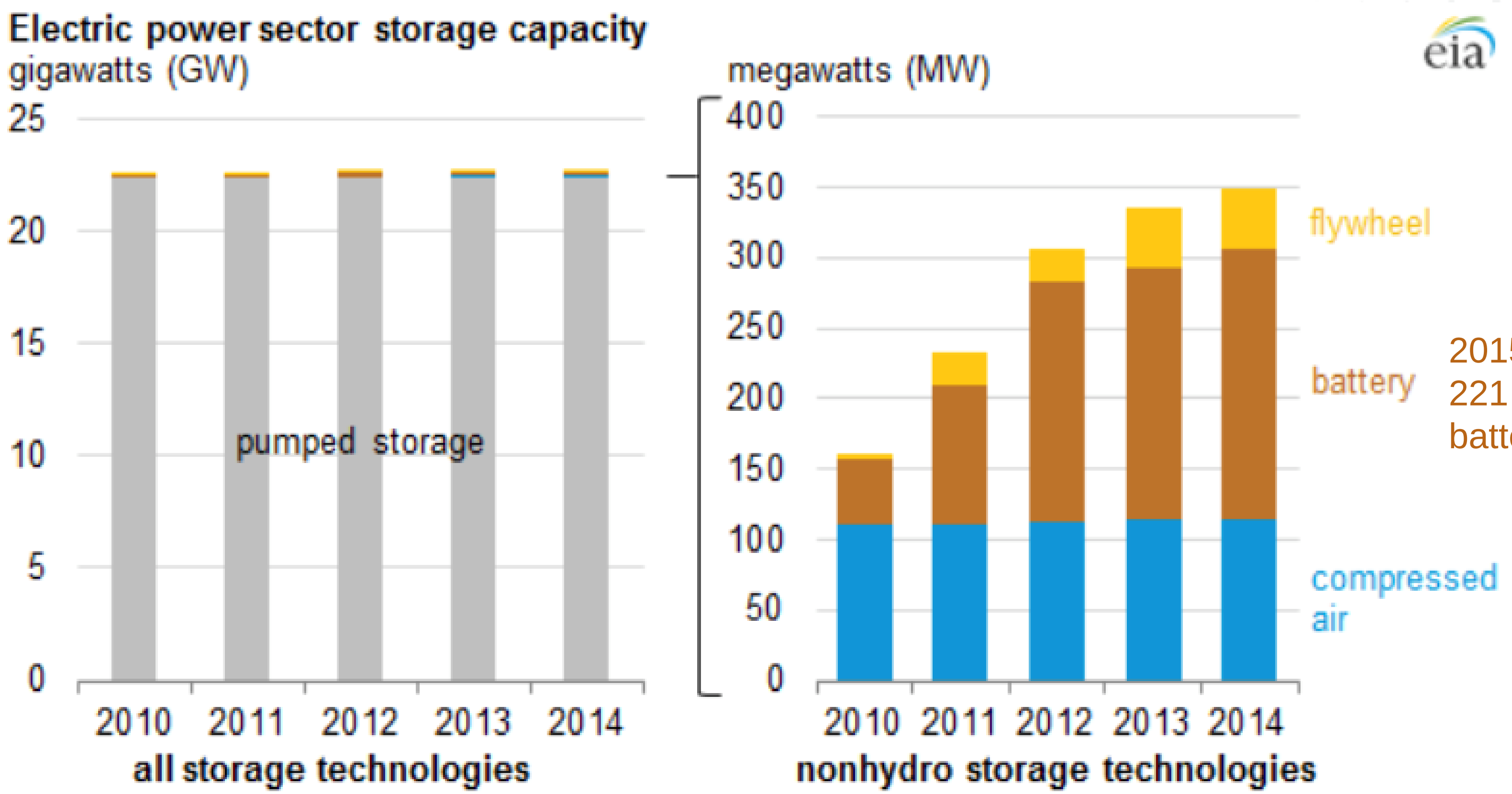
**IONICS FOA Sect. I.E (Technical Performance Targets), pg.22.*

ID	Metric	Value
1.15	Component area over which property values are achieved to within ≥90% uniformity	≥30 cm^2
1.16	Thermal properties	Suitable for cell operation from −20 to 70°C
1.17	Ionic conductivity of conducting phase	≥5E-4 S/cm
1.18	Electrode-level ASR measured at 50% SOC under practical compression conditions	≤50 Ohm-cm^2
1.19	Electrode capacity	≥3 mAh/cm^2
1.20	Number of cycles with 80% capacity retention in a full-cell format at ≥1 mA/cm^2	≥500
1.21	Electrochemical stability	Suitable for use with positive electrode materials that enable metric 1.14
1.22	Mechanical properties of composite electrode	Suitable for cell manufacturing process that enables cells at 100 $/kWh (*i.e.*, suitable for roll to roll processing is preferred)
1.23	Device integration	The creation of a solid-state cathode based on existing metal-oxide electrode materials is preferred; other electrode materials will be considered on a case-by-case basis

Please see IONICS FOA Sect. I.E (Technical Performance Targets), pg. 22 for footnotes elaborating on these metrics

Battery grid storage is growing rapidly

US electric grid averages ~400 GW



2015: added 221 MW of battery storage

Source: U.S. Energy Information Administration, EIA-860 Survey; Sandia National Labs, DOE Global Energy Storage Database

Ironic aspects of building safety codes

Parking a vehicle with >1000 lb battery in a building: no FDNY
Putting a >1000 lb battery on the wall in a building: yes FDNY