Breakthrough Energy Storage at ARPA-E

Susan Babinec: Senior Commercialization Adviser
March 2017: Ft. Lauderdale
Susan.Babinec@hq.doe.gov

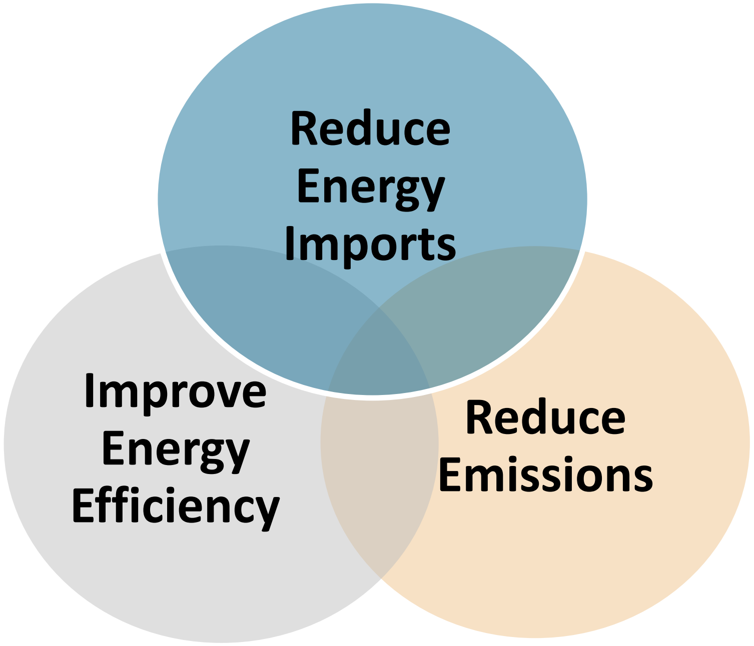
ARPA-E

Founded 2009

DOE Mission & ARPA-E Approach

DOE Goals: Ensure America's

- Economic Security
- Energy Security
- **Technological Lead in Advanced Energy Technologies**



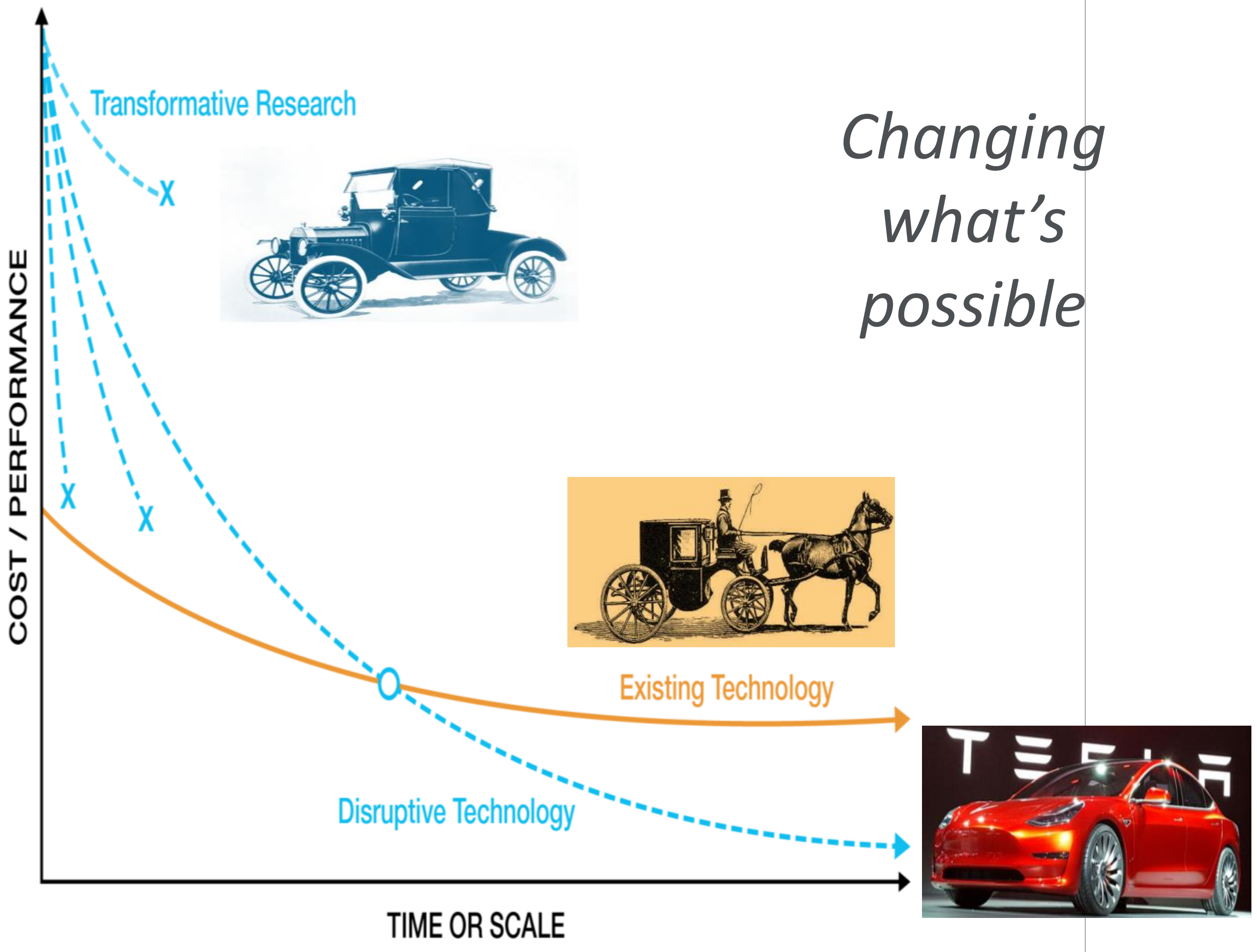
ARPA-E Approach

- High Risk / High Reward Research - - - "BREAKTHROUGH"

"Transformational" Technologies

Our goals/approach are not on a typical roadmap

“TRANSFORMATIONAL” : New Learning Curve



Changing what’s possible

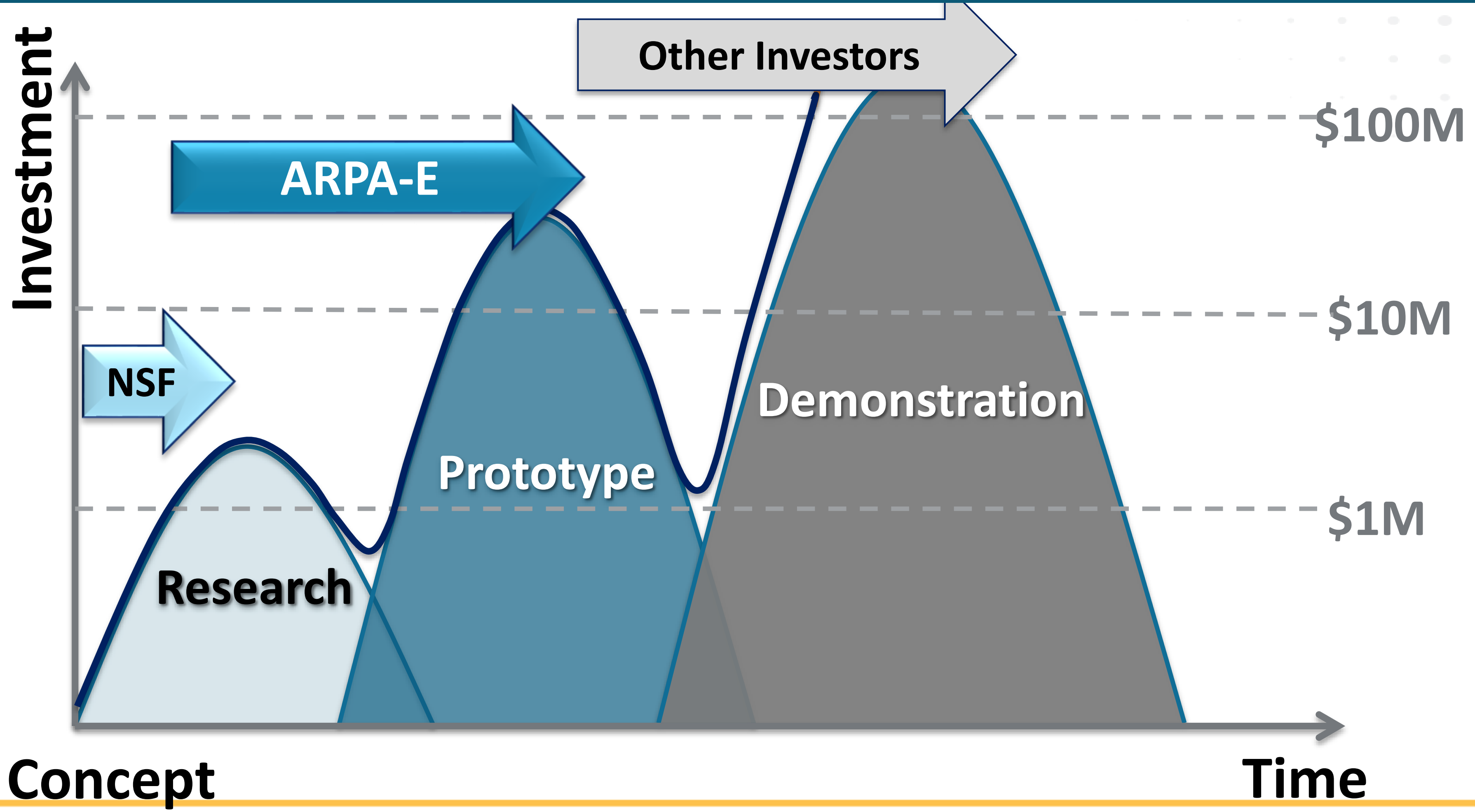
Program Metrics Set for Impact:
technology & economic

a spirited agency debate between agency PDs, commercial & Sr. management

PROGRAM Design: *Significant Technology Risk Reduction & Approach to Markets*

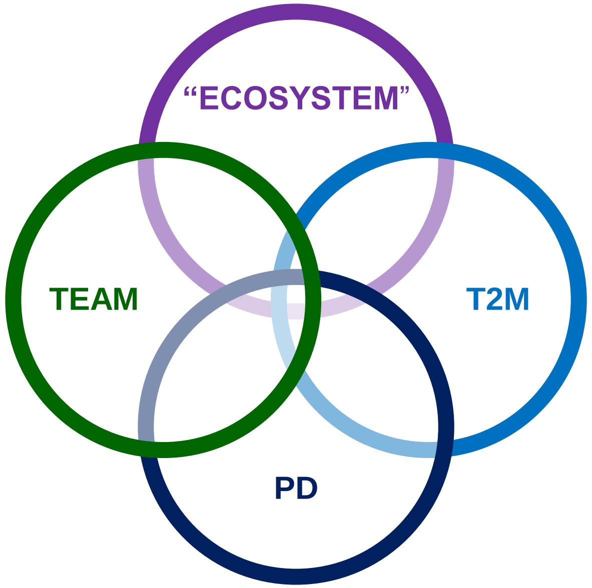
ARPA-E Typical Project: 3 years/$2-5million (NSF: 12-18 mo/~$500K)

3 year runway to work through majority proof of concept, initial manufacturing & economic issues



ARPA-E Implementation – *Addressing Risk*

1. Program objectives & metrics target commercial impact
2. Hands-on project management – quarterly site visits
3. T2M / Technology-2-Market Adviser Coaching



T2M

Preparation for the transition: addressing the non-purely technical

T2M MILESTONES

-IP Landscape - early

-Techno-economic Analysis - early

-Manufacturing – early

-Approach to Market

-Transition Preparation

T2M Adviser coaches teams

ENERGY STORAGE

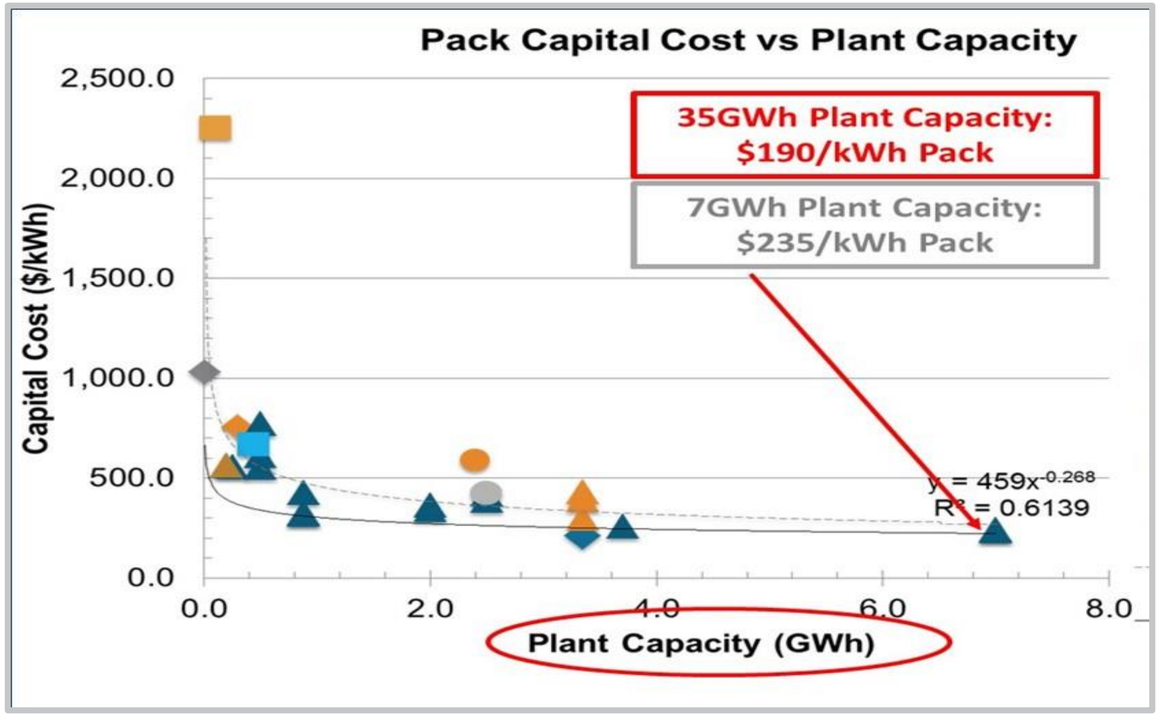
ENERGY STORAGE

TRANSPORTATION	GRID
PERFORMANCE PARITY WITH ICE: CELL: 350-400 WH/KG PACK 250-300 WH/KG $100/KWH PACK	**COST/PERFORMANCE PARITY WITH GRID** **RENEWABLES / SMART GRID TARGET: 2¢ / CYCLE** **$100/KWH / [1000 CYCLES * 80% EFFICIENCY]**

Defining Breakthrough in Dynamic ES Ecosystem

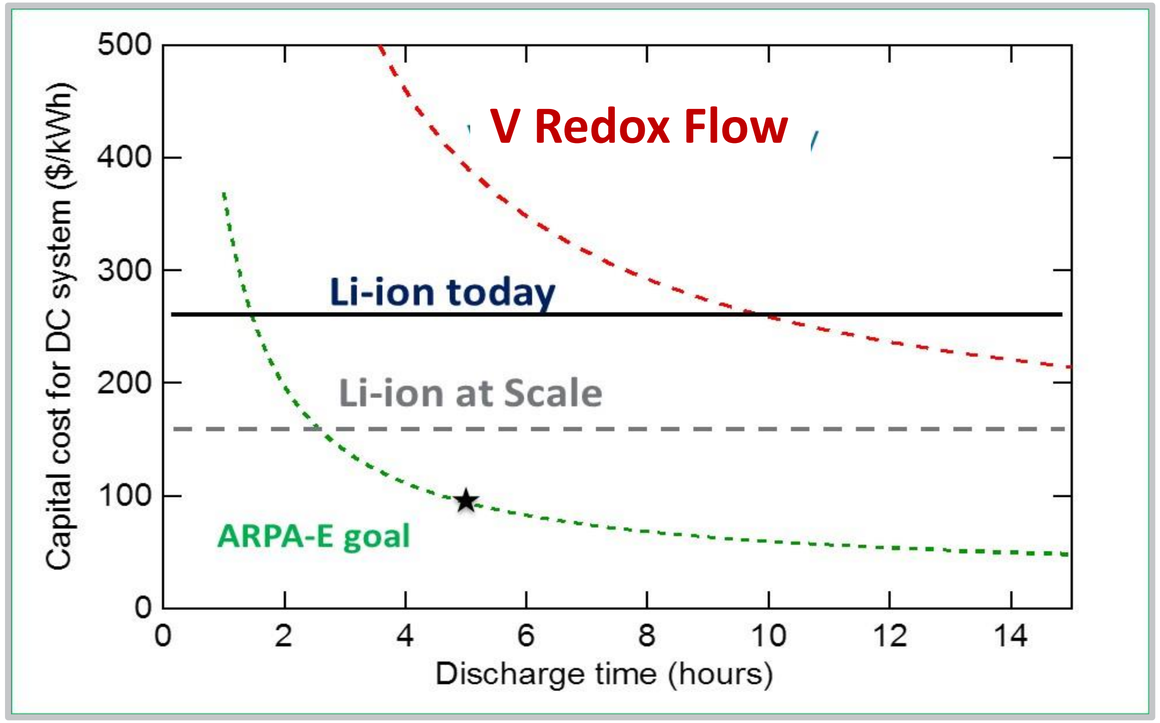
Li-Ion as Transportation & Grid State-of-Art: Cost & Performance Rapidly Changing

Li-Ion Cost:
Manufacturing Scale Sets Cost
(Calendar year is not prime variable)



2015 ARPA-E Analysis – details on request

Renewables / Grid:
Duration is Key: Longer Duration Desirable Now
Flow Battery Cost Advantage At >3-4 hours

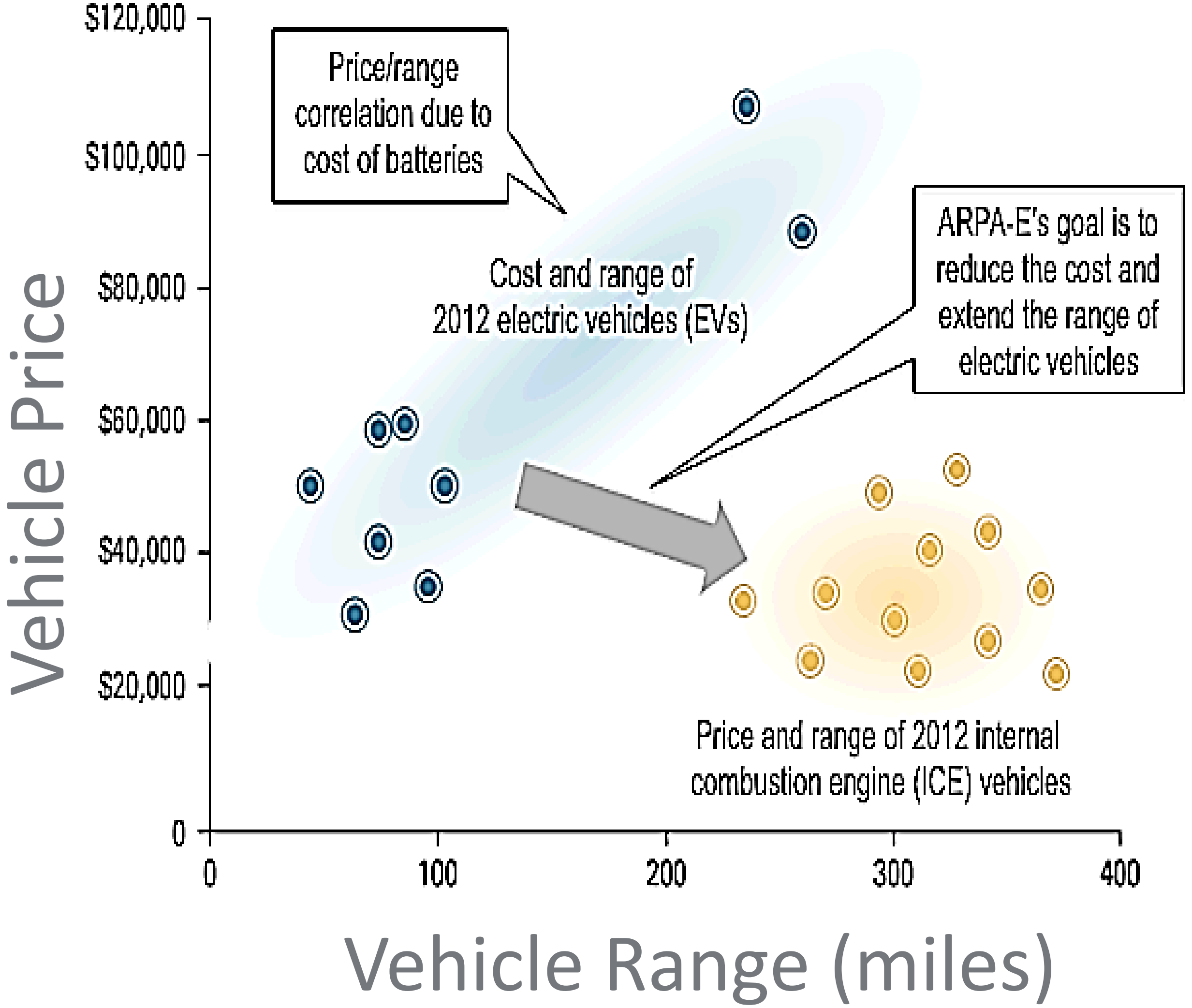


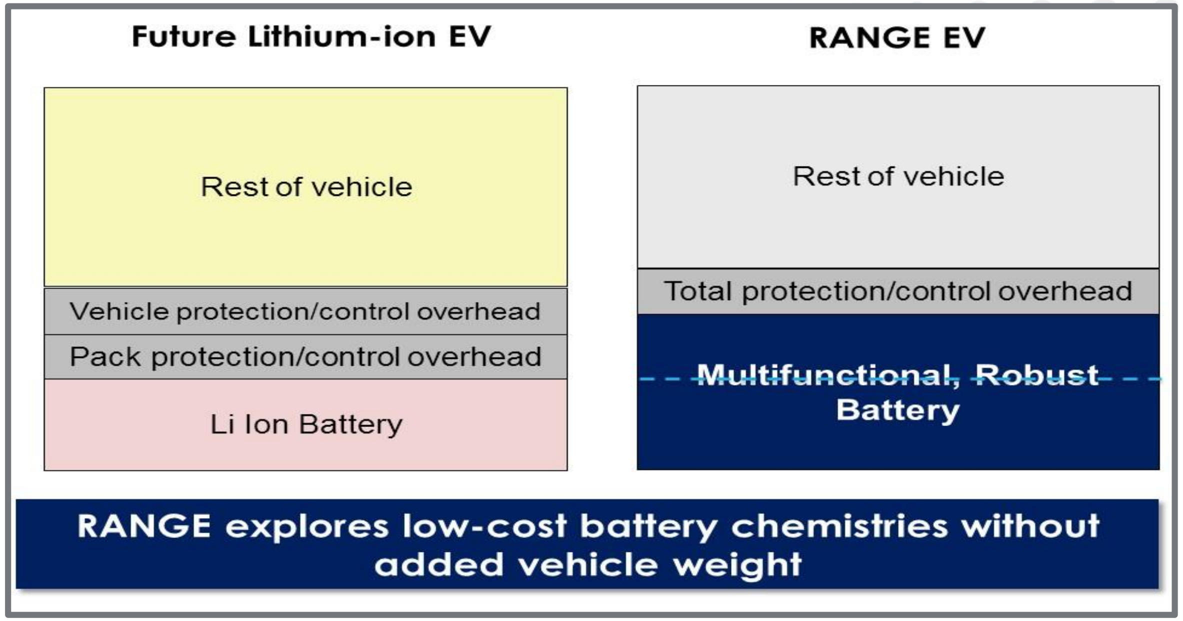
ARPA-E ENERGY STORAGE PROGRAMS

5 Themed Programs / 3 Open Solicitations / ~ $230 million funded / 103 Projects

PROGRAM	WHAT	TRANSPORTATION	STATIONARY
BEEST	High ED / New Chemistry	X	
GRIDS	*Super low cost / New Chemistry*		*X*
AMPED	High ED-High Cycle Life-Low Cost/ BMS	X	X
RANGE	Robust Low Cost High ED /System Approach	X	
IONICS	Enable All/ Breakthrough Separators	X	X
OPEN 2009	All	X	X
OPEN 2012	All	X	X
OPEN 2015	All	X	X

2012 RANGE: *MULTIFUNCTIONAL battery systems with net higher ED at __System Level –__ combine ES & mechanical functions -> reduces net weight /increases range*





PRIMARY METRICS:

- EFFECTIVE SYSTEMS ED: > 150 Wh/kg
- EFFECTIVE SYSTEM COST: <100-150 $/kWh
- 1,000 cycles

arpa·e
CHANGING WHAT'S POSSIBLE

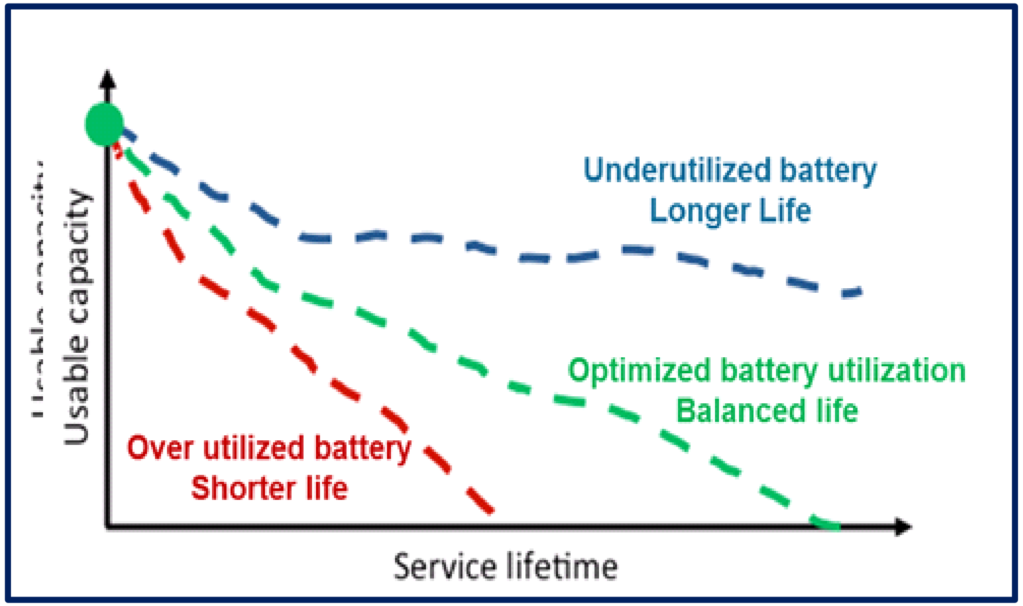
BMS PROGRAM - AMPED: *Higher ED & Cycle Life via More Informed/Flexible Control*

New BMS Paradigms, Software & Hardware

AMPED FOA GOALS:

- Downsize packs by > 25%
- Improve estimation of:
  - State of Charge (SOC)
  - State of Health (SOH)
- Increase charging rates by >2X

Type Pack	% Cell Cost	% Pack Cost
EV	69	31
PHEV	56	44



1. Sensing

- Monitor **internal cell temperature** in real time?
- Monitor **intercalation strain** for SOC/SOH estimation?
- Track physical/chemical states with **optical sensing**?
- Track **gas signatures** of various degradation modes?

2. Modeling & controls

- Employ **real-time physical state and degradation models** to optimize utilization and balancing control?

3. Flexible Power Systems

- Implement **cost effective cell-level power management**?
- Utilize **flexible power architectures** for diff'l diagnostics?
- **Wireless communications** and control
- Design **intra-cell thermal management** systems?

4. Diagnostics & prognostics

- Identify degradation/failure modes quickly with non-destructive **acoustic inspection?**
- Measure **high-precision columbic efficiency** on production cells and practical drive cycles?

Measures of Success: *follow-on funding & spin-outs*

Technology	Awards Sum	# of projects (TOTAL)	# spin-off companies	Private Investments
STORAGE projects	**>$230M**	**103**	**13**	**>$600M**
ALL ARPA-e projects	**>$1.6B**	**>580**	**56**	**>$1.8B**

CHANGING WHAT'S POSSIBLE

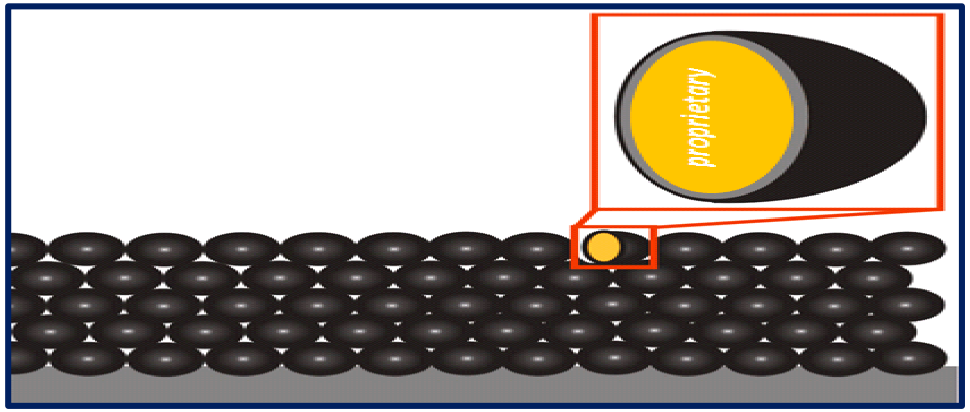
Very High ED Energy Storage: *BEEST, 2009/2012/2015 Opens, IONICs*

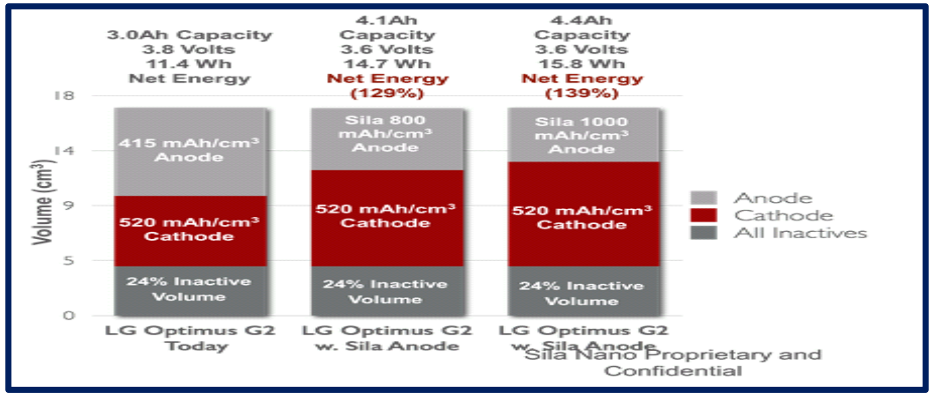
- SIGNIFICANT ACCOMPLISHMENTS
  - **Sila** – High ED, long cycle life Si nanostructured high performance electrodes
  - **24M** – High ED with low cost via novel thick semi-solid Li-Ion
  - **PolyPlus** – Super High ED Li/air & Li/S
  - **Quantum Scape**
  - **ISS** – Ion Storage Systems – University of Maryland Recent Spinout – novel Li Metal
- ON-DECK: IONICS FOA - 2016
  - High ED Li-metal nondendritic batteries – enabled by breakthrough separators

IONICS
16 Project Teams • 3 Technology Areas

Si anodes: *High capacity but significant volume expansion & cycle life issues*

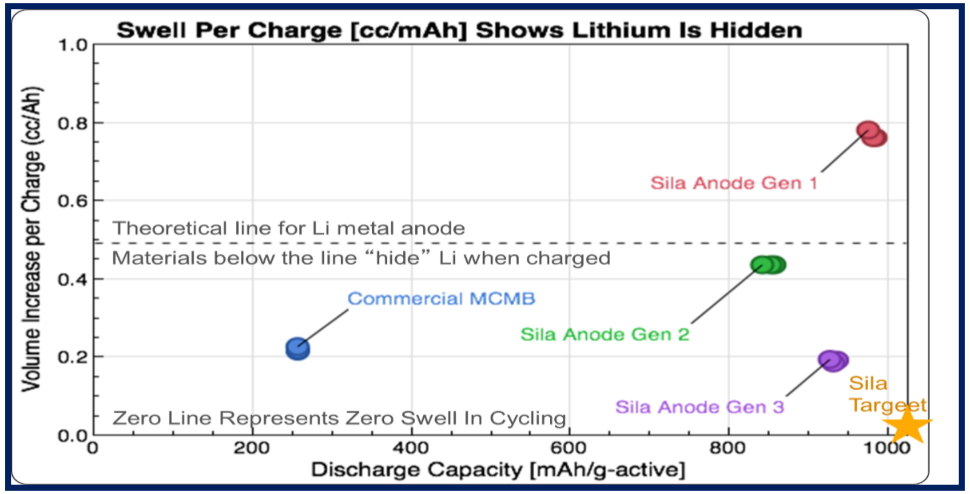
BREAKTHROUGH: Containment of Si expansion within a rigid electroactive solid

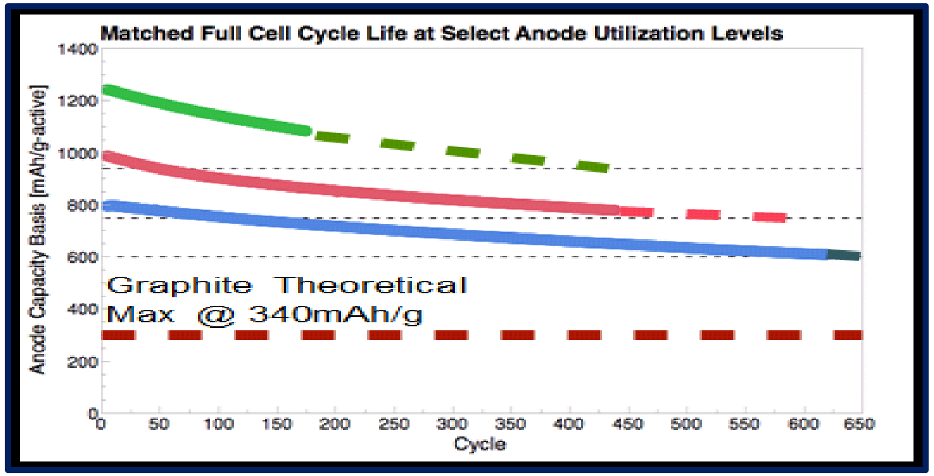




Sila Nanotechnologies

ARPA-E BEEST/2009





In Successful Scale-up Of Very Complex Nanomaterial

BREAKTHROUGH: Increasing Li_xS Solubility via aqueous approach/ stabilizing Li to H_2O

Sulfur: dirt cheap with 4X high capacity of existing → long standing unrealized potential

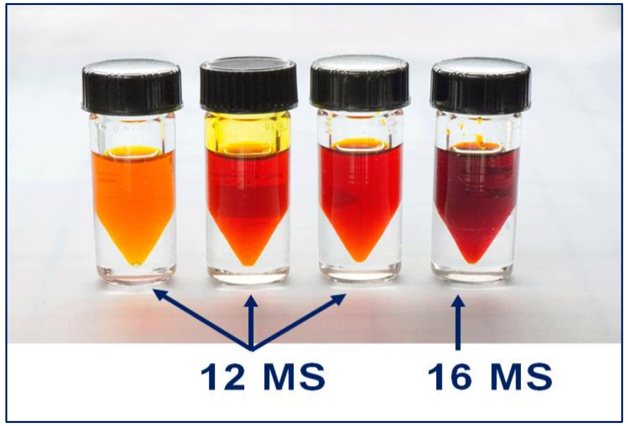
- Low Polysulfide solubility significantly reduces cell ED – OPEN 2012 RESOLVED
- Need innovation for low cost protected Li metal – In progress /ARPA-E IONICs program

- **PolyPlus** - Highly soluble aqueous polysulfides with novel water protected Li metal anode

POLYPLUS

ARPA-E OPEN/2012

ORGANIC SOLVENT
Undissolved Li_2S

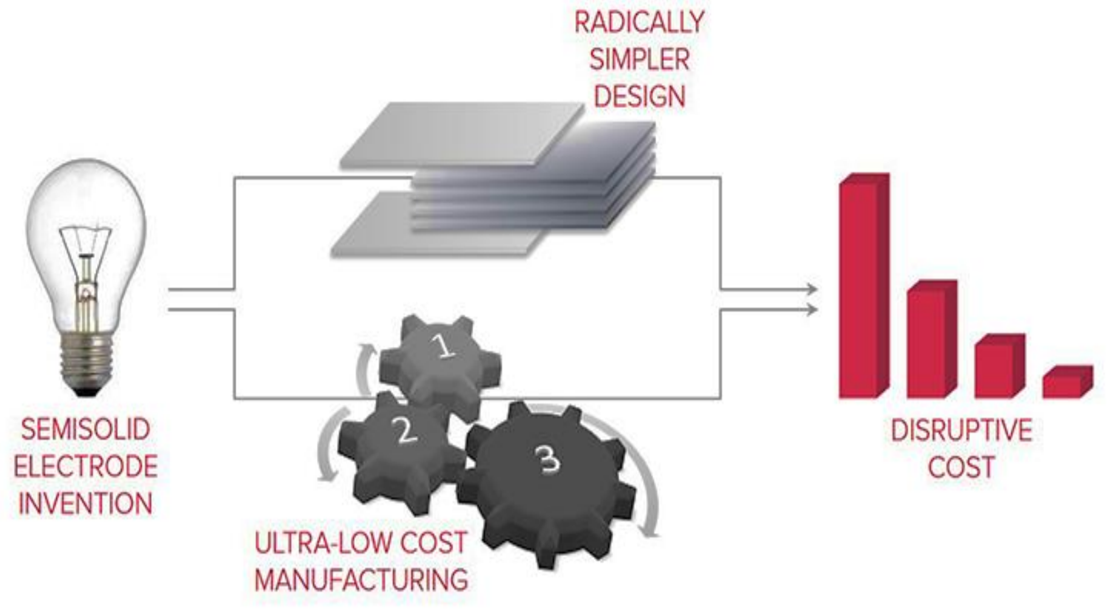


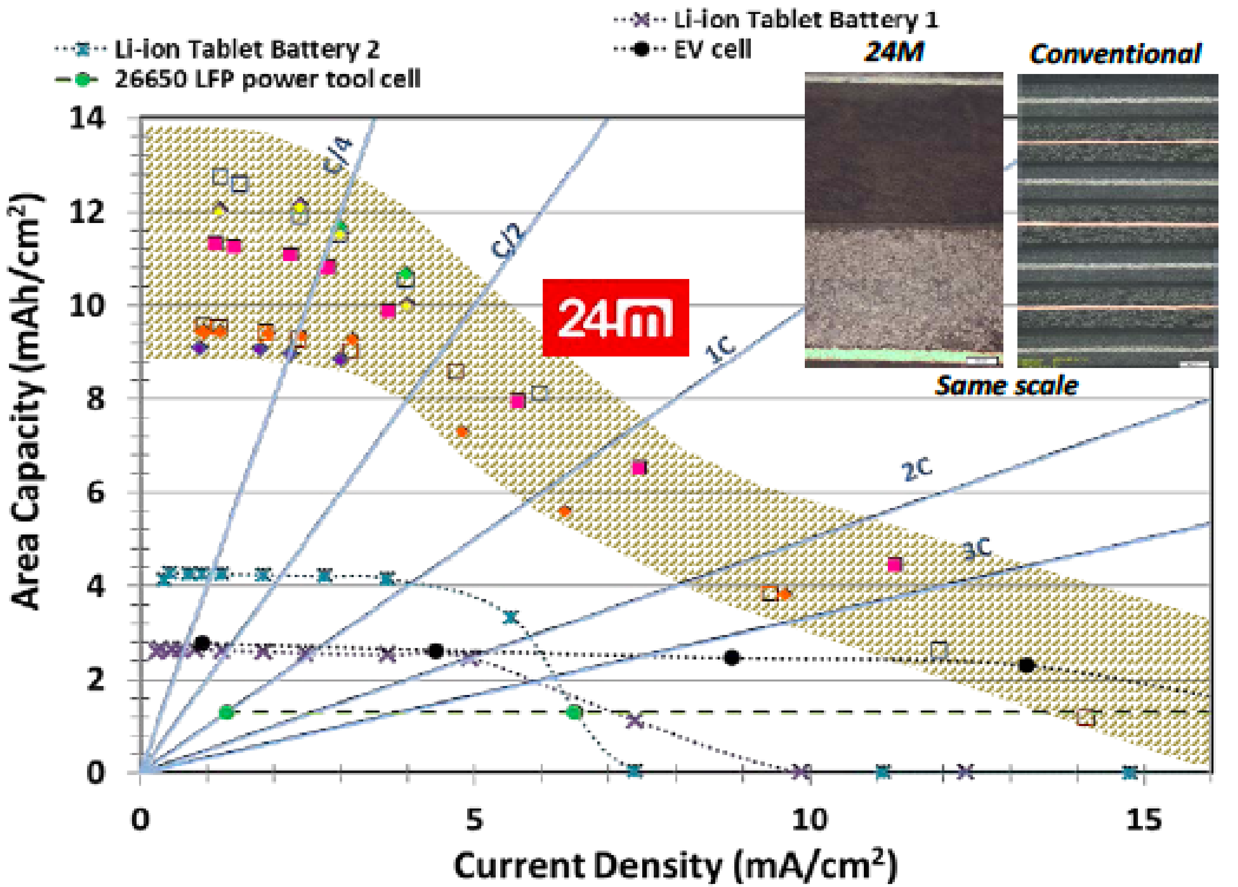
AQUEOUS SOLVENT
Highly soluble Li_2S

Thick Electrodes: *Critical Component of High ED Cells, but prohibitively expensive to manufacture*

BREAKTHROUGH: Semi-Solid electrode – skip traditional expensive coating step

ARPA-E
BEEST/2009

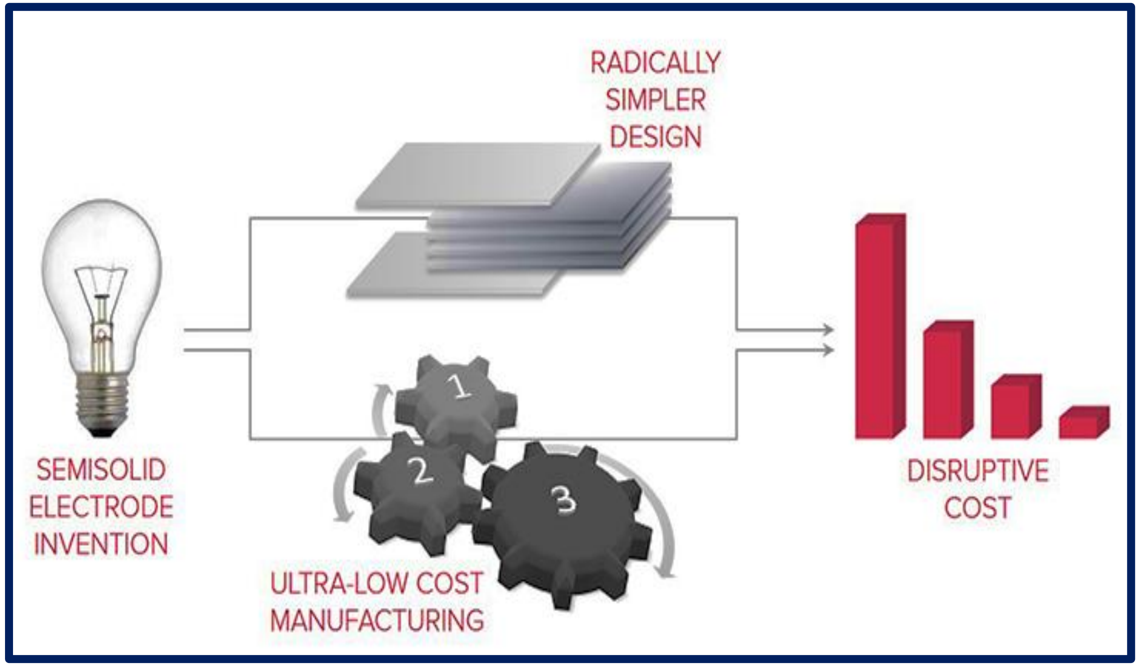


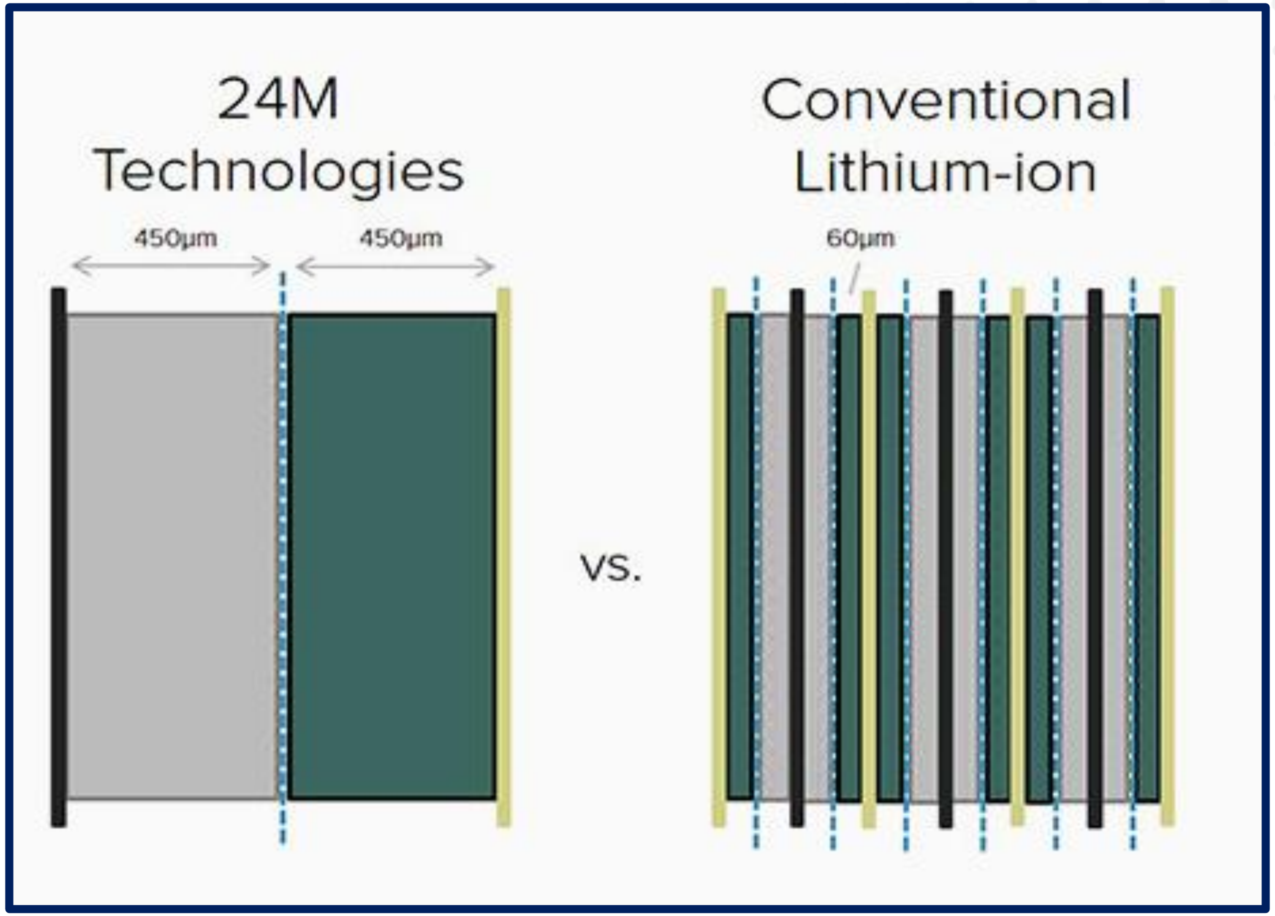


Thick Electrodes: *Critical Component of High ED Cells, but prohibitively expensive to manufacture*

BREAKTHROUGH: Semi-Solid electrode – skip traditional expensive coating step

ARPA-E
BEEST/2009





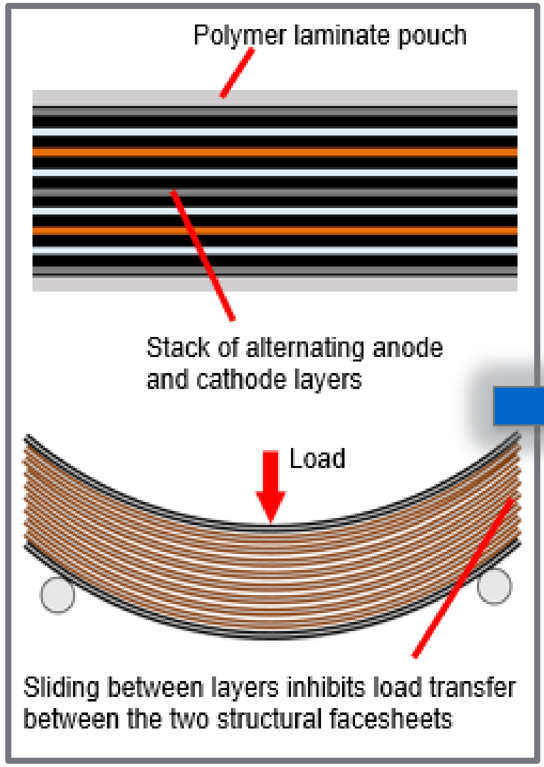
High Net Energy Density: *Total System* Weight is High – redefine "system"

BREAKTHROUGH: Multifunctional Load Bearing battery – High System ED

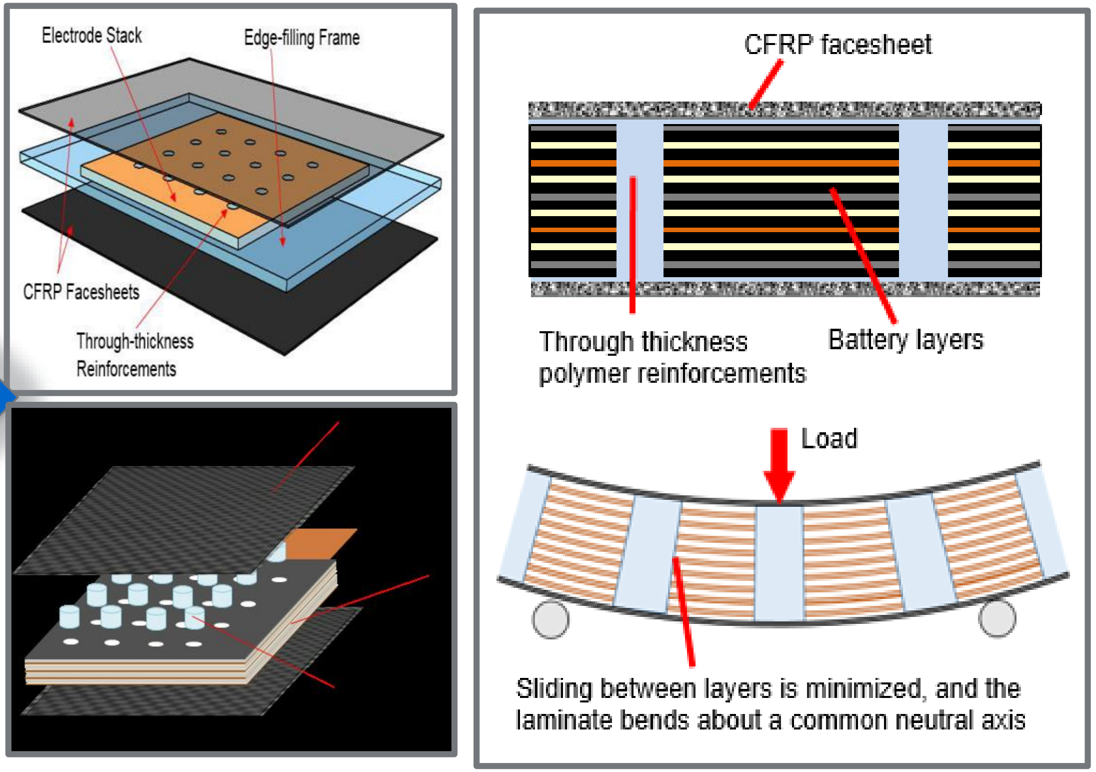
ARPA-E RANGE/2012

Stanford University
Professor Fu-Kuo Chang

Usual Li-Ion



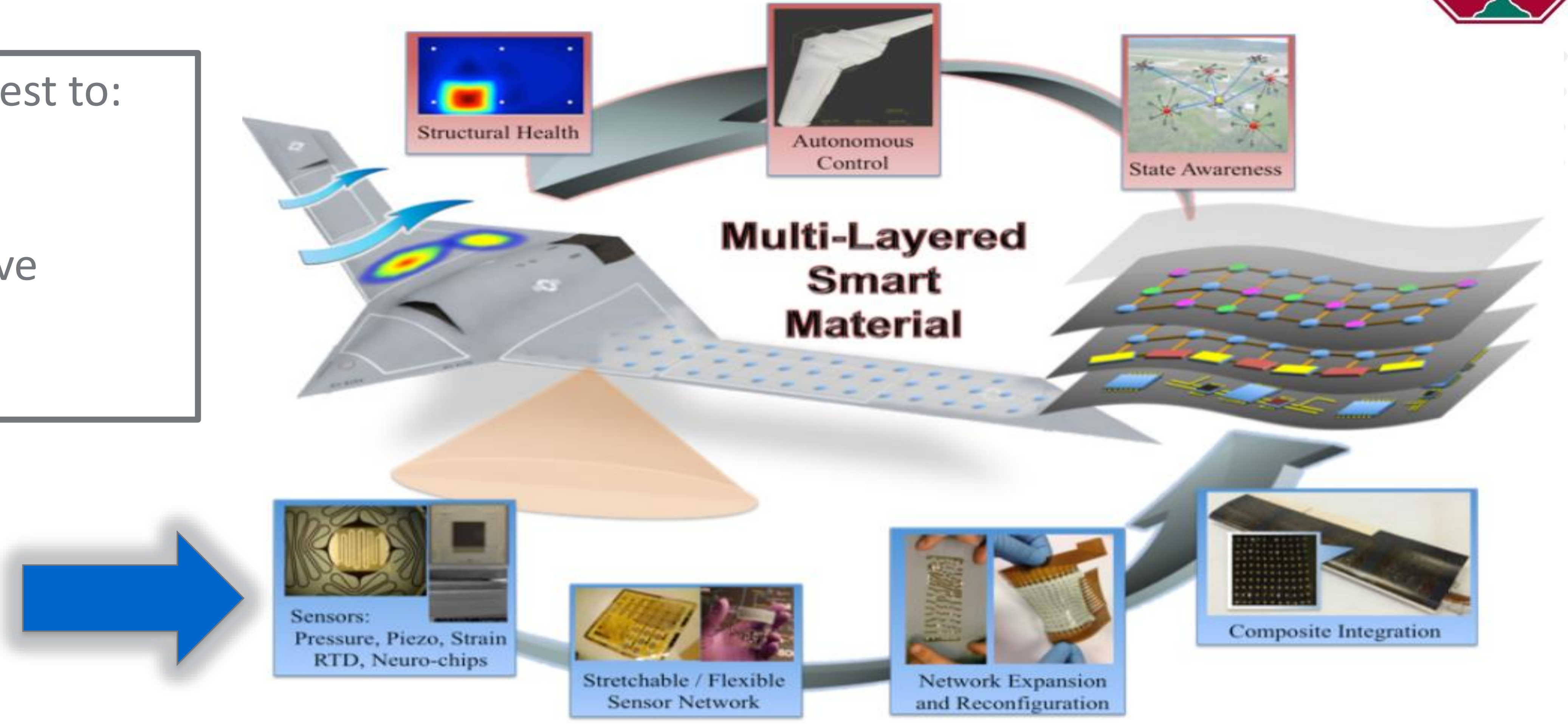
Stanford Multifunctional Composite (MES)



Multifunctional Vision Applied to (air) Transport:

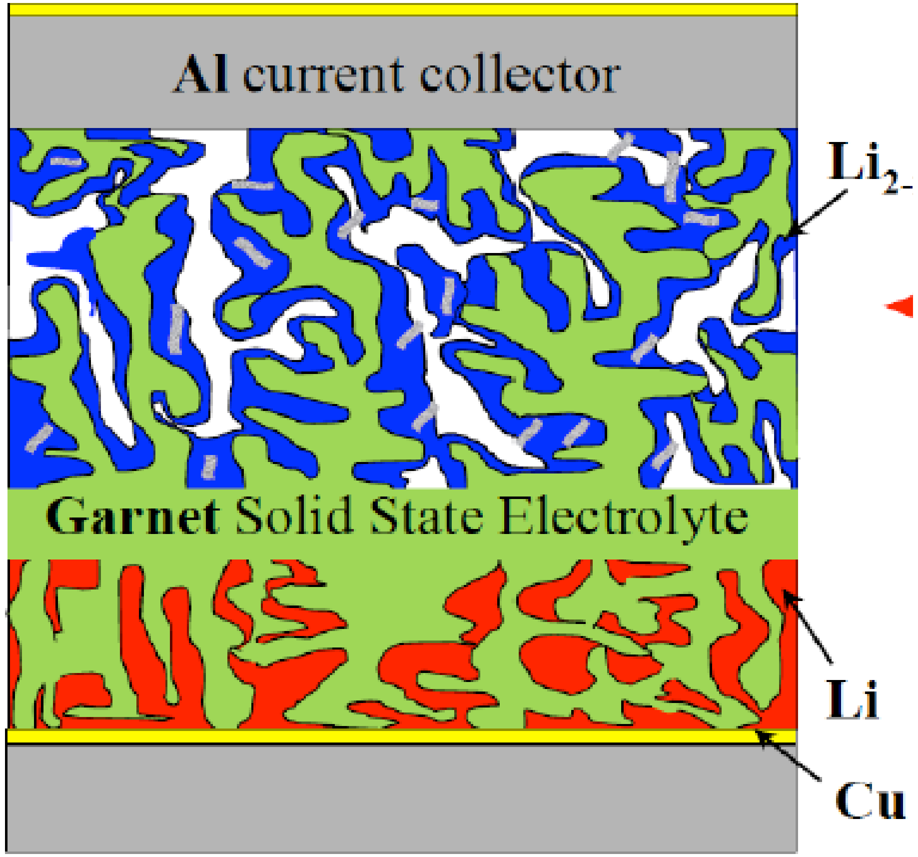
Wings store energy/provide strength & also real-time monitor everything

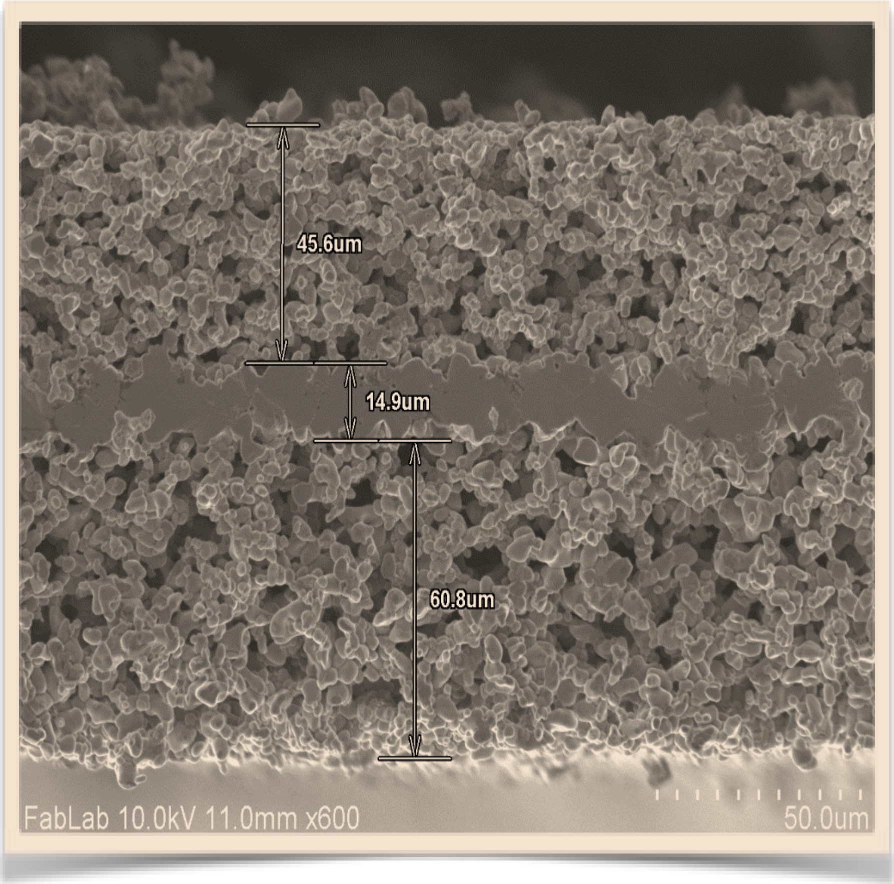
Also of interest to:
- Drones
- Rail
- Automotive
- Bikes
- Other



Li anode: *Dendrites shorten cycle life and are safety hazard*

BREAKTHROUGH: All Solid state/3D Network Reservoir for Mobile Li & Cathode





storage ion systems

Prof. Eric Wachsman U-Maryland

ARPA-E RANGE/20012

Cell Designs, Manufacturing & BMS: Safety & reliability requirements reduce full utilization of capacity

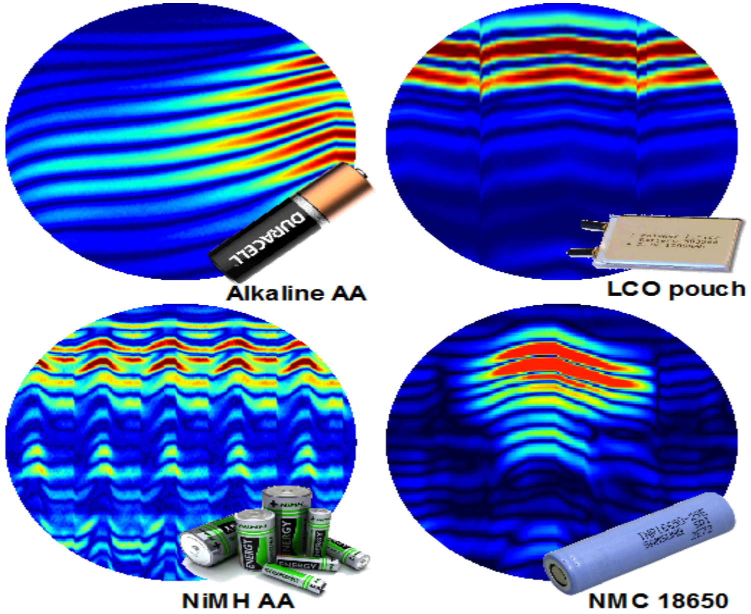
BREAKTHROUGH: ultrasound provides direct/rapid cell SOC/SOH monitoring & Cell Design

ARPA-E RANGE/2012

Feasible
See Batteries Differently

The electrochemical reactions in batteries result in physical changes that sound waves are acutely sensitive to: Formation / QC / SOH / SOC etc.

Echoes + Analytics → Battery quality, health



- Works on any battery
- Sensitive to spatial inhomogeneity
- Higher-fidelity QC and defect detection
- Better *in-operando* measure of SOC/SOH

Super Low Cost Stationary Energy Storage – *GRIDS,* 2009/2012/2015 Open, IONICS

- SIGNIFICANT ACCOMPLISHMENTS
  - Fe/Fe Aqueous flow cell
    - ***ESS** (Energy Storage Systems) of Portland Or – Scaling up and placing in field*
    - Case Western – Professor Robert Savinell
  - All organic aqueous flow cell
    - **Harvard University** – Professor M. Aziz et al
    - University of Southern California – Professor Sri Narayan et al
  - Prussian Blue Chemistry with Super Long Life
    - **Alveo Energy – Dr. Colin Wessells in Palo Alto – Scaling up both cells/packs**
    - Sharp American – Na chemistry
  - **Fluidic Energy** – Zn/Air
  - Urban Electric Power – Reversible Zn/MnO2
  - Primus Power – Zn/Br aqueous flow cell
  - Cadenza – Novel Battery Pack

ESS INC
ENERGY STORAGE SYSTEMS

HARVARD
School of Engineering and Applied Sciences

Alveo Energy

FLUIDICENERGY

Cadenza INNOVATION

- ON-DECK: IONICS FOA – 2016
  - Breakthrough selective/high flux low cost separators

IONICS
16 Project Teams • 3 Technology Areas

Very Low Cost Flow Cells: *Vanadium is Reversible with good kinetics/solubility but expensive*

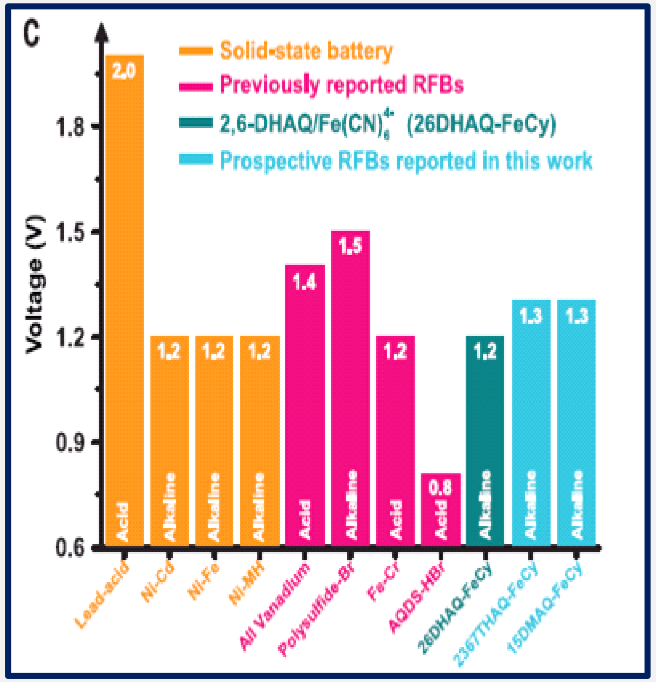
BREAKTHROUGH: No Precious Metals (V) – Aqueous Fe/Fe & All Organic Electrochemistries

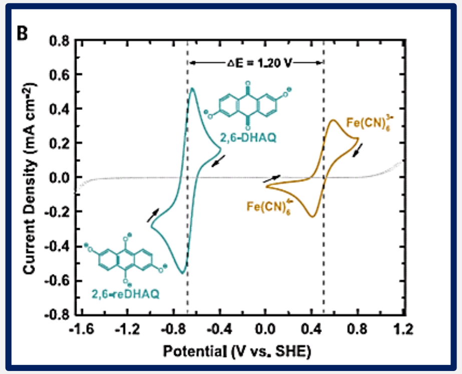
AQUEOUS Fe/Fe

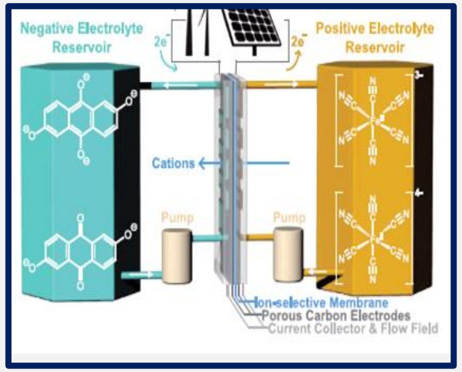
In PRODUCTION

Sonoma CA MICROGRID

AQUEOUS Organic Actives : Harvard & USC





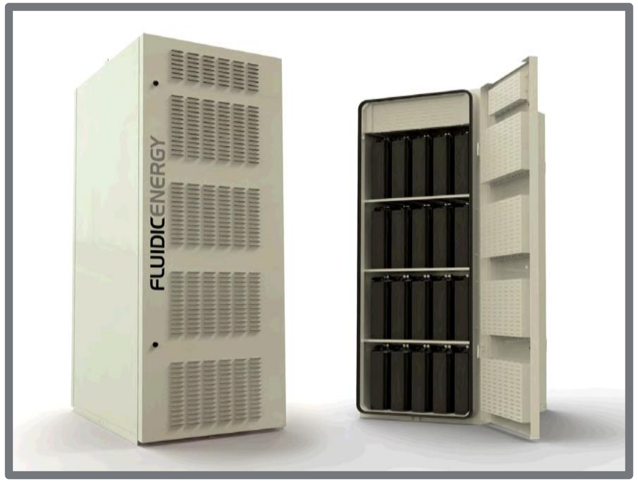


Very Low Cost Storage: Realizing long lived air electrodes low cost actives

BREAKTHROUGH: Reversible low cost Zn/air electrodes

FLUIDICENERGY

- Founded 2006
- Raised $200M
- Deploy since 2011: SE Asia, C America, Africa
- Largest deployment base of any new ES company in the last 10 years.



- Base Materials *as low as $1/kwh*
- Integrated Electronics down to the cell level, allowing remote monitoring and maintenance from anywhere in the world
- Cycle >10,000 discharge hours
- 0-50C - no cooling required
- Scaleable from a few kwh to Mwh,

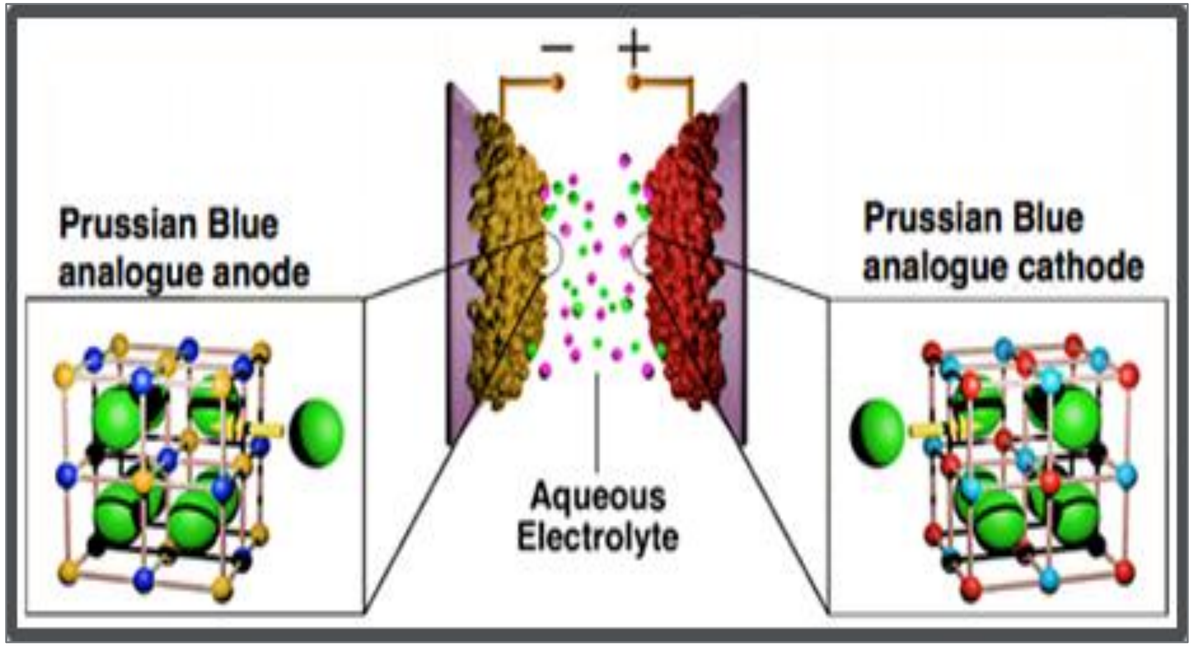
Very Low Cost/Cycle: *Realizing super long cycle life while maintaining low cost*

BREAKTHROUGH: Open framework Prussian Blues: intercalation w/o volume change failure mechanism

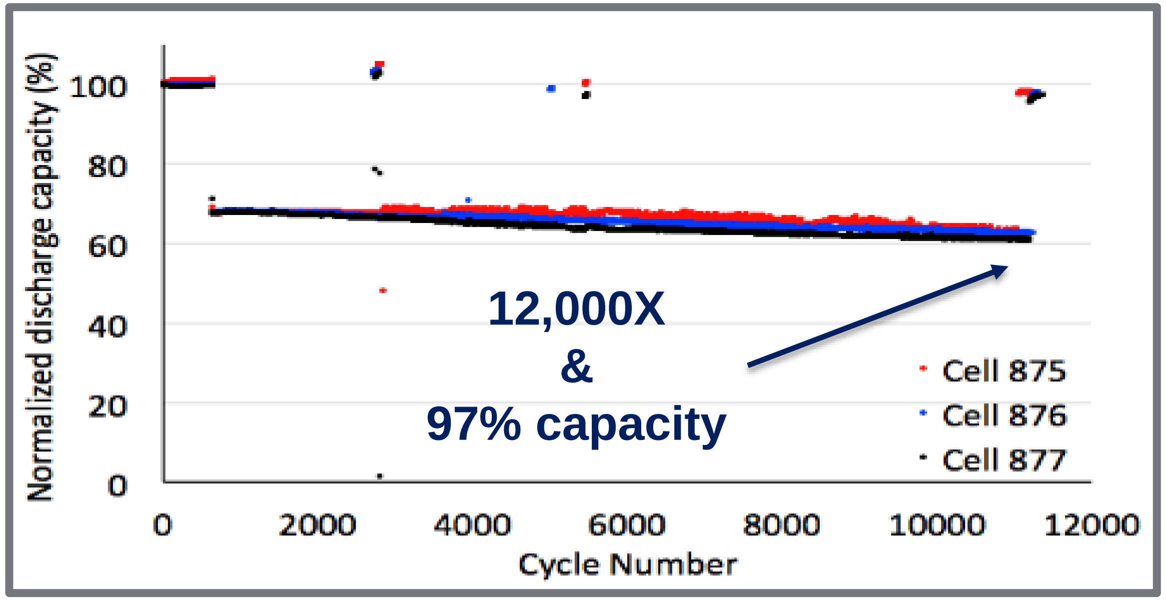
Alveo Energy

ARPA-E
OPEN/2012

Colin Wessells
Stanford → Palo Alto



PROJECTS TO >>20,000 CYCLES
100% DOD, 1C/1C & 5C/5C



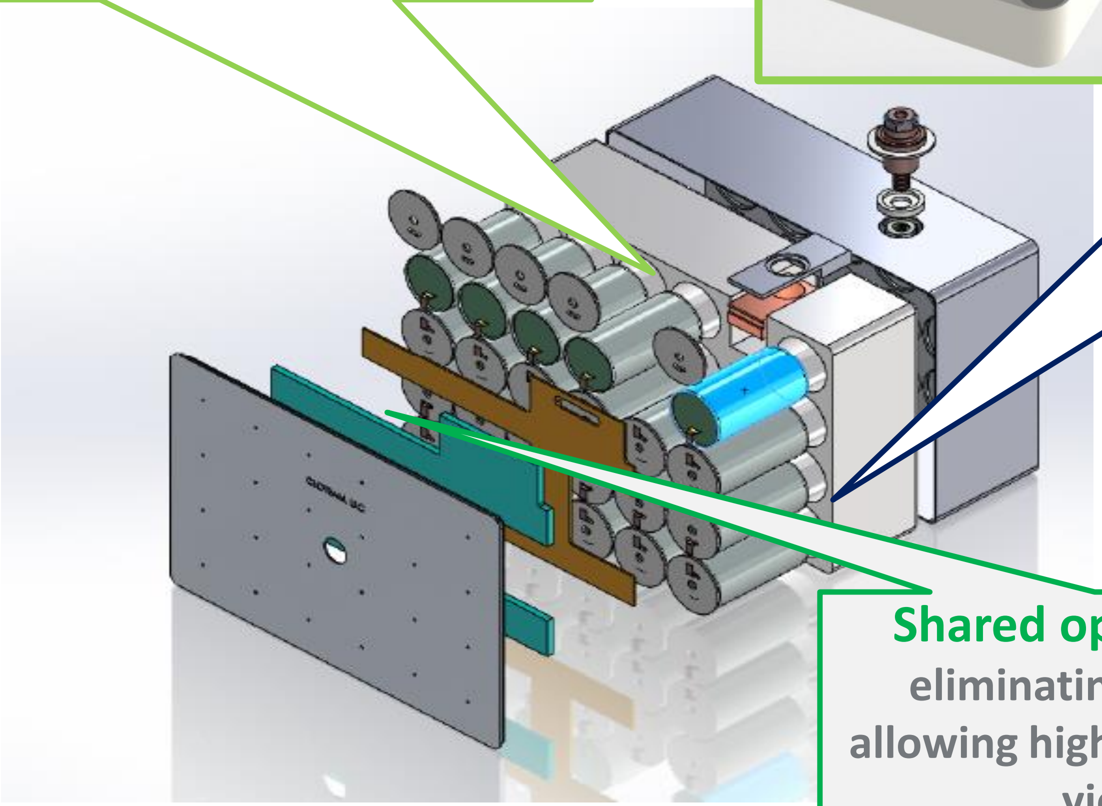
- 45-55 Wh/L
- HIGH POWER: 80% Energy @ 5C
- 5 year Float Life

Safe Pack Assembly & Cell forming Costs are High – ED is Lowered

BREAKTHROUGH: Low Cost High ED Novel Architecture – ceramic JR housing prevents thermal cascading

Engineered **fire-proof ceramic housing** allowing non-cascading, thermal dissipation and crash absorption

Thin aluminum liner protecting jelly roll allowing easy assembly



ARPA-E
RANGE/2012

Cadenza INNOVATION

Shared open formation eliminating components allowing higher JR production yield use

REMAINING PROBLEMS: Separators

1) Separators limitations – Still dendrite issues with High ED Li metal Cells

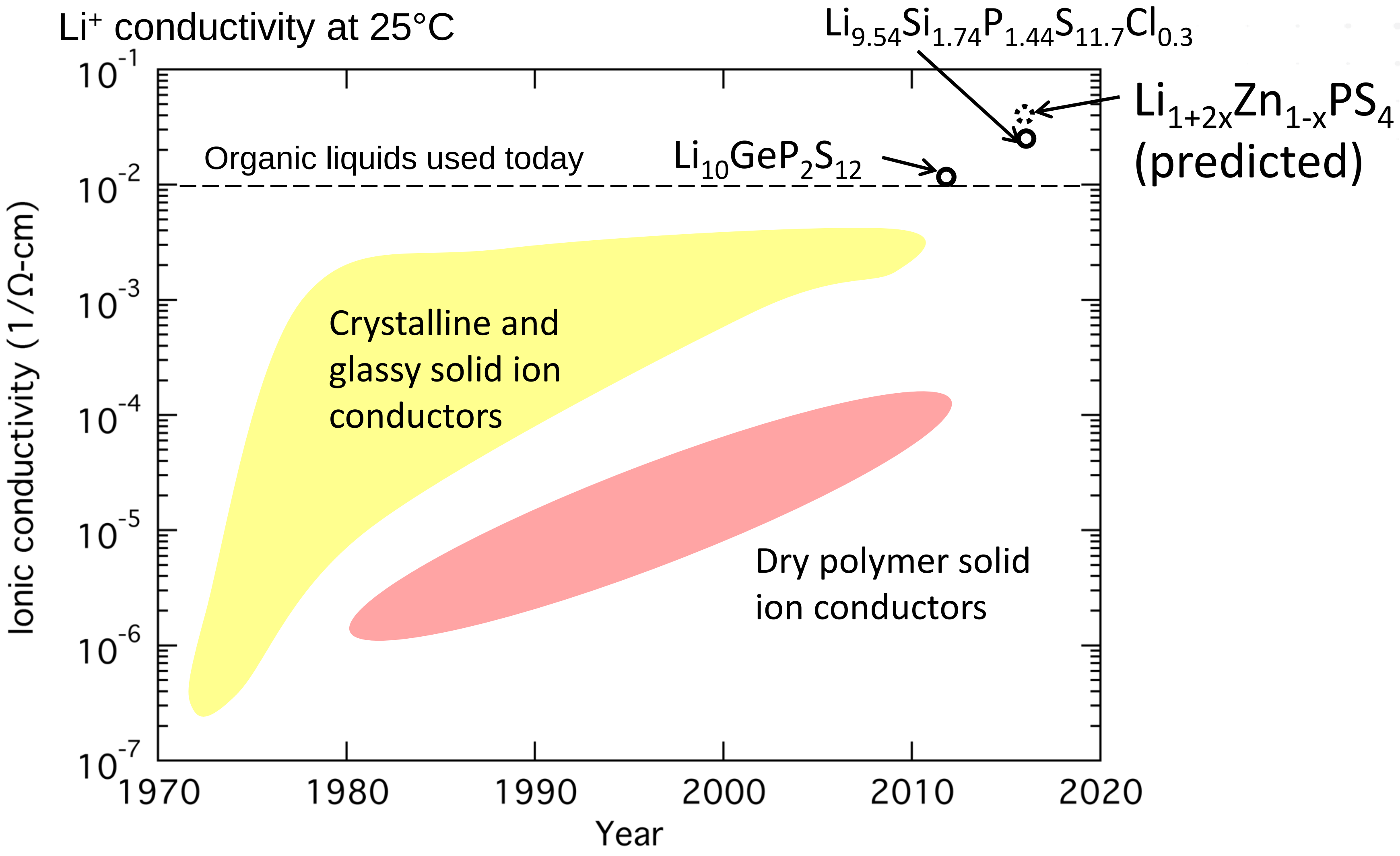
2) Proven Great Chemistries Still Need Breakthrough for Cost Effective Separators

IONICS

Integration and Optimization of Novel Ion-Conducting Solids

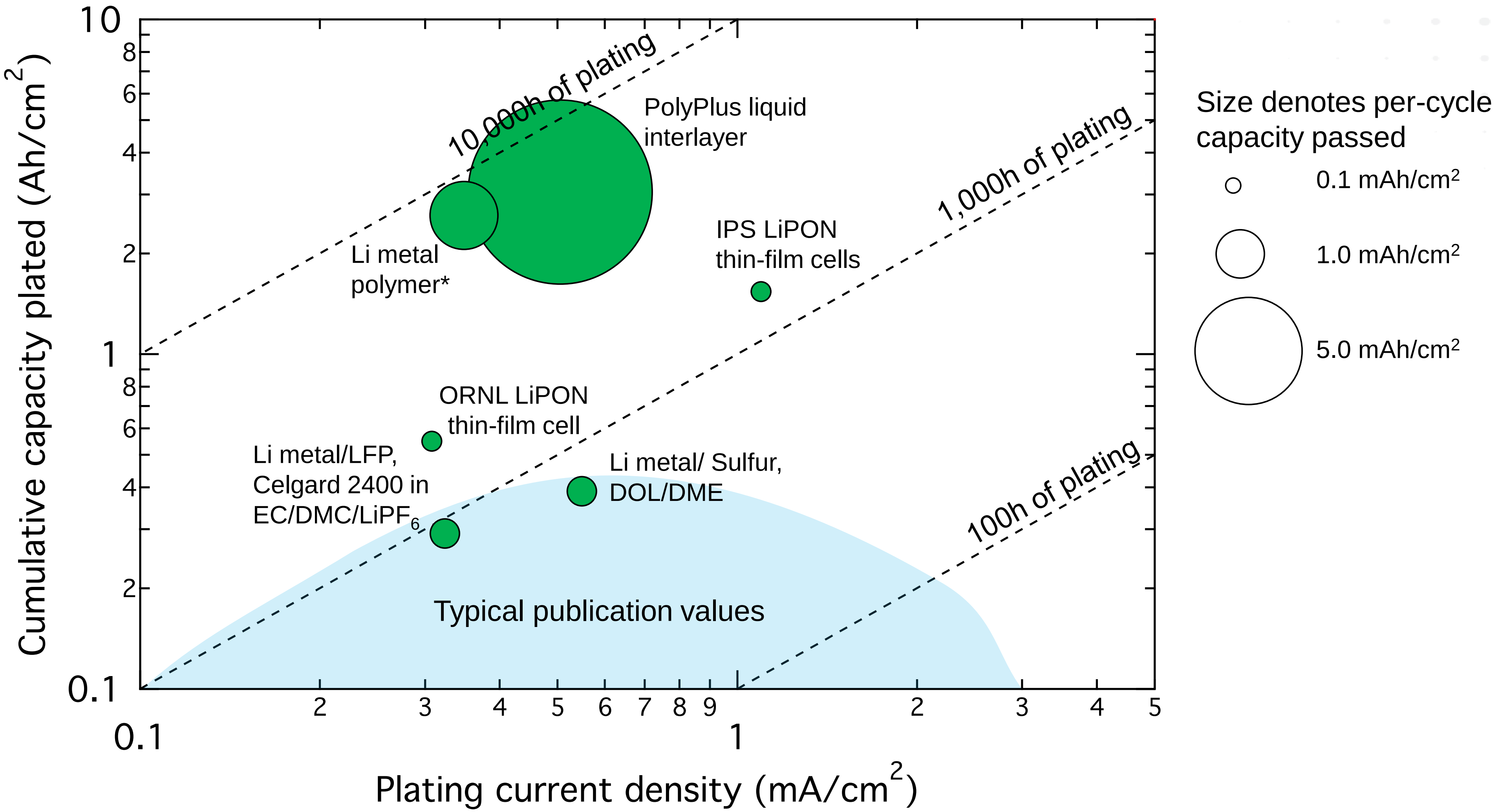
Program Director	Dr. Paul Albertus
Year	2016
Projects	16
Total Investment	$37 Million

Materials breakthroughs: impressive solid-state Li^+ conductivity gains in past 5 years



References: Kamaya et al., Nature Materials, Vol 10, 2011, p. 682-686.
A. Kuhm et al., Phys. Chem. Chem. Phys., Vol. 16, 2014, 14669-14674.

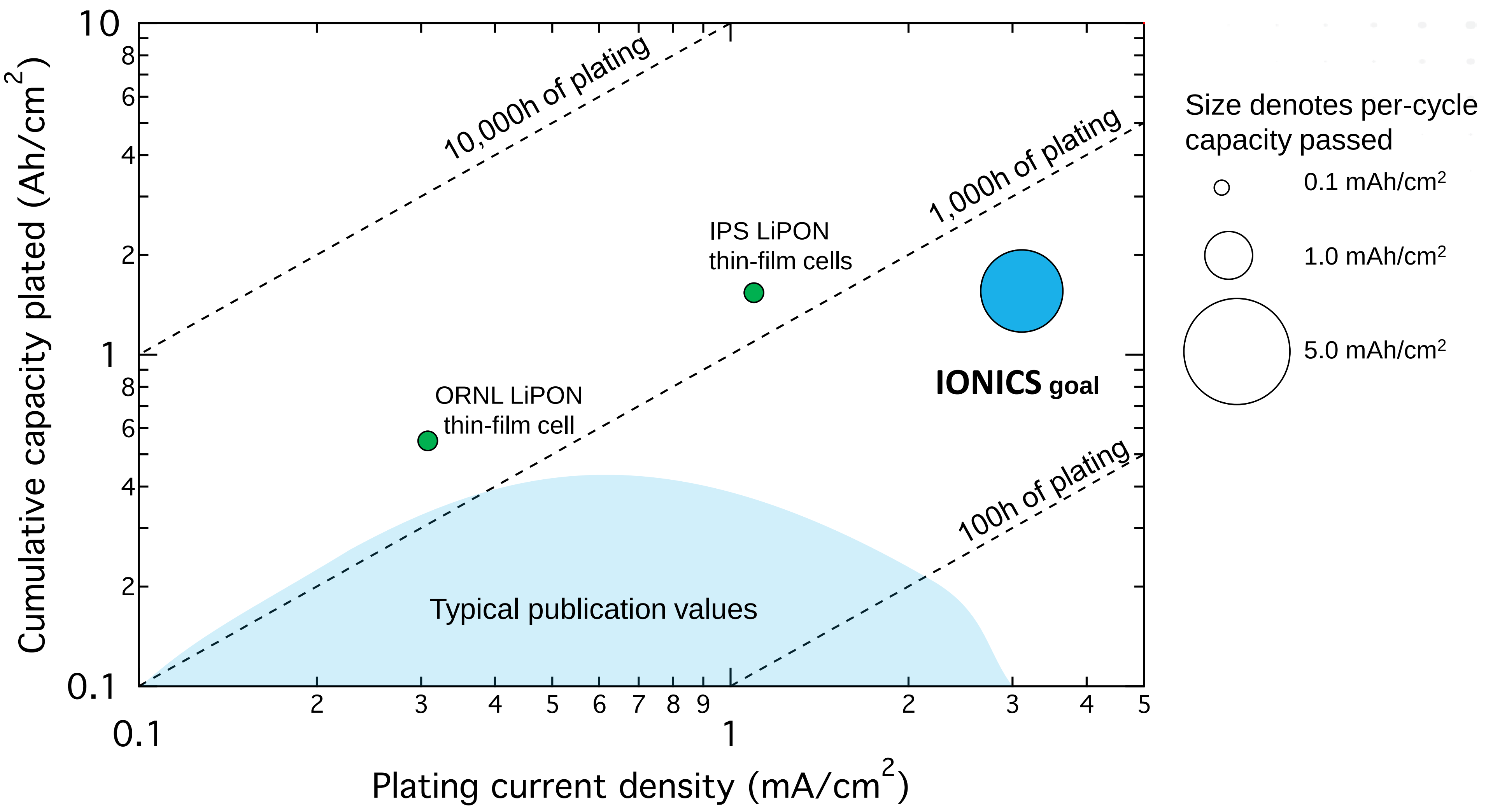
Li metal cycling state of the art



*Inferred loading of 2 mAh/cm^2
Contributors: Nancy Dudney, Kang Xu, and others.

CHANGING WHAT'S POSSIBLE

Li metal cycling: ***solid/solid interface and 25°C***



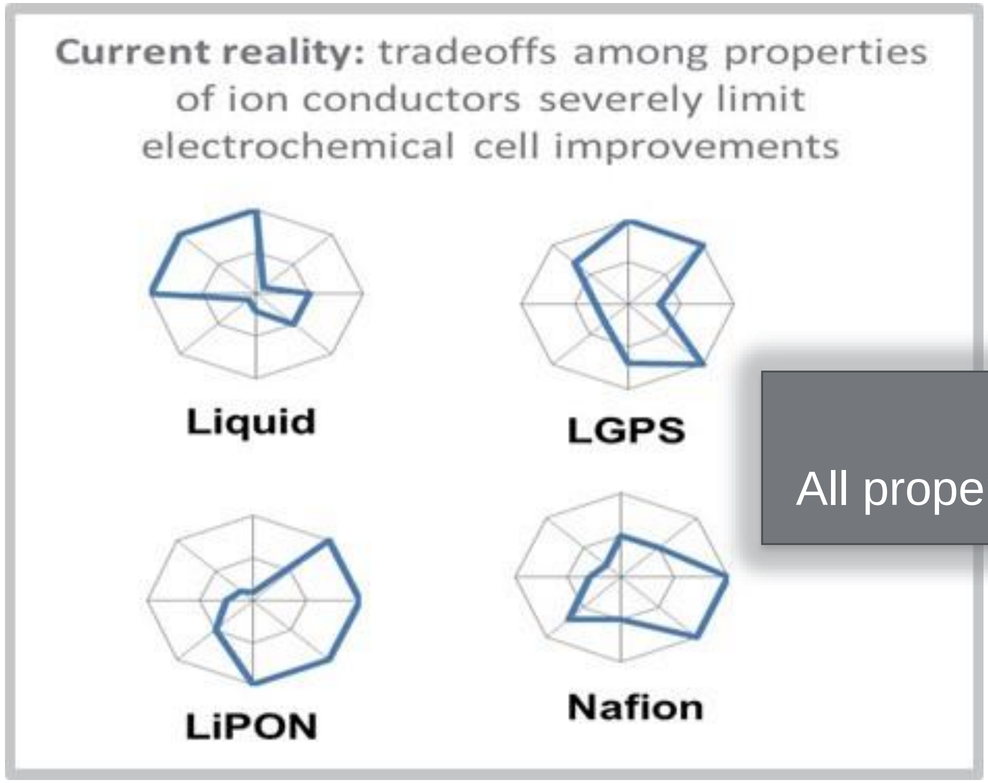
*Inferred loading of 2 mAh/cm^2
Contributors: Nancy Dudney, Kang Xu, and others.

Many Challenges

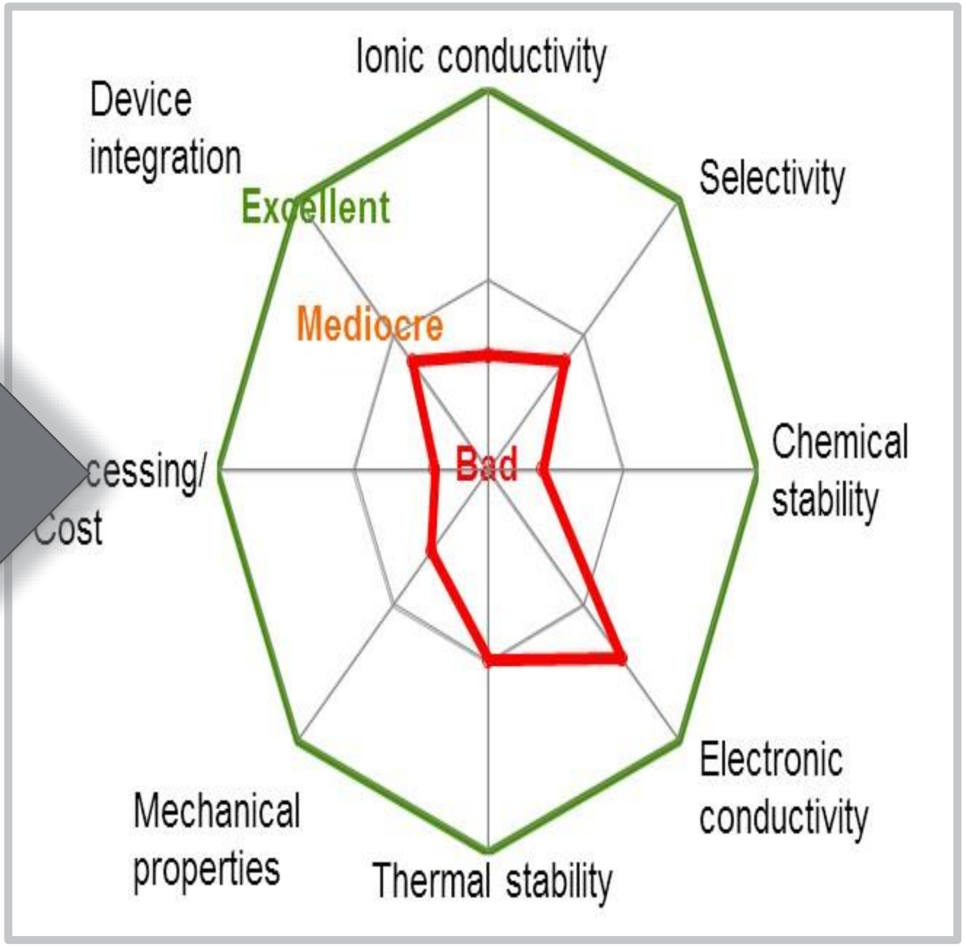
- Materials often brittle
- Cells usually ~1 cm^2 – how to scale these if brittle
- Thick separators – for ease of handling – but high resistance
- Often use coatings (*e.g.*, $LiNbO_3$) on cathode particles
- Many materials not air stable
- Pressure needed to maintain good interfaces

The Promise of Solid State/ Li Metal:

Commercial value requires a suite of properties but academics were focusing on only one or two



IOINICS:
All properties pursued in concert



IONICS

16 Project Teams • 3 Technology Areas

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

POLY PLUS
Iowa State University
Oak Ridge National Laboratory
SILA Nanotechnologies
PennState
University of Colorado Boulder
24M
ionic MATERIALS
UC San Diego

2: Separators for flow batteries

Colorado School of Mines
United Technologies Research Center
Washington University in St. Louis
University of Colorado Boulder

3: Alkaline conductors

University of Delaware
Rensselaer
3M

arpa·e
CHANGING WHAT'S POSSIBLE

THANK YOU


Mark Johnson


Dave Danielson


John Lemmon


Chris Atkinson


Paul Albertus


Sue Babinec


PAT McGRATH


Dane Boysen


Howard Branz


ILAN GUR


Ping Liu


Grigorii Soloveichic


Sven Mumme