CHANGING WHAT'S POSSIBLE

Energy Storage Technology for Transportation

- Li-Ion
- Next Generation Chemistry
- BMS

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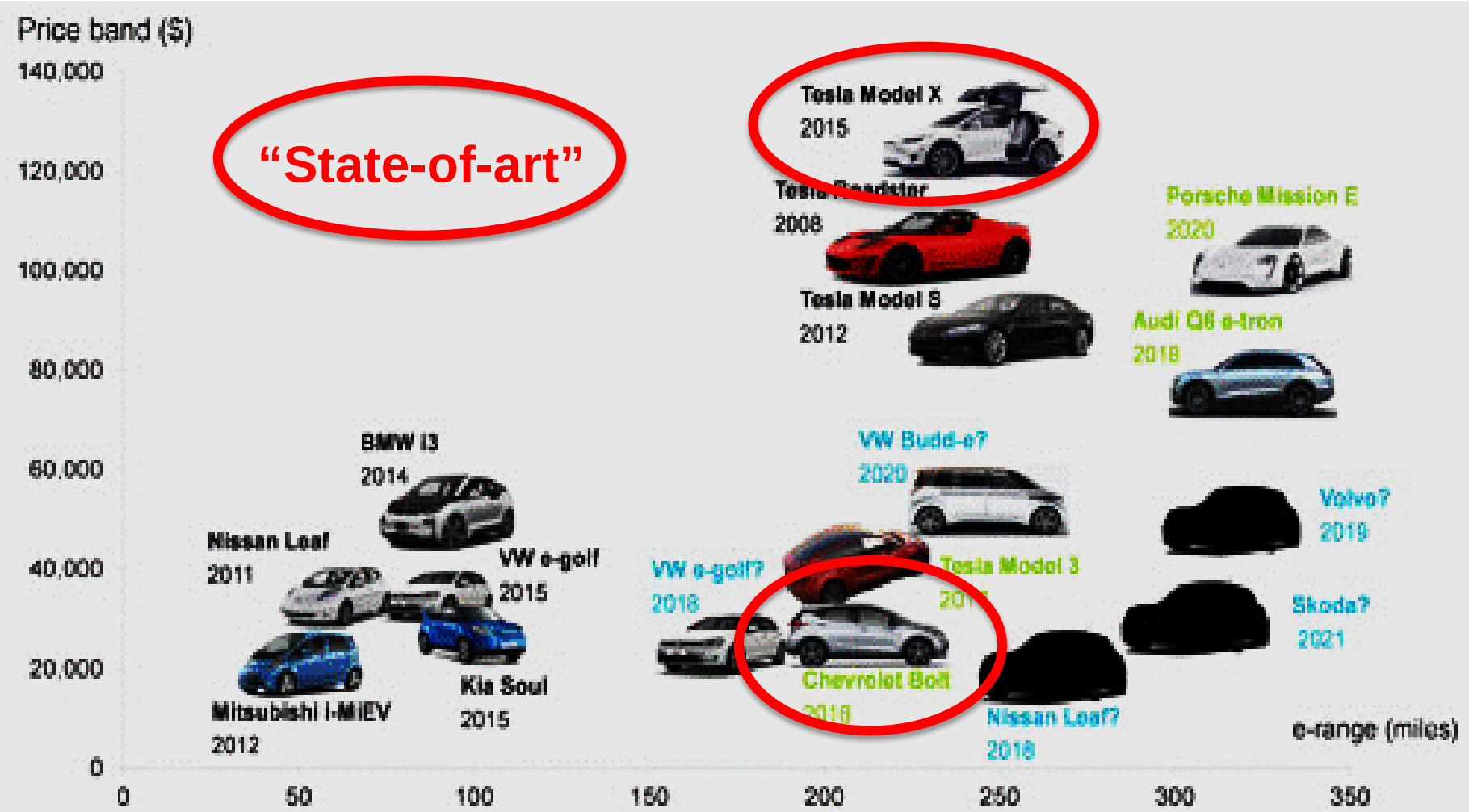
CARB - September 27, 2016

EV model, price, range today: *where is this heading?*



Status

METRIC	DOE GOAL	TESLA (Panasonic "18650)	CHEVY BOLT (LGChem 40 Ah cells)
RANGE (miles)	**200-300**	**200++**	**200**
CELL ENERGY DENSITY (kWh/Kg)	**350**	**280**	**-**
PACK ENERGY DENSITY (kWh/Kg)	**250**	**156**	**310[1]**
PACK COST ($/kWh)	**125**	**235 →190**	**$145**

1 = **(500 Wh/L)**

Numbers…….Numbers……..Numbers

Estimating where all of this is going & how long it might take

In a sea of metrics & rapidly changing statistics

Technology: *who/what will win the race?*

High level comments

- *Amazing global commitment to squeezing every kWh/kg and $/kWh possible out of "Li-Ion:*
  - Battery art (300 cycles) → Battery science (5,000 cycles)
  - Higher voltage cathodes & electrolytes; higher capacity anodes (Si)

- *Demand assuredness spurs capital investment = cost reductions accelerating*
  - High capacity manufacturing = lower cost
  - Plateau will be very close to DOE target (best case may hit?)

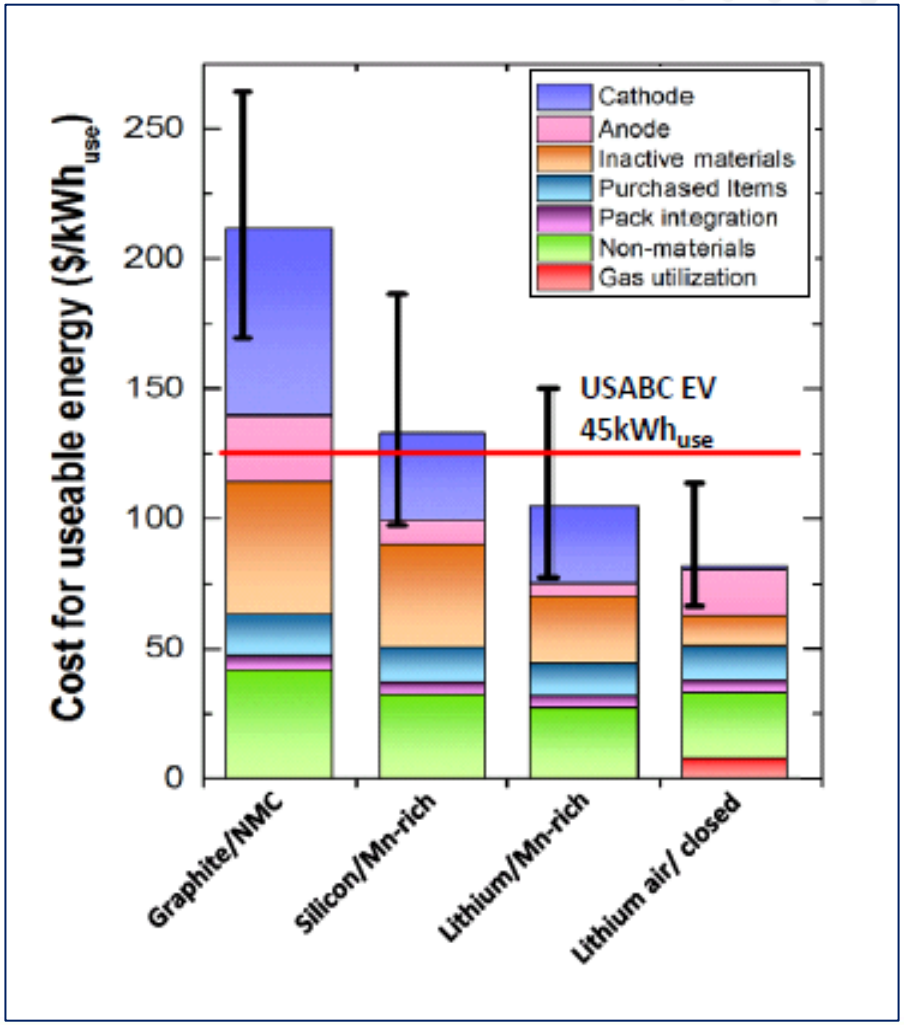
- *Beyond Li-Ion will definitely push to full suite of targeted attributes, but this is ~ten years away (ARPA-E transformational push)*
  - LiS – high capacity super low cost chemistry
  - Solid state – high voltage cells; safer → simpler cells → lower cost *ultimately*
  - Li-Air – fundamental issues now understood, very very long term

DOE - *Extensive modeling to estimate outcomes*

TARGETS:

WHAT	TARGET
Anode	600+ mAh/g
Cathode	300+ mAh/g
Electrolyte	5V stability
Cell (40 AH)	350 Wh/kg & 750 Wh/L
Pack	250 Wh/kg & 400 Wh/L

- BEST CASE SCENARIOS:
  - All chemistry problems solved & theoretical performance achieved
  - Favorable engineering achieved
  - High volume manufacturing cost reductions



Chinese EV Market Roadmap

	Present	2017 >200mile/300km	2020 >300mile/500km
Cathode	NCA, NCM, LMO, LFP(China)	NCA, Ni-rich NCM(622)	NCA, Ni-rich NCM(811)
Anode	Graphite	Graphite	Graphite + Si(several type)
Electrolyte	▪High preformance: Long life, High power, Low temp. & high temp. Stability ▪High Voltage (4.35V or higher) ▪Safety: Inflammable additives, solid type??		
Separator	▪Coating separator or coating electrode(depend on OEM) ▪ New materials for coatless separator		

Try to increase the cell capacity, but not a big change in chemistry over our expectation.
Will need Li excess type or another materials after 2020 for more capacity.

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Technology Components

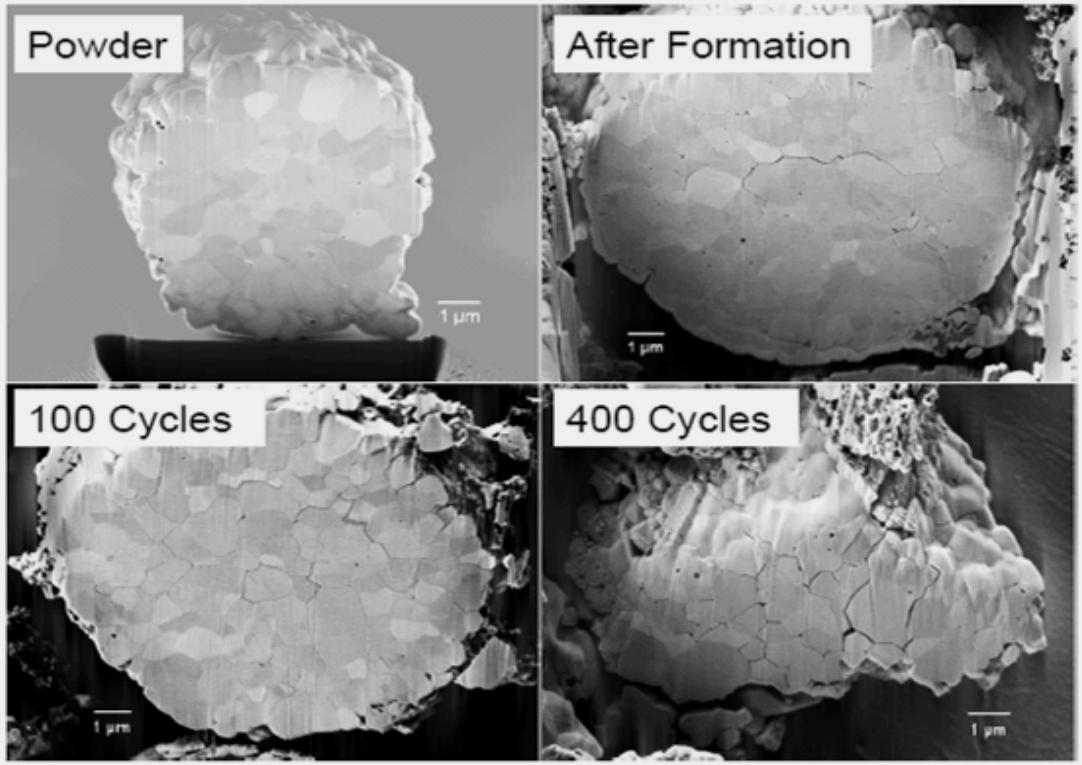
- **Higher ED chemistries:** *more Ni & Si*
  - Ultimately push the cost down
  - Increase EV range -
    - Reduces the cost-of-ownership ultimately
    - Increases demand
- **High voltage cathodes:** *Higher Ni content in NCA and NMC*
  - Fundamental structural issue: expand/contract leads to particle fracture
  - Stability issues beyond 4.2V: carbonate based electrolyte stability limit issue
    - Stabilize the electrolytes
    - Cathode surface modifications
- **Higher capacity anodes:** *Move towards Si*
  - Si anode = 4X graphite: volume expansion/stability issue significantly resolved
  - Implementing as: pure graphite → graphite + (x%) Si → pure Si
- **Electrolytes** – primarily increase voltage stability → solid state
- **Separators** – improved safety & ease of use by increased thermal stability
- **Long Cycle Life** – LTO anodes & excellent manufacturing= enable electric busses

Cathode: complex bulk & surface issues better understood

<u>Clump of Primary Particles separate during cycling</u>

1) Decrease electrical contact; increase impedance; lower capacity/power
2) Increased surface area for electrolyte oxidations

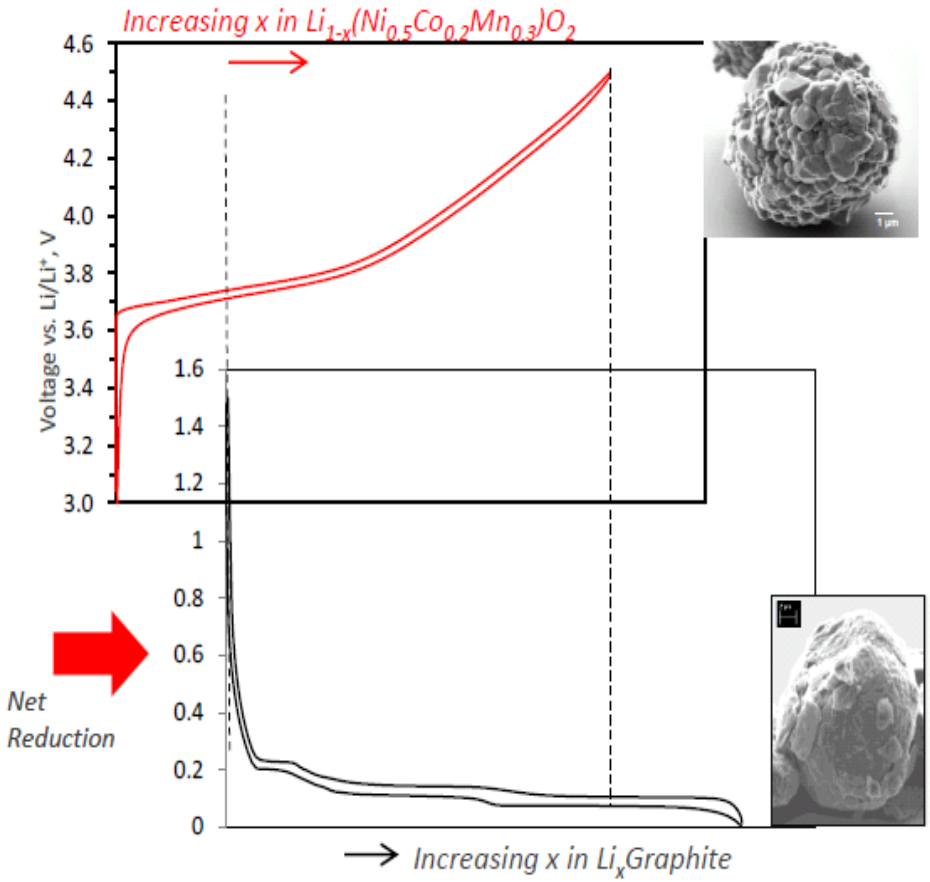
Focused ion beam – scanning electron microscopy (FIB-SEM)



Complexity Builds when Coupling Complex Behaviors to graphite anodes

Cell capacity loss & impedance increases at high voltages

- Data from harvested electrodes show
  - Li-trapping in negative SEI is main contributor to capacity fade
  - Positive electrode is main contributor to impedance rise
- Data from RE cells show electrode potential window shifts during cycling
  - Reduces utilization of electrode active material
  - Causes positive electrode to cycle at higher SOCs
  - Increases potential at negative electrode during cell discharge

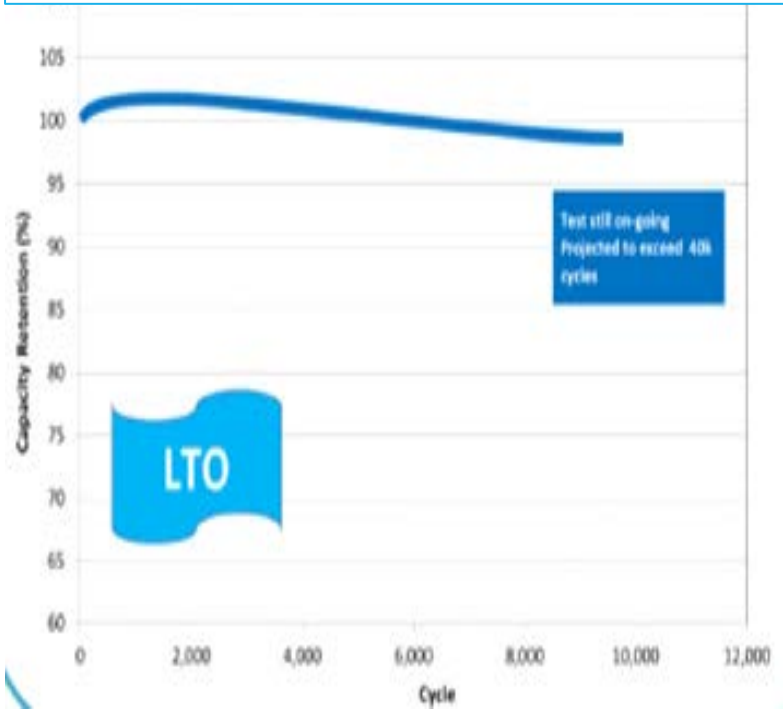


High Cycle Life / High Power: LTO

XALT Energy

- High Power Cells are important in start/stop (and HEV)
  - Typical of higher cycle life applications
    - HEV
    - Electric busses
- High Cycle life
  - Fundamentally long cycle life materials – LTO
  - *High precision manufacturing*

2c/2c; 100% DOD; Room Temp



~95% Retention: 10,000 Cycles

New technologies: Si, LiS, Solid State

Typical Timing:

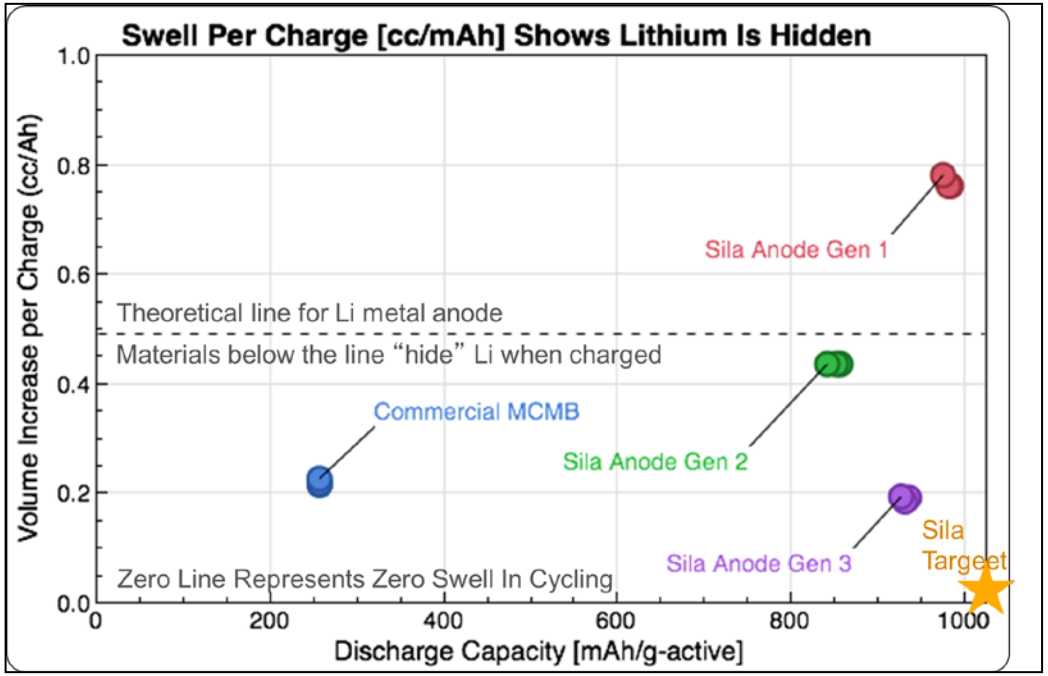
- ~6 years bench to first pilots
- 10+ years to starting full commercial implementation
- 20 years for fully adopted

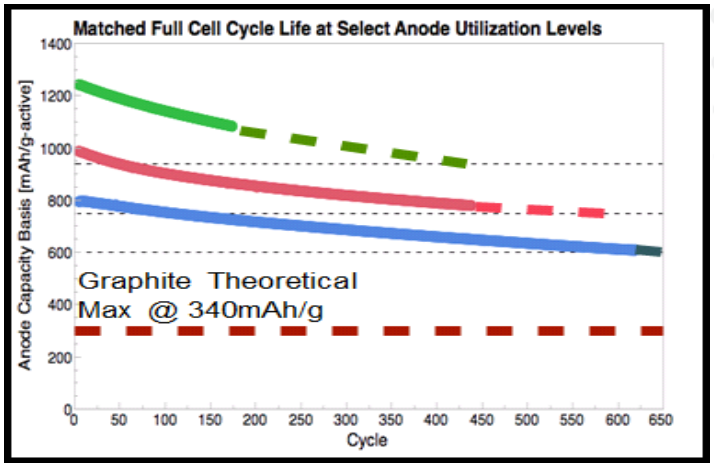
Technical Innovation is flourishing in the US

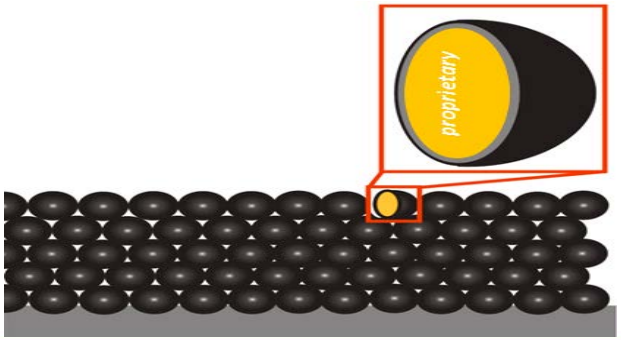
UNFORTUNATELY Ecosystem for innovators is highly inefficient

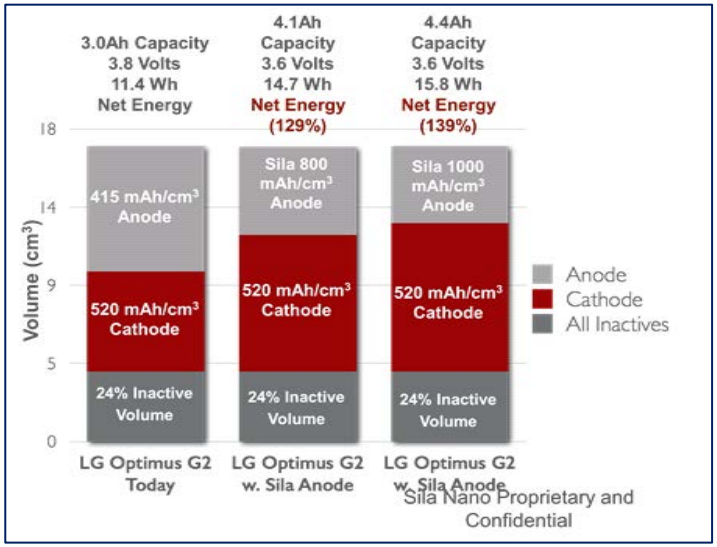
Sustained & robust support system can improve timing to market

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





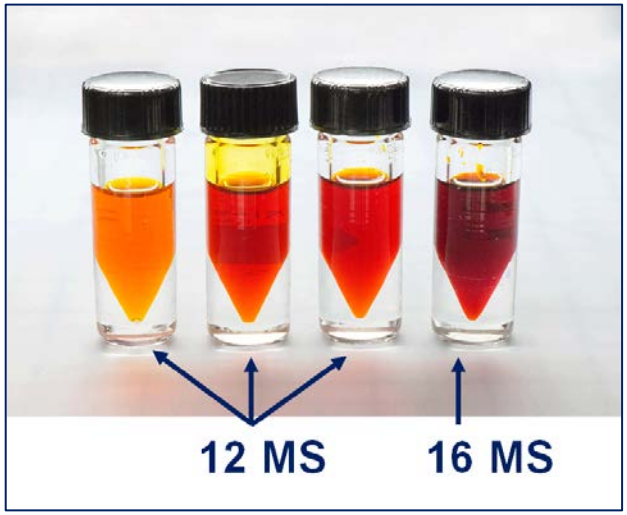




LiS – *Realizing the low cost/high capacity dream*

- Sulfur: dirt cheap with 4X high capacity of existing → unrealized potential
  - Low Polysulfide solubility reduces cell ED – RECENTLY RESOLVED
  - Need innovation for Li metal – In progress /ARPA-E IONICs program
- Polyplus and Highly soluble polysulfides- aqueous cells

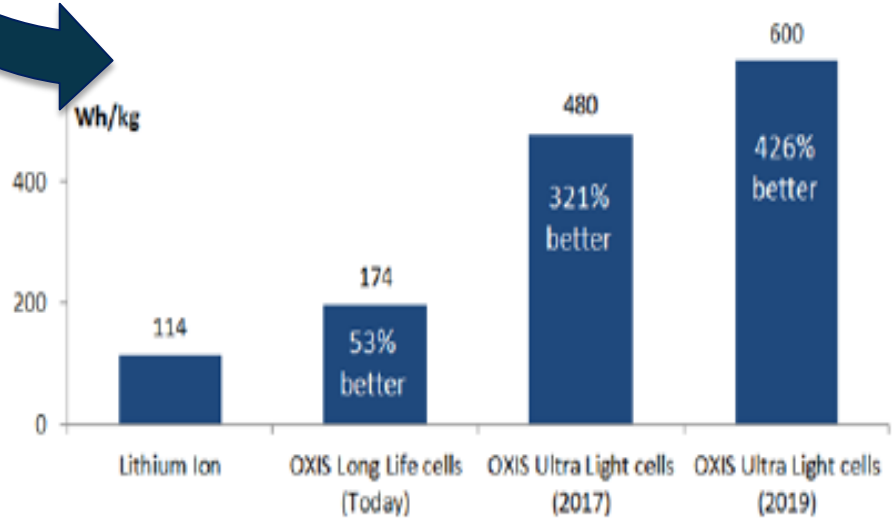
ORGANIC SOLVENT
Undissolved Li_2S



AQUEOUS SOLVENT
Highly solube Li_2S

Leaders in LiS

- Sion Power (US)
- PolyPlus (US) – v. significant breakthrough but pilot stage
- Argonne National Labs – huge effort, including flow cells
- Oxis Energy (Eng.) – preproduction with 310 Wh/kg



	Li-S	Li-Ion
Wh/Kg	2500	580
Wh/L	2660	1810

The Promise of Solid State:

problem – commercial implementation requires a suite of properties, but academics were focusing on the metric of their expertise.

LETTERS

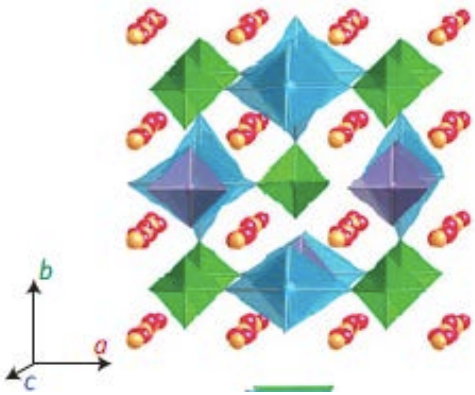
PUBLISHED ONLINE: 31 JULY 2011 | DOI: 10.1038/NMAT3066

nature materials

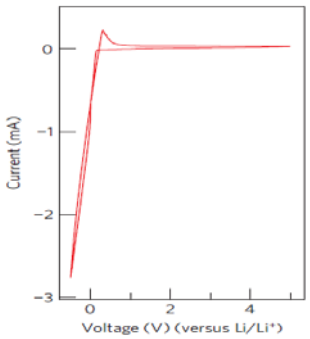
A lithium superionic conductor

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

Solid conductivity equal to liquid!



But…



"Chemical Stability"

Material is not stable against Li metal – forms resistive interfacial layer

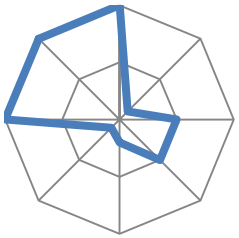
No mention of:

- Mechanical properties
- Electrical conductivity
- Thermal stability
- Processing
- Device integration

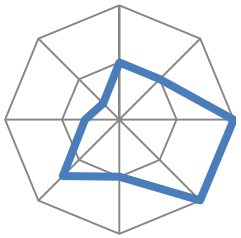
ARPA-E on Solid State - *having it all, and at the same time*

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

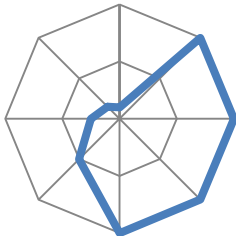
This program: *from the beginning* pursue a full set of attributes by overcoming technically difficult tradeoffs



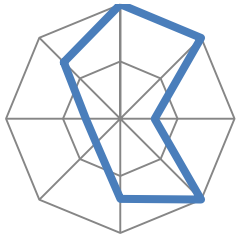
Liquid



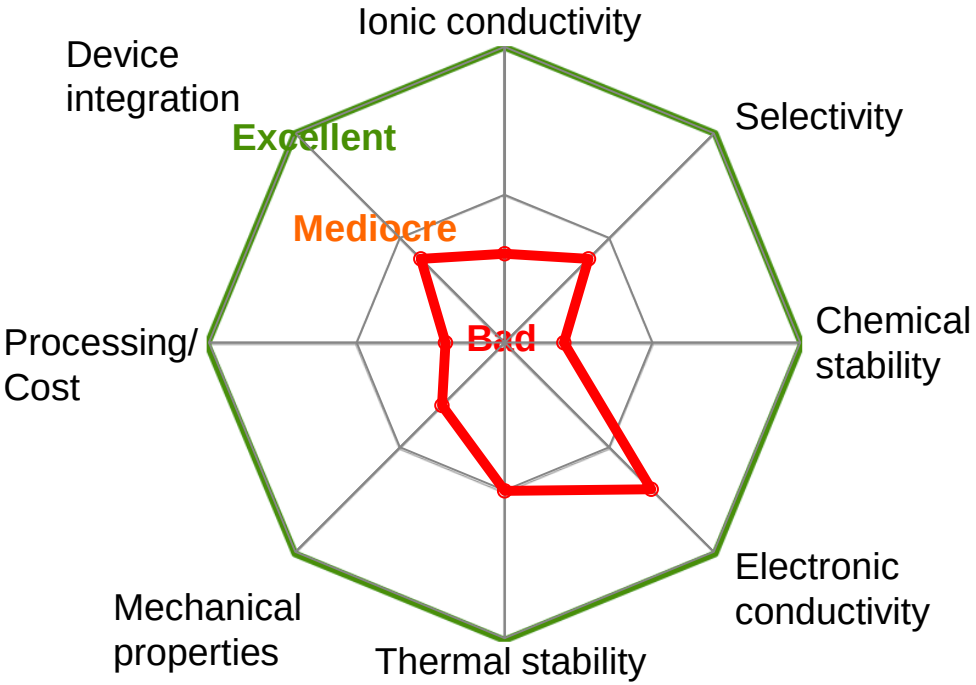
Nafion



LiPON



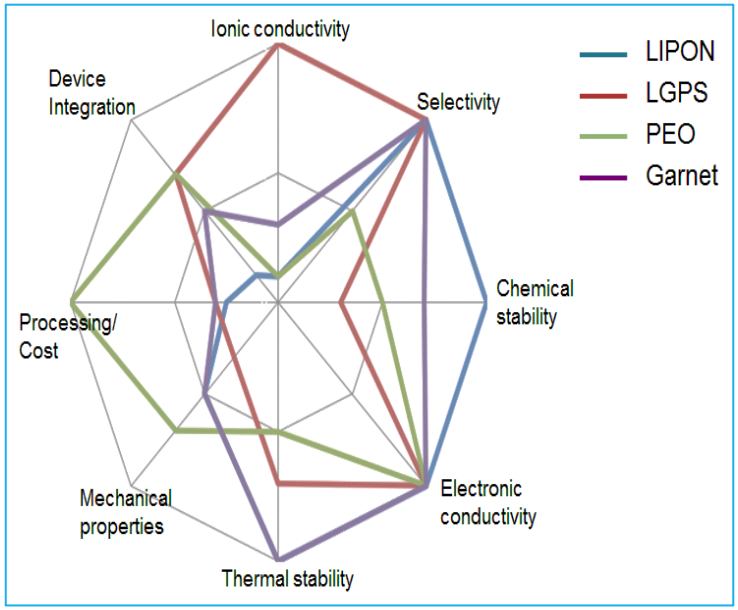
LGPS

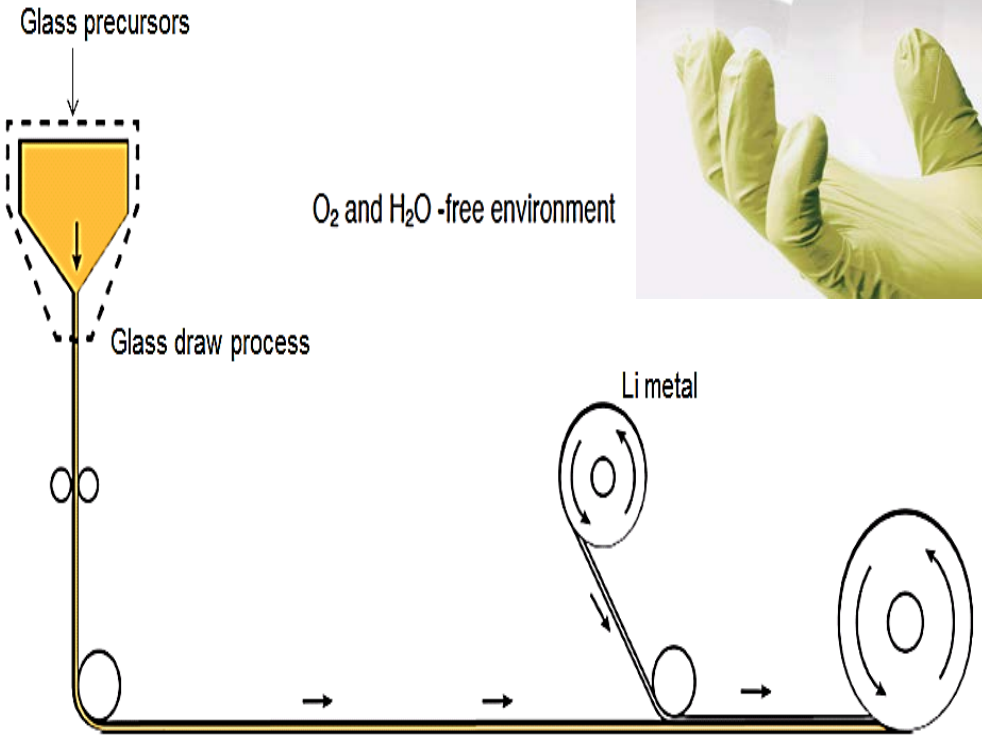


Example: continuous (not batch) production of Li Conducting Glass ribbons in research: combining materials science & processing

Polyplus/Schott Glass, Iowa State for example

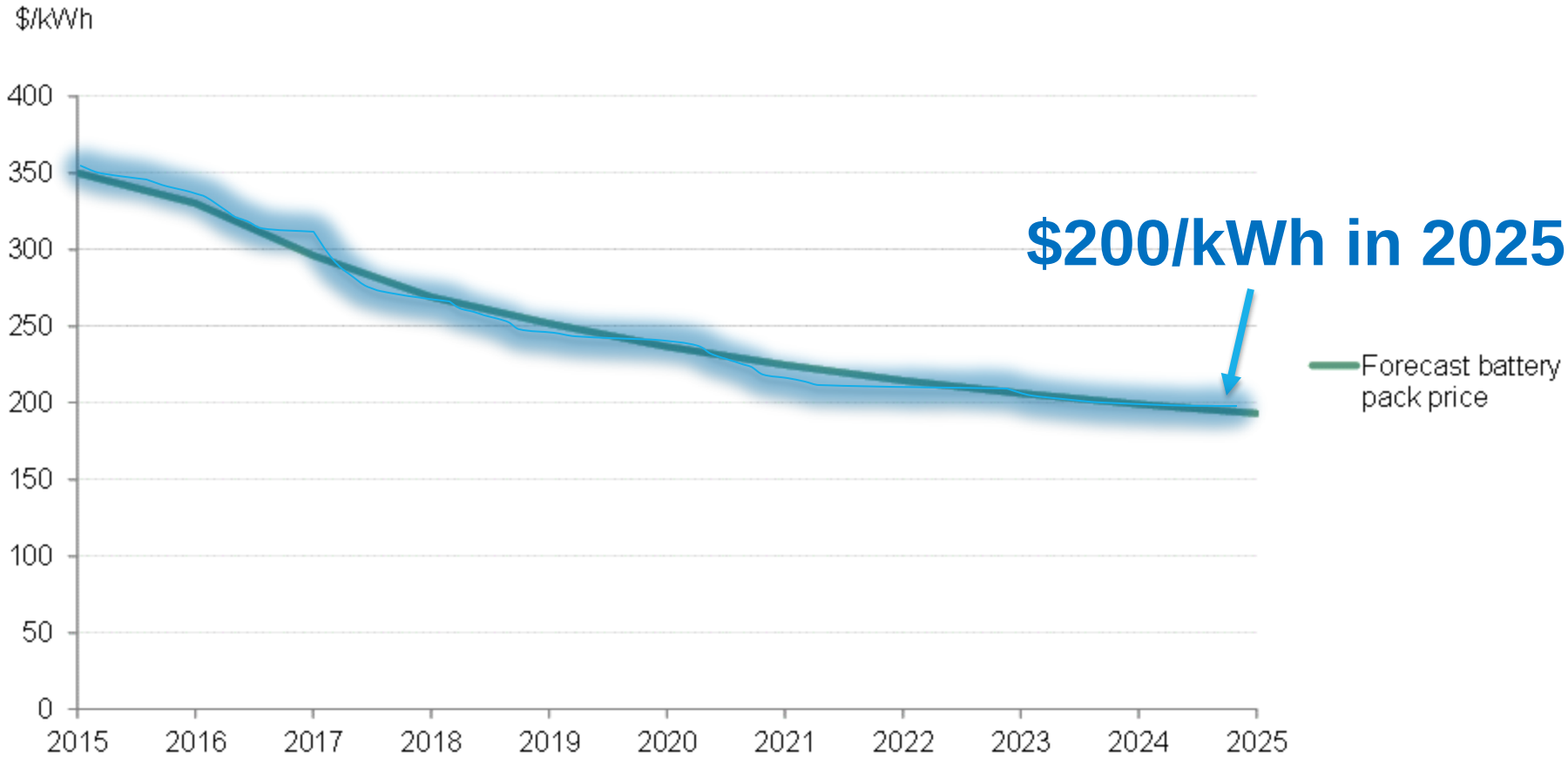
Top Candidate SS Li Conductors





COST PROJECTIONS

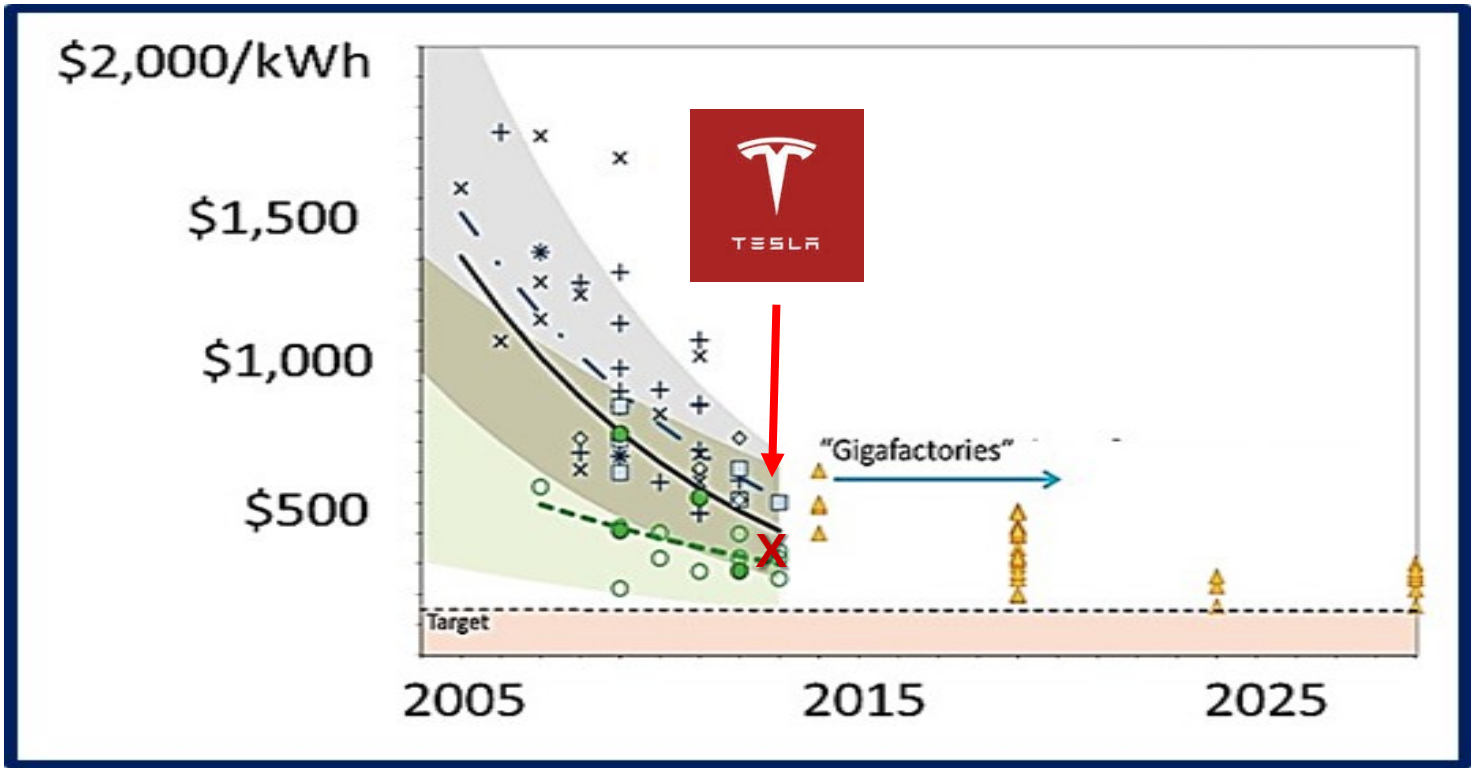
Cost Projections: where will Li Ion Plateau?



SOURCE; Bloomberg New Energy Finance

Capital Complexity: *A Commonly (mis)Used Reference*

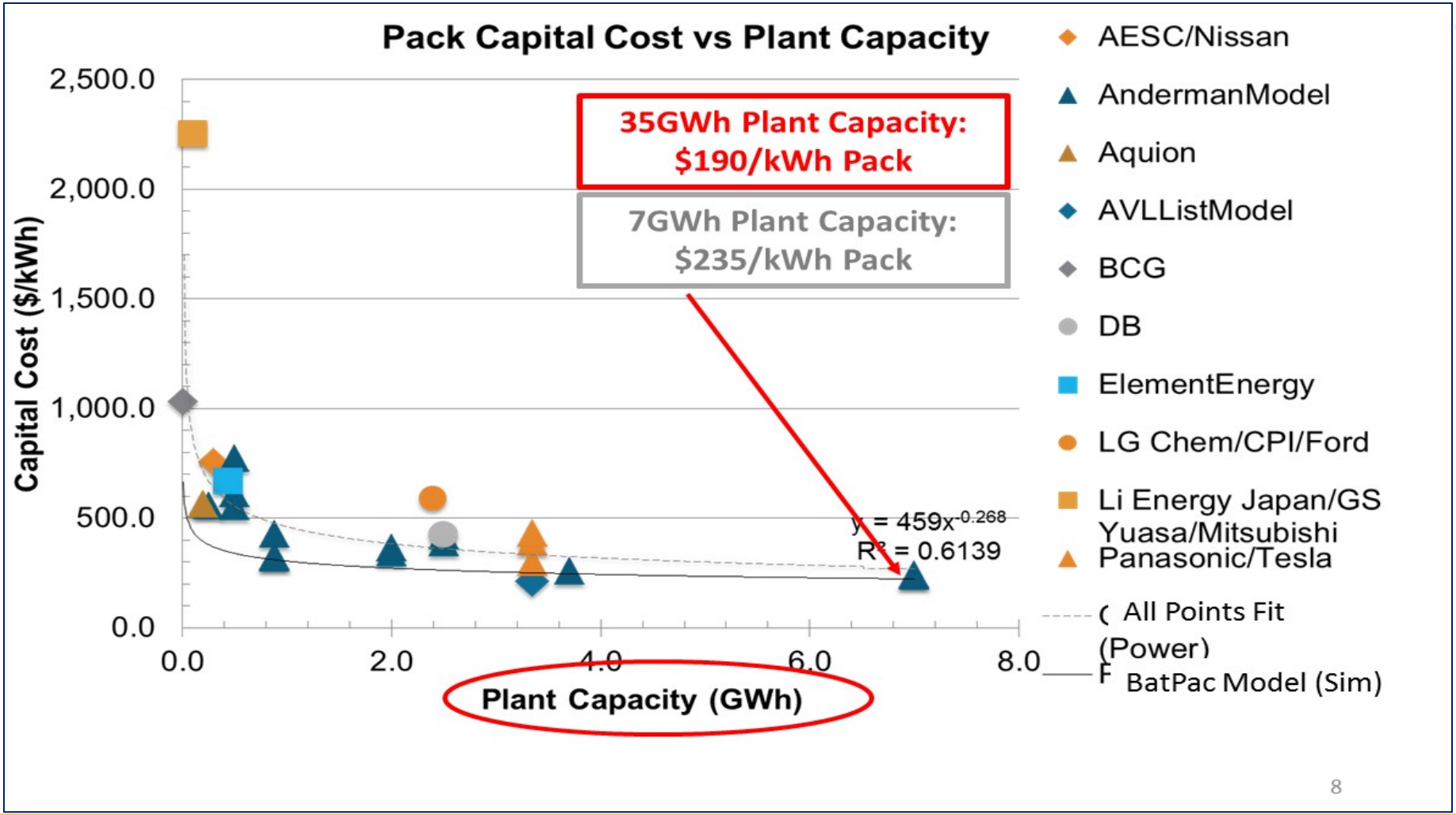
(2015: Nature Climate Change – Nykvist- on BEVs)



- **Scatter is real – magnitude reflects the level of maturity**
  - Technical
  - Manufacturing
- Much of this data is aggregated; many instances of multiple counting
- An alternative very useful plot vis cost vs. manufacturing volume at a single plant
  - In many ways time is a proxy for volume & maturity

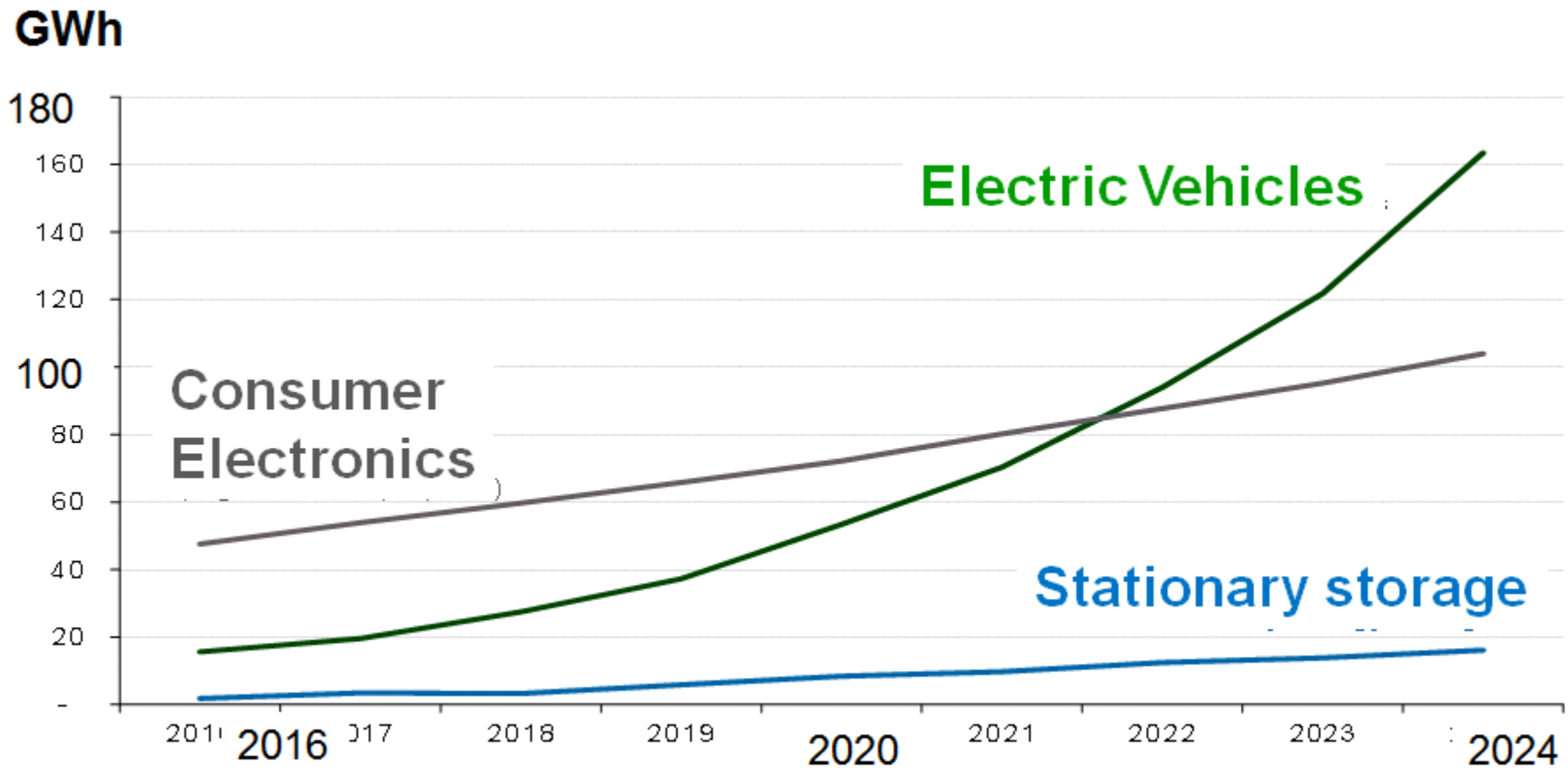
Li-Ion Cost/Volume Relationship

Gigafactory scale & mature manufacturing ->
volume price near/slightly above USABC target



MANUFACTURING CAPACITY:

Global Li-Ion demand by application 2016-2024 (GWh)



Source: Bloomberg New Energy Finance, Avicenne

BMS: Improving upon the basics at ARPA

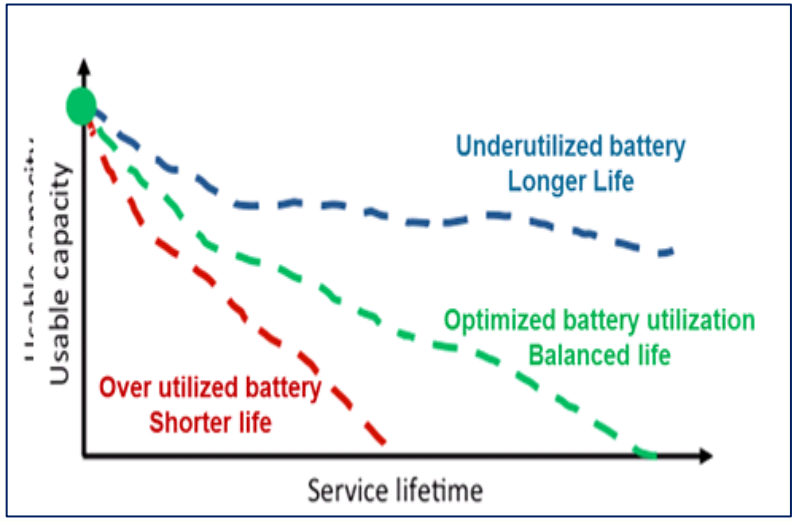
Type Pack	% Cell Cost	% Pack Cost
EV	69	31
PHEV	56	44

ARPA : breakthrough sensing, control, and architectures to:

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

Key challenges for battery systems:

- Cost
- Safety
- Usable capacity (e-miles)
- Performance (charge/discharge rate)



THANK YOU!

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