Vehicle Technologies Office

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

BAT343: Silicon and Intermetallic Anode Portfolio Strategy Overview

June 13, 2023

Brian Cunningham (DOE)

Overview

- Vehicle Technologies Office Energy Storage Overview
- Cost Scenarios for Different Chemistries
- VTO Roadmap
- Silicon Anode History & Status
- Silicon Anode Focus Areas
- Highlights
- Wrap-up

VTO Energy Storage R&D Overview and Strategy

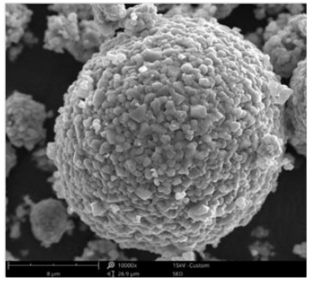
CHARTER: Develop battery technology that will enable large market penetration of electric drive vehicles

GOALS: **By 2025** bring pack level costs down to **$100/kWh** → **By 2030** bring pack costs down to **$75/kWh**

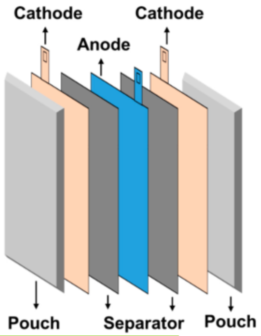
*Critical Materials-free, use of recycled materials, and capable of fast charge

Energy Storage R&D

- **Battery Materials Research (BMR) TRL 2-3**



- **Applied Battery Research (ABR) TRL 3 - 4**



- **Battery Development TRL 3 - 6**

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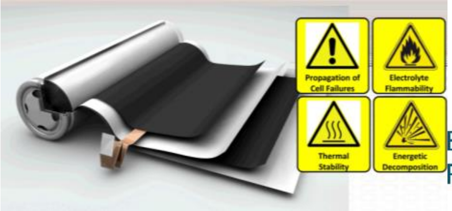
UNITED STATES ADVANCED BATTERY CONSORTIUM

- **Battery Testing, Design, & Analysis**



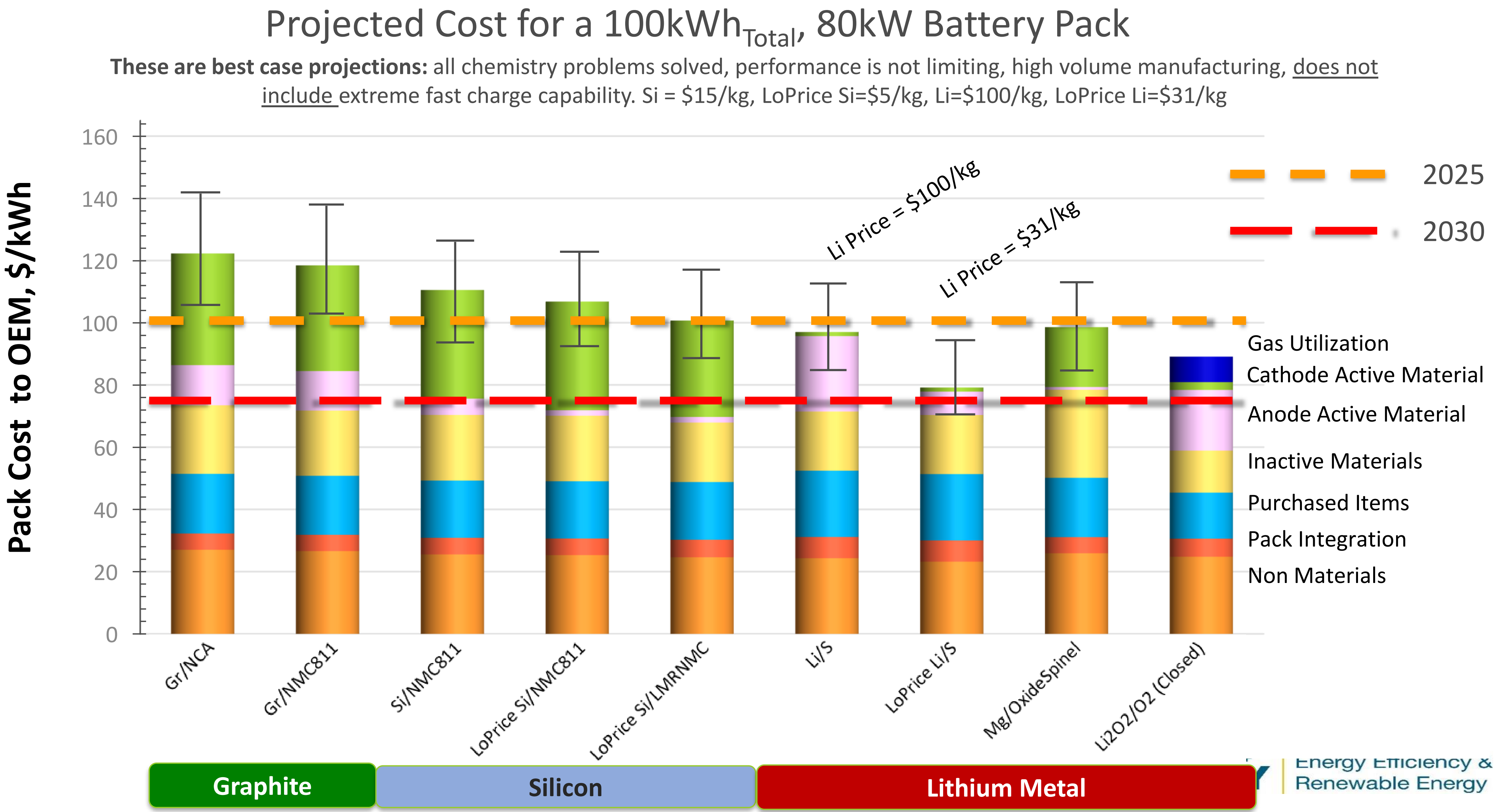
Other Topic Areas

- **Manufacturing**
- **Recycling**

ReCell
ADVANCED BATTERY RECYCLING

Energy Efficiency & Renewable Energy

What Chemistries Can Help Meet DOE's Cost Goal?



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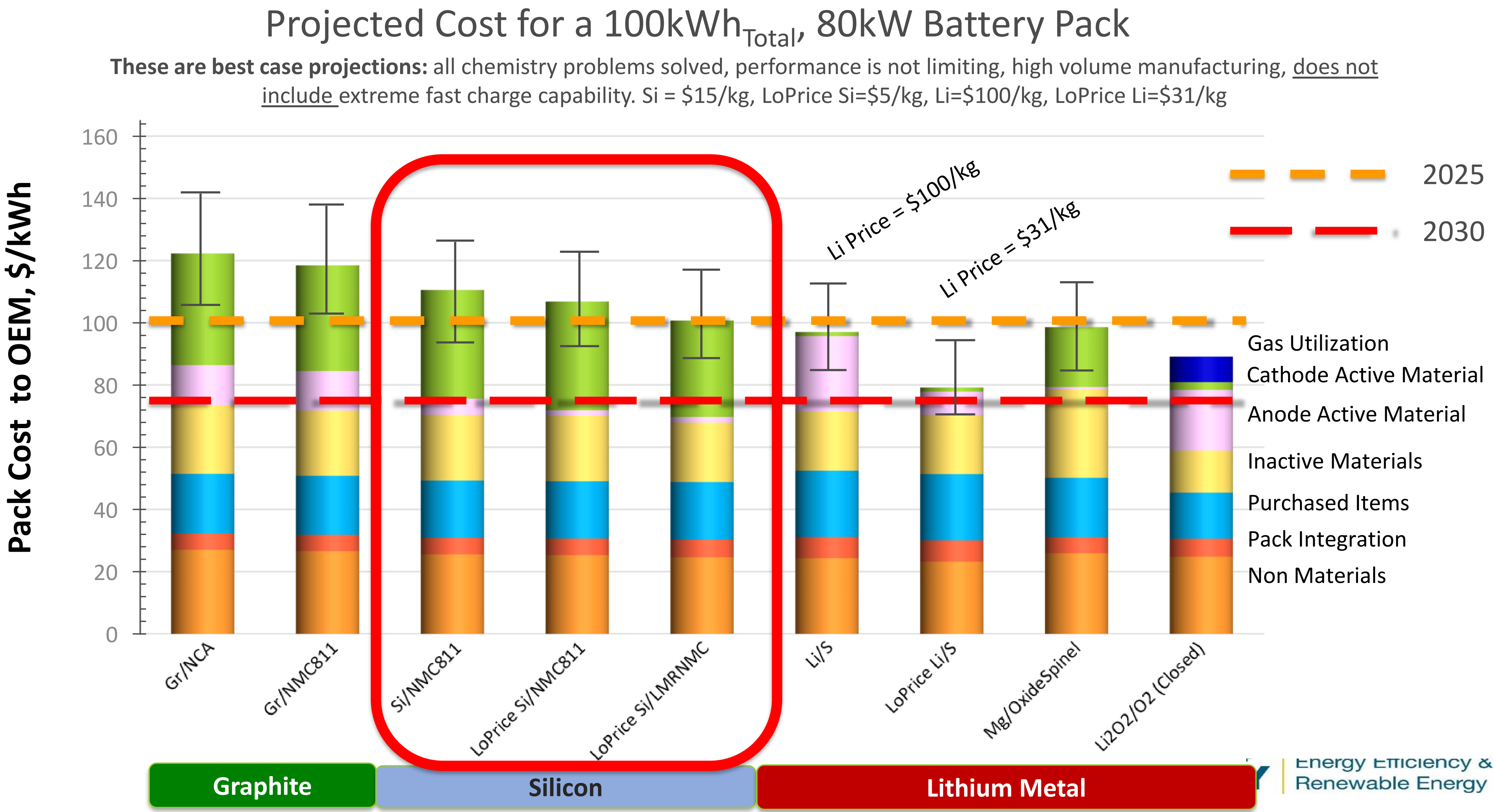
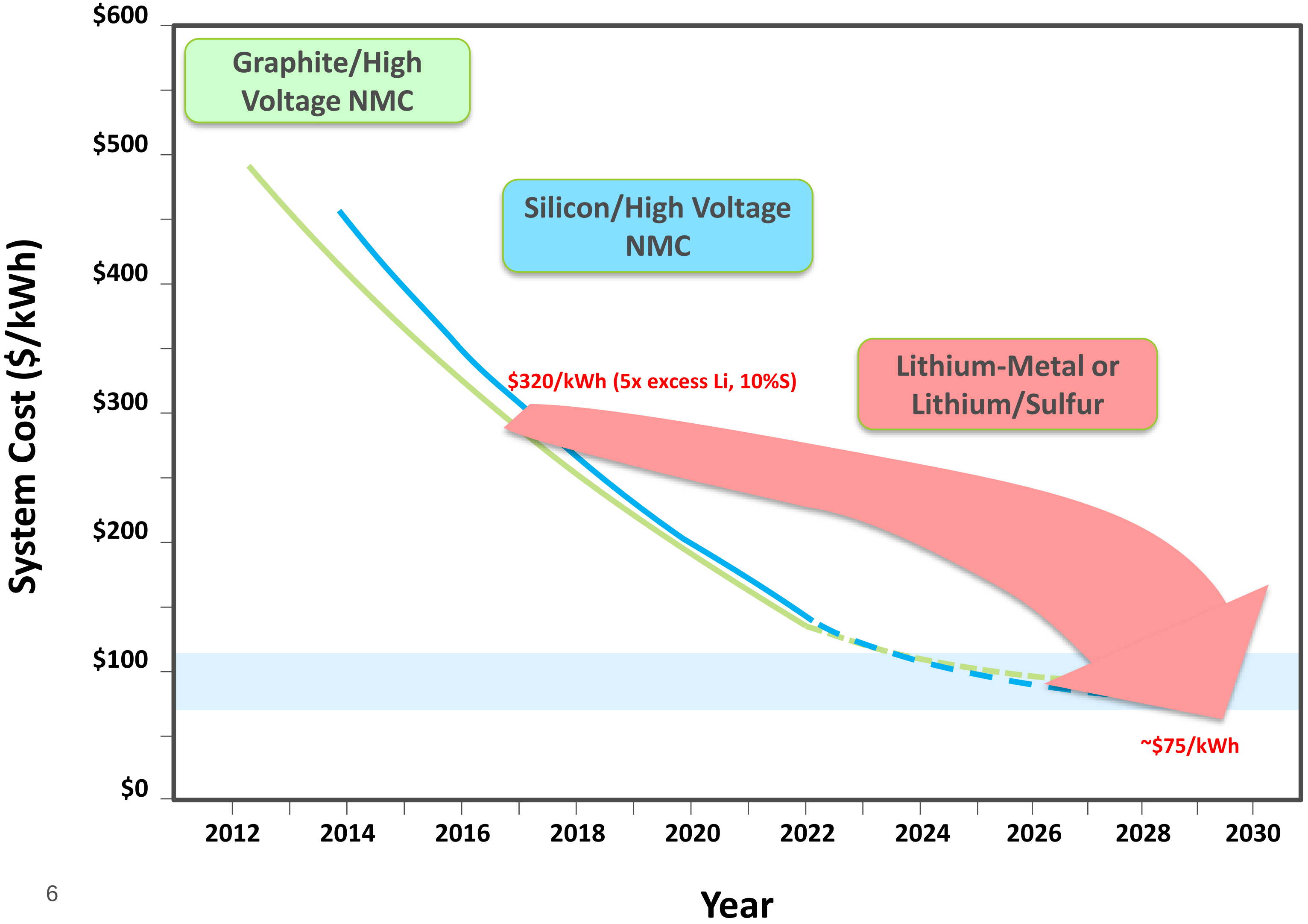


Energy Efficiency & Renewable Energy

DOE Vehicle Technologies Battery R&D Roadmap

GOAL: Research new battery chemistry and cell technologies in order to reduce the cost of electric vehicle battery packs to less than $75/kWh by 2030 (cost parity with ICE).



Graphite/High-Capacity Cathode

- Higher cathode capacity
- Low/no Cobalt
- Recycling & fast charge

Silicon/High-Capacity Cathode

- Higher anode capacity
- Cycle/calendar life
- Fast charge

Lithium-Metal & Li/Sulfur

- Solve cycle life/ catastrophic failure
- reduce excess lithium and electrolyte

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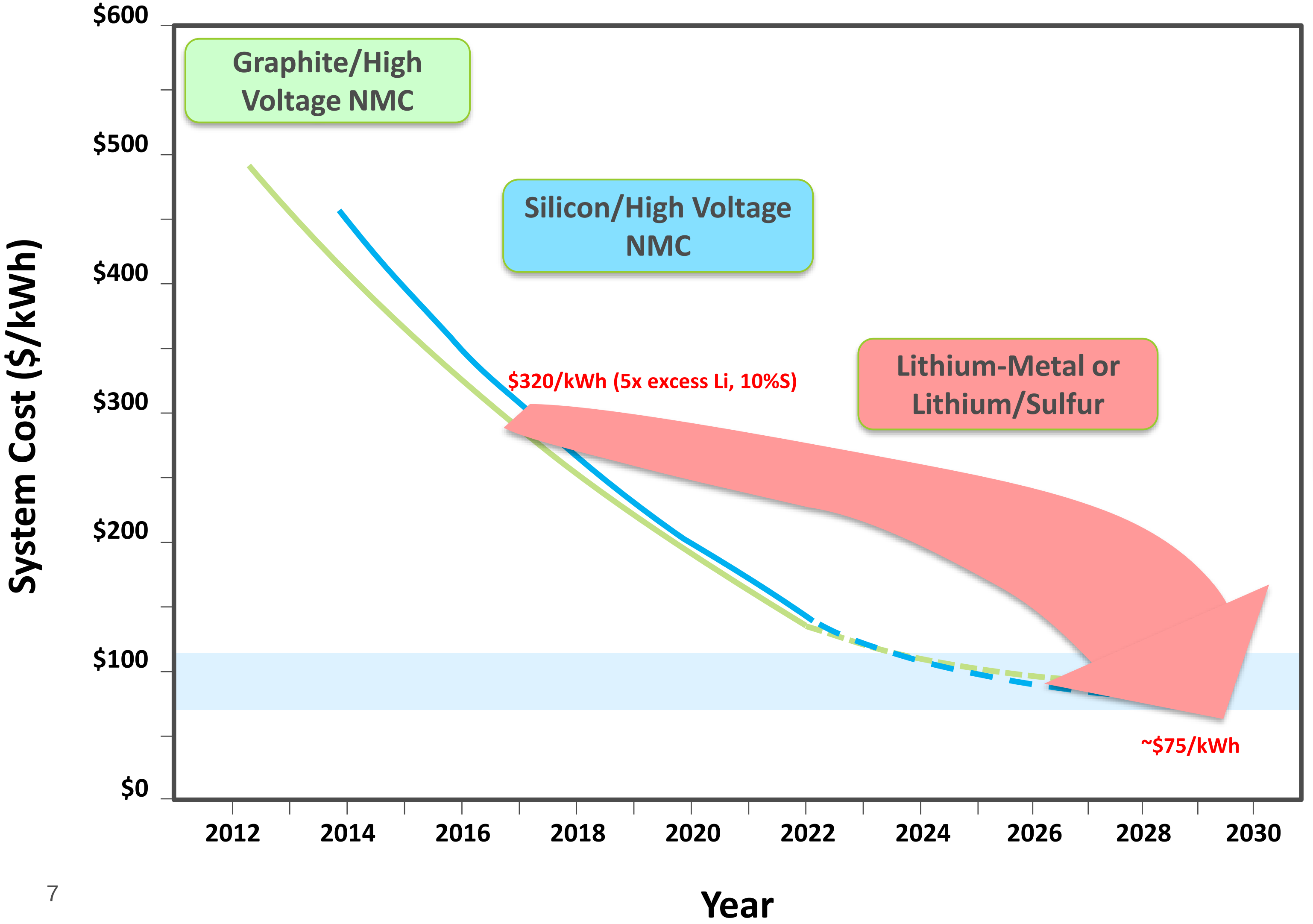

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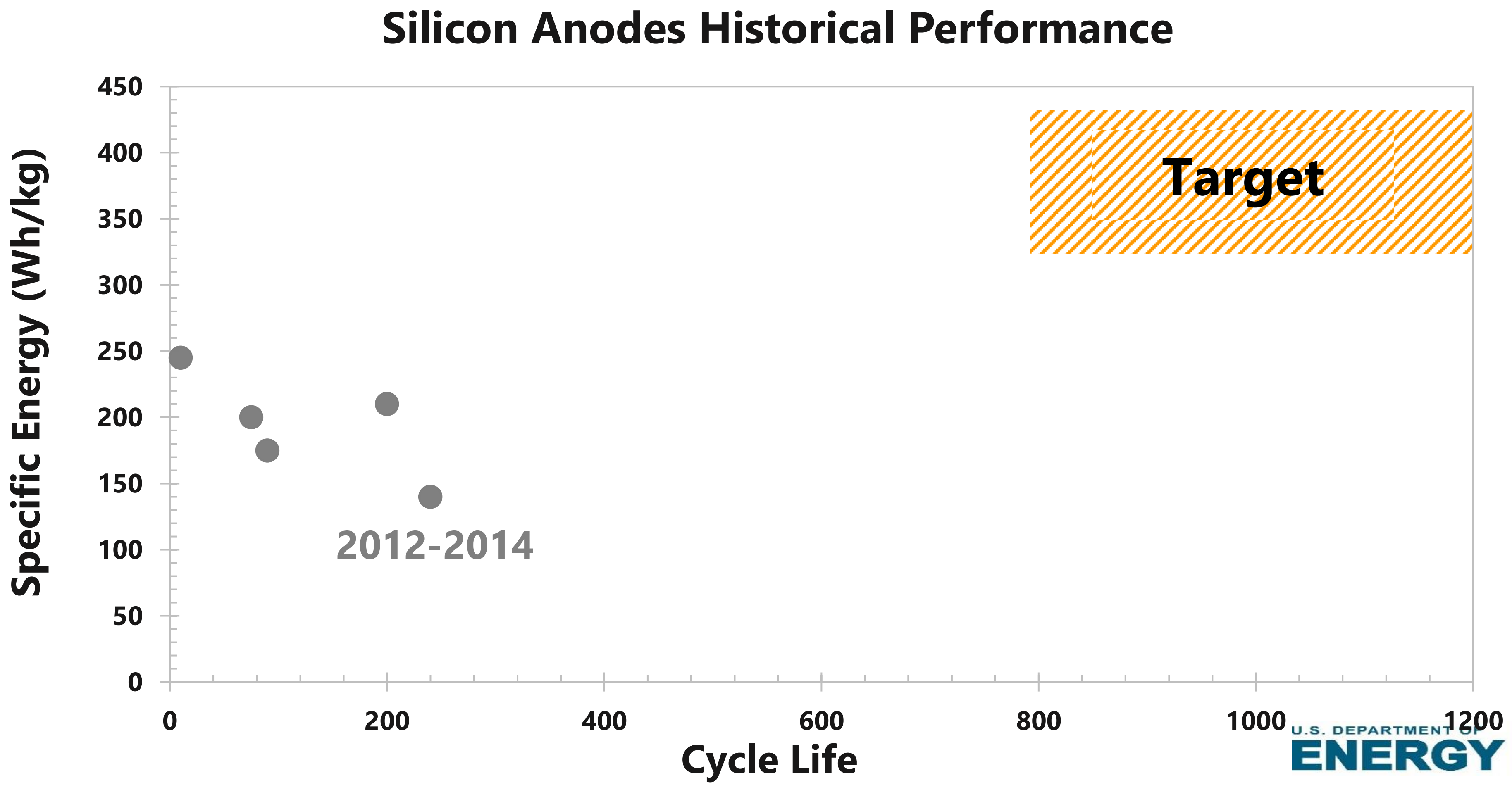
Silicon Anodes: Key Technical Results

Targets

- 1,000+ mAh/g & 350+ Wh/kg
- 10 years & 1000 cycles

Challenges

- Large first-cycle irreversible loss
- Low cycle and calendar life / High capacity fade



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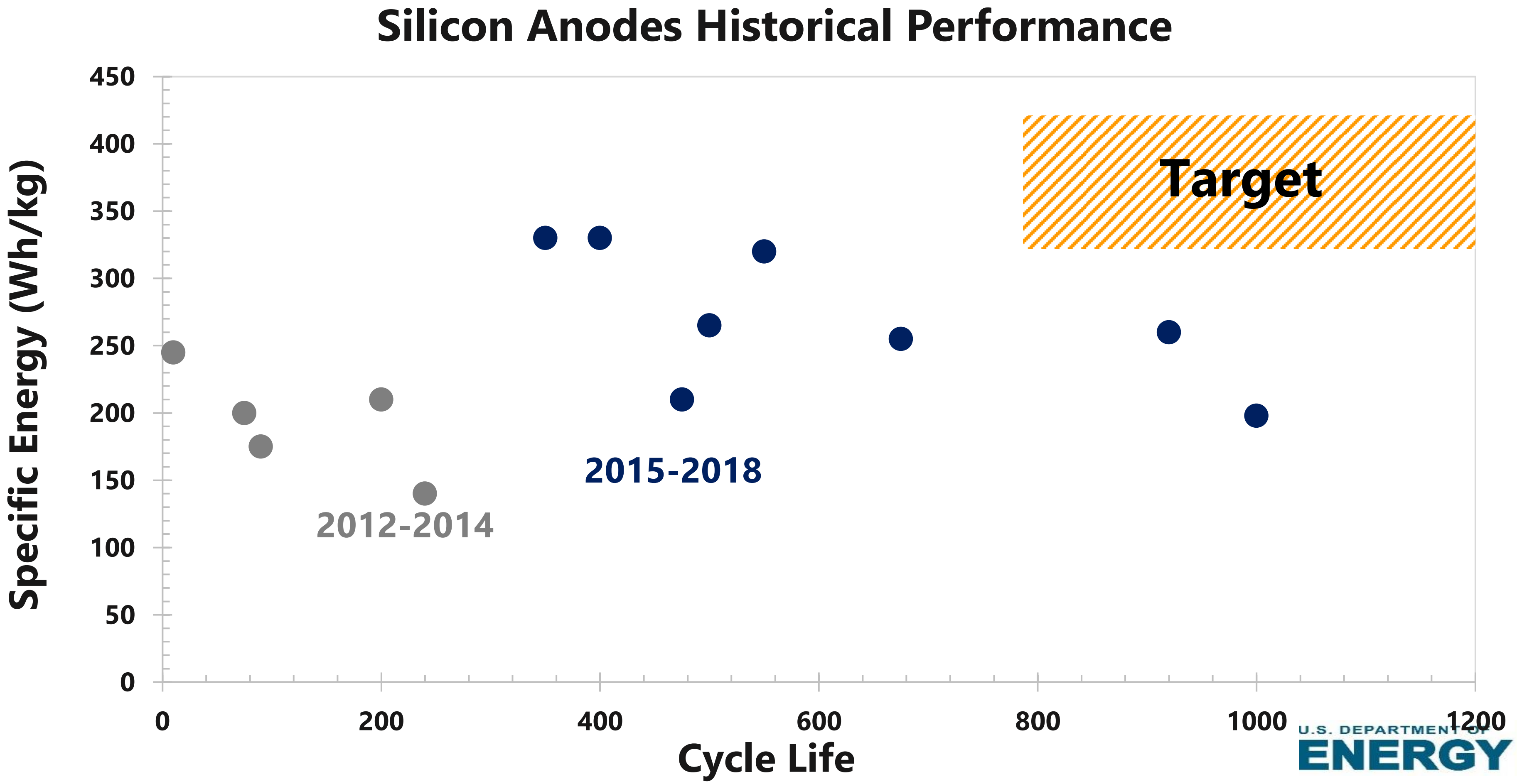

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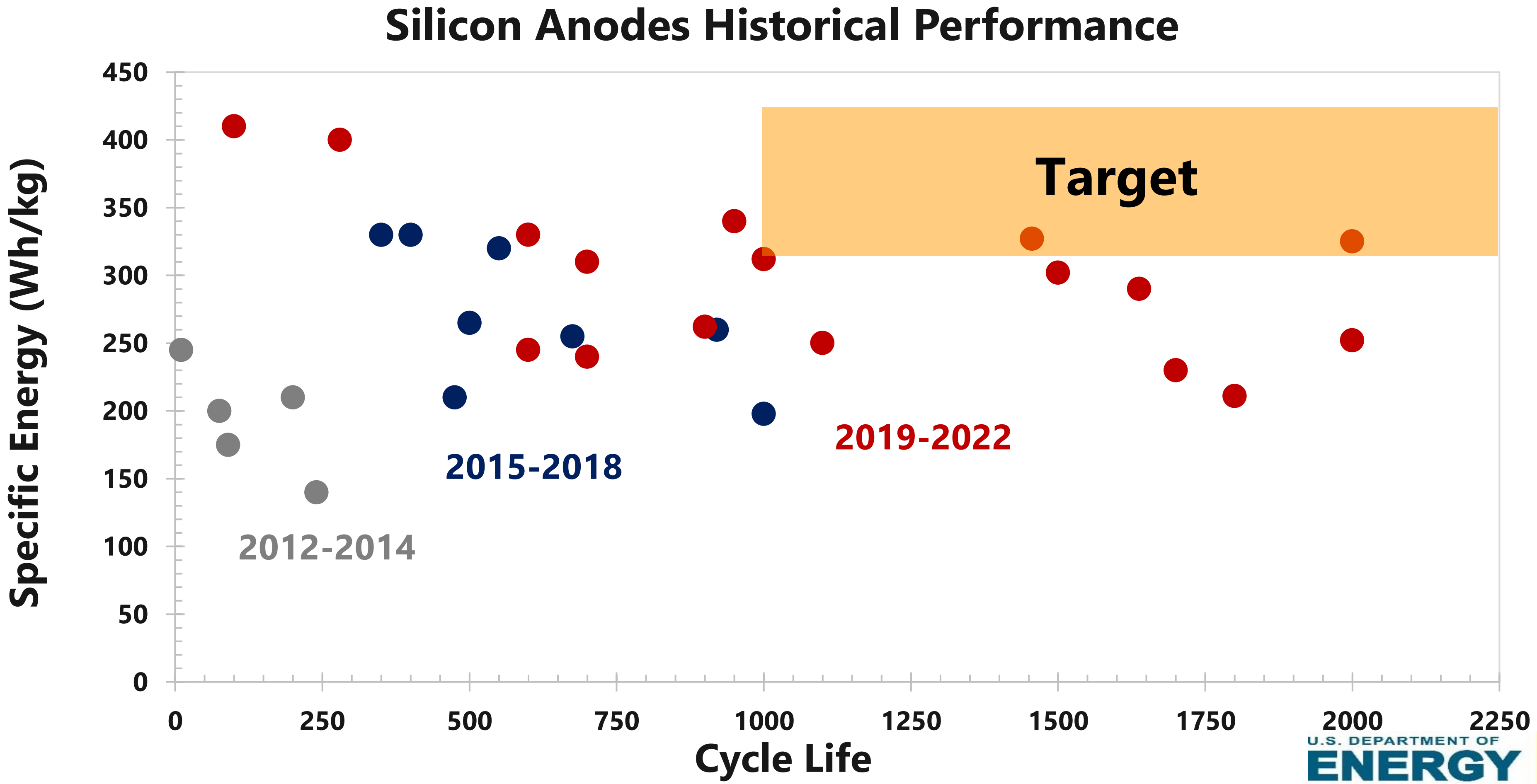

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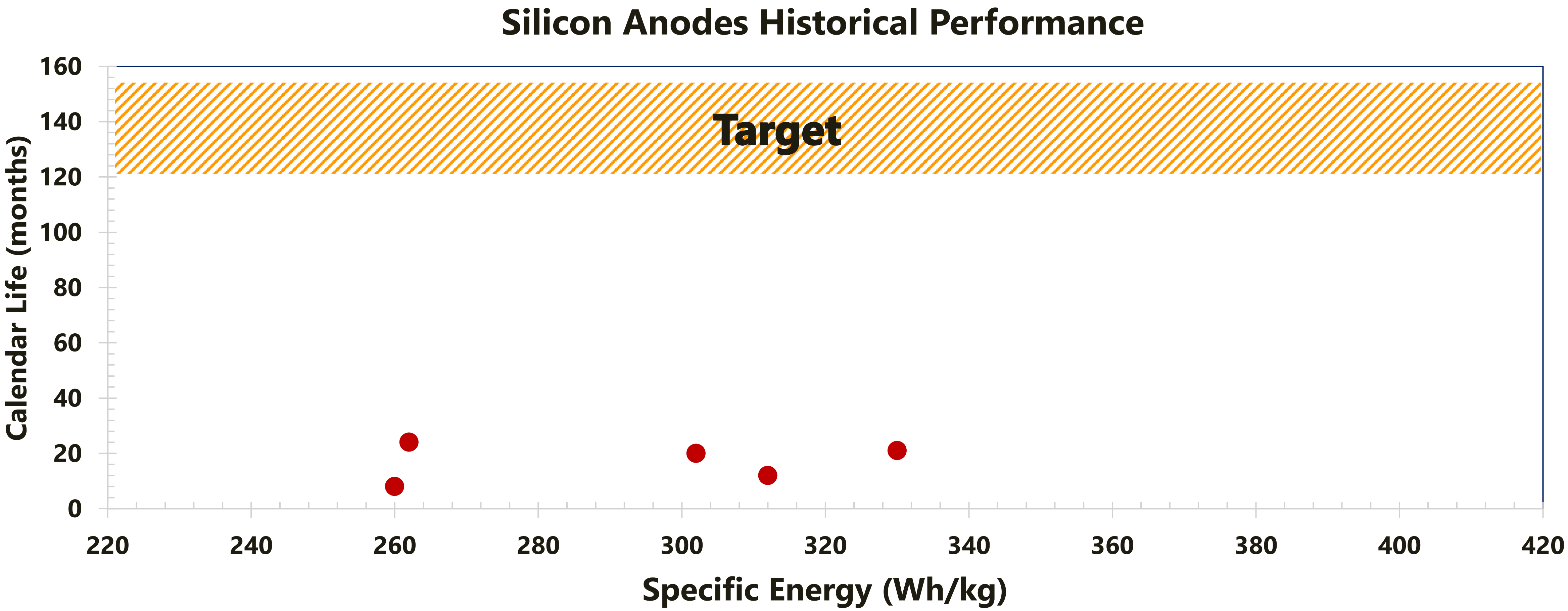

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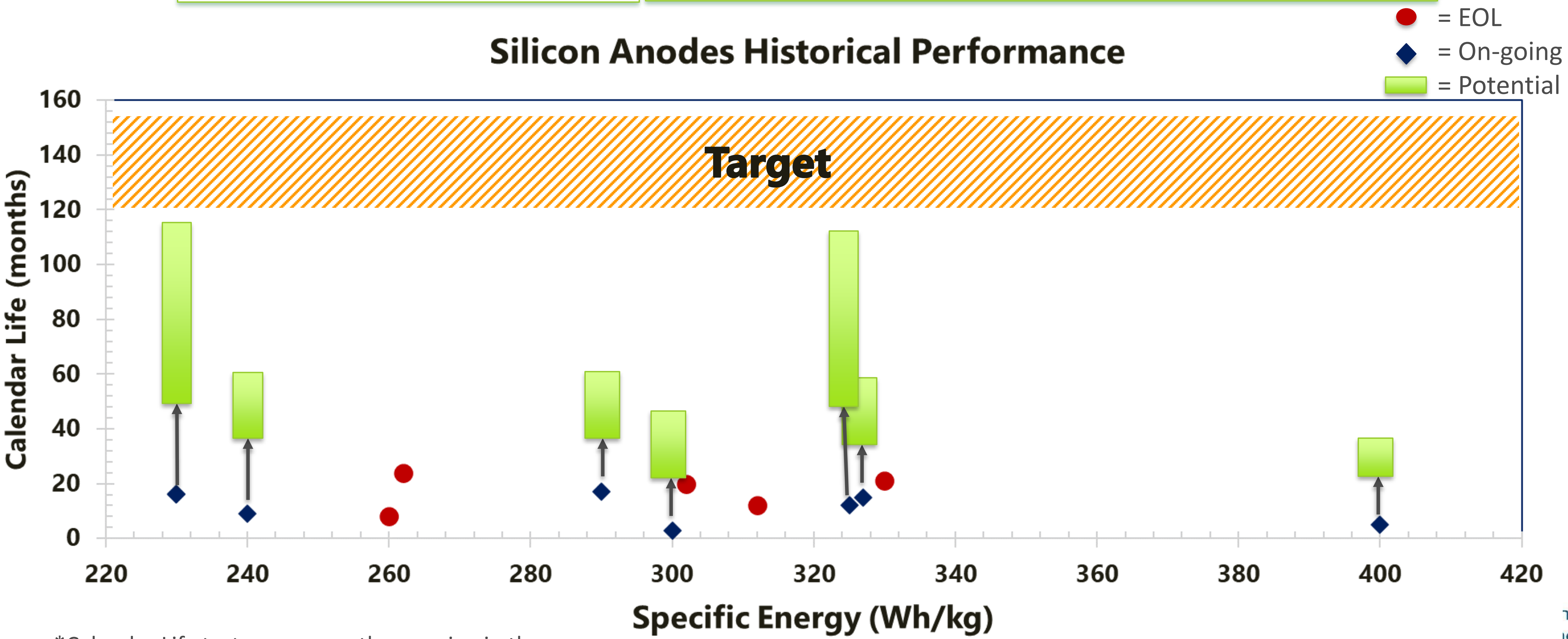

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VTO Silicon Anode Focus Areas

Through a collaboration of Universities (Seedlings, FOAs), National Labs (Seedings, SCP, FOAs), and Industry Partners (USABC, FOAs), develop Silicon Anode Technologies across a range of TRLs to meet VTO's goals.

Goal: Develop a Silicon Anode that can deliver 350 Wh/kg, 10-year calendar life, and 1,000+ cycles.

Battery Materials Research (BMR)
TRL 2-3

Applied Battery Research (ABR)
TRL 3 - 4

Battery Development
TRL 3 - 6

Seedlings

Silicon Consortium Project (SCP)

FOAs

USABC
UNITED STATES ADVANCED BATTERY CONSORTIUM

Approaches to Improving Silicon Calendar Life

Approach	Silicon Consortium	USABC	Enovix	Group14	Sila Nano	Solid Power	Univ of MD	SUNY Stoneybrook	Univ of DE
Si coating	X	X		X	X		X		X
Si doping	X	X							
Novel Electrolytes	X	X	X		X	X	X	X	
Novel Si and electrode structures	X	X	X	X	X			X	
Modeling/ Diagnostics	X	X					X	X	X

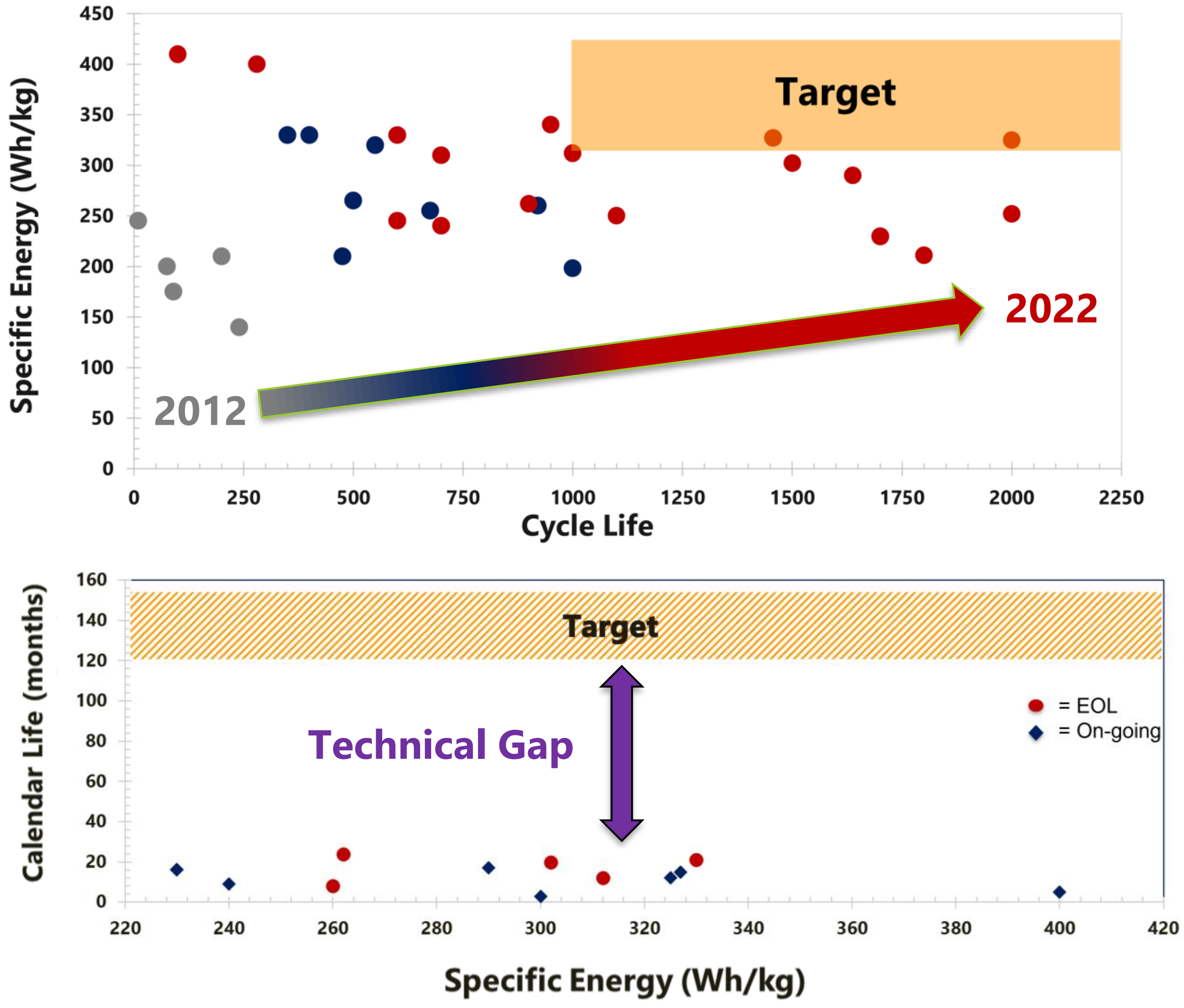
Silicon Consortium Project (SCP)

Goal: To understand calendar life issues for silicon anodes to enable automotive applications.

Silicon cell limitations: Cycle life and capacity have improved significantly, but calendar life achieves only ~10% of the target.

Understanding the issues: Historically, Si anode research has focused on the volume expansion (~320%) during lithiation. However, other failure mechanisms such as the limited calendar life of Si cells demonstrates that a passivating SEI does not form.

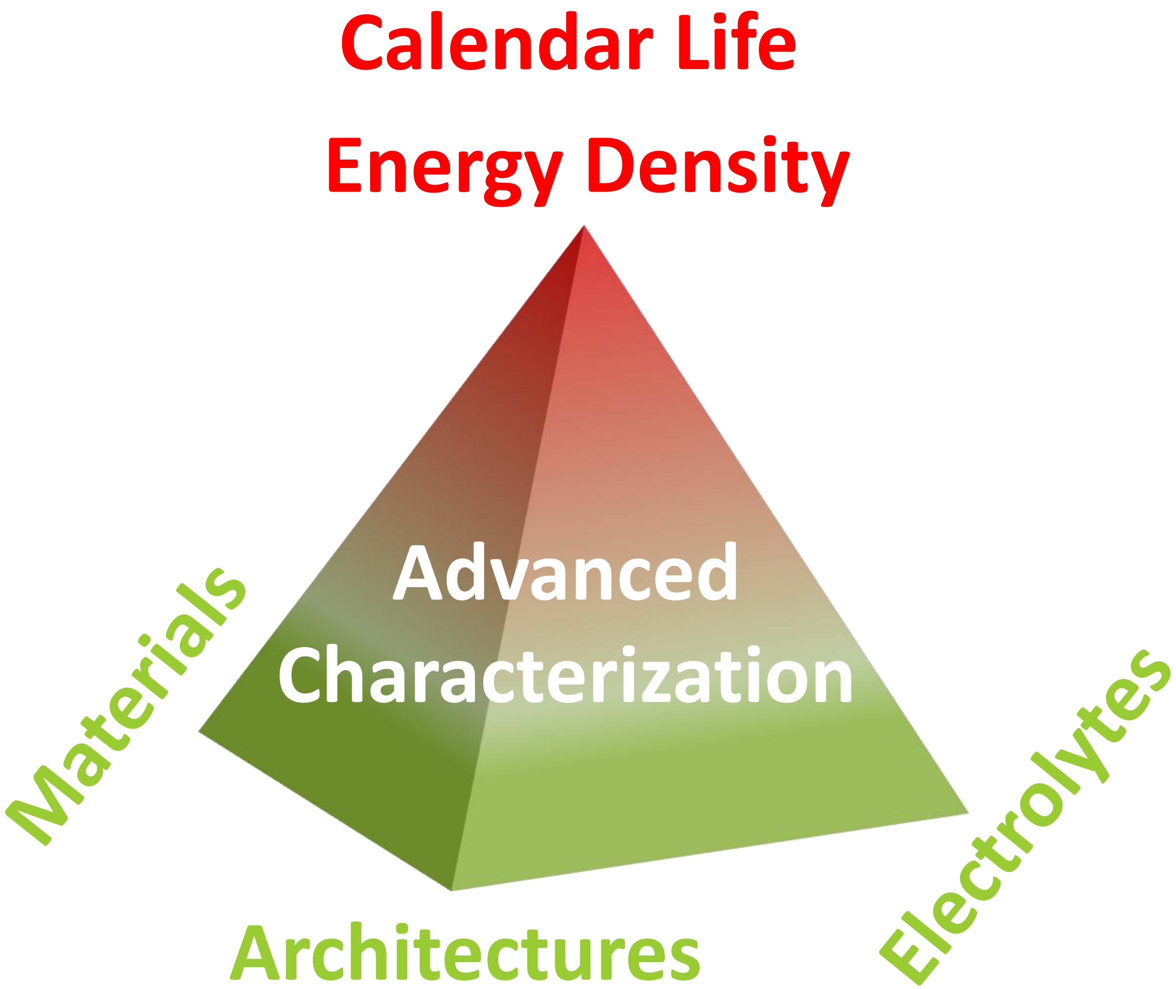
This project uses a knowledge-based approach to the development of scalable solutions to the calendar life in silicon cells, using defined stage gate feedback loops in an integrated team that is focused on the full cell solutions. The team is divided into six interconnected thrusts to achieve the goal.



Performance gap in the calendar life of silicon cells.

Silicon Consortium Project (SCP)

Six Interconnected Research Thrusts



SCP Goal: Deliver >2Ah full cells with Si-based anodes that achieve:

1,000 cycles at C/3, useable energy >**375** Wh/kg, energy density >**750** Wh/L, and a calendar life >**10** years

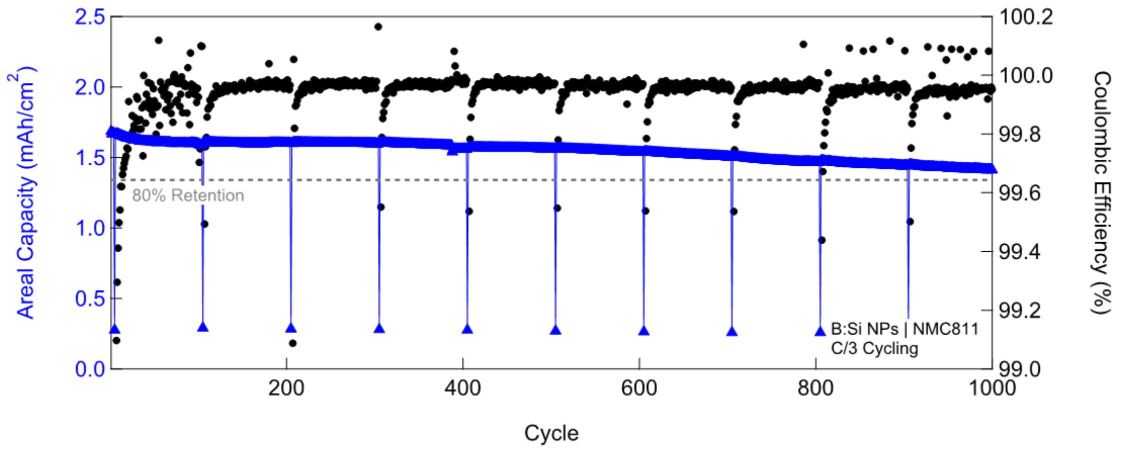
FY23Q4 Milestone: Deliver >2Ah full cells with Si-based anodes that achieve:

1,000 cycles at C/3, useable energy >**350** Wh/kg, energy density >**700** Wh/L, and a calendar life >**5** years

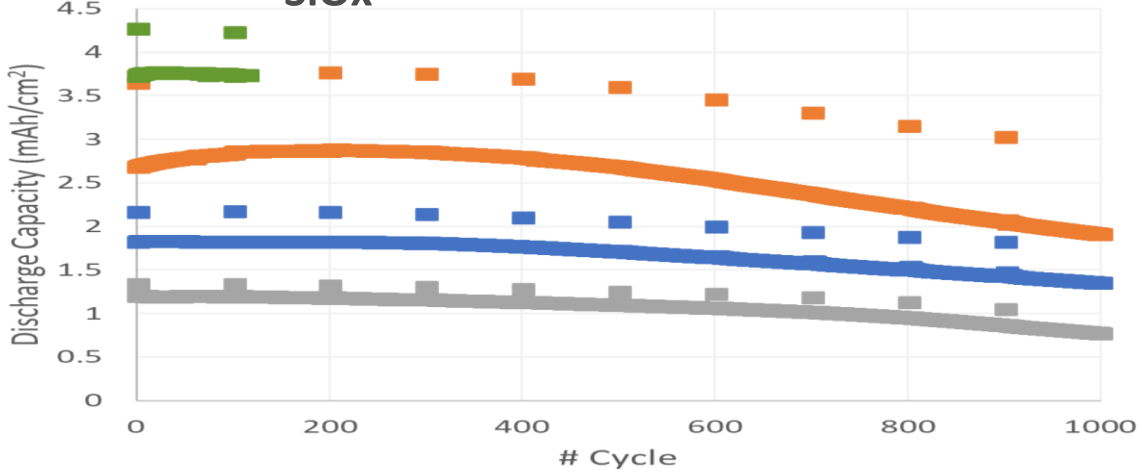
Silicon Consortium Project: Materials Development

To understand the causes of calendar life we require multiple silicon types that demonstrate good cycling performance.

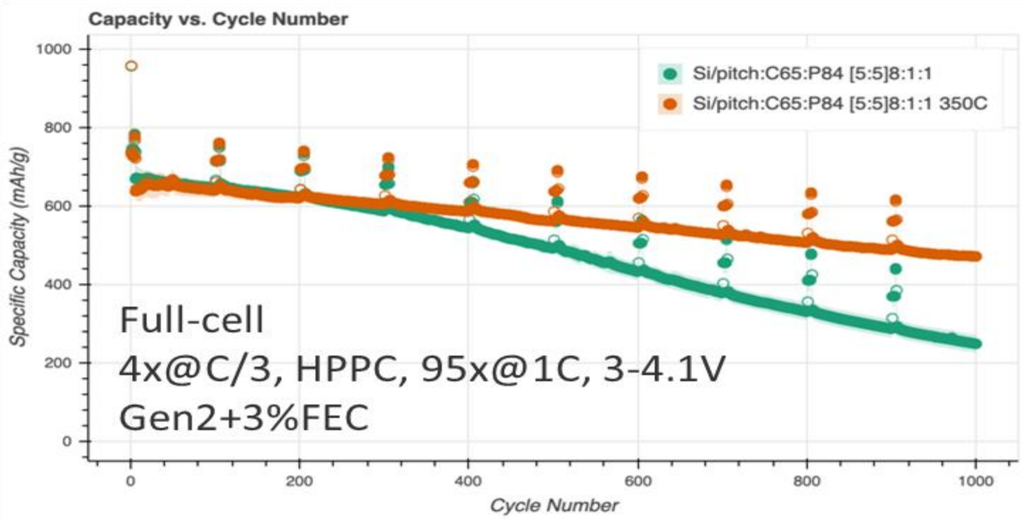
Prelithiated PECVD B:Si | | NMC811



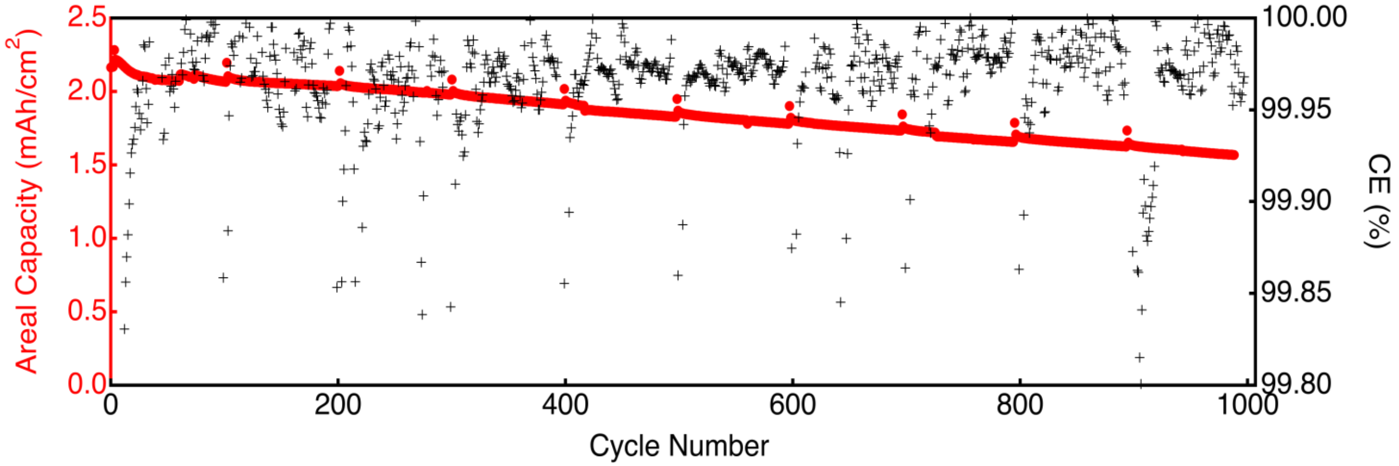
SiOx



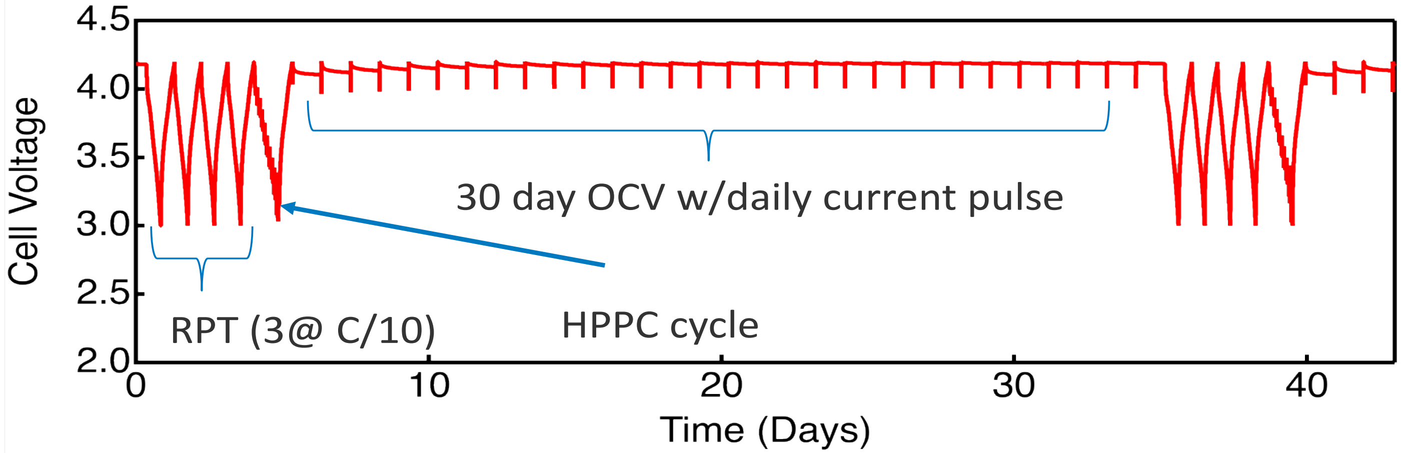
Carbon Coated – PECVD Si@Pitch



PECVD Si@PEO



Silicon Consortium Project: Accelerated Calendar Life Protocols

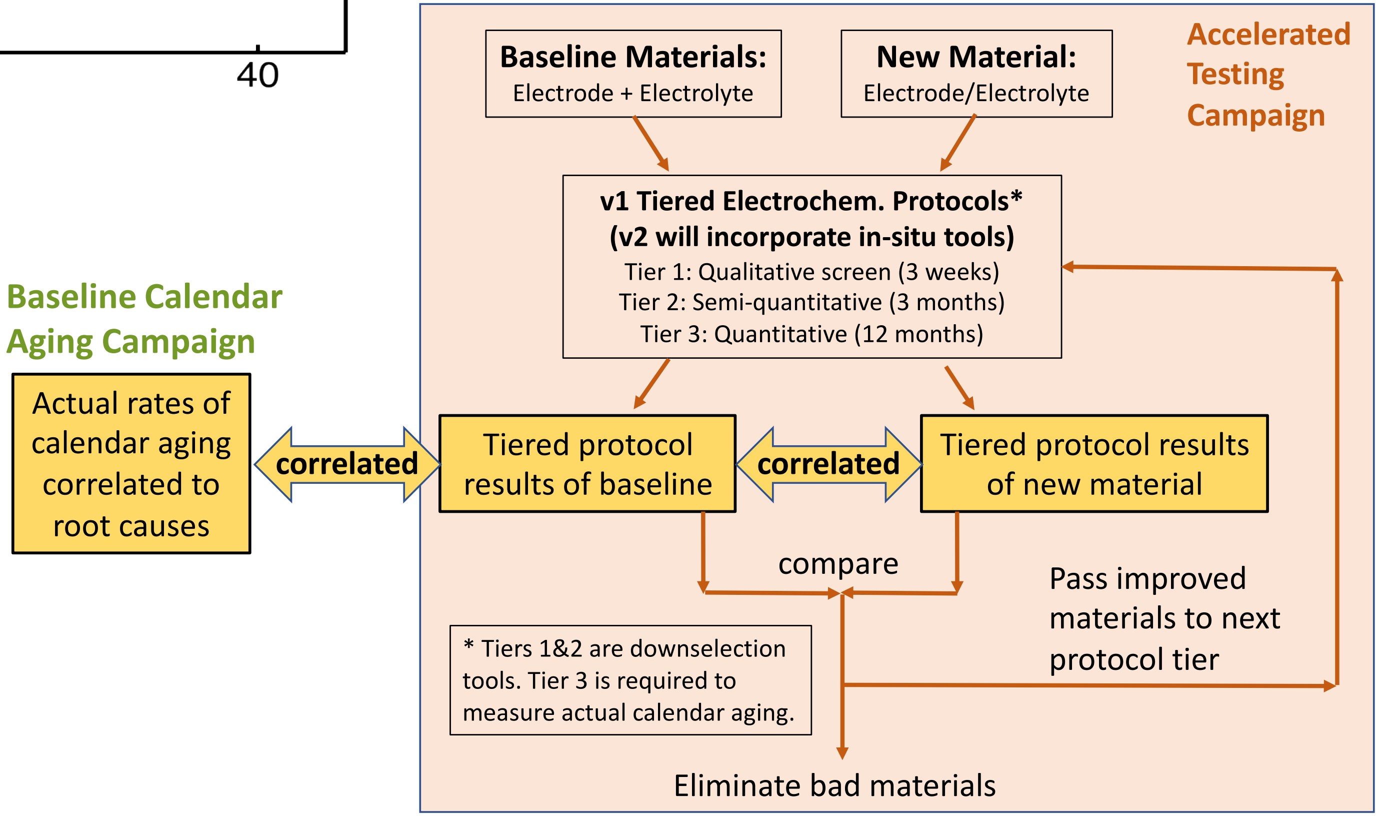


A three-tiered system acts as a stage gate process for materials development and the accelerated testing of hypotheses.

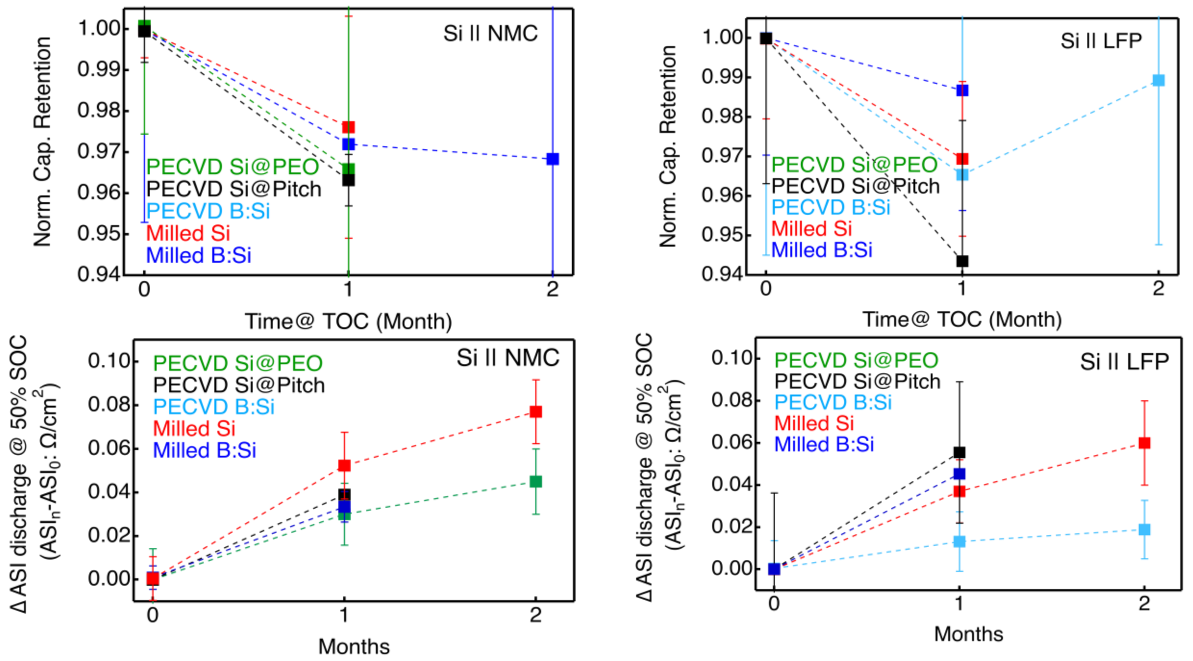
Tier 1 (V-hold screening in LFP coin cell)
~3 week test, excess Li
(fast & easy but qualitative,
semi-quantitative with advanced analysis)

Tier 2 (OCV-RPT aging in LFP coin cell)
~3 month test, excess/limited Li
(fast AND quantitative and avoids cathode effects)

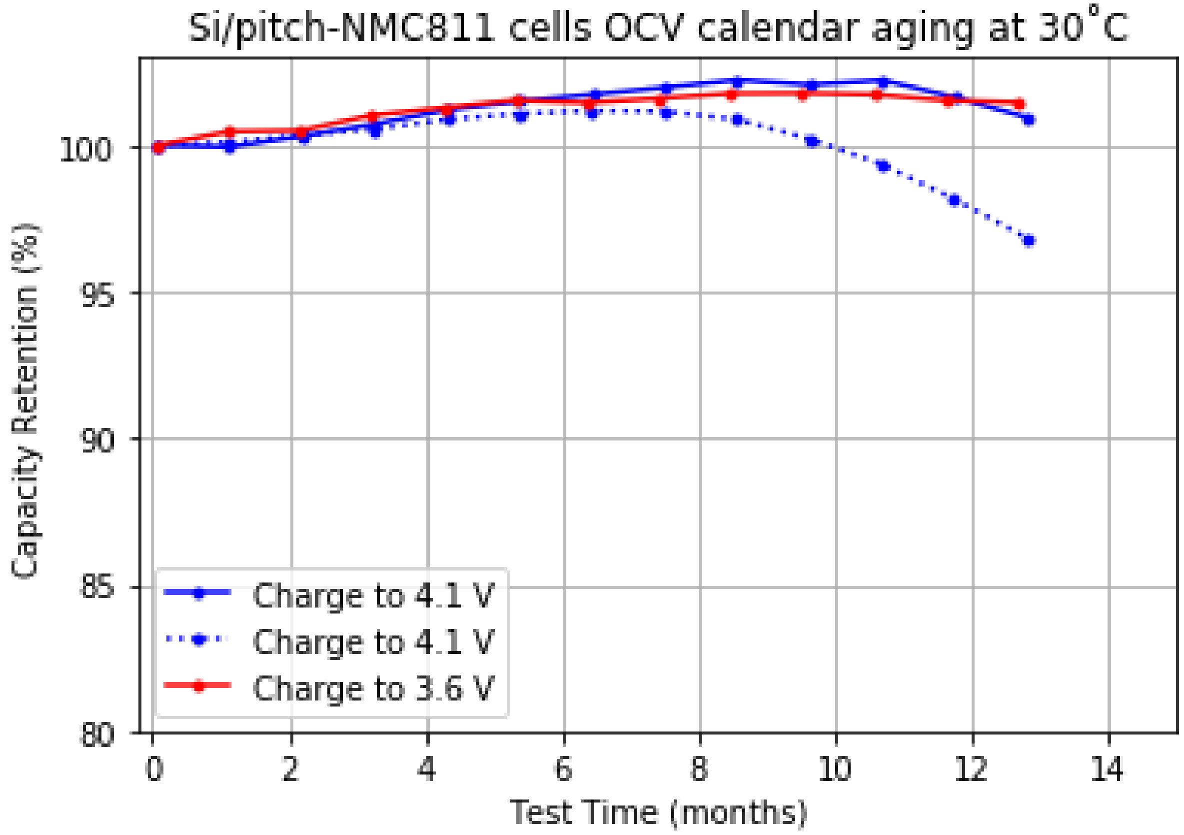
Tier 3 (OCV-RPT (USABC) aging in NMC coin/pouch cell)
12+ month, Si-NMC, essentially USABC test
(most representative long term calendar aging)



Silicon Consortium Project: Early Calendar Life Data



-Normalized capacity retention is the same within error for all silicon's and both cathodes for the first two months
- Change in ASI is similar for all samples paired with NMC with some small changes emerging. B:Si shows minimal impedance gain against LFP



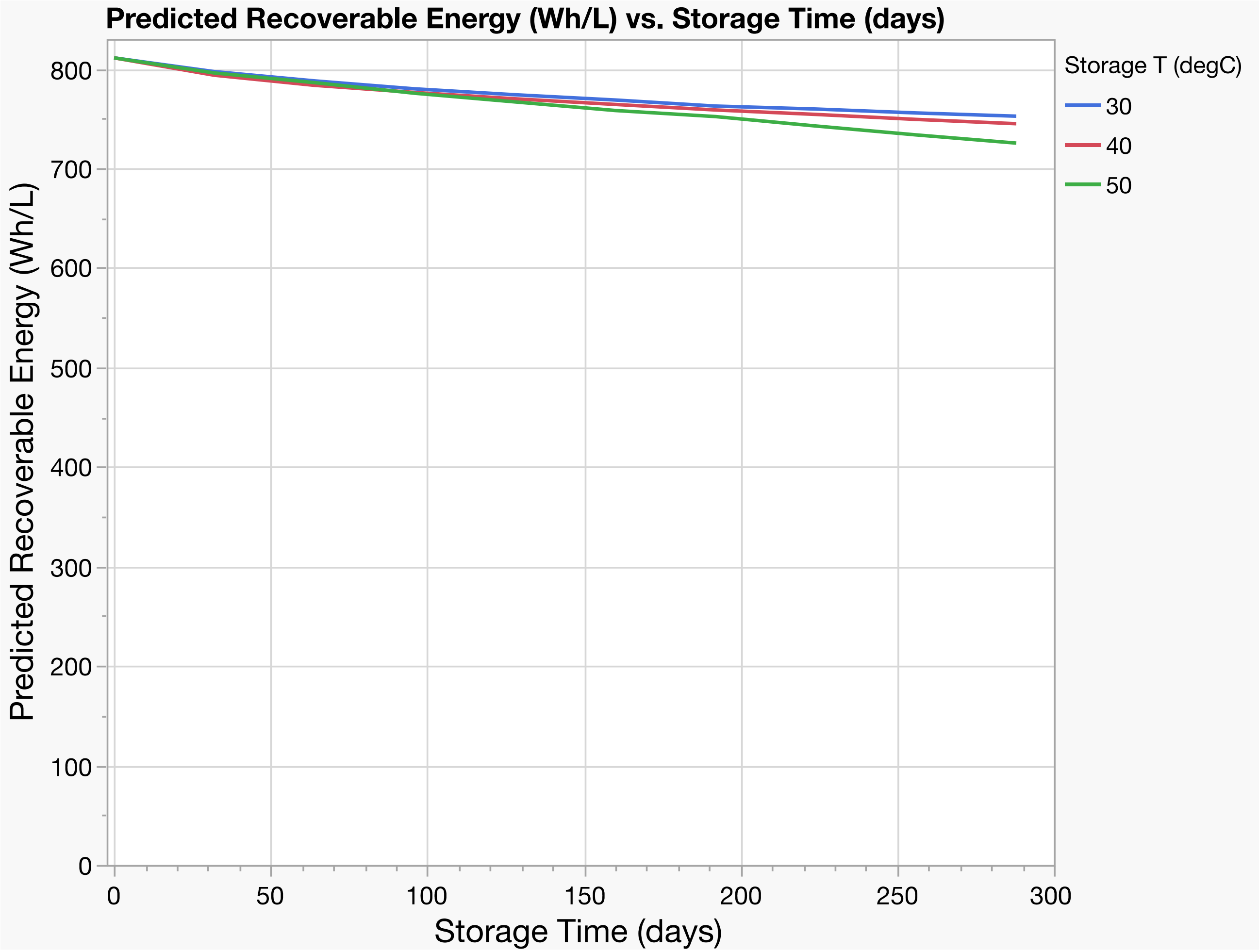
Testing begun in 2022 using an OCV hold

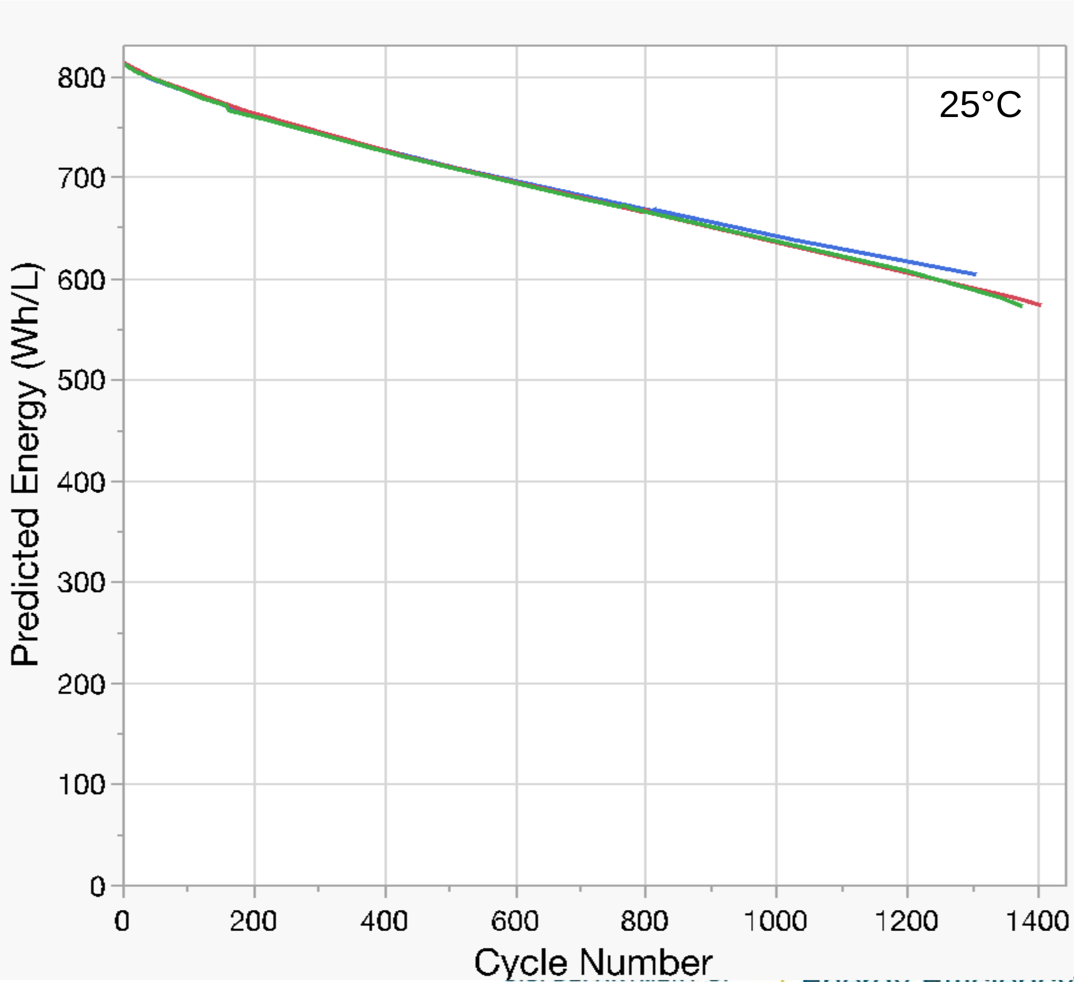
Tier 3 protocol

Data collected from the tier 3 protocols will be evaluated using a ML/AI approach.

2020 EERE VTO FOA for Silicon Anodes

Interim demo cells built by prototyping partner with improved particle and electrode
0.5C Charge + CV to 0.05C, 0.33C Full Discharge, 2.5-4.2V





Group14: Lithium-Silicon Batteries to Displace Internal Combustion Engines

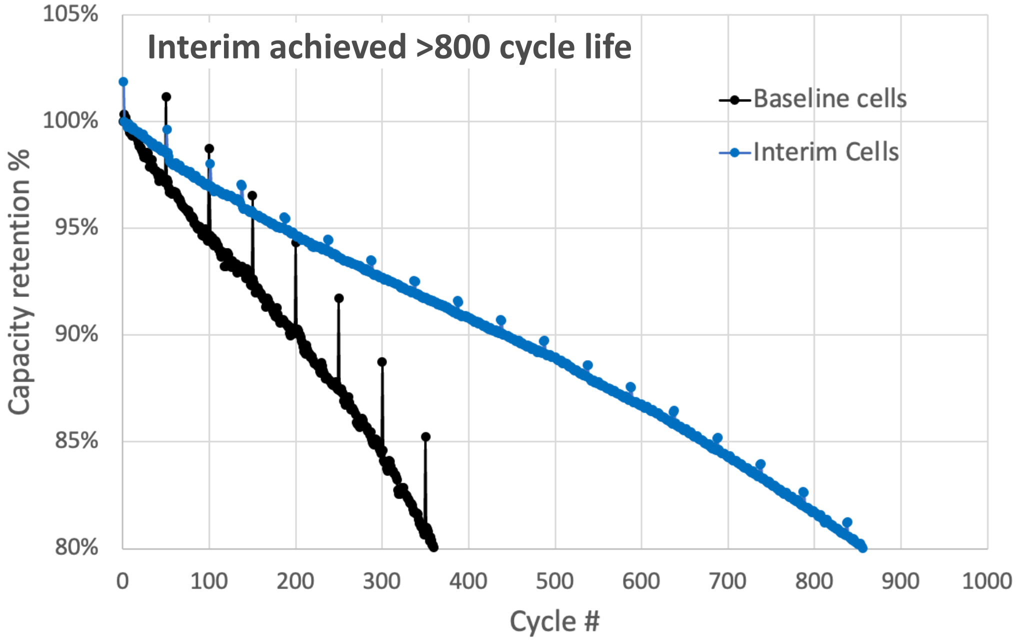
GROUP14

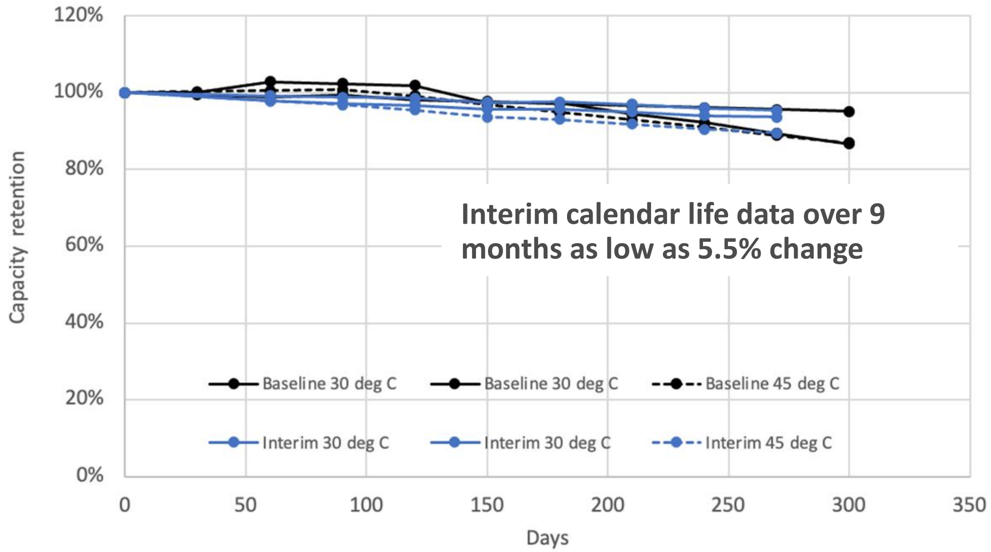
Alignment of leading industry and national lab partners along the battery supply chain

- Next-gen silicon anode material SCC55™ (Group14)
- Conductive additive optimization (Cabot)
- Electrolyte optimization (Silatronix)
- Binder optimization (Arkema)
- Advanced characterization of each component (PNNL)
- Battery design optimization (Farasis)

Demonstrated continuous improvements in optimizing key battery components

Cell Property	Metric Unit	Year 1 Target	Achieved Baseline	Year 2 Target	Interim Achieved	Year 3 Target	Final Achieved
Useable Specific Energy @ C/3	Wh/kg	>340	**>340**	>340	**>340**	>350	TBD
Useable Energy Density @ C/3	Wh/L	>750	**>800**	>750	**>800**	>750	TBD
Calendar Life (<20% energy fade)	Years (to 20% fade)	>3	-	>5	-	>10	TBD
Cycle Life (C/3 deep discharge to <20% energy fade)	Cycles (to 20% fade)	>300	**>350**	>600	**>800**	>1000	TBD

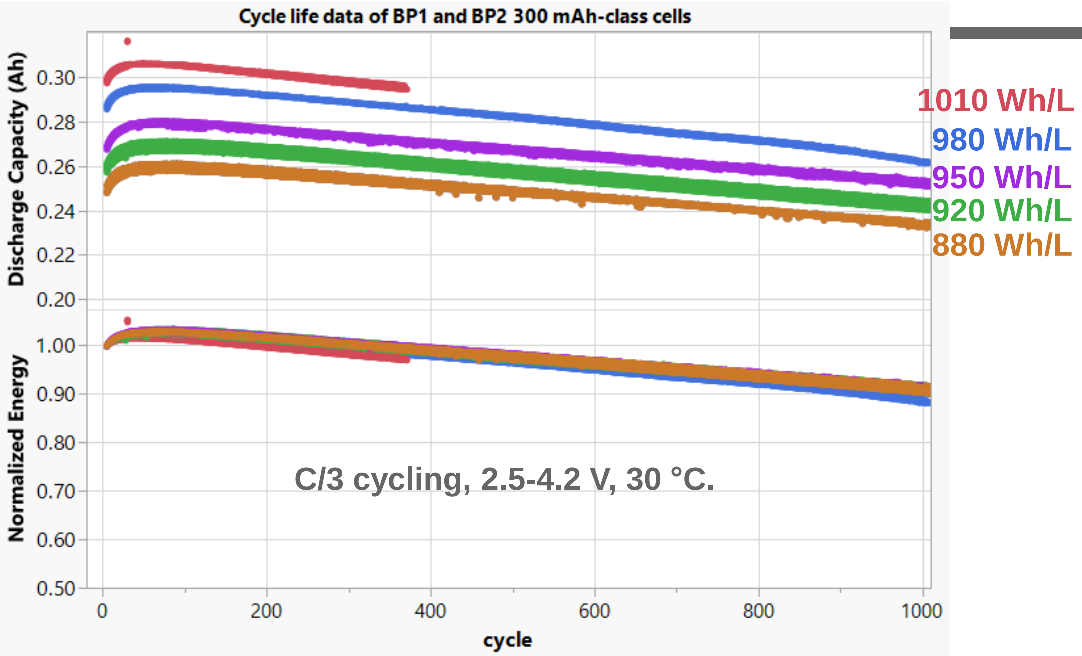


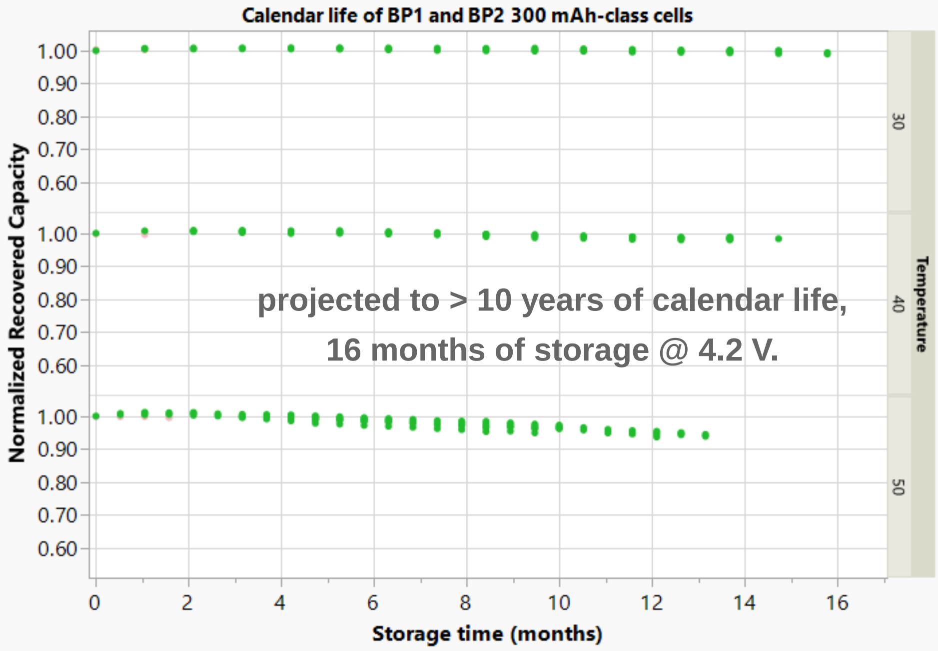


EE0009188: Structurally and Electrochemically Stabilized Si-rich Anodes for EV Applications

Summary of achievements (FY2021-2022)

- **>1000 cycles achieved** on 4 cell designs using 100% active Si anodes and NMC 622 cathodes. 5th cell design projected to exceed 1000 cycles with > 5 mAh/cm^2 cathode loading.
- **Projected >10 years of calendar life after >1 year of storage tests**, using recovered capacity from cells stored at 30 °C, 40 °C, 50 °C, 60 °C and 70 °C at 4.2 V.
  - >95% recovered capacity after 14 months @ 4.2 V, 50 °C.
  - >98% recovered capacity after 15 months @ 4.2 V, 40 °C.
  - >99% recovered capacity after 16 months @ 4.2 V, 30 °C.
- **Core energy density** (i.e. anode, cathode, current collectors, and separator) **ranged from 850 Wh/L to 1010 Wh/L.**
  - Packaged energy density ranged from 500 Wh/L to 600 Wh/L in a 300 mAh sized cell.
- Packaged energy density projection in 100 Ah-size cell:
  - with NMC622: 800 Wh/L, 270 Wh/kg.
  - **with NMC811: 920 Wh/L, 320 Wh/kg.**



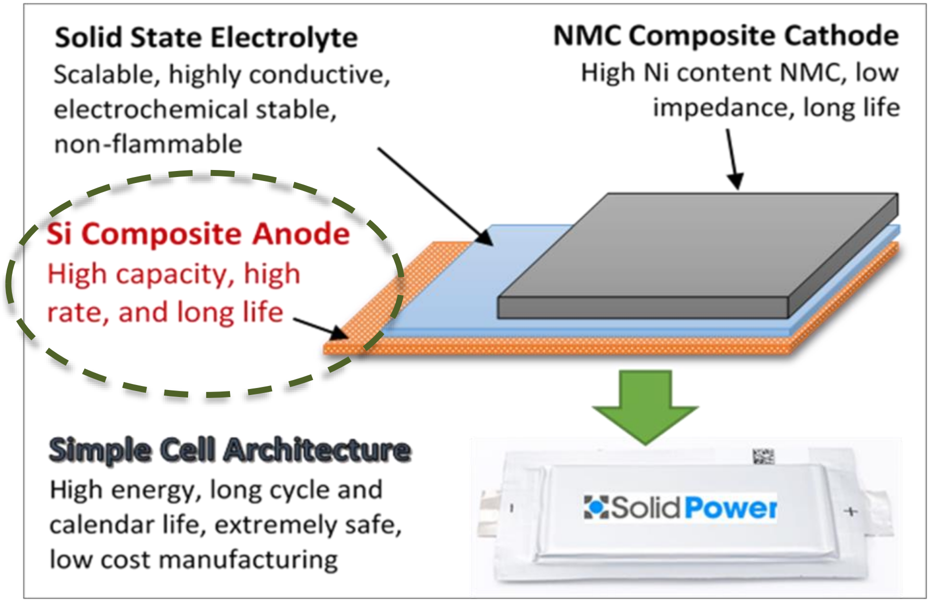


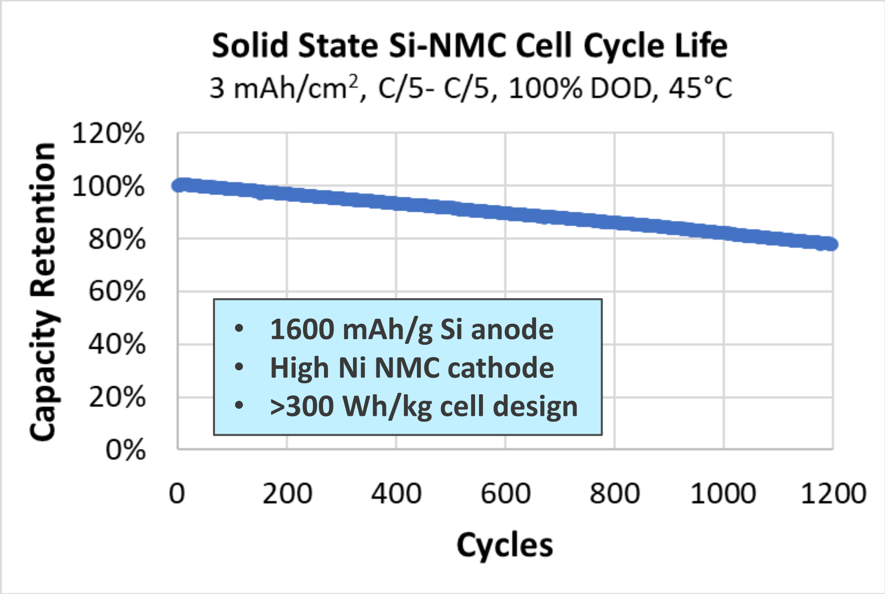
Silicon FOA Highlights – All Solid State Si Pouch Cell

- **Developed a high energy all-solid-state Si composite anode**
  - 1500 - 2000 mAh/g capacity (at electrode level)
  - Roll-to-roll electrode coating process
- **Demonstrated long cycle life and calendar life in Si-NMC all-solid-state pouch cells**
  - Cycle life of 1100 at C/5 – C/5, 45°C (> 300 Wh/kg cell design)
  - Calendar life @ 50°C: Day 96, 3.0% capacity fade (average of 3 cells)

Slot-die Si anode coating

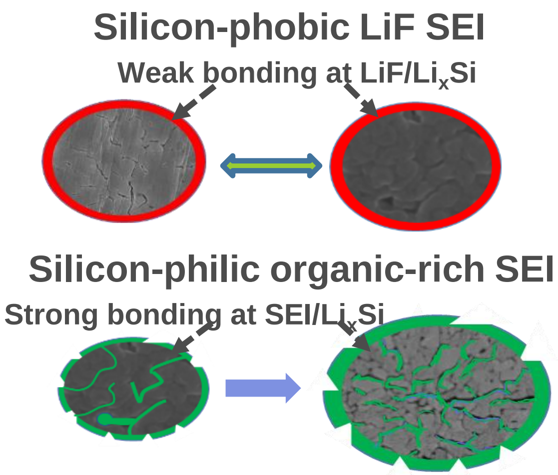
Solid state Si pouch cell



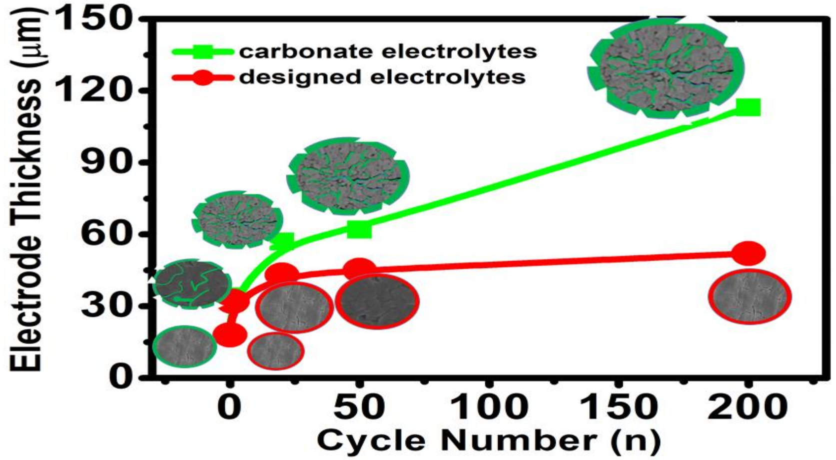


Electrolyte Design for Li-ion Batteries using Micro-sized Si (µSi) Anode - University of Maryland

Electrolyte should be able to form LiF-rich SEI on µSi

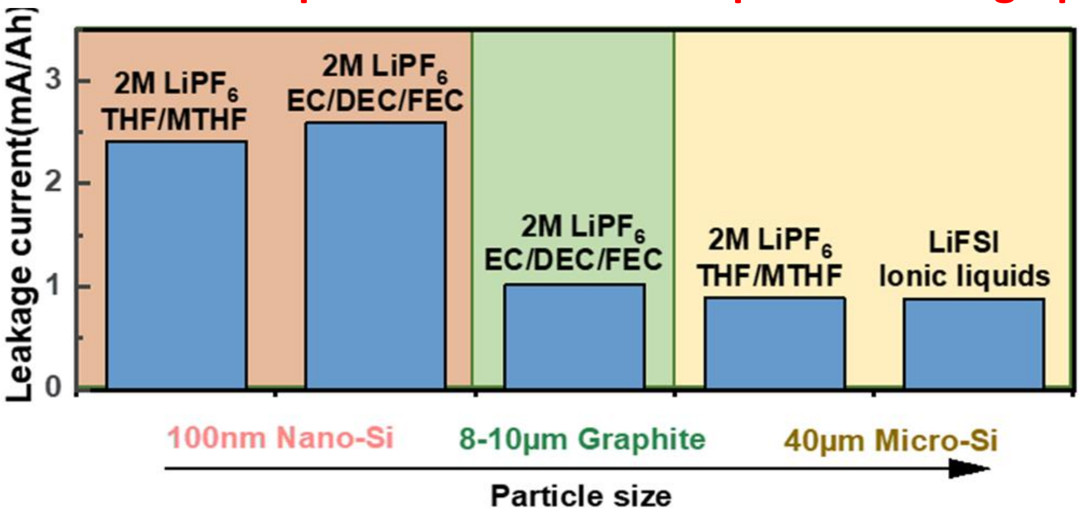


- LiF SEI does not crack but organic-inorganic SEI cracks due to the weaker binding of µSi to LiF SEI than to organic-inorganic SEI.
- Cracked organic-inorganic SEI allows electrolytes penetration and forms new SEI in pulverized µSi. However, stable LiF can block electrolyte penetration enabling µSi electrode to maintain thickness and enhance the cycle life and calendar life.



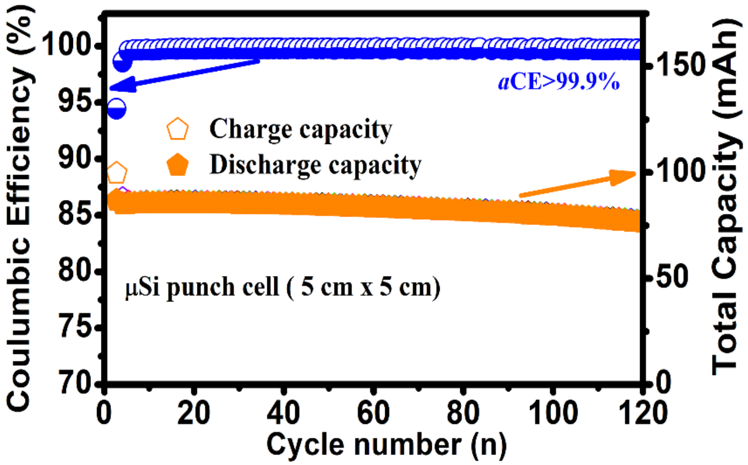
µSi electrode thickness change along cycles in two electrolytes

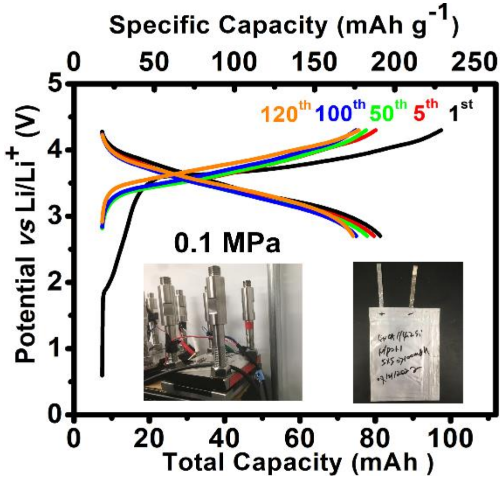
Calendar life of µSi with LiF SEI is comparable with graphite



Leakage currents of 100nm Si, 10µm graphite, and 40µm Si during voltage hold in different electrolytes

Cycling of NCA/µSi pouch cells in designed electrolyte is stable





Electrochemical performance of 100 mAh NCA/Si (5µm) pouch cell in designed electrolytes without pre-lithiation (4 mAh cm^{-2}, N/P of ~1.1)

Silicon Portfolio FOA and USABC Partners

University of Delaware 1743

Sila

Nanoramic™ LABORATORIES

microvast™

Stony Brook University

GROUP14

FARASIS

amprius

Solid Power

IONBLOX

University of Maryland 1856

enovix

APPLIED MATERIALS®

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https://www.energy.gov/eere/vehicles/vehicle-technologies-office