Advanced High-Performance Batteries for Electric Vehicle (EV) Applications

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Amprius, Inc.

June 18-21, 2018

BAT241

Overview

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Timeline

- Start date: January 2015
- End date: September 2018
- Percent complete at end of FY2017: ~75%

Budget

- Total project funding:

  $5,501,098
  - DOE share: $2,750,549
  - Contractor share: $2,750,549
- FY17 received: $1,878,788
- FY18 projected: $1,418,875

Barriers

- Performance
  - Energy Density
  - Specific Energy
  - Cost
- Life
  - Cycle Life
  - Calendar Life

Partners

- Amprius – Project Lead

Objectives

Project Objectives

- Match silicon nanowire anodes with an advanced (high capacity and high energy density) cathodes and state-of-the-art cell components
- Develop, test and deliver 2Ah, 10Ah and 40Ah Li-ion cells with silicon nanowire anodes that meet the USABC 2020 goals
- **Main final performance targets:**
  - 350 Wh/kg and 750Wh/L at EOL
  - 2:1 Power:Energy ratio
  - 1,000 DST cycle life

Addresses Barriers

- Increases ***energy density and specific energy*** by reducing the mass and volume of the anode material
- Reduces the amount of anode material needed (high capacity per gram), reducing the ***cost*** per Ah
- Increases ***cycle life*** of cells with silicon anodes by optimizing the material in Amprius' rooted nanowire structure

Relevance:

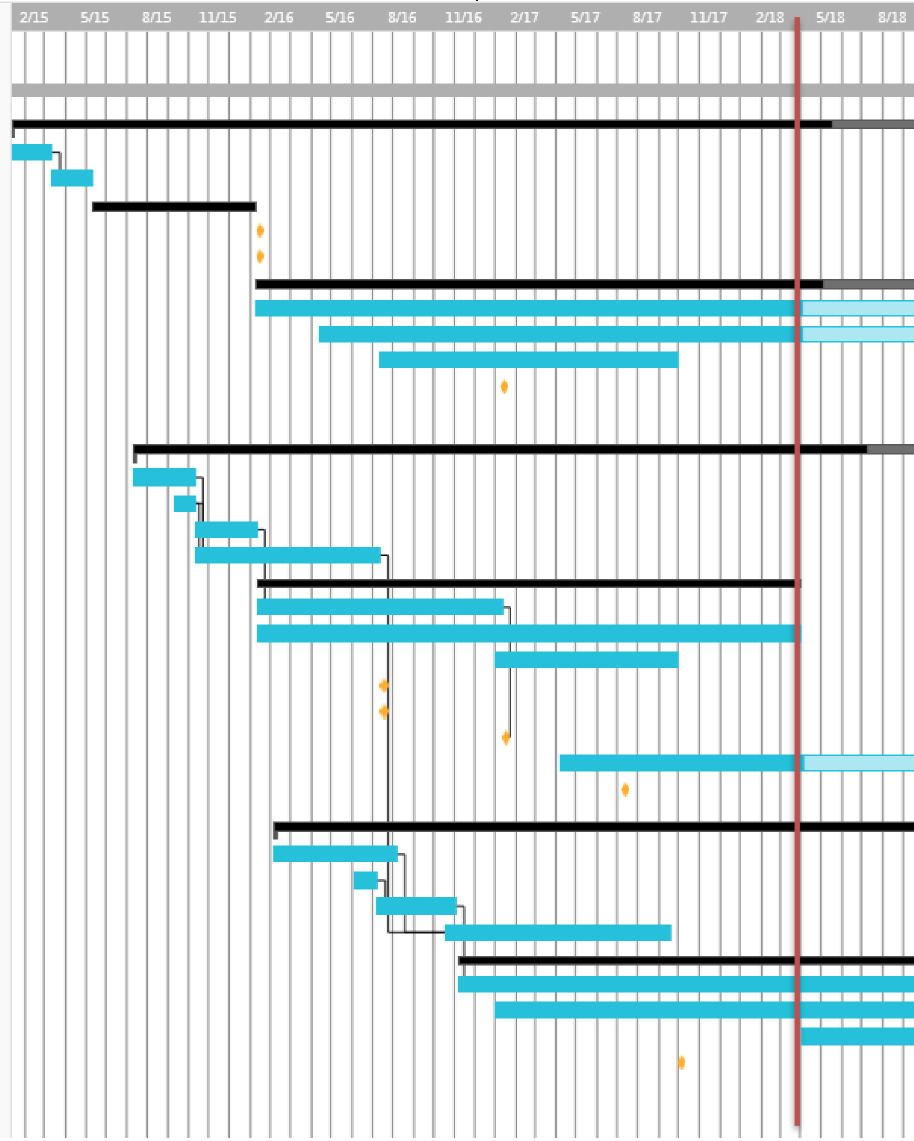
Milestones and Timing

Month/Year	Milestone or Go/No-Go Decision	Status
Jan-16	Milestone/Deliverable: • Deliver 30 pouch cells with a capacity ≥ 2 Ah, energy density ≥ 750Wh/L, specific energy ≥ 350Wh/kg, DST cycle life ≥ 750	Complete
Jan-17	Milestone/Deliverable: • Achieve ≥ 800 Wh/L, ≥ 380 Wh/kg and ≥ 850 cycles in a ≥ 2 Ah cell • Deliver 30 pouch cells with a capacity ≥ 10 Ah, energy density ≥ 850Wh/L, specific energy ≥ 400 Wh/kg, and DST cycle life ≥ 750	Complete
Jul-17	Milestones: • Achieve ≥ 850 Wh/L, ≥ 400 Wh/kg and ≥ 1,000 cycles in a ≥ 2 Ah cell • Achieve ≥ 875 Wh/L, ≥ 415 Wh/kg and ≥ 850 cycles in a ≥ 10 Ah cell • Achieve ≥ 850 Wh/L, ≥ 400 Wh/kg and ≥ 750 cycles in a ≥ 40 Ah cell	Partially Complete
Sep-18	Deliverable: • Deliver 30 pouch cells with a capacity ≥ 10 Ah, energy density ≥ 850 Wh/L, specific energy ≥ 350 Wh/kg, and DST cycle life ≥ 1,000	On Track

Relevance:

Milestones and Timing

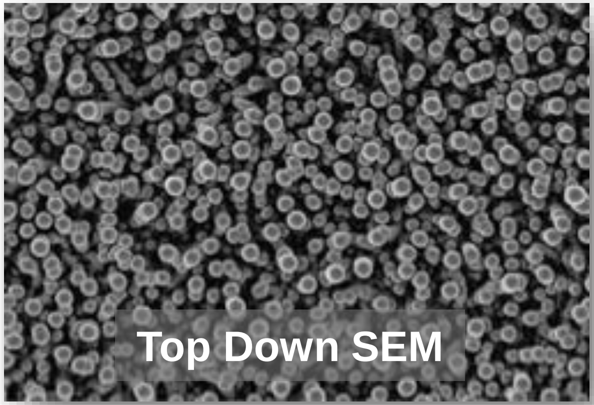
USABC 2015	start	end	94%
1. 2Ah Baseline cell development	**01/12/15**	**10/01/18**	**90%**
1.1. Cell level gap measurement & analysis	01/12	03/11	100%
1.2. Baseline anode and cell design and components sourcing	03/12	05/11	100%
1.3. Iterative design validation, gap mitigation	**05/12/15**	**01/08/16**	**100%**
D1: 30 2Ah cells with 750Wh/L, 350Wh/kg, 750 cycles	01/11	01/11	100%
G1: Gap analysis and mitigation selection	01/11	01/11	100%
1.4. Cell optimization activities	**01/11/16**	**09/28/18**	**85%**
1.4.1. Energy and cycle life development	01/11	09/28	82%
1.4.2. High & low temperature performance development	04/13	09/28	80%
1.4.3. Mechanical, electrical, and thermal abuse testing	07/13	09/29	100%
M1: 800Wh/L, 380Wh/kg, 850 cycles	01/09	01/09	100%
M2: 850 Wh/L, 400Wh/kg, 1,000 cycles	10/01	10/01	0%
2. 10Ah Interim cell development	**07/13/15**	**09/28/18**	**93%**
2.1. Anode form factor scale-up	07/13	10/09	100%
2.2. Anode and cell design and components selection	09/10	10/09	100%
2.3. Anode and cell materials and components sourcing	10/12	01/11	100%
2.4. Anode fabrication and validation	10/12	07/12	100%
2.5. Iterative design validation, anode production, cell assembly	**01/12/16**	**03/30/18**	**100%**
2.5.1. Assembly optimization	01/12	01/10	100%
2.5.2. Performance evaluation	01/12	03/30	100%
2.5.3. Mechanical, electrical, thermal abuse	01/02	09/29	100%
M3: 850Wh/L, 350Wh/kg, 500 cycles	07/13	07/13	100%
G2: Development design selected	07/13	07/13	100%
D2: 30 10Ah cells with 850Wh/L, 400Wh/kg, 750 cycles	01/11	01/11	100%
2.6. Performance optimization activities	04/06	09/28	67%
M4: 875Wh/L, 415Wh/kg, 850 cycles	07/07	07/07	100%
3. 40Ah Vehicle cell development	**02/08/16**	**09/28/18**	**100%**
3.1. Anode form factor scale-up	02/08	08/05	100%
3.2. Anode and cell design and components selection	06/06	07/07	100%
3.3. Anode and cell materials and components sourcing	07/08	11/02	100%
3.4. Anode fabrication & validation	10/19	09/19	100%
3.5. Iterative design validation, anode production, cell assembly	**11/07/16**	**09/28/18**	**100%**
3.5.1. Assembly optimization	11/07	09/27	100%
3.5.2. Performance evaluation	01/02	09/27	100%
3.5.3. Mechanical, electrical, thermal abuse	04/03	09/28	100%
M5: 850Wh/L, 400Wh/kg, 750 cycles	09/29	09/29	100%
D3: 30 40Ah cells with 937.5 Wh/L, 437.5 Wh/kg, 1,000 cycles	09/28	09/28	100%
D3: 22 10Ah cells with improved Cycle and Calendar life	09/28	09/28	0%



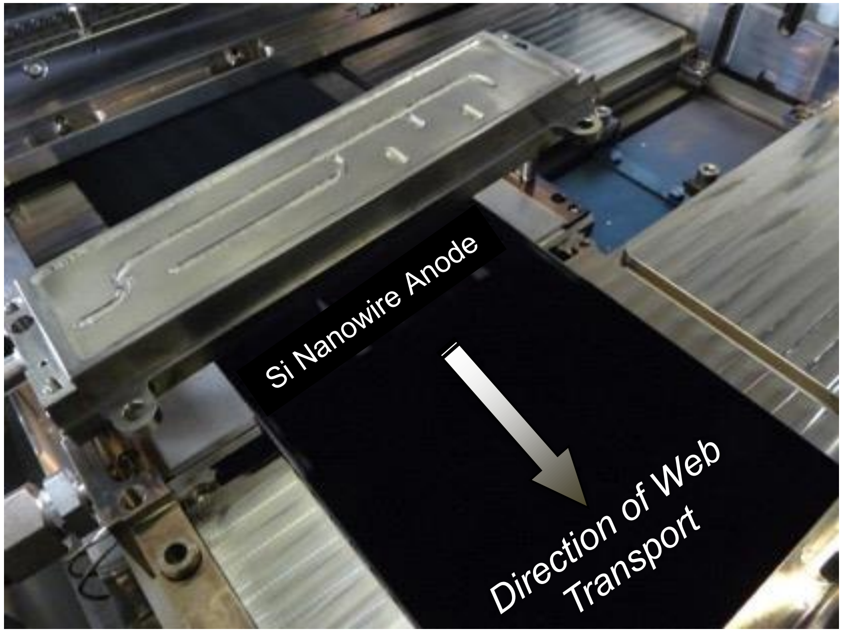
Approach:

Silicon Nanowires enables high energy

Amprius' growth-rooted silicon nanowires enable silicon to swell and contract successfully, without compromising the battery's mechanical stability



- 1/3-1/5th of graphite anode thickness
- High content active silicon materials (100%)
- Ideal and adjustable porosity distribution
- High mass loading (2-3 mg/cm^2)
- High conductivity and connectivity
- Low tortuosity – high rate capability



Pilot line tool for roll-to-roll production of double-sided, rooted silicon nanowire anodes installed in Sunnyvale, CA

Amprius Path to USABC Goals

Match silicon nanowire anodes with advanced (high capacity and high energy density) cathodes and state-of-the-art cell components

Develop anode and other cell components in a 2 Ah cell form factor to mitigate gaps in performance toward USABC goals

De-risk form factor scale-up in an intermediary cell form factor of 10 Ah

Develop 40 Ah cells that meet USABC goals in a VIFB—/99/300 cell size designation

FY 2017 Accomplishments

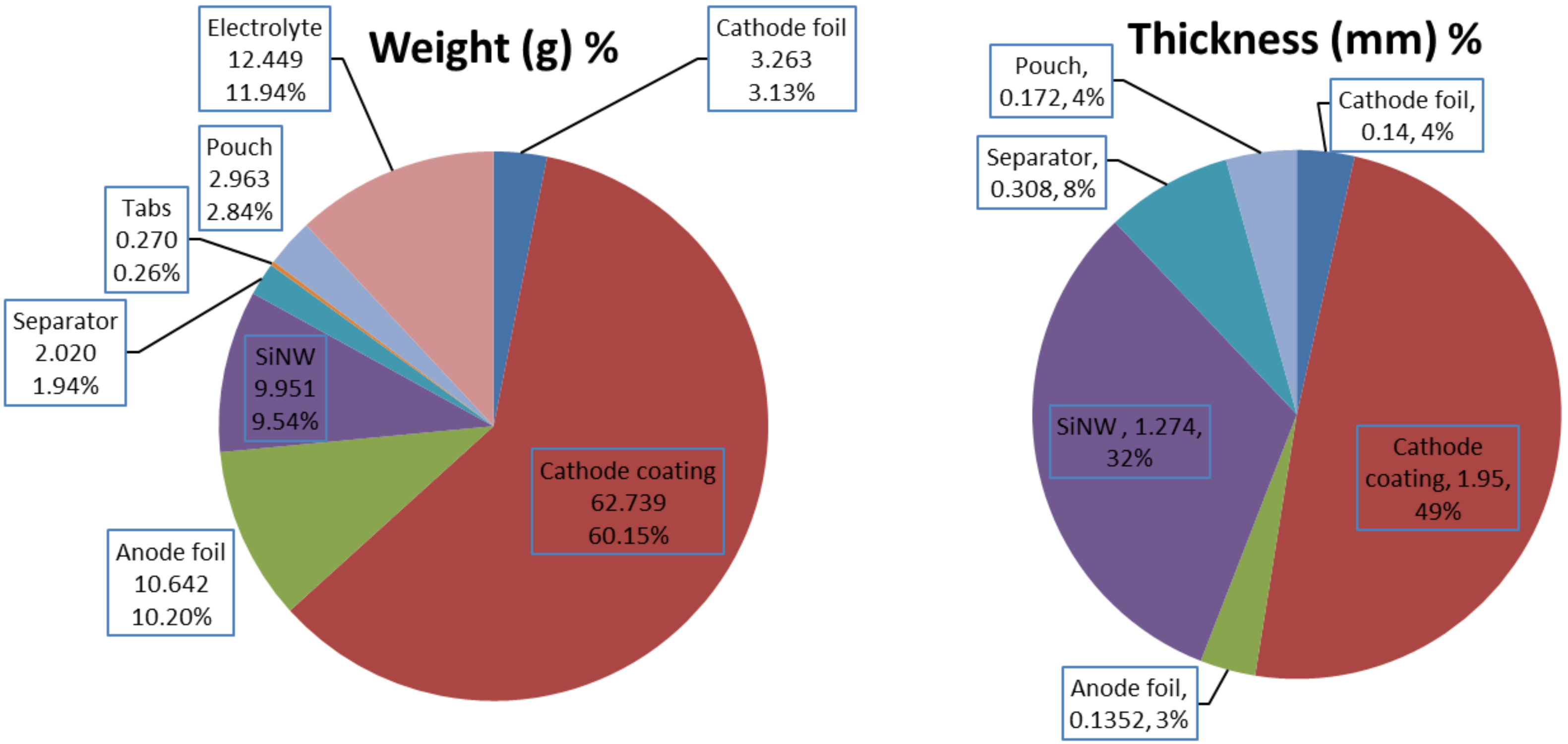
- Delivered thirty 10Ah Silicon Nanowire-NMC cells to INL and SNL for performance and safety evaluation, ~15% energy performance improvement over Year 1 cells
- Completed the gap chart analysis – with results exceeding performance targets for many criteria
- DST cycle life – Exceeded 300 cycles with 70% Ni NMC cathode
- Matched silicon nanowire anodes with higher capacity NCM cathodes
- Developed SiNW/NCM 45Ah cell form factor with specific energy of 350Wh/kg and 925Wh/L

Gap Analysis - Energy

The silicon nanowire anode has a capacity of 1200-1600mAh/g, depending on the cathode loading and capacity

In silicon nanowire cells cathode material dominates both the weight and the volume of the cell

Example in 10Ah cell:



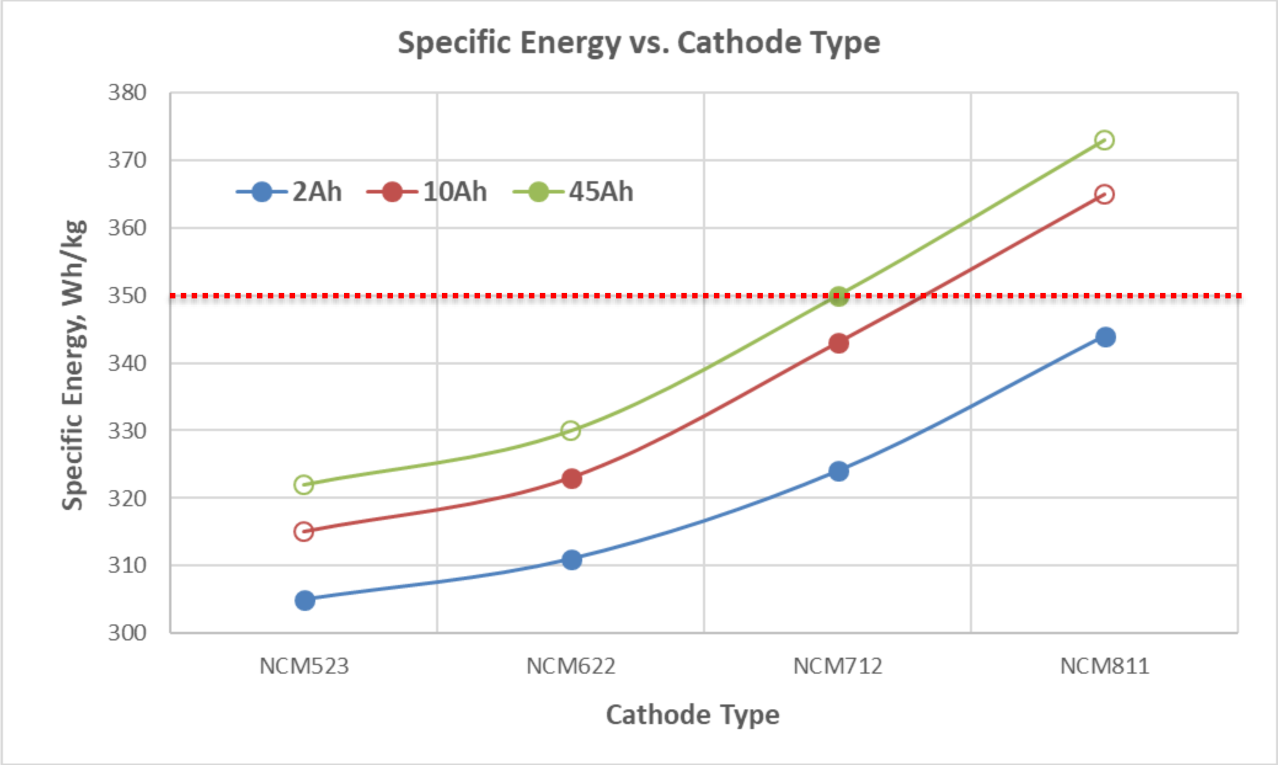
The cathode material is key to improving specific energy

Gap Analysis - Energy

Amprius cells significantly exceed USABC 2020 Energy Density – ex. 45Ah measured at 925Wh/L vs. 750Wh/L target, enough for 20% reserve to end of life (EOL)

The USABC 2020 Specific Energy target of 350Wh/kg can be met in 45Ah cells only with some high capacity NCM materials

Amprius evaluated a variety of materials and sources in FY2017:



USABC 2020 target

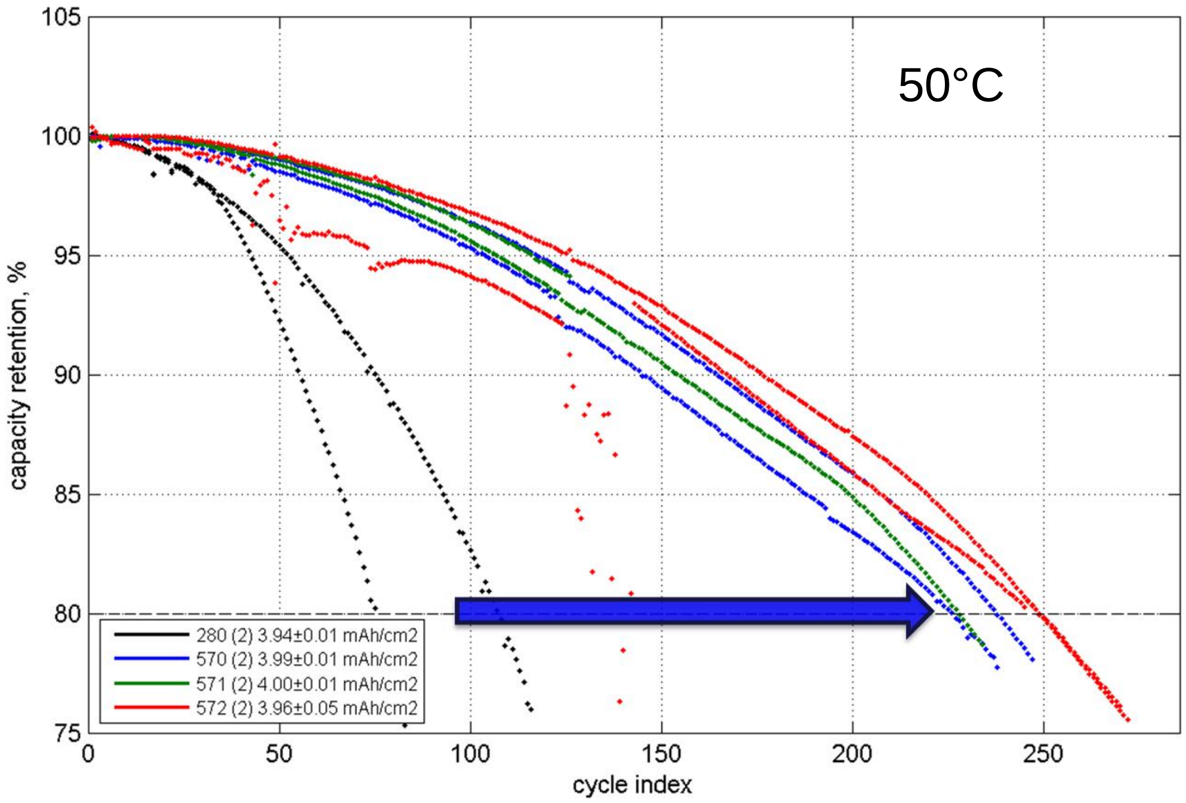
* Open circles represent projections based on measured data (filled symbols)

NCM with 70% or higher Ni content is necessary to meet Specific Energy target

Gap Analysis – Cycle Life/High Temp

Cycle Life and High Temperature stability were identified in Year 1 as gaps in performance

New electrolyte formulations were developed for high temperature performance

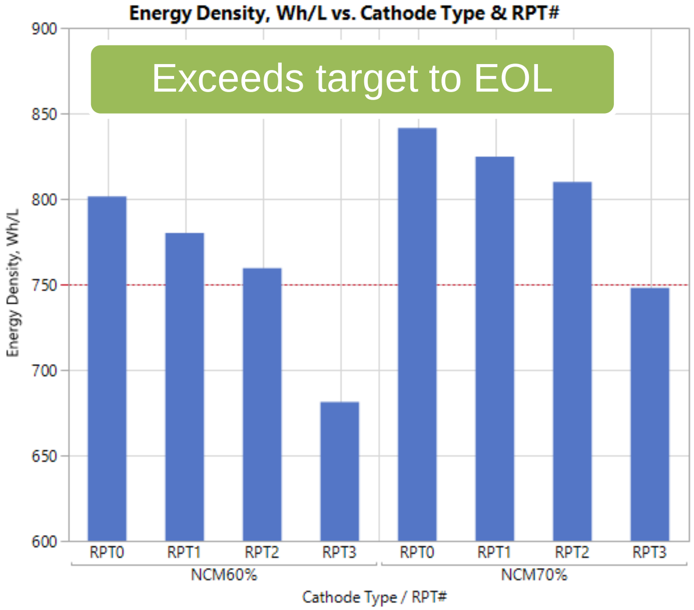


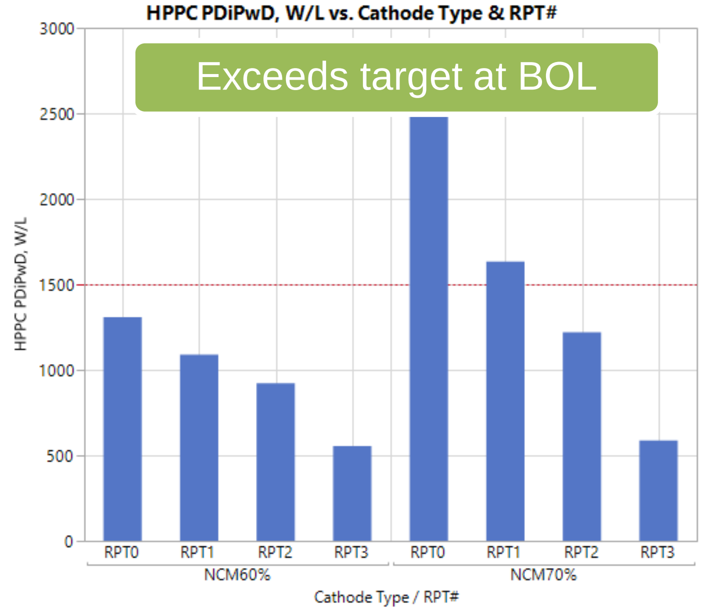
*Si/NCM-70%Ni, 0.5C/0.5C, 2.75-4.1V

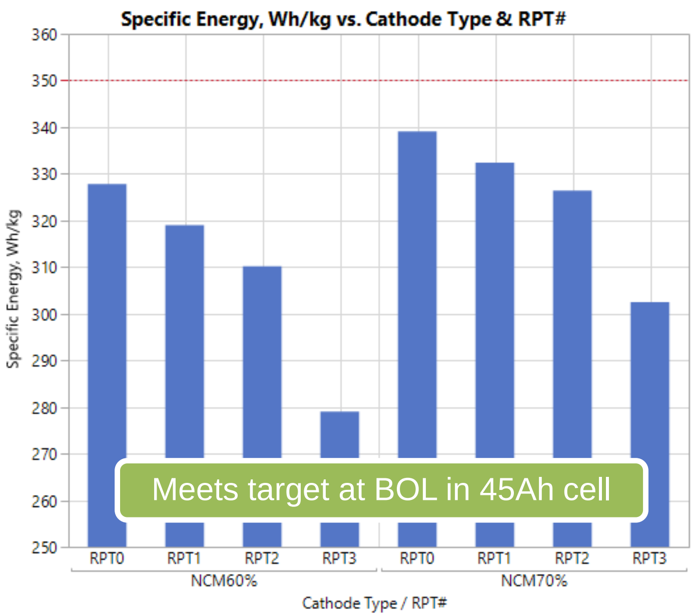
150% improvement in Cycle Life at 50°C

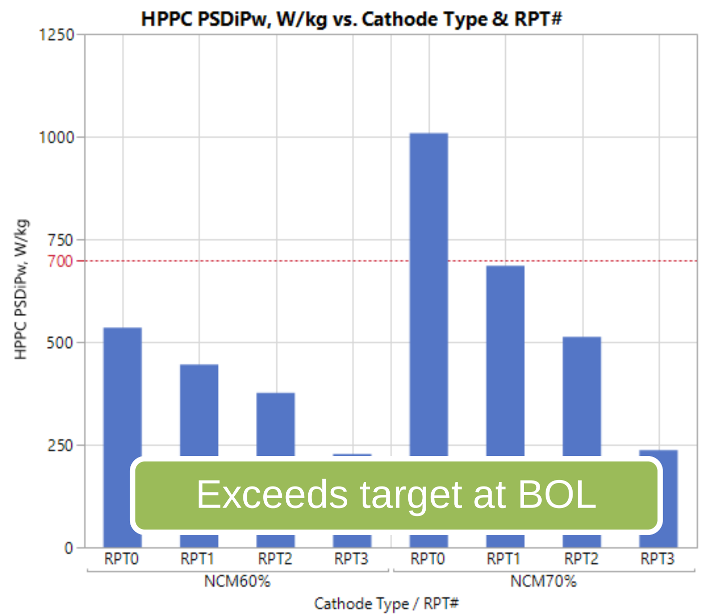
Technical Accomplishments:

Gap Analysis – DST Cycle Life









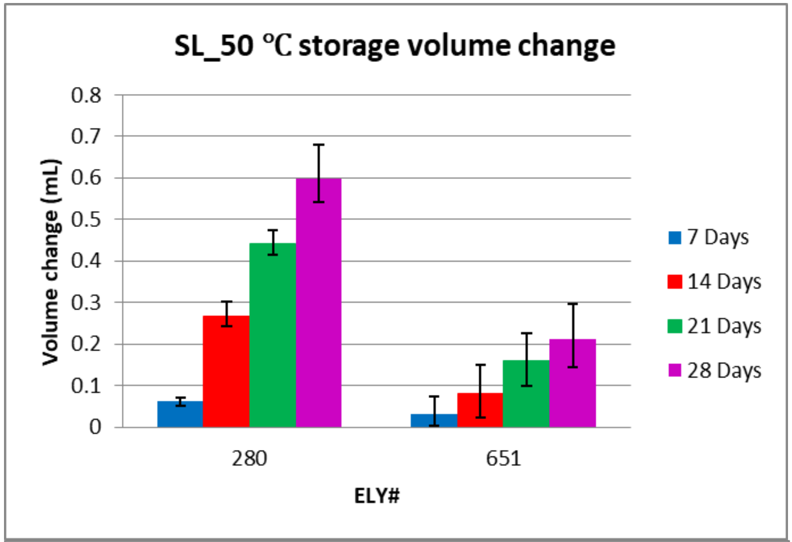
Si/NCM-70%Ni meet all energy and power targets at the beginning of life

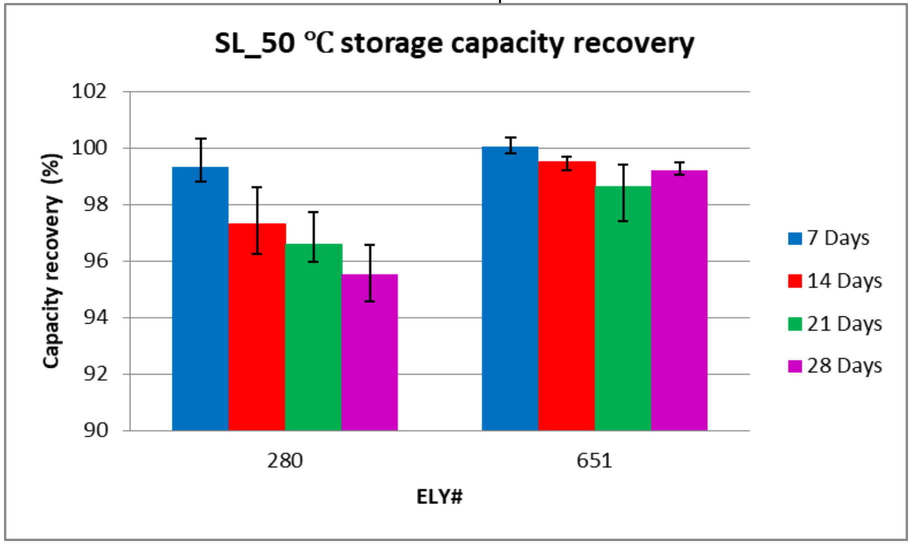
DST cycle life is limited by power drop to about 320 cycles

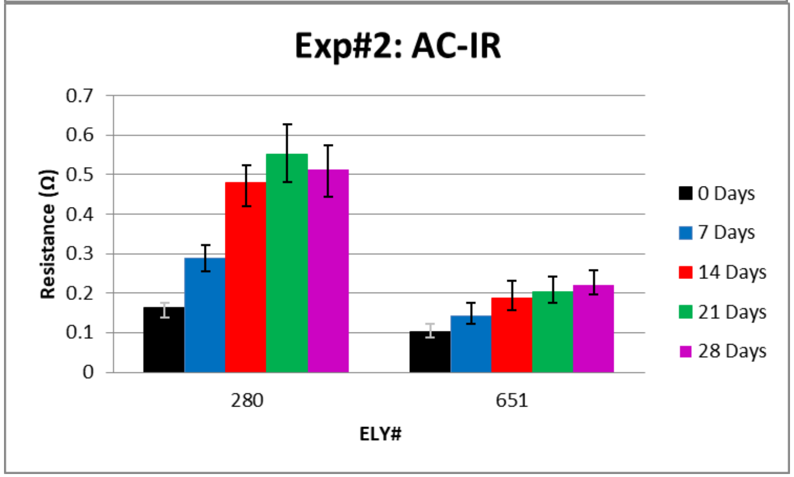
Results confirmed by tests at Idaho National Laboratory

*Si/NCM-70%Ni, 10Ah cells, at 30°C

Gap Analysis – Calendar Life







The cell volume change was measured by the immersion method

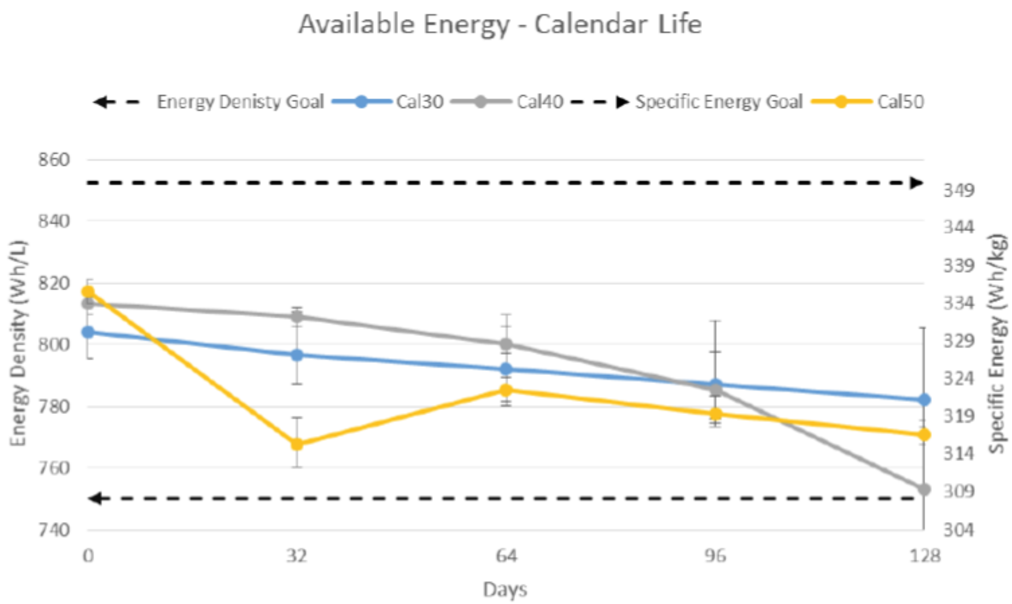
New electrolyte formulation significantly reduces gas formation during storage at 50°C

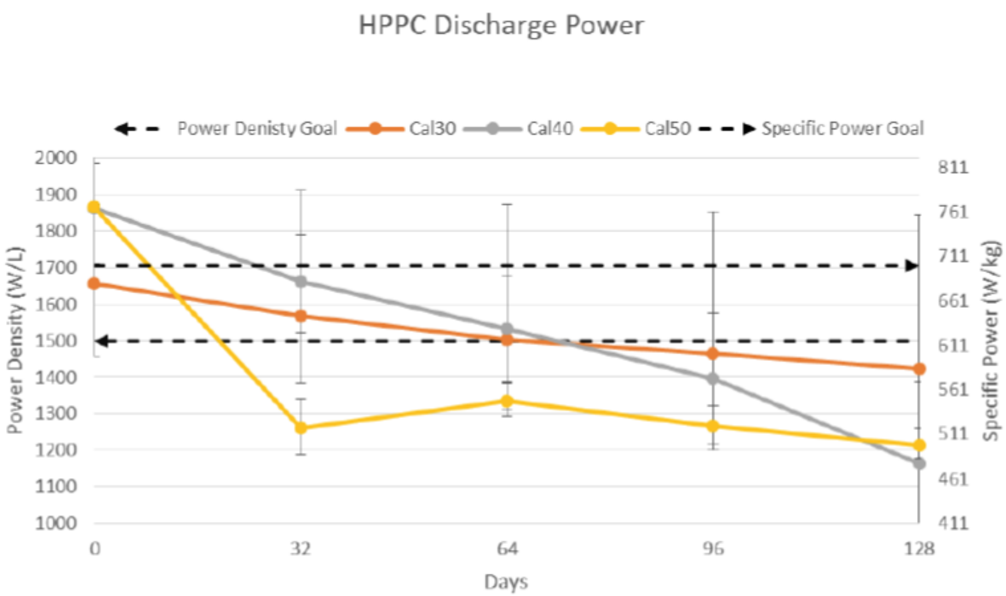
Both AC-IR resistance (power capability) and Recovered Capacity are improved with new electrolyte formulation – good for Calendar Life

*Si/NCM-70%Ni, stored at full charge (4.1V)

Technical Accomplishments:

Gap Analysis – Calendar Life





Only 2.8% energy fade at RPT4 (after 4 months); test continues

Very significant improvement over Year 1 cells, which lasted only 2 months at 50°C

Unclear correlation between aging temperature and fade rate

*Si/NCM-70%Ni, 10Ah cells

Gap Analysis – Other Tests

High Rate Charge – Pass with 84.5% restored in 15 min. (goal >80%)

Thermal Performance – <10% from goal (62% energy vs. 70% goal at -20°C)

Survival Temperature – Pass at -40°C and +66°C

Self-Discharge Test – Pass; cells lost 0.1% over 30-day open-circuit stand (target <1%)

Gap Table for SiNW cells with NCM cathodes

Characteristics at 30°C and BOL	Units	USABC Goals – Cell Level	Amprius Year 2 Cell Level	Amprius Year 1 Cell Level	Comments
Peak Discharge Power Density, 30 s Pulse	W/L	1500	2085/1686	2245/2545	From HPPC/PPT
Peak Specific Discharge Power, 30 s Pulse	W/kg	700	857/685	906/1025	From HPPC/PPT
Peak Specific Regen Power, 10 s Pulse	W/kg	300	654	646	VmaxPulse>Vmax100
Available Energy Density @ C/3 Discharge Rate	Wh/L	750	830	758	Beginning of Life
Available Specific Energy @ C/3 Discharge Rate	Wh/kg	350	342	306	Beginning of Life
Available Energy @ C/3 Discharge Rate	kWh	N/A	0.01	0.009	Beginning of Life
Calendar Life	Years	15	>1	<1	Under Evaluation
DST Cycle Life (80% DOD)	Cycles	1000	~320	~550	

Gap Table for SiNW cells with NCM and LCO cathode

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Characteristics at 30°C and BOL	Units	USABC Goals – Cell Level	Amprius Q8 (Vendor 2) Cell Level	Amprius Q7 (Vendor 1) Cell Level	Comments
Selling Price @ 100K units	$/kWh	$100	TBD	TBD	
Operating Environment	°C	-30 to +52	-30 to 52	-30 to 52	
Normal Recharge Time	Hours	< 7 Hours, J1772	3 Hours	3 Hours	
High Rate Charge	Minutes	80% ΔSOC in 15 min	85% ΔSOC in 15 min	86% ΔSOC in 15 min	
Maximum Operating Voltage	V	N/A	4.1	4.1	
Minimum Operating Voltage	V	N/A	2.5	2.5	
Peak Current, 30 s	A	400	8.25	8.25	From Peak Power test
Unassisted Operating at Low Temperature	%	> 70% Useable Energy @ C/3 Discharge Rate at -20°C	~62% Useable Energy @ C/3 Discharge rate at -20 °C	> 72% Useable Energy @ C/3 Discharge rate at -20 °C	
Survival Temperature Range, 24 Hr	°C	-40 to+ 66	-40 to 66	-40 to 66	
Maximum Self-discharge	%/ mon	< 1	0.1%	0.2%	

40Ah vehicle cell development

Multiple 40Ah cells were assembled in 2017 with anode from the R2R pilot line

70% Ni NCM was selected for 40Ah cell demonstration

DCIR was 193 mOhm*cm^2, similar to lower capacity cells

Initial measurements met model target:

- Capacity: 45.9 Ah at C/5 rate
- Cell weight = 450.7g
- Cell size = 6.0x96x288mm (body only)
- **350 Wh/kg and 925 Wh/L**

Further cell builds on hold to focus on Cycle Life and Calendar Life improvement

Response to Reviewer Comments

Amprius thanks reviewers for the positive comments and for the interest shown in the silicon nanowire technology. Amprius agrees that cycle life and calendar life are major obstacles toward EV applications, and has allocated significant resources in Year 2 of the program toward these goals. Although significant progress was made in both cycle life and calendar life directions, the performance is still far from the end goals. Year 3 work is focused even more on these two shortcomings.

Amprius addressed the cost of the nanowire technology question by installing and operating the roll-to-roll anode line, including for the fabrication of anode for the 40Ah cell format. Based on the precursor efficiency utilization and line throughput, it is estimated that a line with a capacity/throughput 5-10 times higher is needed in a production facility of at least 30MWh annually to reach cost parity with graphite cells.

Collaborations:

Team Overview

Amprius is the only project team member. However, Amprius works with multiple partners for cathode and electrolyte development:

BASF
Toda
Posco
Ecopro
L&F Materials
CamxPower
Forge Nano

BIC Indiana
Iontensity
University of Michigan
Wuxi Amprius

BASF
Daikin
ShanShan
Panaxetec
Solvay
Wildcat

Remaining Challenges and Barriers

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Sourcing high energy density coated cathodes and materials

- NMC materials are produced in a variety of formulations and structures. Selecting a material with high capacity and high cycle life requires a large number of trials and coating conditions of high quality – similar to those in state of the art commercial cells

Cycle life improvement

- Amprius continues to increase the cycle life by optimizations of the electrolyte formulation, anode structure, cathode materials and coating, operating voltage and separator type

High temperature stability and Calendar Life

- Amprius will continue to optimize the electrolyte formulation for minimum gas formation reactions at high temperature with Ni-rich NCM cathodes. Coatings on cathodes are also developed in collaboration with cathode vendors. A systematic evaluation of the effect of maximum operating voltage on Calendar Life started.

Energy density and specific energy

- Although specific silicon nanowire-cathode combinations exceed USABC targets at beginning of life, the margin needs to be higher in order to meet the targets at end of life
- High energy density and specific energy cells usually have lower cycle life. Optimizations and improvements in one direction have to be verified for effects on the rest of specifications

Future Activities – Through FY2018

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Continue cell optimizations to increase energy, cycle life and calendar life

- Evaluate operational voltage range effect on cycle life
- Use design of experiment methodology to reduce the number of experiments for screening and optimization of new electrolyte formulations
- Fast screen electrolyte at elevated temperature (50°C) by cycle life and storage
- Verify best electrolyte formulations in 2Ah and 10Ah form factors

Finish testing 10Ah cell performance toward gap table specifications

- Evaluate all electrical specifications in parallel with Idaho National Laboratory
- Collaborate with Sandia National Laboratory for safety evaluation

Deliver end of project cells with improved Cycle Life and Calendar Life

Any proposed future work is subject to change based on funding levels

Summary

Amprius assembled and evaluated cells with silicon nanowire anodes and NMC cathodes that achieved 350Wh/kg and 925Wh/L in the 45Ah form factor

Amprius assembled, delivered and evaluated cells with silicon nanowire anodes and Ni-rich NCM cathodes that achieved over 340 Wh/kg and 830 Wh/L and cycled over 320 DST cycles

The Calendar Life of Si/NCM cells was significantly improved by electrolyte and formation protocol development, even while increasing the energy density of the cells by using NCM cathodes with increased nickel content