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

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ES241

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Overview

Timeline

- Start date: January 2015
- End date: January 2018
- Percent complete: 40%

Barriers

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

Budget

- Total project funding:

  $5,501,098
  - DOE share: $2,750,549
  - Contractor share: $2,750,549
- FY16 received: $1,401,243
- FY17 projected: $2,802,499

Partners

- Amprius – Project Lead

Relevance:

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	On Track
Jan-18	Deliverable: • Deliver 30 pouch cells with a capacity ≥ 40 Ah, energy density ≥ 937.5 Wh/L, specific energy ≥ 437.5 Wh/kg, and DST cycle life ≥ 1,000	On Track

Relevance:

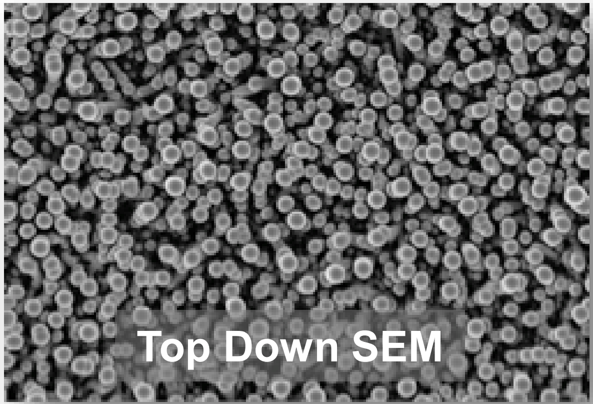
Milestones and Timing

USABC 2015	start	end	66%
1. 2Ah Baseline cell development	**01/12/15**	**07/12/17**	**82%**
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**	**07/11/17**	**64%**
1.4.1. Energy and cycle life development	01/11	07/11	80%
1.4.2. High & low temperature performance development	04/13	07/11	75%
1.4.3. Mechanical, electrical, and thermal abuse testing	07/13	07/11	25%
M1: 800Wh/L, 380Wh/kg, 850 cycles	01/11	01/11	0%
M2: 850 Wh/L, 400Wh/kg, 1,000 cycles	07/12	07/12	0%
2. 10Ah Interim cell development	**07/13/15**	**08/31/17**	**69%**
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**	**08/31/17**	**67%**
2.5.1. Assembly optimization	01/12	01/10	100%
2.5.2. Performance evaluation	01/12	08/31	75%
2.5.3. Mechanical, electrical, thermal abuse	01/02	08/31	0%
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	0%
2.6. Performance optimization activities	01/12	07/07	0%
M4: 875Wh/L, 415Wh/kg, 850 cycles	07/07	07/07	0%
3. 40Ah Vehicle cell development	**02/08/16**	**01/05/18**	**37%**
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	45%
3.5. Iterative design validation, anode production, cell assembly	**11/07/16**	**01/04/18**	**12%**
3.5.1. Assembly optimization	11/07	01/04	20%
3.5.2. Performance evaluation	01/02	01/04	10%
3.5.3. Mechanical, electrical, thermal abuse	07/03	01/04	0%
M5: 850Wh/L, 400Wh/kg, 750 cycles	07/07	07/07	0%
D3: 30 40Ah cells with 937.5 Wh/L, 437.5 Wh/kg, 1,000 cycles	01/05	01/05	0%

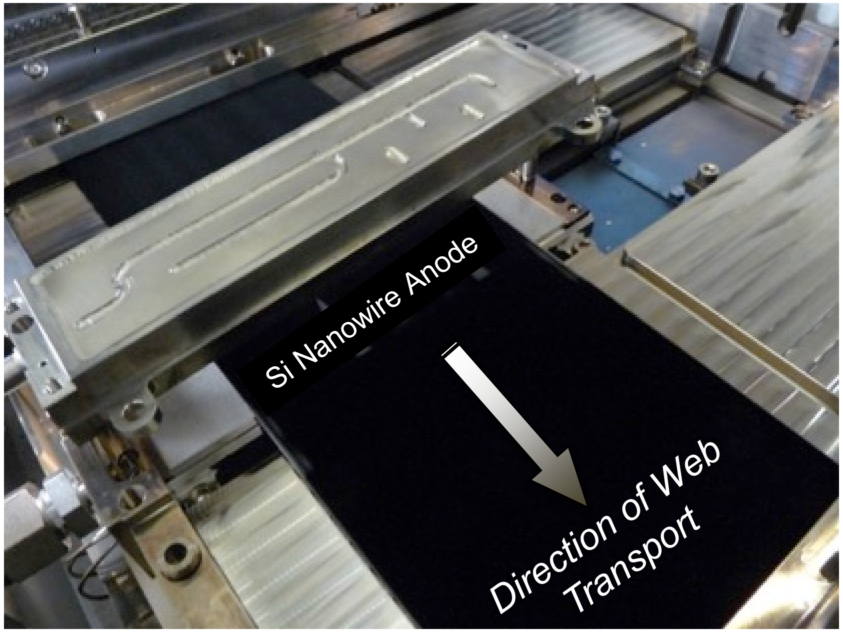
Approach:

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



During Q1 2017, Amprius qualified for production a first of its kind pilot line tool for roll-to-roll production of double-sided, rooted silicon nanowire anodes

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

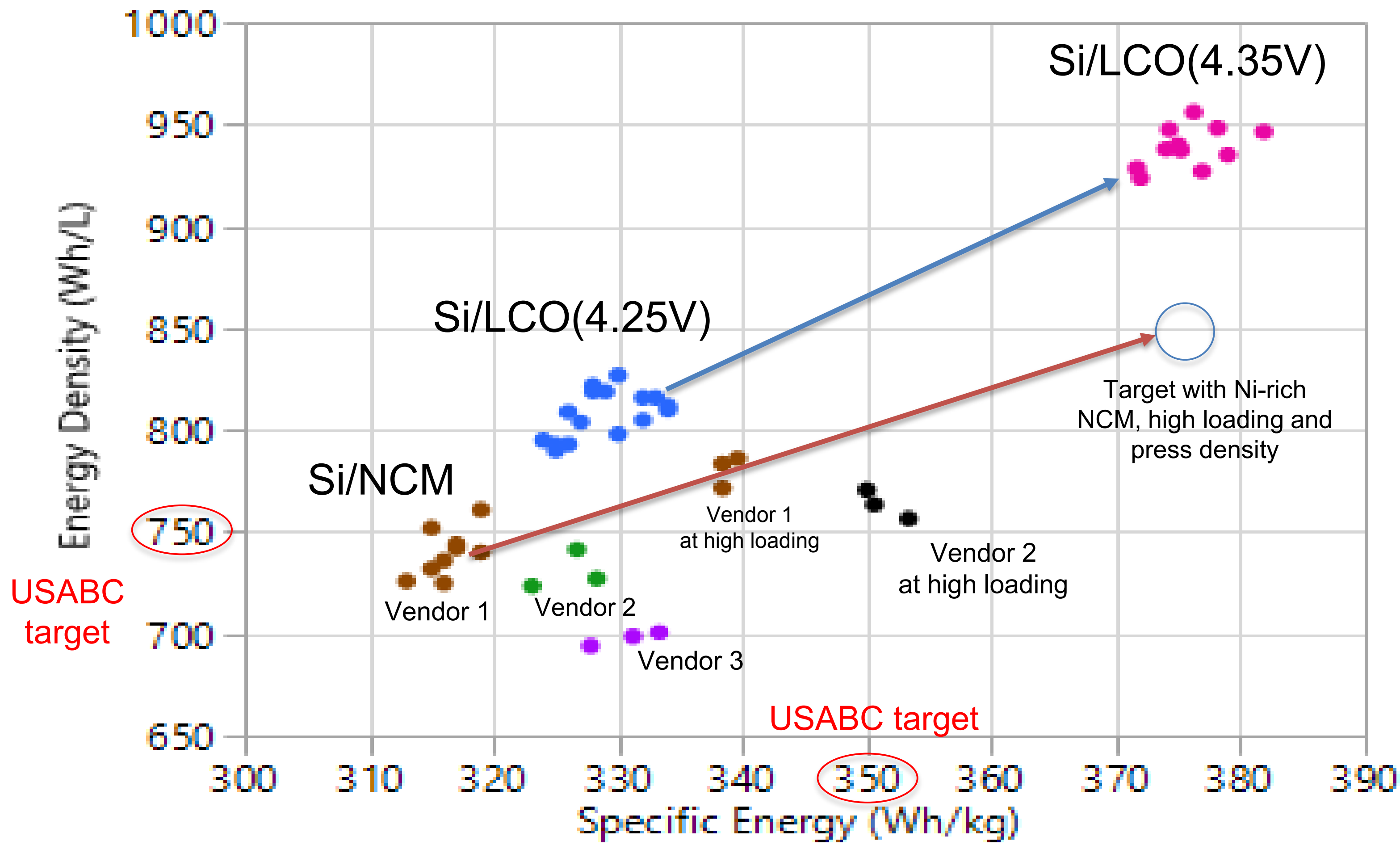
De-risk form factor scale-up in an intermediary cell form factor of 10 Ah

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

FY 2016 Accomplishments

- Delivered 30 Silicon Nanowire-NMC cells to INL and SNL for performance and safety evaluation
- Completed the gap chart analysis – with results exceeding performance targets for many criteria
- DST cycle life – Exceeded 500 cycles with NMC cathode and 300 cycles with LCO cathode
- Matched silicon nanowire anodes with higher capacity NCM cathodes
- Developed SiNW/NCM 10Ah cell form factor with specific energy of 340Wh/kg and 830Wh/L

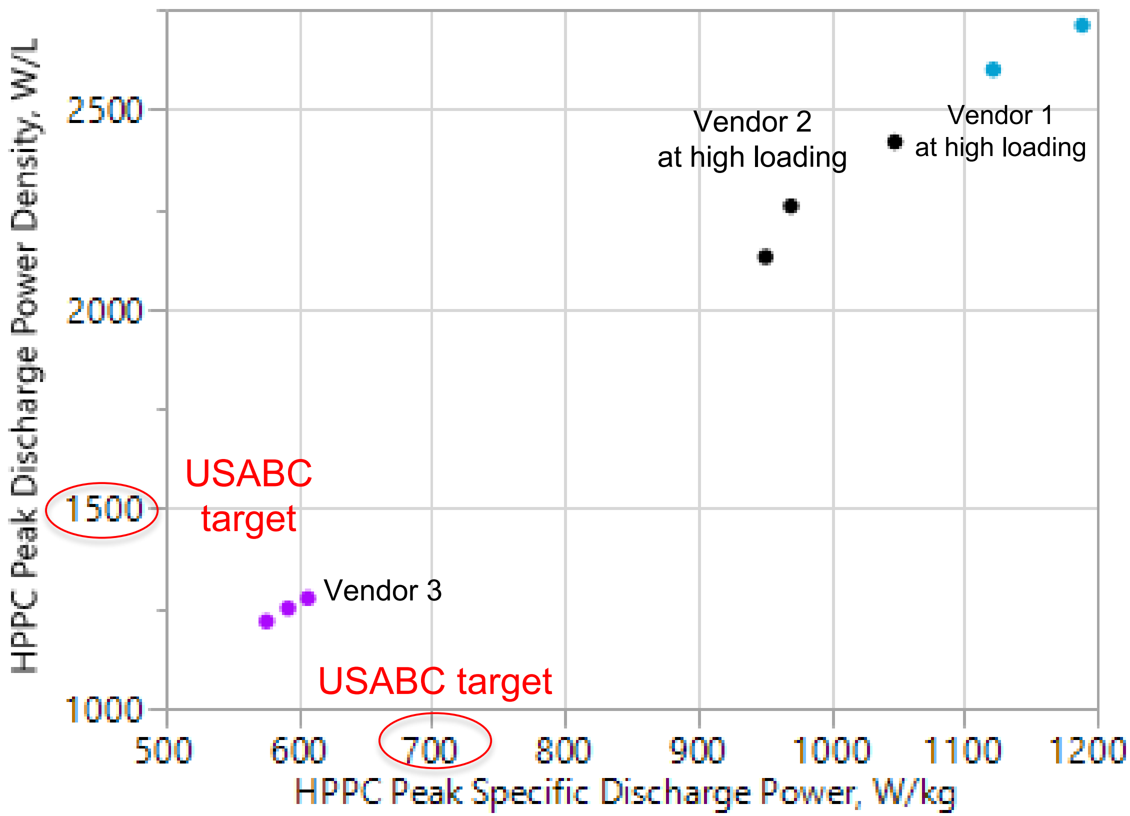
Gap Analysis - Energy



- All cells had the same form factor, capacities in the 2.6-3.1Ah range
- Cathode energy density and specific energy has to be higher than that of NMC523 – minimum 180 mAh/g
- Advanced cathodes meet the requirements

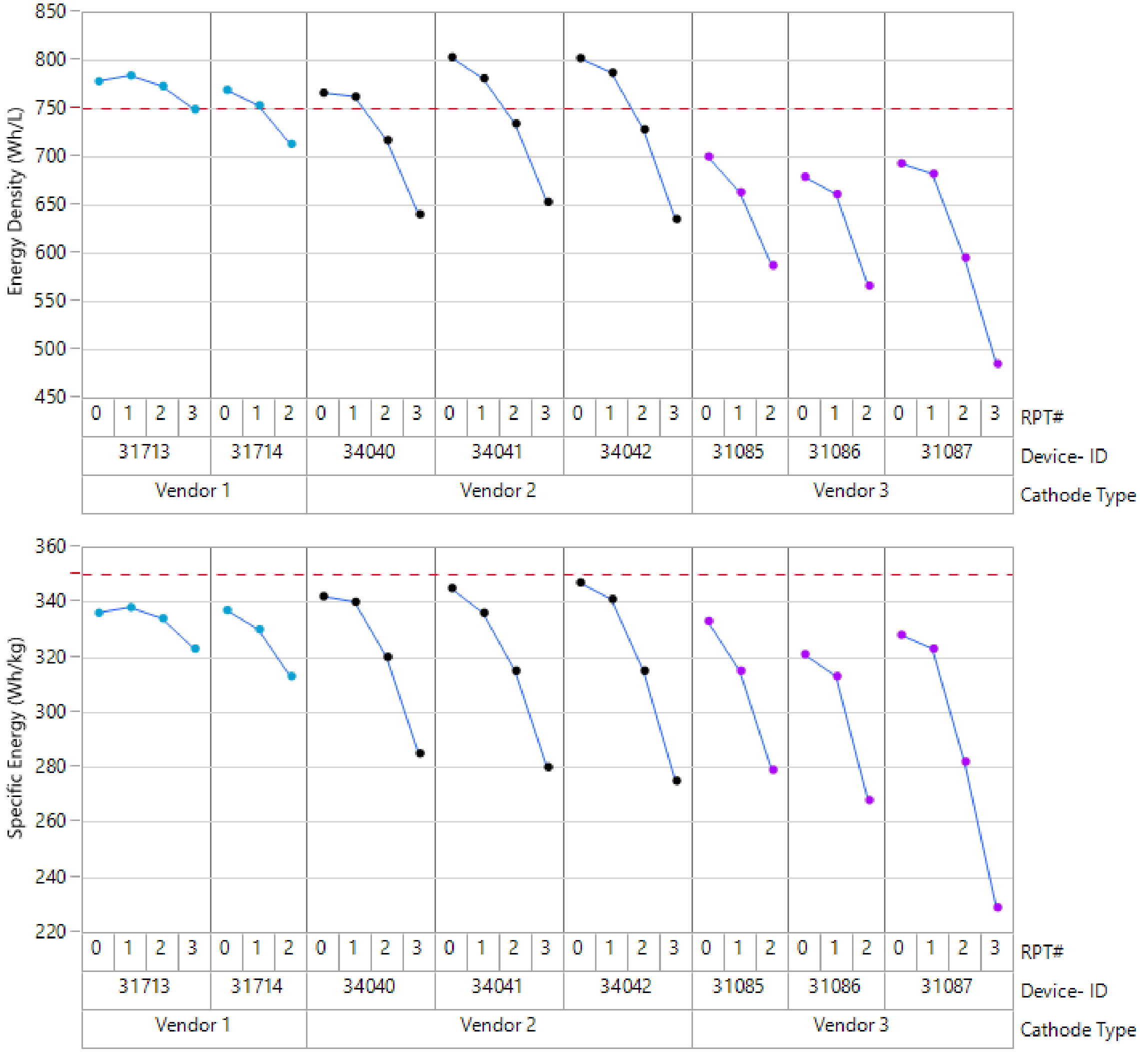
Technical Accomplishments:

Gap Analysis - Power



- •All cells had the same form factor, capacities in the 2.6-3.1Ah range
- •Peak Power Values were measured by HPPC test at beginning of life
- •Initial power performance exceeds EOL targets by more than 20% - good reserve for operational life

Gap Analysis – DST Cycle Life

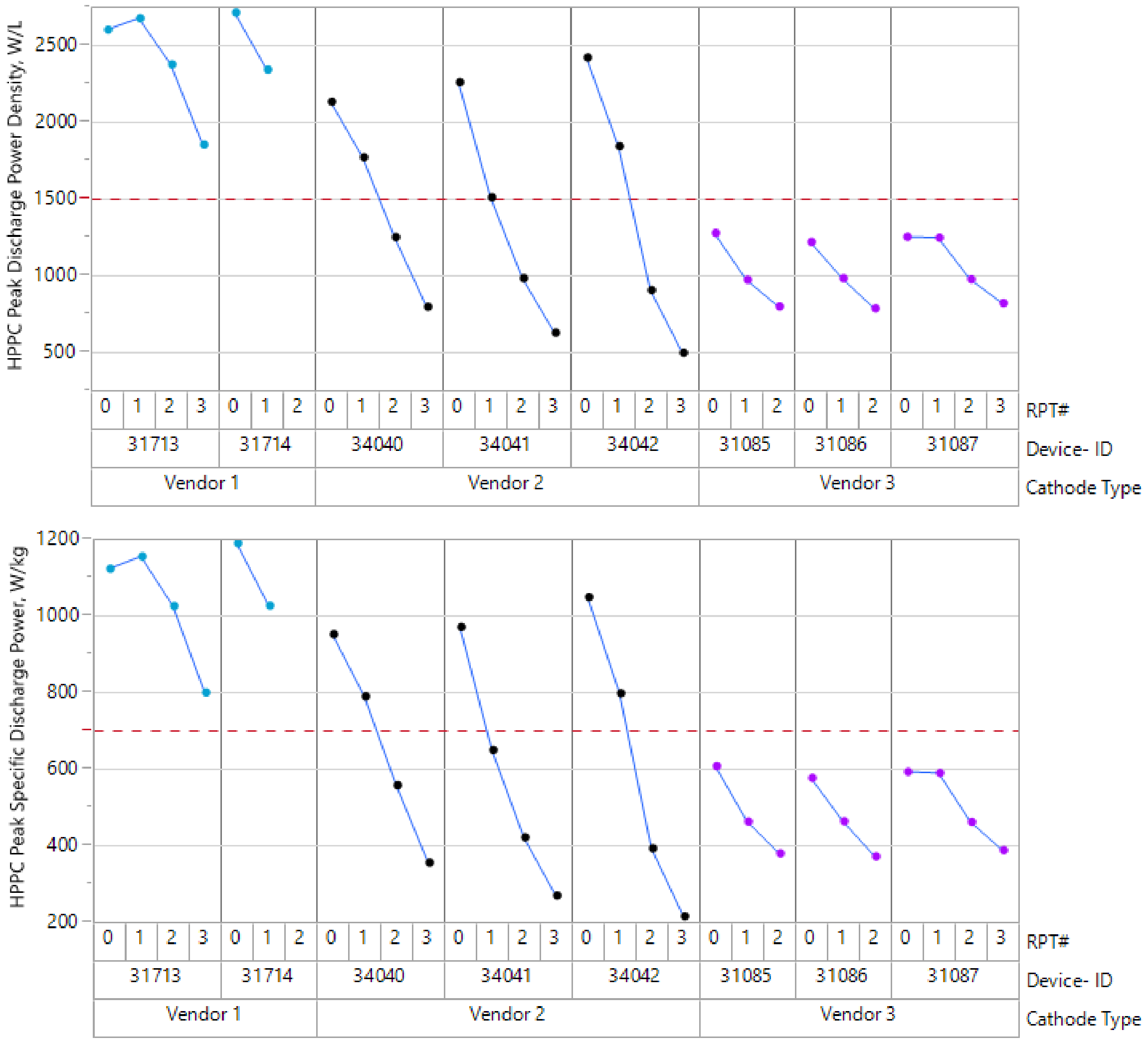


- All cells (2.6-2.8Ah) were tested by DST cycle life at 30^{o}C
- Vendor 1 cathode has the lowest capacity among the three, but is coated at high loading (48mg/cm2) by Amprius China
- Vendor 2 cathode was coated by Amprius China at a loading of 46mg/cm2 (double side) and pressed to ~3.5mg/cm3
- Vendor 3 cathode has higher capacity than Vendor 2 powder, but was coated by US supplier and has lower loading, press density and active content

•Reference Performance Tests (RPT) were performed every 120 cycles (~32 days)

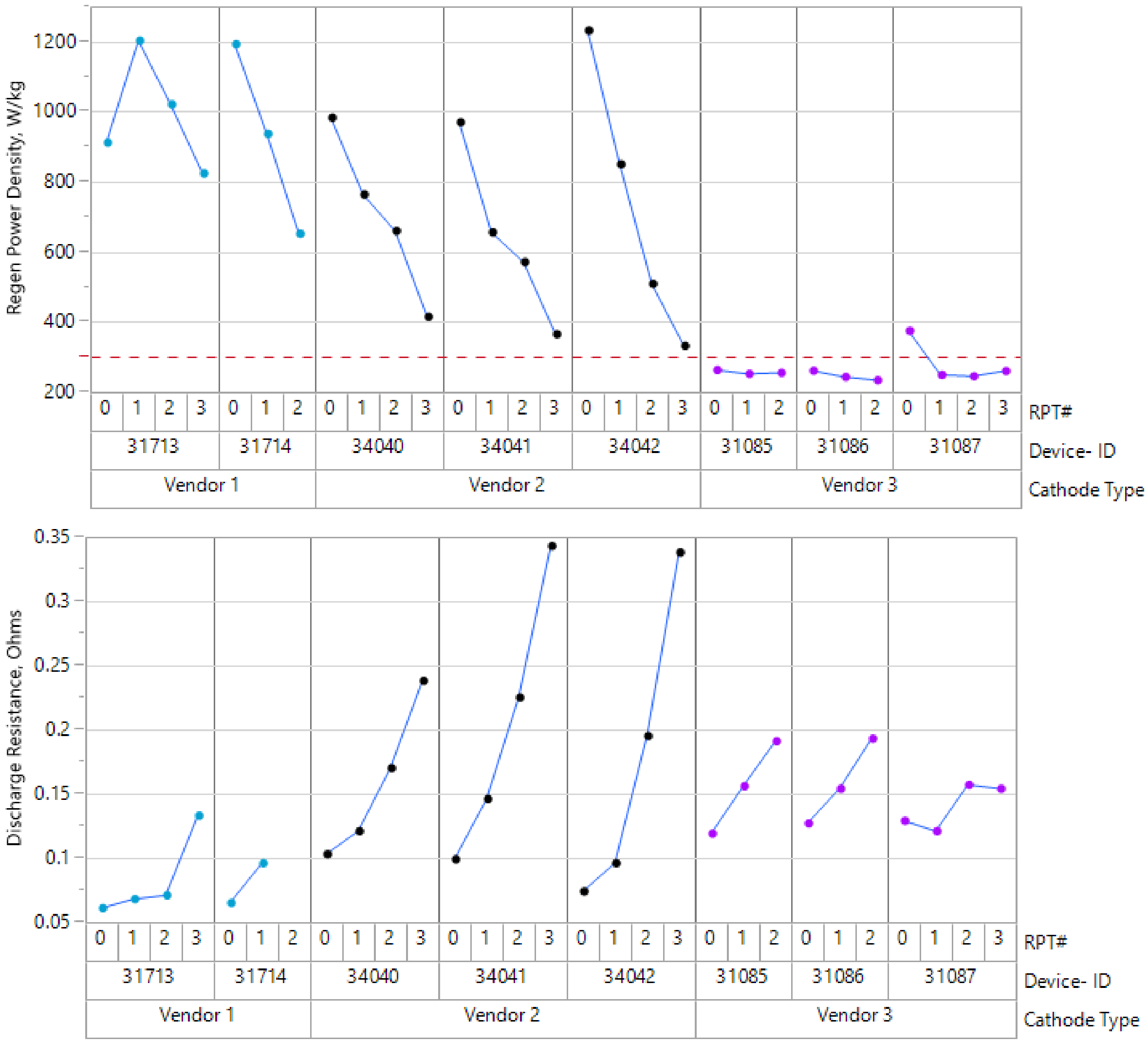
•The energy performance is close to target at beginning of life

Gap Analysis – DST Cycle Life



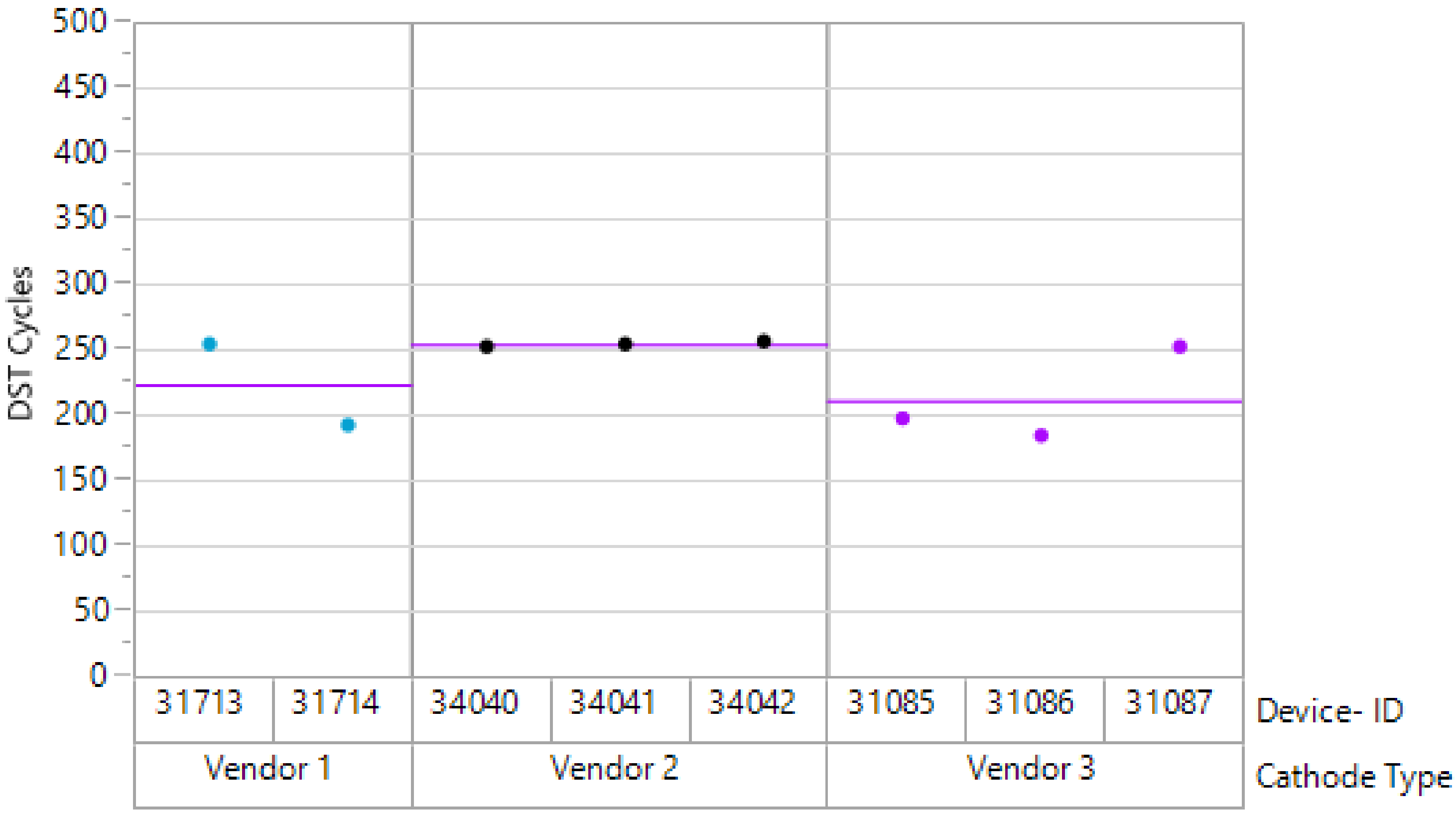
- Power performance with Vendor 1 cathode exceeds targets over the entire cycle life
- Vendor 3 cathode performance is probably limited by the coating quality
- Power performance with Vendor 2 degrades faster than with the other cathodes

Gap Analysis – DST Cycle Life



- •Regen Power exceeds target over the entire cycle life
- •Discharge resistance reflects power performance
- •Vendor 1 cathode has the best power behavior

Gap Analysis – DST Cycle Life



- DST Cycle Life was limited by electrolyte optimized for cycle life at low rates and not for power retention

Technical Accomplishments:

Gap Table for SiNW cells with NCM cathodes

Characteristics at 30°C and BOL	Units	USABC Goals – Cell Level	Amprius Q8 (Vendor 2) Cell Level	Amprius Q7 (Vendor 1) Cell Level	Comments
Peak Discharge Power Density, 30 s Pulse	W/L	1500	2405/2715	2245/2545	From HPPC/PPT
Peak Specific Discharge Power, 30 s Pulse	W/kg	700	990/1116	906/1025	From HPPC/PPT
Peak Specific Regen Power, 10 s Pulse	W/kg	300	1061 at 1% DOD	646 at 1% DOD	VmaxPulse>Vmax100
Available Energy Density @ C/3 Discharge Rate	Wh/L	750	837	758	Beginning of Life
Available Specific Energy @ C/3 Discharge Rate	Wh/kg	350	337	306	Beginning of Life
Available Energy @ C/3 Discharge Rate	kWh	N/A	0.01	0.009	Beginning of Life
Calendar Life	Years	15	TBD	<1	Under Evaluation
DST Cycle Life (80% DOD)	Cycles	1000	~250*	~550	

Technical Accomplishments:

Gap Table for SiNW cells with NCM and LCO cathode

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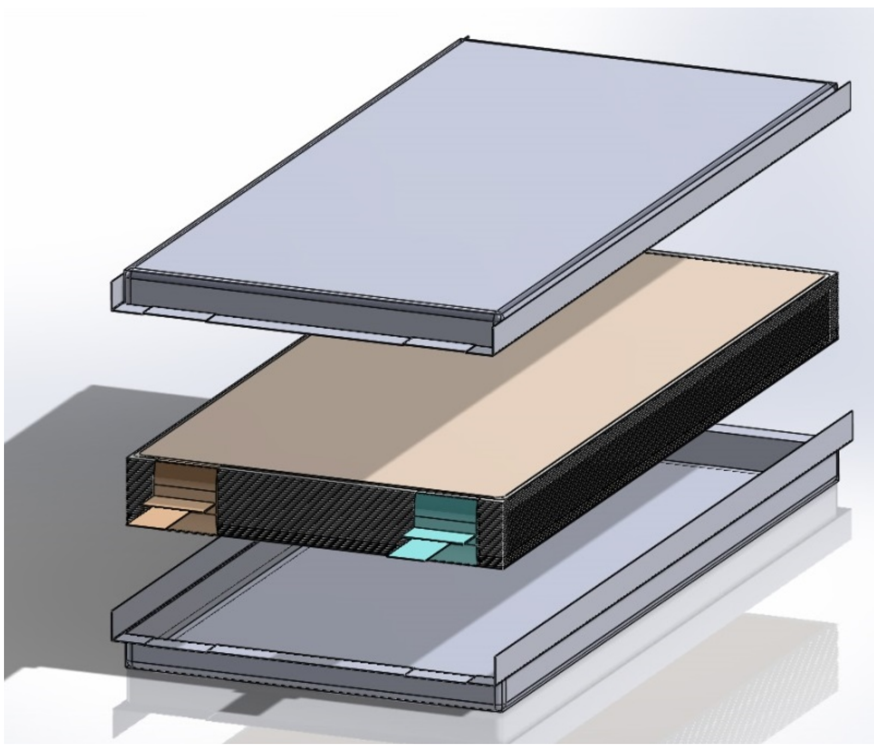
Characteristics at 30°C and BOL	Units	USABC Goals – Cell Level	Amprius Q8 (Vendor 2) Cell Level	Amprius Q7 (Vendor 1) Cell Level	Comments
Selling Price @ 100K units	$/kWh	$100	TBD	TBD	
Operating Environment	°C	-30 to +52		-30 to 52	
Normal Recharge Time	Hours	< 7 Hours, J1772	3 Hours	3 Hours	
High Rate Charge	Minutes	80% ΔSOC in 15 min		86% ΔSOC in 15 min	
Maximum Operating Voltage	V	N/A	4.15	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		> 72% Useable Energy @ C/3 Discharge rate at -20 °C	
Survival Temperature Range, 24 Hr	°C	-40 to+ 66		-40 to 66	
Maximum Self-discharge	%/ mon	< 1		0.2%	

10Ah cell development

Amprius produces anodes in the form factor required by the >10 Ah Silicon-NCM cells

Cell	Ah	Wh	Wh/L	Wh/kg	W/L_{HPPC}	W/kg_{HPPC}	W/kg_{HPPC} Regen	Av. En.	W/L_{PPT}	W/kg_{PPT}
1	10.5	34.2	838	336	1548	621	571	Pass	2375	952
2	10.5	34.1	814	337	1488	616	409	Pass	2212	916

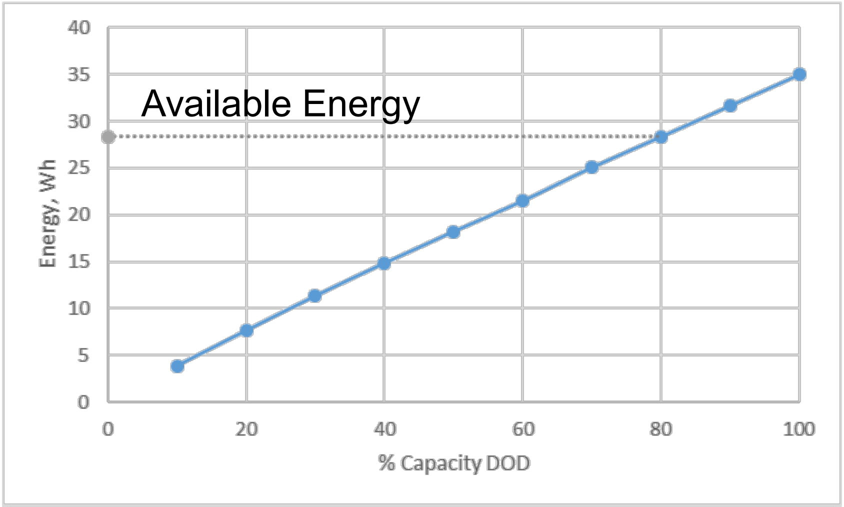


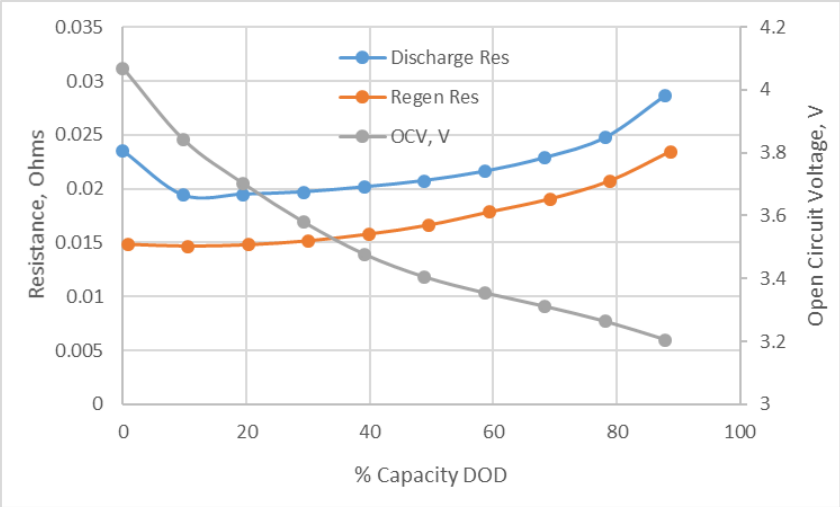
Cell Specifications:

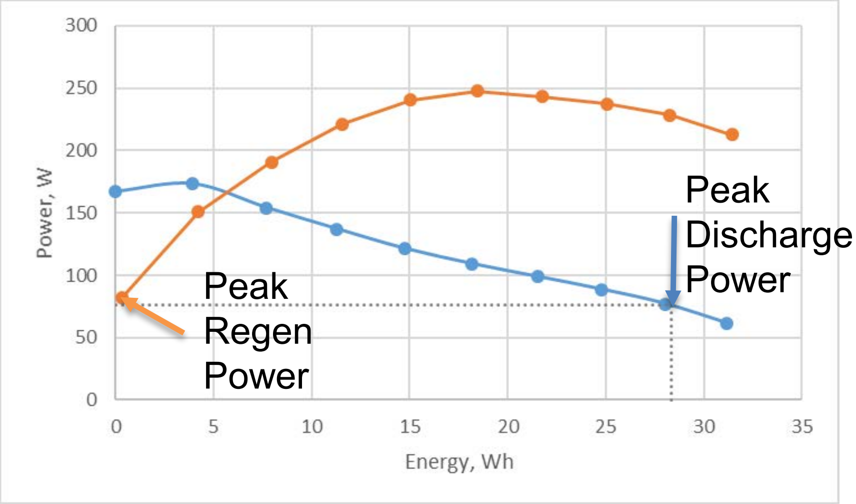
- Rated Capacity: 10.2 Ah at C/3 rate
- Vmax100 = 4.15V
- Vmin0 = 2.5V
- Cell weight = 104.5g
- Cell size = 8x51x109mm
- 335 Wh/kg and 835 Wh/L

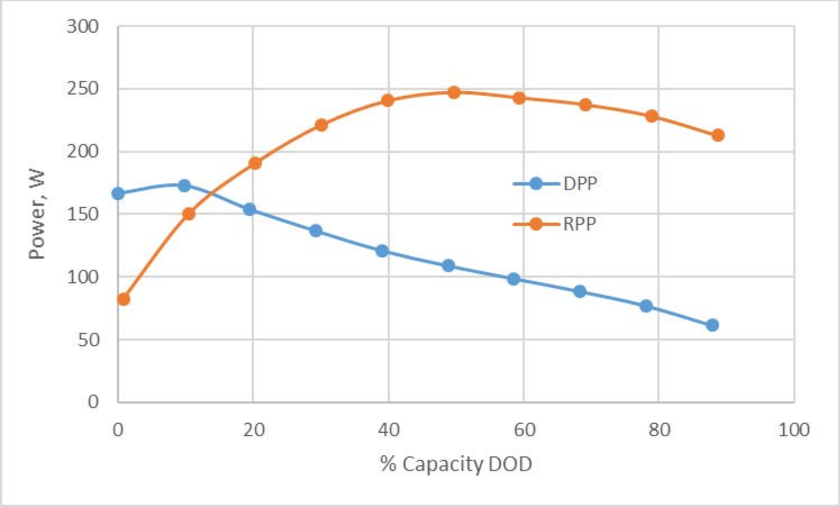
10Ah cell development

Initial Reference Performance Test data







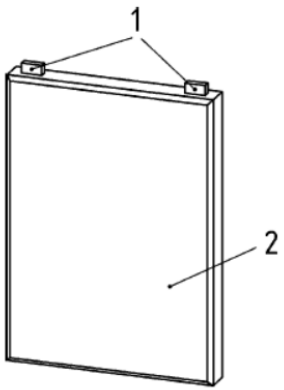


Technical Accomplishments:

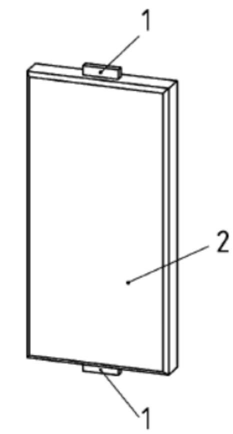
40Ah vehicle cell development

Designation[a] (A1A2A3A4N1/N2/N3)	Design dimensions				
	T	W	h	p	p'
VIFA—/130/221	-	130	221	-	-
VIFA—/161/227	-	161	227	-	-
VIFA—/162/142	-	162	142	-	T/2
VIFA—/164/226	-	164	226	-	-
VIFA—/164/232	-	164	232	-	-
VIFA—/210/121	-	210	121	-	-
VIFA—/244/190	-	244	190	-	-
VIFA—/253/172	-	253	172	-	-
VIFA—/270/135	-	270	135	-	-
VIFA—/280/180	-	280	180	-	-
VIFA6/249/192	5,9	249	192	124	2,95
VIFA9/136/230	9	136	230	30	4,5
VIFA9/216/262	6,00-9,00	216	262	-	-
VIFA11/223/224	<11	223	224	-	-
VIFA13/330/162	13	330	162	-	t/2
VIFA19/343/245	18,5	343	245	80	9
VIFB—/99/300	0	99	300	0	0
VIFB—/121/243	-	121	243	-	t/2
VIFB—/126/325	-	126	325	-	-
VIFB—/128/310	-	128	310	-	-
VIFB—/128/325		128	325		
VIFB—/134/290	-	134	290	-	-
VIFB—/144/251	-	144	251	-	-
VIFB—/159/291	-	159	291	-	-
VIFB—/172/254	-	172	254	-	-
VIFB—/173/235	-	173	235	-	-
VIFB—/210/260	-	210	260	-	-
VIFB5/136/251	3,00-5,00	136	251	-	-

[a] Details for designation see clause 5.



a) Type A



b) Type B

Cell Model Specifications with current cathode:

- Rated Capacity: 40 Ah at C/3 rate
- Vmax100 = 4.2V
- Vmin0 = 2.5V
- Cell weight = 382g
- Cell size = 5.0x99x300mm
- 348 Wh/kg and 902 Wh/L

Cell components sourcing and tooling is complete

Response to Reviewer Comments

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Question 1, Reviewers 3 and 4: “too much emphasis on cobalt-based cathode materials”

- Answer: During the first year Amprius used LCO cathodes as basis for comparison, having developed cells mostly with LCO until then. All 2Ah and 10Ah cells developed in FY16 included NMC type cathodes.

Question 3: “No collaborations in this project”

- Based on previous projects experience, Amprius has not limited the choice of cathode or other materials by teaming with one of the cathode suppliers. However, Amprius has collaborated on this project with BASF, Toda, Posco, Ecopro, L&F and CamxPower on matching cathode for silicon nanowire, and with BIC Indiana and University of Michigan for cathode coating. Amprius has also collaborated with BASF, Daikin, ShanShan, Panaxetec and Solvay for electrolyte and additive development.

Question 4: “No details regarding the approach for cathode and anode developments are given”

- As mentioned above, Amprius collaborates with many vendors for the development of cathode powders (type, coatings) and electrolyte formulations and additives. These materials and formulations are further developed in house, typically by design of experiment methodologies for screening and optimization. The metrics that are measured correspond to USABC targets for cell performance, including those that present the largest gaps toward goals.

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

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, and separator type

High temperature stability and Calendar Life

- Amprius will continue to optimize the electrolyte formulation for minimum gassing reactions at high temperature with Ni-rich NCM cathodes. Coatings on cathodes are also developed in collaboration with cathode vendors.

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 FY2017

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

- Evaluate new, higher energy cathode materials (minimum 185 mAh/g)
- Use design of experiment methodology to reduce 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

Develop the 40Ah cell form factor

- Iterate cell assembly and evaluate performance
- Assemble final cells deliverables

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

Summary

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Amprius assembled and evaluated cells with silicon nanowire anodes and NMC523 cathodes that achieve 315 Wh/kg and 740Wh/L and cycle over 500 DST cycles

Amprius assembled and evaluated cells with silicon nanowire anodes and Ni-rich NCM cathodes that achieve over 335 Wh/kg and 830 Wh/L and cycle over 250 DST cycles

Amprius developed a 10Ah cell that met design specifications and reduced the performance gap toward USABC goals; full evaluation is in progress

Amprius scaled-up the hardware and processes for a 40Ah form factor, the deliverable for the last year of the project