High Energy Lithium Batteries for Electric Vehicles

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Envia Systems

2016 DOE Vehicle Technologies Program
Annual Merit Review and Peer Evaluation Meeting
June 6–10, 2016 - Washington D.C.

Project ID: ES247

Program Overview

TIMELINE

- Project start date: Jun 2014
- Project end date: Jun 2017
- Percent complete: ~60%

BARRIERS

- Meet USABC EV energy and power cell specs
- Meet cycle life and calendar life
- Enable a cell cost target of 100$/kWh

BUDGET

- Total project funding:
  - ✓ DOE share: $3,859,246
  - ✓ Envia & partners share: $3,859,246
- Funding received in FY2015: $1,404,866
- Funding for FY2016: $1,549,386

PARTNERS

Nanoscale Components

A123 SYSTEMS

DAIKIN

AsahiKASEI

3M

DUPONT

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Project Relevance

- **Goals:**

  Develop high capacity cathode and anode materials, screen commercial electrolytes and separators, optimize pre-lithiation process and integrate to build high capacity pouch cells that meet the USABC electric vehicle (EV) battery goals for CY 2020

- **Project Timeline:**

Year 1				Year 2				Year 3			
Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12

Project start date: June 26, 2014

- **Barriers and Tasks:**

✓ Develop high capacity cathode and anode materials and electrodes

✓ Mitigate cycle life challenges associated with Si anodes and Li-rich cathodes

✓ Develop an economical and manufacturable pre-lithiation process

✓ Cell development to ensure meeting the cell metrics, safety and cost targets

- **Deliverables:**

  Demonstrate & deliver cells that meet the USABC EV cell targets with independent validation from the National Labs (INL, SNL, & NREL)

- **USABC EV Cell Targets for 2020:**

End of Life Characteristics at 30°C	Units	Cell Level
Peak Discharge Power Density, 30 s Pulse	W/L	1500
Peak Specific Discharge Power , 30 s Pulse	W/kg	700
Peak Specific Regen Power , 10 s Pulse	W/kg	300
Useable Energy Density @ C/3 Discharge Rate	Wh/L	750
Useable Specific Energy @ C/3 Discharge Rate	Wh/kg	350
Useable Energy @ C/3 Discharge Rate	kWh	N/A
Calendar Life	Years	15
DST Cycle Life	Cycles	1000
Selling Price @ 100K units	$/kWh	100
Operating Environment	°C	-30 to +52
Normal Recharge Time	Hours	< 7 Hours, J1772
High Rate Charge	Minutes	80% ΔSOC in 15 min
Maximum Operating Voltage	V	N/A
Minimum Operating Voltage	V	N/A
Peak Current, 30 s	A	400
Unassisted Operating at Low Temperature	%	> 70% Useable Energy @ C/3 Discharge rate at -20 °C
Survival Temperature Range, 24 Hr	°C	-40 to+ 66
Maximum Self-discharge	%/month	< 1

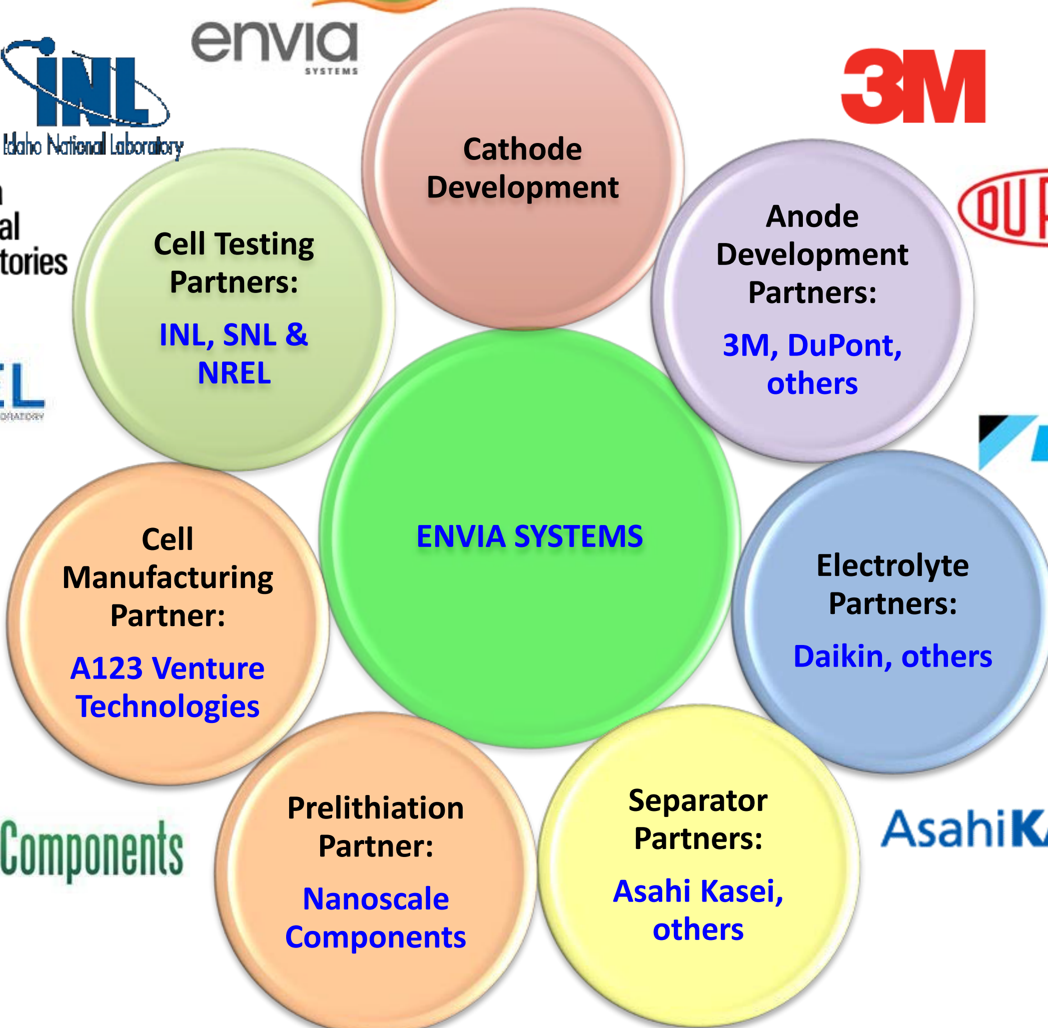
Project Milestones and Gates

Current Status

2016 →

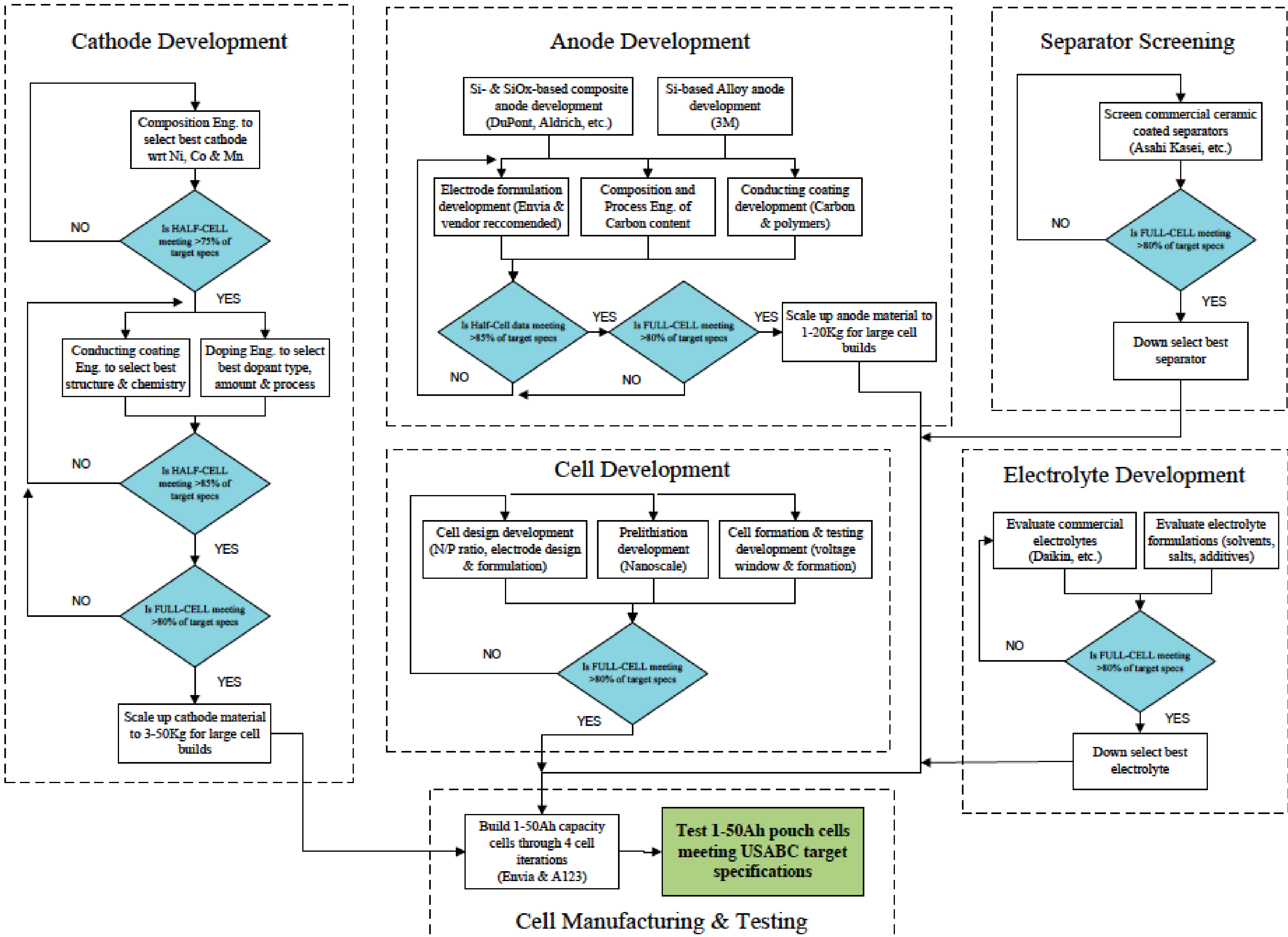
Task Number	Major Project Tasks	PROJECT TIME												Current Status
		YEAR 1				YEAR 2				YEAR 3				
		Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	
8	**MAJOR PROJECT DELIVERABLE SUMMARY**													
6.1.5	Ship 12 (twelve) 20Ah baseline cells fabricated by Envia to selected National Labs for independent testing		◆											Baseline (complete)
6.2.14	Build and test 1Ah cells from cell build #1 as an internal build and report and use learning for future cell builds					◆								Build #1 (complete)
6.3.14	Ship 27 (twenty-seven) 20Ah capacity cells fabricated by A123 from cell build #2 to the National Labs for independent testing							◆						**Build #2 (ongoing)** Expected in Q8
6.4.9	Build and test 20Ah cells from cell build #3 as an internal build and report and use learning for final cell build									◆				
6.5.14	Ship 27 (twenty-seven) 50Ah capacity cells fabricated by A123 from cell build #4 to the National Labs for independent testing											◆		
7.1.3	Deliver final USABC project cell cost model												◆	
8.1	Final USABC project report												◆	
9	**REVIEW AND DECISION GATES**													
9.1	Down-select best cathode composition (Li, Ni, Co, Mn & amount of $Li^{2}MnO^{3}$), conducting coating (polymer, carbon or metallic) and dopant to be integrated in 1Ah cells from cell build #1				◆									complete
9.2	Down-select best prelithiation process conditions (lithiation loading, time, speed, drying, handling, etc.) to build 1Ah cells from cell build #1				◆									complete
9.3	Down-select and focus material development efforts on the most promising Si-based anode approach from development on Si-alloys and Si-C and SiO_x-C composites					◆								complete
9.4	Freeze best separator material to be used in remaining cell builds					◆								ongoing
9.5	Down-select best prelithiation process conditions (lithiation loading, time, speed, drying, handling, etc.) to build 20Ah cells from cell build #3							◆						
9.6	Freeze best cathode composition, conducting coating, dopant and process conditions to build 20Ah cells from cell build #3								◆					
9.7	Freeze best Si-based anode material composition, coating and process conditions to build 20Ah cells from cell build #3								◆					
9.8	Freeze best electrolyte formulation to be used in remaining cell builds								◆					

Development Areas & Partners



Envia has partnered with leaders in their respective fields to develop materials, processes and cells which will meet the USABC EV cell goals

Approach Strategy



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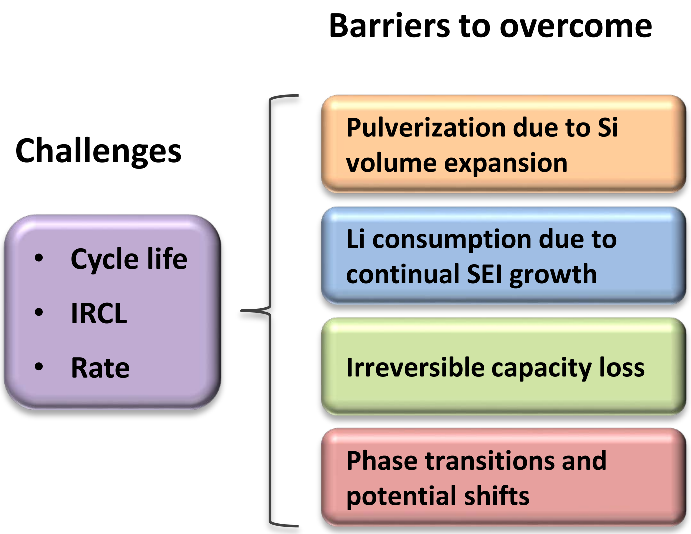
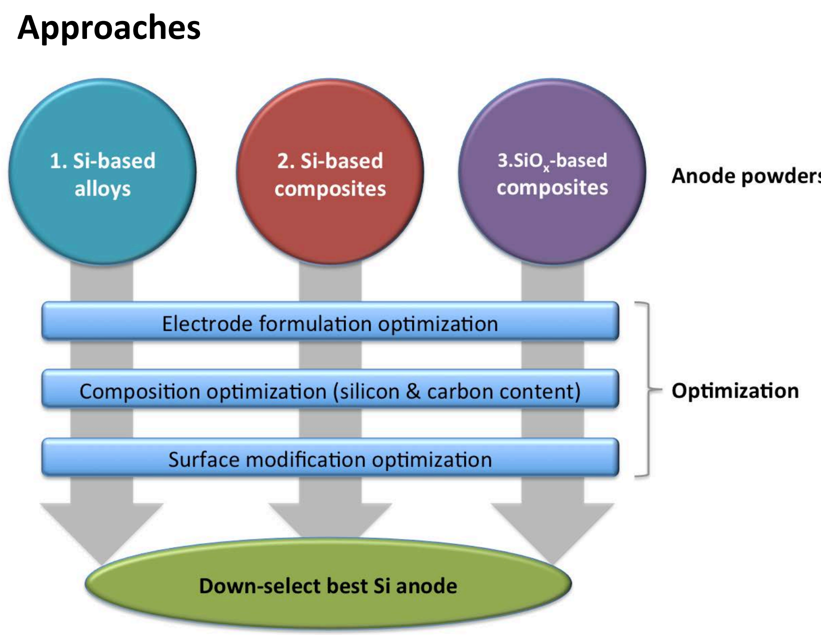
Si-based Anode Challenges & Development

Si-based anode Advantages:

Silicon-based anodes are attractive alternatives to graphite because Silicon can alloy 4.4 Lithium ions per silicon ($Li_{4.4}Si$) resulting in an extremely large theoretical capacity of 4200 mAh/g versus graphite's 372 mAh/g.





Envia develops proprietary Si anodes by using commercially available Si-based materials (Si-based alloys & nSi- and SiO_x-based composites) and applies its electrode formulation, processing, and coating know-how to further improve the performance of the silicon anodes

Surface Modification of SiO-based Anodes

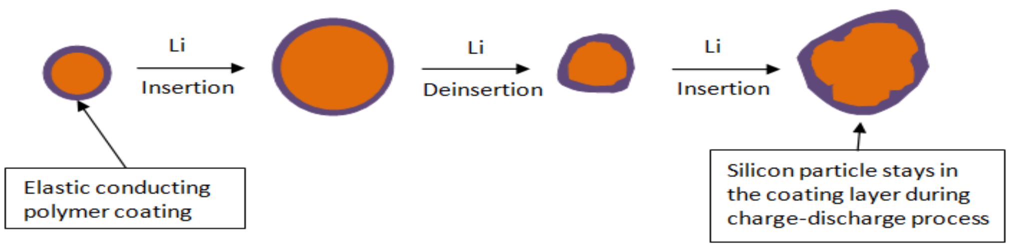
SiO_x-Polymer Composites Anode Development:

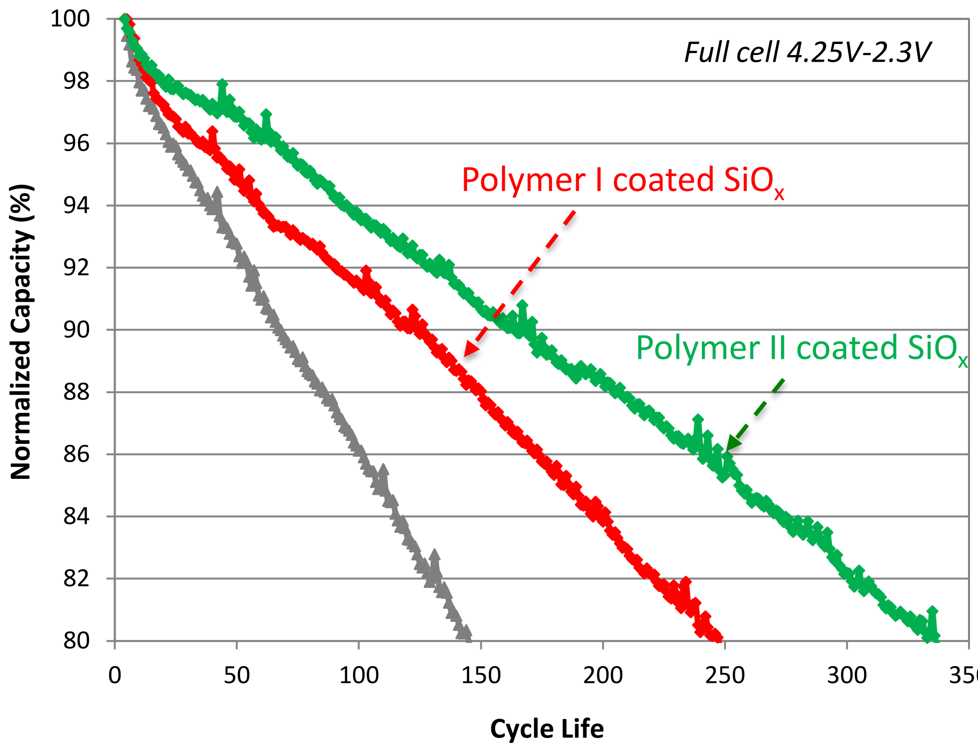
Elastic conducting polymer coatings can:

(1) Improve particle integrity by reducing pulverization

(2) Increase electronic conductivity

(3) Passivate surface and stabilize SEI growth





Significant cycle life improvement is observed for the Polymer-SiO_x composite anodes in coin-cell Full-cells

- Cycle life improvement of 100 & ~200 cycles is observed for polymer I-SiO_x and polymer II-SiO_x composites, respectively
- **Polymer I-SiOx** composite has been successfully scaled-up to Kg levels to build large cells & evaluate cycle life
- **Polymer II-SiO_x** composite is currently being optimized and scaled up to Kg levels
- Large pouch cells are under validation

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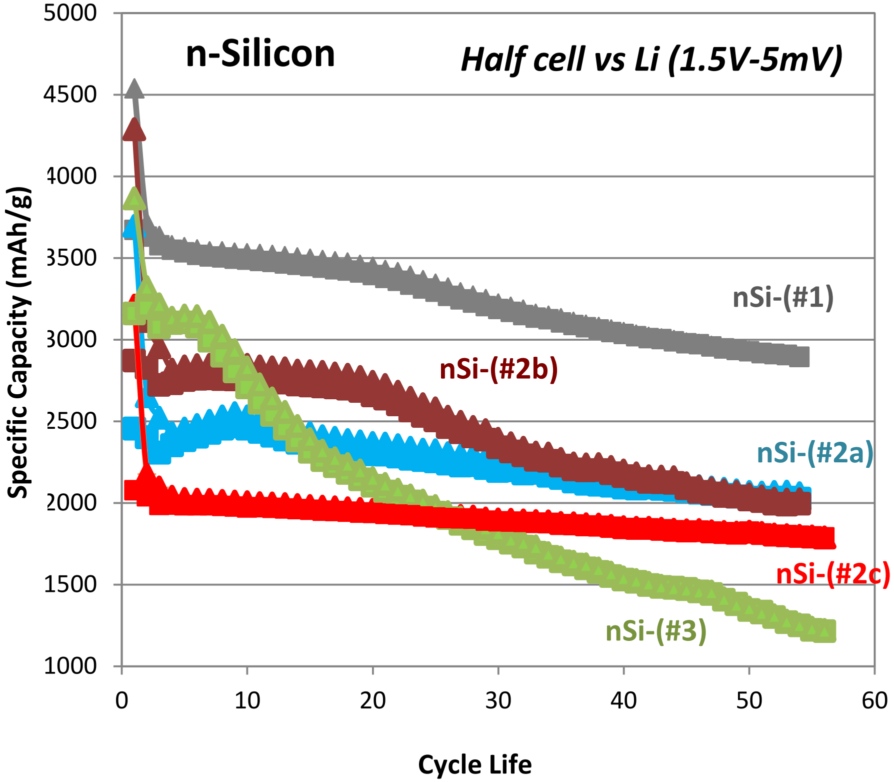
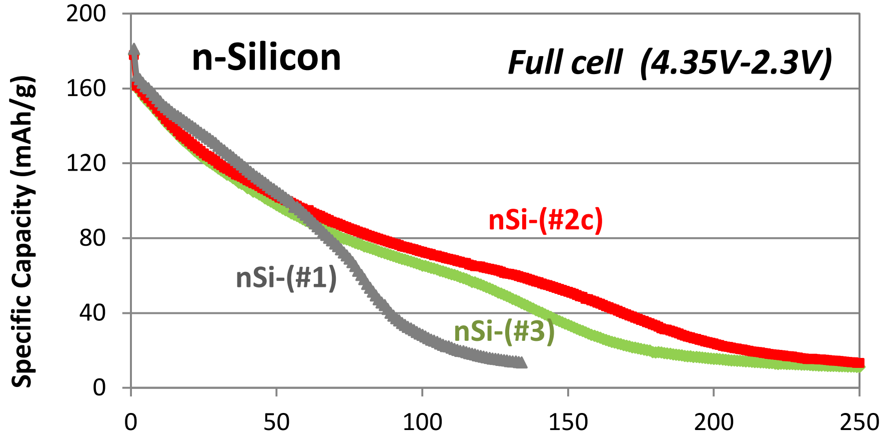
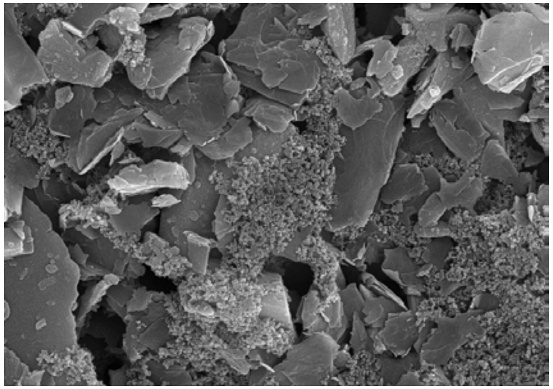
Si-based Anode Development





n-Si from different vendors with different particle size, surface area and IRCL were evaluated in HC and FC CCs

n-Si/SiO Anode Blends



NEXT STEPS:

Evaluate n-Si/SiO anode blends to further increase specific capacity and cycle life by enabling new cell designs while precisely engineering the morphology and environment of the anode electrode

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Cathode Development & Challenges

HEV, PHEV & EVs have different battery requirements ranging from power characteristics to cycle life. Envia solves the problem at the materials level by tailoring the cathode for each application

Morphology:

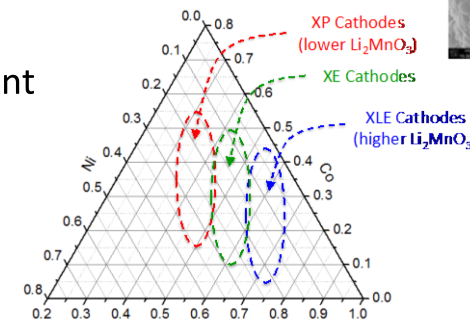
- Particle size, shape, distribution, tap density & porosity

Composition:

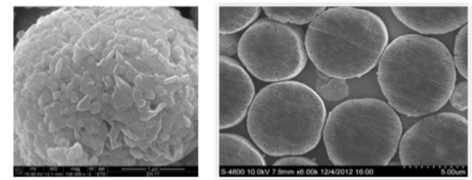
- Ni, Co, Mn ratio, & Li_2MnO_3 content
- Dopants & concentration

Nanocoating:

- Chemistry: fluorine, oxide, etc.
- Thickness & uniformity



HCMR™ Cathode Phase Diagram



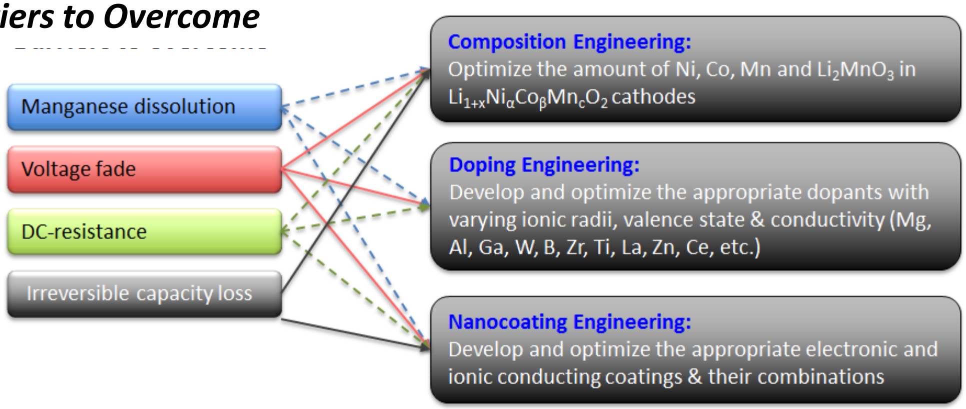
morphology

Nanocoating

HCMR™ Type	C/10 Capacity Range at 4.6V-2.0V (mAh/g)	Status
XP	200 ~ 220	Commercialization
XE	225 ~ 240	R&D
XLE	240 ~ 280	R&D

Areas of Development

Barriers to Overcome



Based on capacity, average voltage, DC-R, usable energy and cycle life, HCMR^{TM} cathode C#24 was down-selected with optimized composition, dopant and coating

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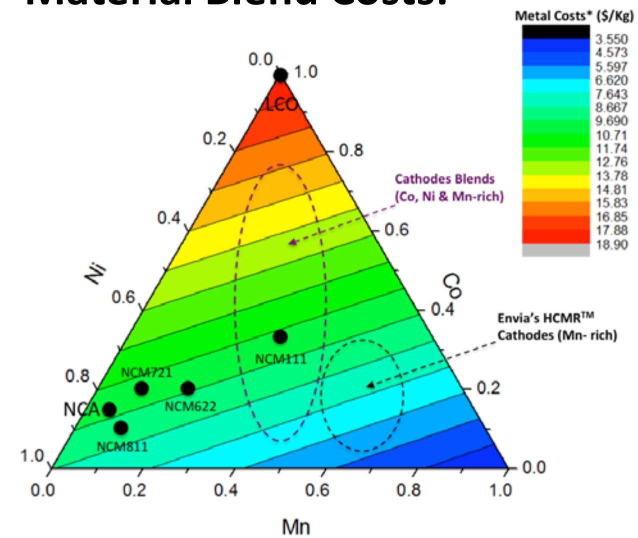
Cathode Blend Development Strategy

In order to meet the challenging USABC EV cell targets, blending of cathodes to leverage each of their strengths is required

Blending Strategy:

Mn-rich Cathode		Ni-rich or Co Rich Cathode
High Capacity		High Capacity
Improved Safety		Poor Safety
Low Cost		High Cost
High DC-R	→ **Cathode Blend with combined benefits** ←	Low DC-R
Poor Electrode Density		High Electrode Density
Low Average Voltage		High Average Voltage
Voltage Fade		No Voltage Fade

Material Blend Costs:



* Cathode metal costs are calculated from publicly traded Ni, Co & Mn metal prices from 10-1-15

- Mn-rich blended cathodes with Co-rich or Ni-rich cathodes can enable high gravimetric and volumetric energy (350 Wh/kg and 750 Wh/L) when paired with Silicon anodes while meeting safety and cost requirements ($/kWh)
- Multiple cathode blends are being evaluated in coin-cells and pouch cells

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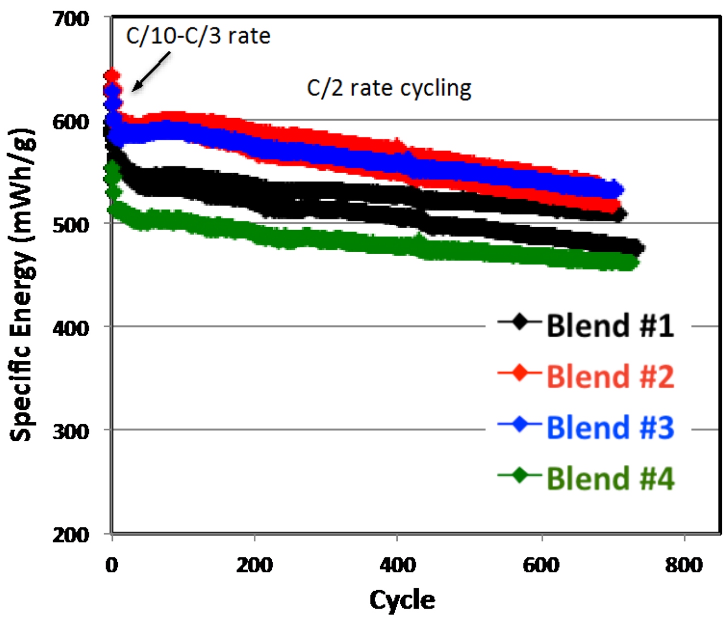
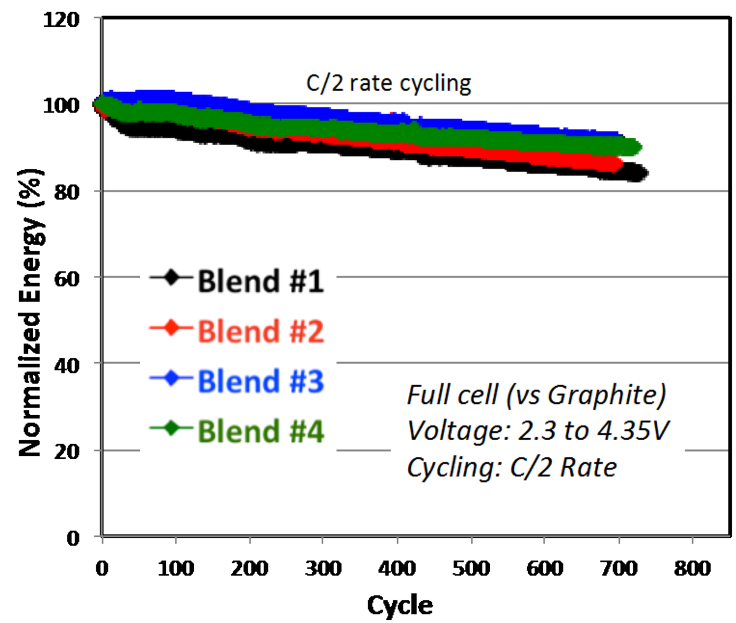
Cathode Blend Development *(Full-cell data)*

Full cell vs Graphite (coin cells)

- Cycle life studies from different cathode blends (#1-#4) vs graphite are ongoing in CC-FCs
- Specific energy based on active material weight (mWh/g) is higher for cathode blend #2 & #3
- Cycle life >700 cycles before reaching 80% energy retention is observed across all cathode blends when cycled between 2.3V to 4.35V in graphite full-cell coin cells





NEXT STEPS (Cathode Development):

1. Continue evaluating cycle life from cathode blends (coin cells and pouch cells)
2. Continue scale-up of promising cathode blends to support cell development and upcoming cell builds

Pre-lithiation of Si-based Anodes

Advantages of Pre-lithiation:

1. Pre-lithiation enables the integration of high capacity Si-based anodes, by precisely compensating the high irreversible capacity loss (IRCL)
2. In the absence of pre-lithiation, compensation of the IRCL would come from the cathode which is the priciest component in the cell
3. Pre-lithiation has also been shown to improve the cycle life in various materials

Nanoscale's roll-to-roll electrochemical pre-lithiation is safe, low-cost & scalable	
Safer manufacturing	No lithium metal is used, eliminating a key fire risk
Safer cells	No lithium metal is in cells, eliminating tendency to form dendrites
Better uniformity	Electrochemical method offers more control than powder dispersion
Less swelling	Partial expansion occurs during pre-lithiation, before cell assembly
Less expensive	Lithium salt used is much less expensive than metal

Envia has partnered with Nanoscale Components to use its low cost, roll-to-roll manufacturable pre-lithiation process to fabricate large capacity pouch cells

Status of Pre-lithiation Development

STATUS:

1. Nanoscale used its 1st generation roll-to-roll pilot line to successfully pre-lithiate SiO_x-based anodes that Envia and A123 assembled into 1Ah pouch cells
2. Nanoscale completed its 2nd generation large scale roll-to-roll pre-lithiation pilot line which is 5x wider and 10x faster throughput than the 1st generation line, with capability of supporting large-format high-capacity (>20 Ah) pouch cells
3. In order to reduce stress in the electrode and enable the required high Silicon pre-lithiation dose, an optimized thermal processing step, precisely tailored electrode formulations, and precisely laid-down coatings are required
4. Promising SiO-based anode formulations have been down-selected, anode rolls have been coated and pre-lithiation in 2nd generation roll-to-roll line is ongoing

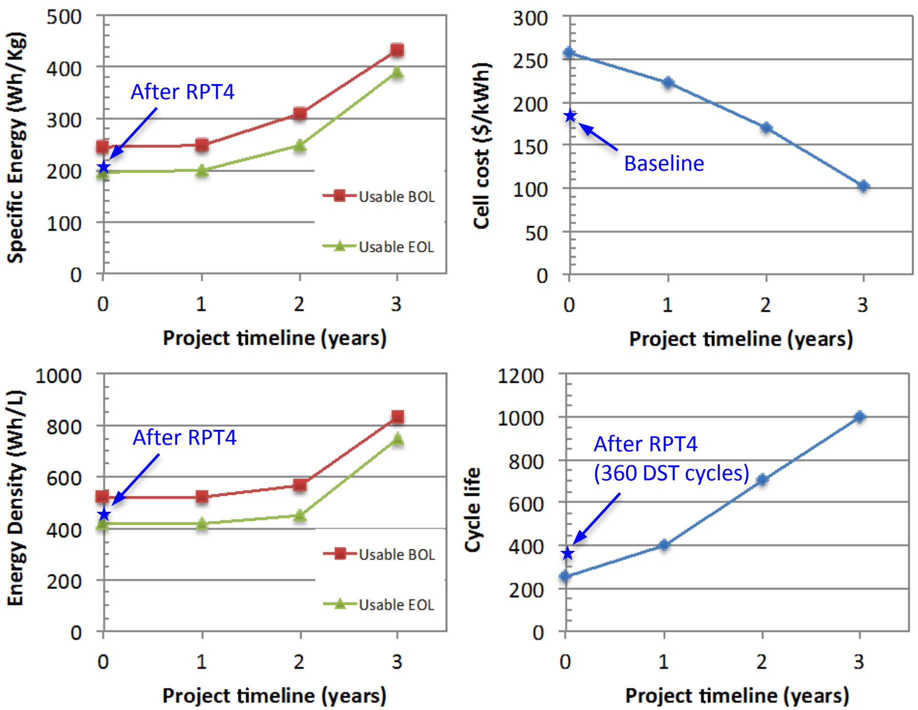
NEXT STEPS:

1. Fine-tune roll and coating design to allow successful large-format, high dosage pre-lithiation
2. Fine-tune pre-lithiation recipe to optimize process conditions for future cell builds
3. Continue to pre-lithiate sufficient Silicon anodes to support cell development and large cell builds

Cell Development

Program Goals:

Develop, optimize and integrate advanced materials, cell components and pre-lithiation process into high capacity pouch cells meeting the USABC EV battery goals for 2020



Gap analysis *(based on Baseline EOL targets)*

End of Life Characteristics at 30°C	Units	Cell Level (EOL)	Baseline Cell Targets (EOL, usable)	Baseline Cell RPT0 (BOL, usable)	Baseline Cell RPT4 (usable)
Peak Discharge Power Density, 30 s Pulse	W/L	1500	832	1884	686
Peak Specific Discharge Power , 30 s Pulse	W/kg	700	392	849	307
Peak Specific Regen Power , 10 s Pulse	W/kg	300	238	516	377
Useable Energy Density @ C/3 Discharge Rate	Wh/L	750	416	520	445
Useable Specific Energy @ C/3 Discharge Rate	Wh/kg	350	196	245	199
Useable Energy @ C/3 Discharge Rate	kWh	N/A		77	62
Calendar Life	Years	15		0	0.333
DST Cycle Life	Cycles	1000		0	360
Cost @ 100K units	$/kWh	100		183	183
Operating Environment	°C	-30 to +52	-30 to +52		
Normal Recharge Time	Hours	< 7 Hours, J1772	< 7hr	< 7hr	< 7hr
High Rate Charge	Minutes	80% ΔSOC in 15 min	>80	83	
Maximum Operating Voltage	V	N/A		4.35	4.35
Minimum Operating Voltage	V	N/A		2.3	2.3
Peak Current, 30 s	A	400		50.0	50.0
Unassisted Operating at Low Temperature	%	> 70% Useable Energy @ C/3 Discharge rate at -20°C		65.3	
Survival Temperature Range, 24 Hr	°C	-40 to+ 66	-40 to+ 66		
Maximum Self-discharge	%/month	< 1	< 1	0.9*	
Battery scaling factor (BSF)	# of cells	288 (96s, 3p)	768 (96s, 8p)	768 (96s, 8p)	768 (96s, 8p)
Baterry capacity	Ah	>40	21	21	21

- 21Ah baseline cells completed RPT4 for DST cycling (360 DST cycles) & 30°C Calendar life (120 days)
- Gap chart shows the final USABC program (EOL, usable) and Baseline (EOL, usable) cell targets
- Gap chart coloring is based on **Baseline EOL cell targets**

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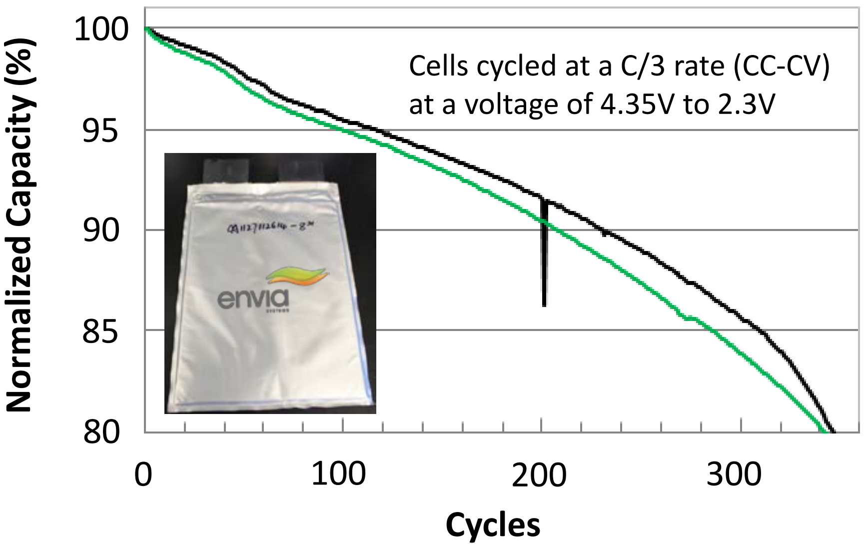
Failure Analysis of Cycled Baseline Cells

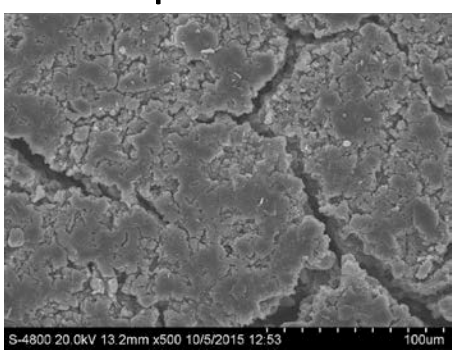
21 Ah Baseline Cells CC-CV cycle testing



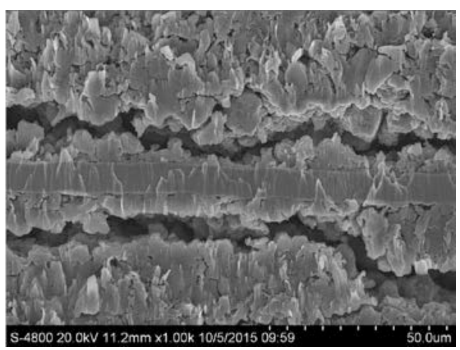
Postmortem analysis of cycled cells:

1. Physical inspection (pouch cell, cathode, anode, separator, electrolyte, tabs, etc.)
2. SEM analysis of anode and cathode
3. XRD analysis of cycled electrodes
4. Electrochemical studies of cycled electrodes

Anode Top view SEM



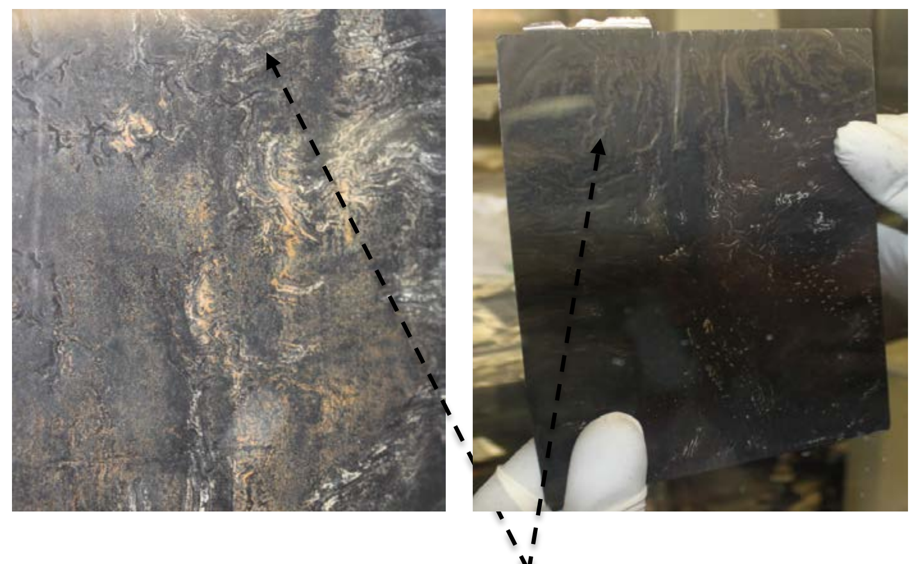
Anode SEM cross-section



Anode delamination and cracking appears to be one of the main failure modes

Anode

Cathode

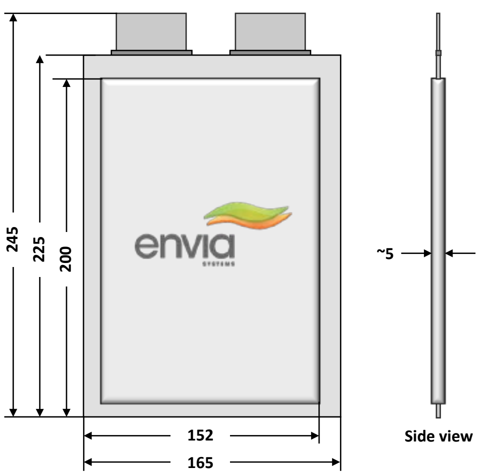


Channels

Cell Development Strategy

Strategy:

- Integrate and optimize various anode and cathode compositions and formulations, material coatings, electrolyte formulations and cell designs (density, loading, N/P, etc.) into high capacity pouch cell designs
- Focused cell development on smaller 21 Ah capacity, ~260 Wh/kg cells (similar capacity to baseline cells), where 275 Wh/kg specific energy is achieved from the 40 Ah capacity cell format

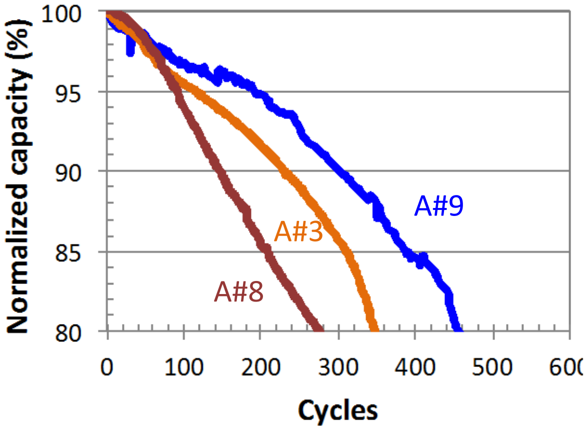


Approximate dimensions in mm

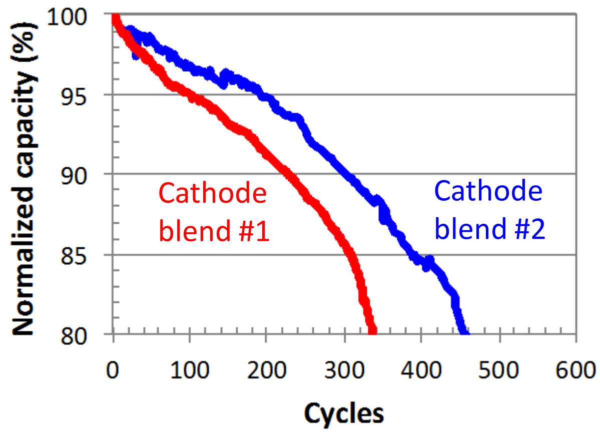
		Units	40Ah	21Ah
Positive	Active Material	N/A	HCMR™-XP Blend	HCMR™-XP Blend
	Cathode ID	N/A	C#8 + Commercial blend	C#8 + Commercial blend
	Electrode area per side	cm^2	266.96	266.96
	Electrode density	g/cc	High (>3)	High (>3)
Negative	Active Material	N/A	SiO_x-C Composite	SiO_x-C Composite
	Anode ID	N/A	Vendor #2 SiO_x-C	Vendor #2 SiO_x-C
	Electrode area per side	cm^2	273.6	273.6
	Electrode density	g/cc	Medium (~1)	Medium (~1)
Separator		N/A	S#1	S#1
Cell Weight		g	515	283
Prelithiation		N/A	SLMP™	SLMP™
Estimated Capacity, C/3-Rate		Ah	40.5	21.2
Energy Density, C/3-Rate (terrace)		Wh/L	554	500
Specific Energy, C/3-Rate		Wh/kg	**273**	**260**

Cell Development *(Cycle life)*

Anode formulation

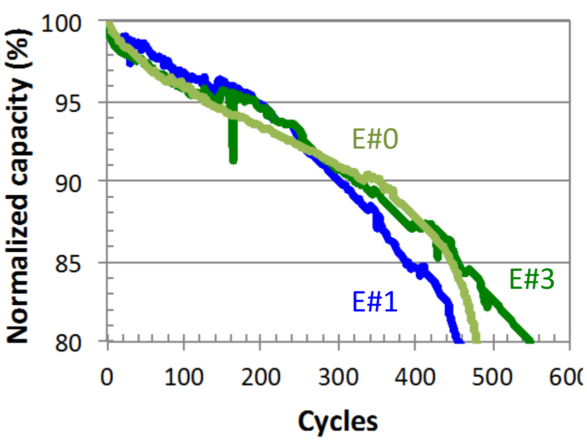


Cathode composition

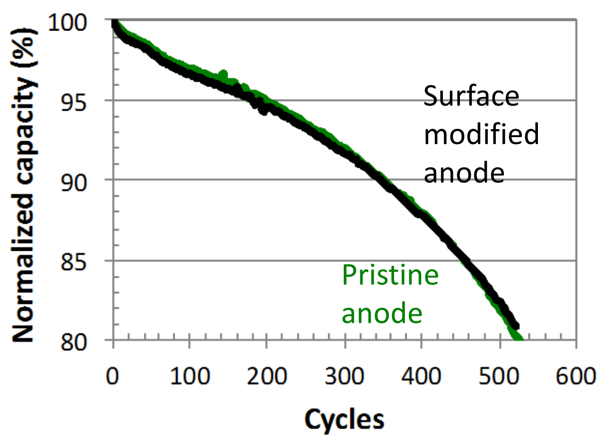


21 Ah capacity, ~260 Wh/Kg cycle life data

Electrolyte formulation



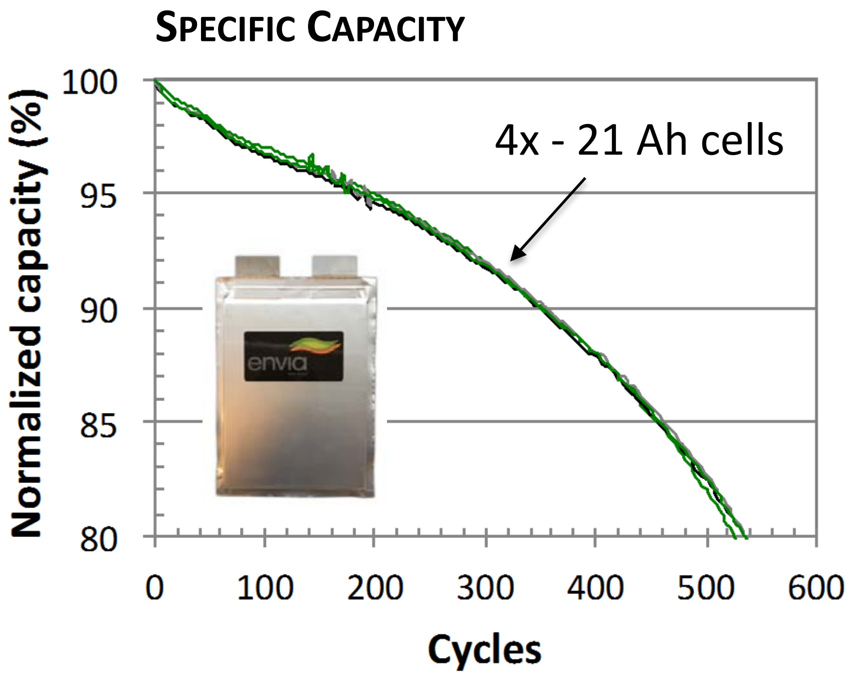
Surface modifications

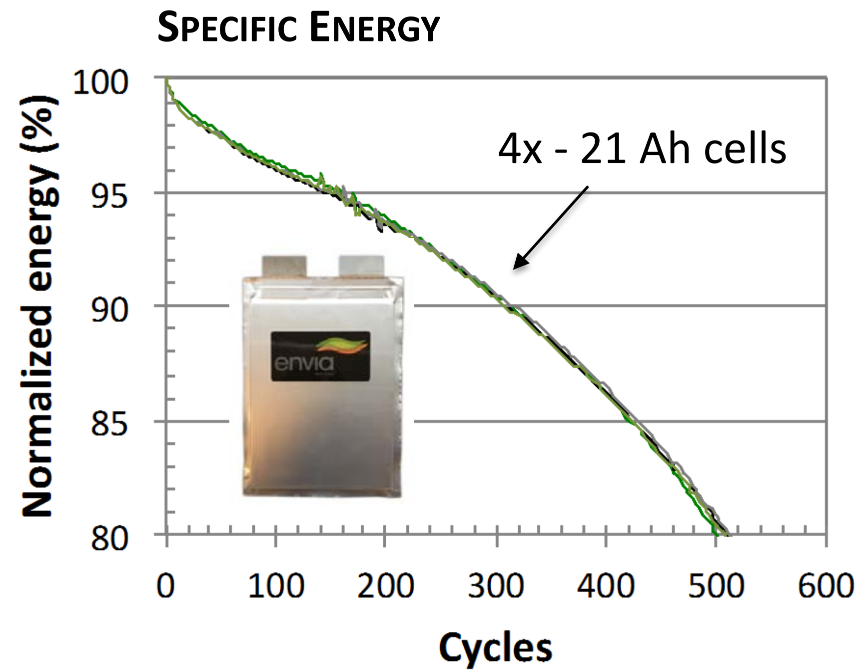


- Achieved **>500 cycles** before reaching 80% capacity retention from 21 Ah, ~260 Wh/kg cells that incorporate high Si content (>50%) anode formulations, NMC cathode blends, electrolyte formulations and surface modifications
- Ongoing cell development is focusing on pouch cells with an energy of 275 Wh/kg and cycle life of 700 cycles
- Next cell build by A123 will integrate best anode, cathode, separator, electrolyte & electrochemical pre-lithiation

Note: Cells cycled at a C/3 rate, CC/CV, 4.35V-2.3V

Cell Development Status





Envia has achieved **>500 cycles** before reaching 80% capacity and energy retention from **21 Ah** capacity, **~260 Wh/kg** specific energy **(equivalent to ~270 Wh/kg in a 40Ah cell)** pouch cells that incorporate **>50% Si content**

Note: Cells cycled at a C/3 rate, CC/CV, 4.35V-2.3V

Summary

- Achieved **>500 cycles** from 21 Ah, ~260 Wh/kg pouch cells that incorporate promising high Si content (>50%) anode formulations, NMC cathode blends, electrolytes formulations and surface modifications
- Anode development is ongoing with respect to composition, coatings and electrode morphology engineering to down-select best anode material
- Down-selected promising cathode blend showing cycle life >700 cycles composed of NMC cathode components
- 2nd generation large scale roll-to-roll pre-lithiation pilot line was complete and is currently being used to pre-lithiate promising anode formulations
- Cell tear-down and failure analysis of cycled cells is ongoing to understand and mitigate failure mechanisms

NEXT STEPS:

1. Incorporate down-selected materials, validated cell designs and electrochemical pre-lithiation to build large capacity cells
2. Down-select best materials and pre-lithiation processing for future cell builds
3. Continue cell failure analysis to understand and mitigate cell failure modes

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Acknowledgements

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- This work was performed under the guidance and support from the USABC technical work group: Oliver Gross (program manager), OuJung (OJ) Kwon, Meng Jiang, Jack Deppe, Matthew Shirk, Matthew Keyser and Leigh Anna Steele
- This work was performed with processes, materials, cell components and guidance from the various partners: Nanoscale Components, A123 Systems, Daikin America, Asahi Kasei, 3M, and DuPont

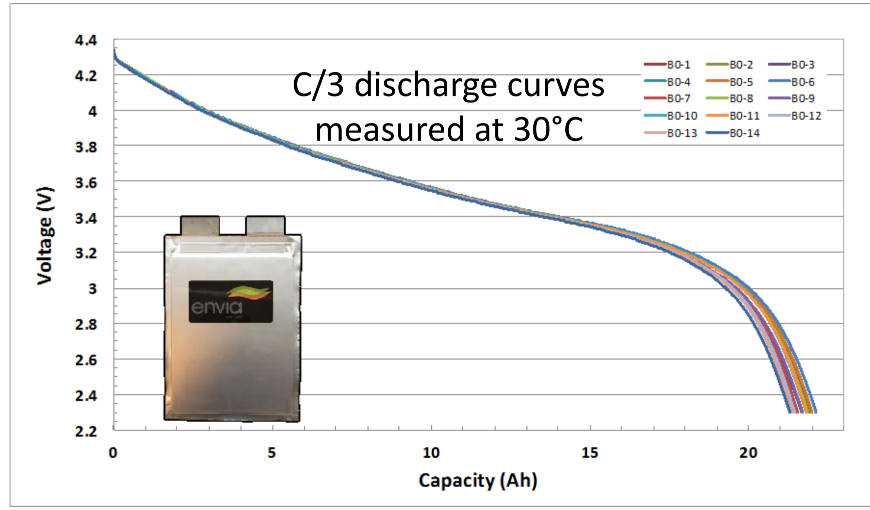
Technical Back-up Slides

Baseline Cell Results

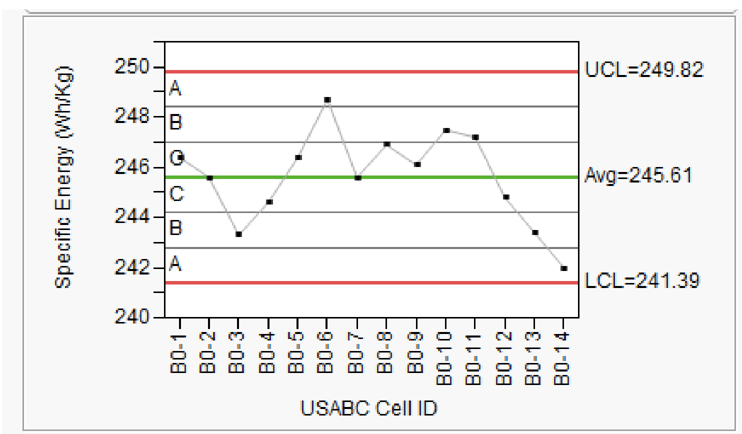
Baseline Cell Design:

		Units	Design #2
Positive	Active Material	N/A	HCMR™-XP Blend
	Cathode ID	N/A	C#8 + Commercial blend
	Electrode area	mm^2	26696
	Electrode density	g/cc	High (>3)
Negative	Active Material	N/A	SiO_x-C Composite
	Anode ID	N/A	Vendor #2, Composition #1
	Electrode area	mm^2	27360
	Electrode density	g/cc	Medium (~1)
Separator		N/A	S#1
Cell Weight		g	298.7
Estimated Capacity, C/3-Rate		Ah	21.4
Energy Density, C/3-Rate		Wh/L	419
Specific Energy, C/3-Rate		Wh/kg	**249**

Specific Capacity (Ah)



Specific Energy (Wh/Kg)



- 21Ah capacity baseline cells are currently testing for capacity, energy, power, cycle life, calendar life & temp performance at both Envia and INL
- Preliminary results suggest baseline cells met the target design and show reproducible capacity (21.7 +/- 0.2Ah) and energy (245.6 +/- 1.8Wh/Kg)