

# **High Energy Density and Specific Energy Batteries with Silicon Nanowire Anodes**

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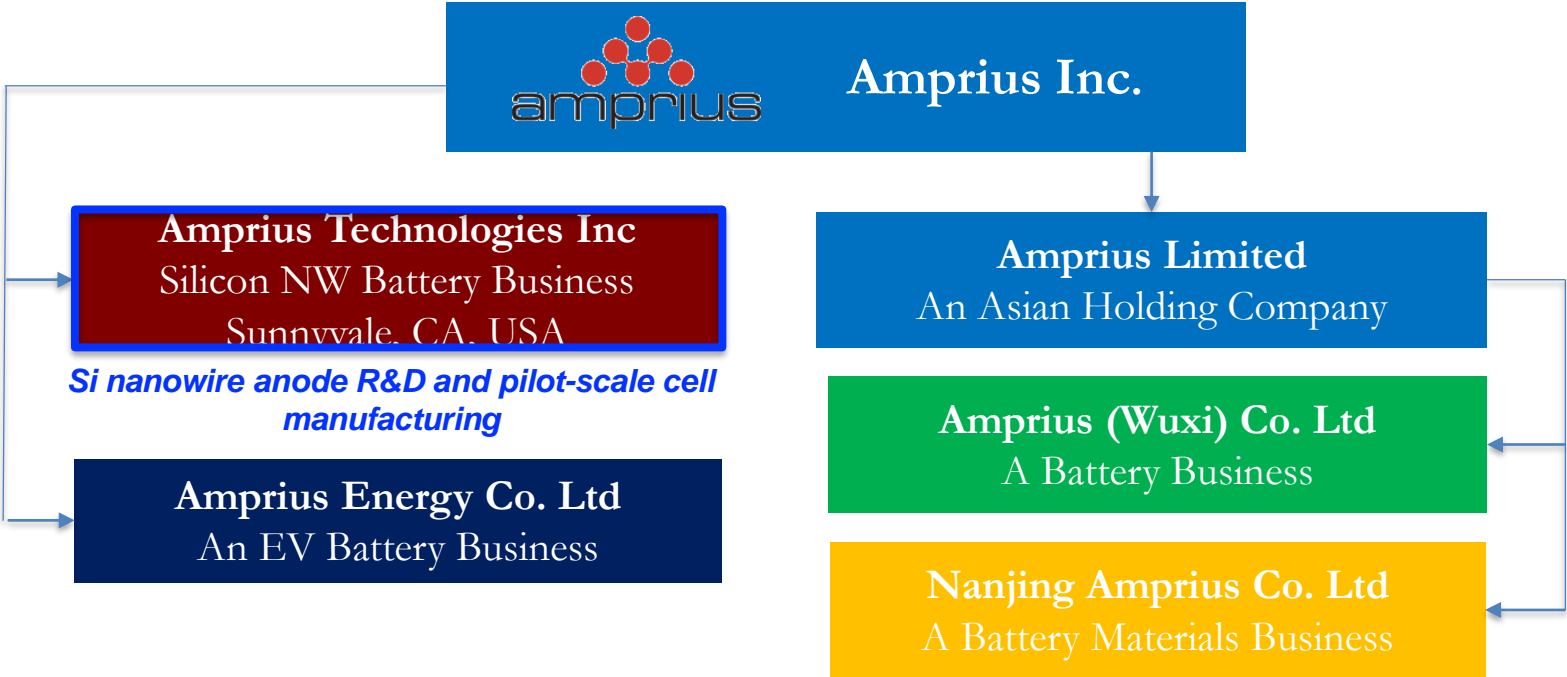


# Amprius Technologies Snapshot



- **TECHNICAL LEADERSHIP:** Amprius is a pioneer and the established leader in silicon anode materials and high energy density lithium ion batteries.
- **BEST PERFORMANCE:** Amprius has the highest energy density lithium ion cells in use in the world based on 100% Silicon nanowire anode technology.
- **COMPREHENSIVE PLATFORM:** Amprius' technology platform includes silicon nanowire, silicon nanowire anode manufacturing, electrochemistry, high capacity cathodes and high energy cell designs.
- **IN DEMAND:** Amprius has attracted much attention. Amprius Technologies is already designed into a HAPS program and the company is selling cells for smartphones, wearables, and drones. Developing cells for electric vehicles and robotics.

# Amprius Organization



-  a JV between Amprius and Wuxi IDG
-  in progress

# Amprius R&D and Manufacturing Centers



California R&D & Pilot Line – silicon nanowire anode and other advanced materials.



Wuxi Manufacturing Center – advanced batteries and manufacturing technologies.



Nanjing R&D Center – silicon/graphite materials and enhanced cathodes development.



Ulm, Germany R&D Center – advanced EV battery development.

# Objectives



Produce Ultra-High Capacity Silicon Nanowire Anodes for Li Ion Cells that have the Highest Energy Density Available

Amprius Technologies' Cells are Game Changers for Mission Critical Applications

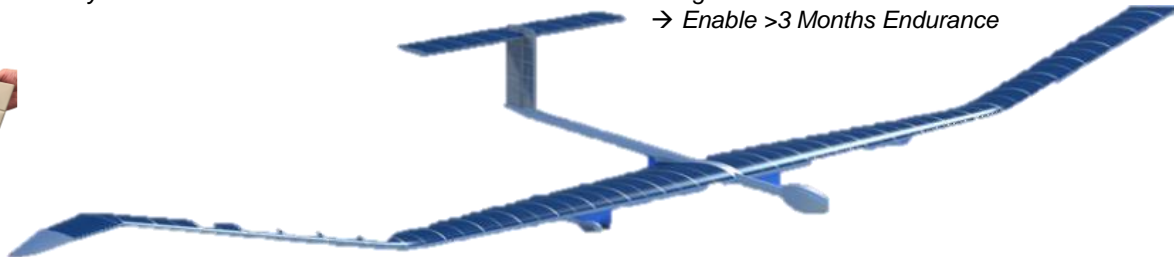
*Power Cells for Quads  
→ Enable Very Long Endurance  
(World Record with Major Defense Contractor)*



*Cells for Lightweight Drones  
→ Enable >4 hr Missions  
(>2x current endurance)*



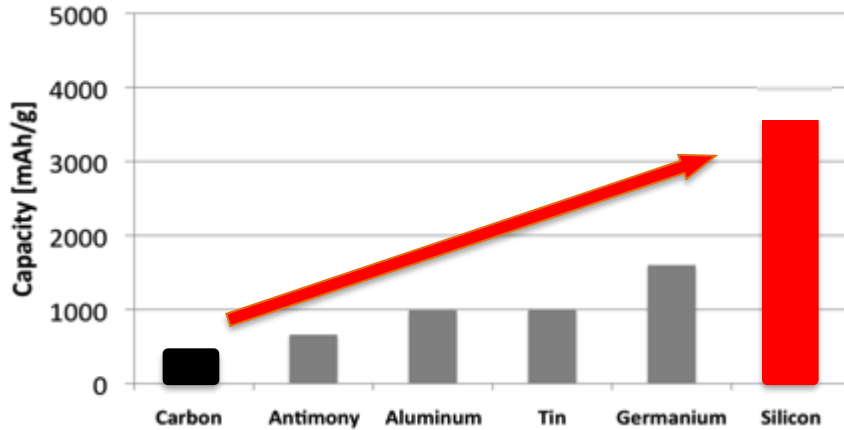
*Cells for High Altitude Pseudo Satellites  
→ Enable >3 Months Endurance*



*Cells for Conformal-Wearable Pack  
→ Enable 40% lower weight for Army*



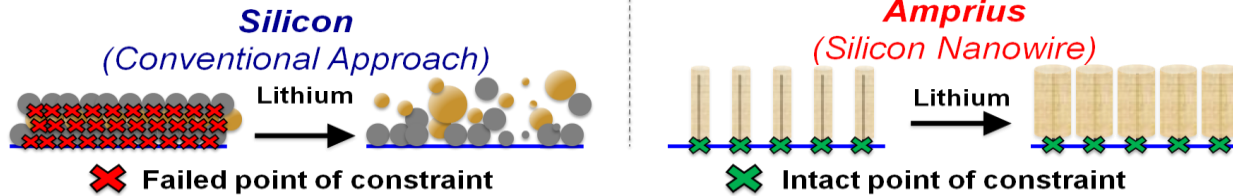
## Silicon has 10X Capacity vs. Carbon



### Amprius solutions enable:

- \* Longer endurance / operation
- \* Smaller and/or lighter devices
- \* More functionalities
- \* Broader applications

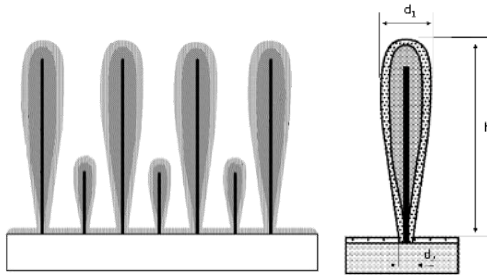
- *The design and manufacturing of silicon-containing anodes remains a major challenge in research and industry.*
- *Amprius' Silicon Nanowire technology is a proven solution.*



## Fundamental Problem of Silicon-Containing Anode

- *Silicon swells 300% when charged with Lithium*
- *Silicon gets pulverized after a few charge/discharge cycles*
- **Amprius' solution:**
  1. *nanowires tolerate volume expansion and are rooted to substrate*
  2. *nanowires have micro and macro porosity that accommodate swell*
  3. *Surface treated to improve Solid-Electrolyte-Interphase & cycle life*
  4. *Anode thickness is reduced to half of a graphite electrode thickness*

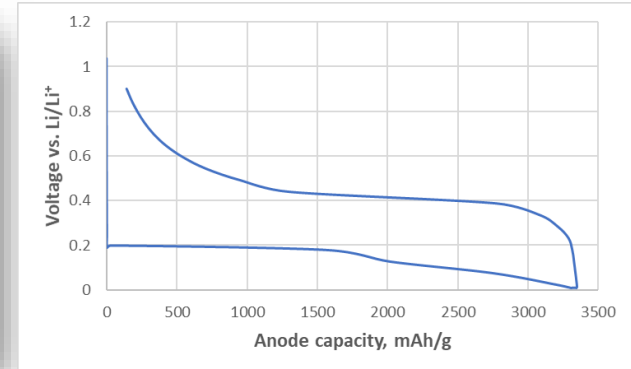
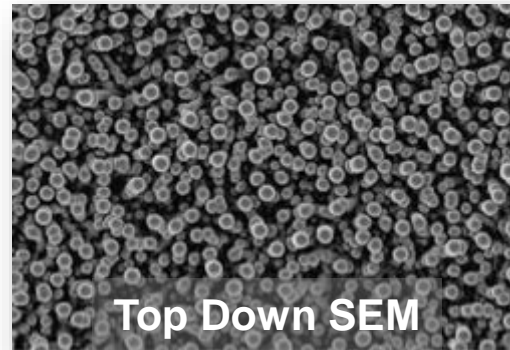
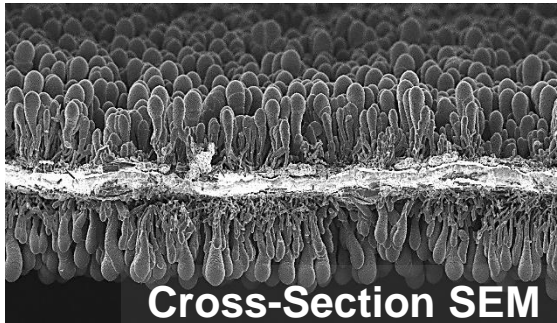
# Silicon Nanowire Structure



(54) STRUCTURALLY CONTROLLED DEPOSITION OF SILICON ONTO NANOWIRES  
(71) Applicant: Amprius, Inc., Sunnyvale, CA (US)  
(72) inventors: Weijie Wang, Sunnyvale, CA (US); Zuqin Liu, Sunnyvale, CA (US); Song Han, Foster City, CA (US); Jonathan Bornstein, Cupertino, CA (US); Constantin Ionel Stefan, San Jose, CA (US)  
(21) Appl. No: 14710,103

## Major advantages:

- Highest content active silicon material (100%)
- High conductivity and connectivity (rooted to substrate)
- Low tortuosity – high rate capability
- Ideal and adjustable porosity distribution
- High mass loading (2-3 mg/cm<sup>2</sup>)
- High first cycle efficiency





# Manufacturing Platform for Continuous Roll-to-Roll Anode Production

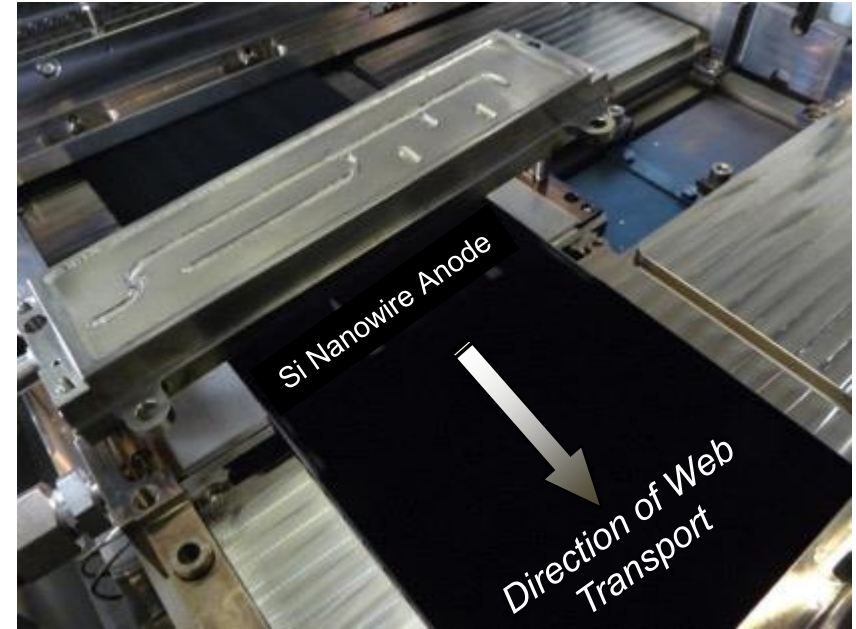


## Replaces:

- Graphite powder mixing
- Slurry mixing
- Roll coating (2x)
- Drying
- Calendaring

## Bare Foil In → Finished Anode Out

- **Pilot Tool capable of ~300 kWh/year**
- At 50 MWh/year near \$/Ah parity with graphite *but* 40% higher energy density

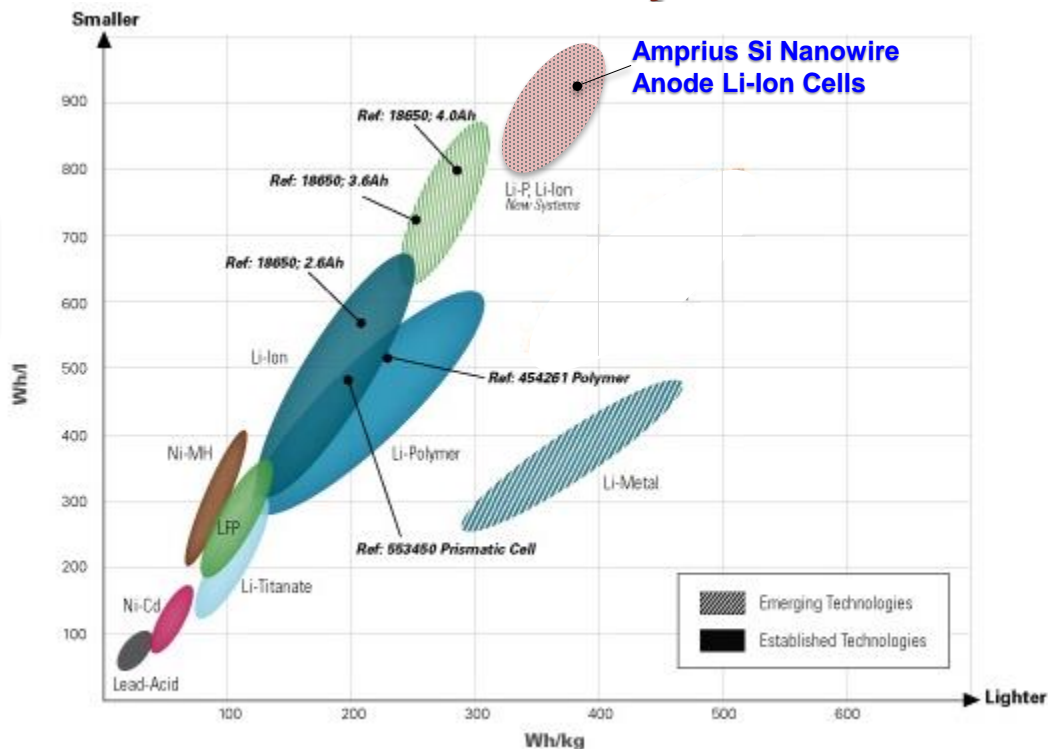


*Pilot line tool for roll-to-roll production of double-sided, rooted silicon nanowire anodes installed in Sunnyvale, CA*

# Battery Landscape

## Comparison of Energy Densities for Various Battery Chemistries

Silicon nanowire anode cells are far ahead of all other advanced Li-ion systems.

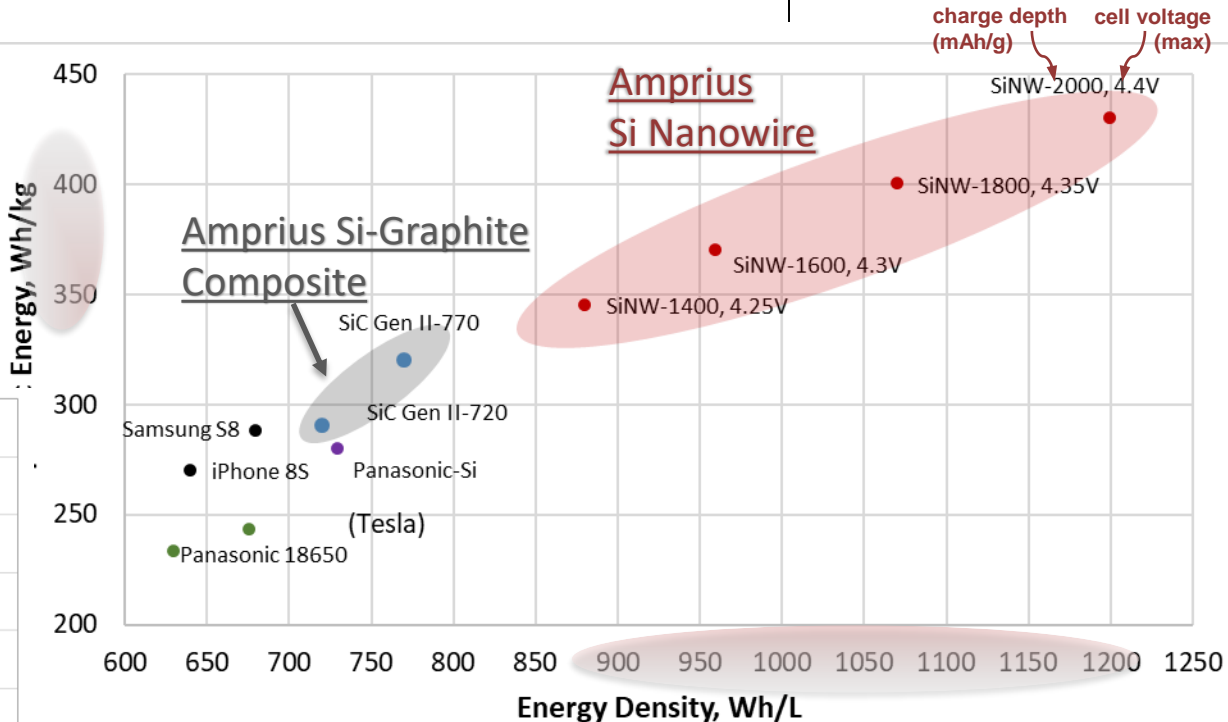
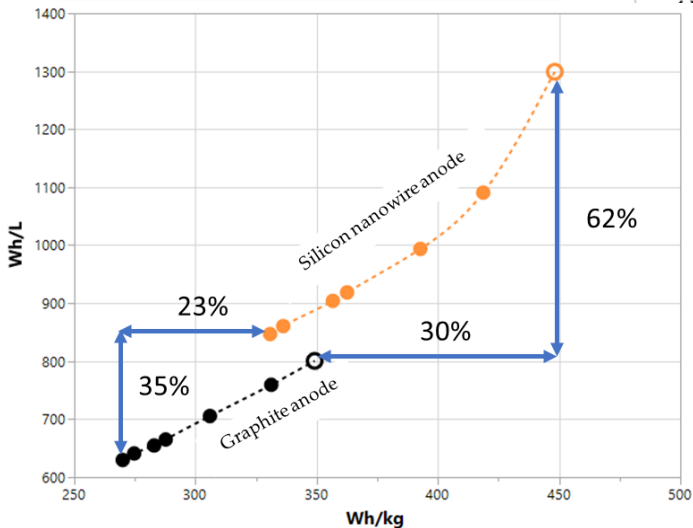


# Li-ion Battery Landscape



**Silicon nanowire technology** performance is adjustable by voltage & charge depth

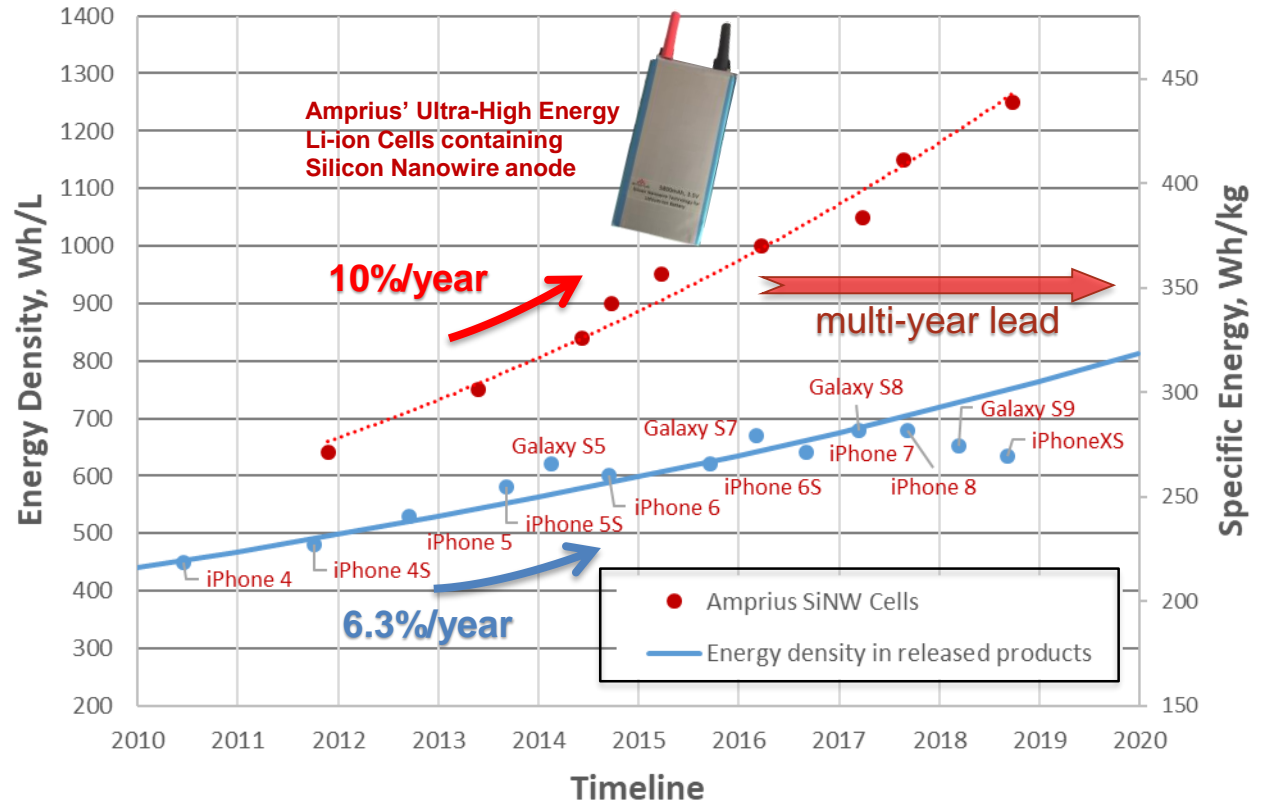
A unique feature of the Si nanowire anode with variable capacity utilization



# Silicon Nanowire many years ahead



Si nanowire anode cells are many years ahead of batteries for tier-1 products



# Amprius Technologies High Energy Products: Span 4 Ah – 14 Ah Cells



Worlds highest energy density and specific energy Li-ion Cells



Product ID	Capacity Ah	Energy Wh	Wh/L	Wh/kg
ANW4.0-455056	4.0	14.5	1150	424
ANW8.1-4551107	8.1	29.3	1220	430
ANW14.2-8051110	14.2	51.2	1244	437



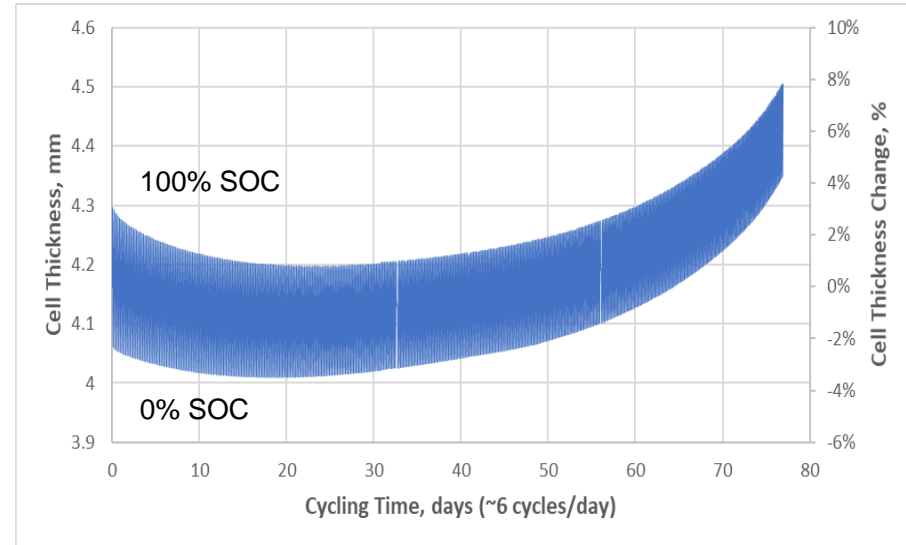
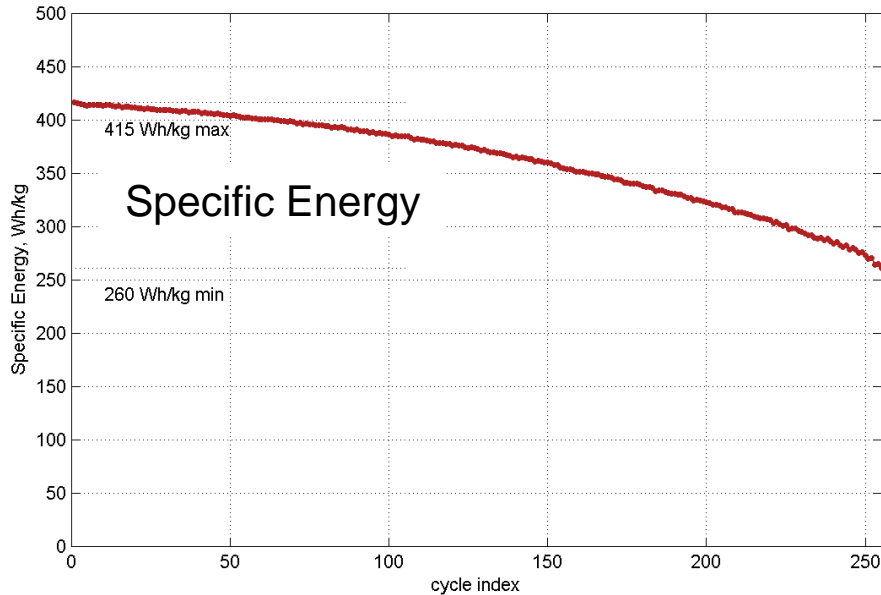
Voltage range 2.75-4.35V, measured at C/5 rate,  
Operating temperature range: -20 °C to 45 °C

The 2018 version of ANW4.0-455056 reaches 440Wh/kg at C/10

# Amprius Technologies High Energy Products: Cycle Life – Lower Rate Drone Applications



## High Voltage LCO Cathode



**C/5 rate, for High Altitude Drone applications**

# Amprius Technologies High Energy Products: Safety



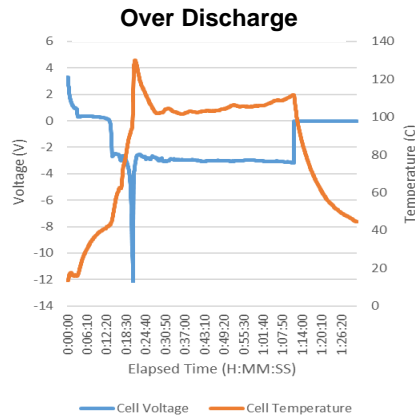
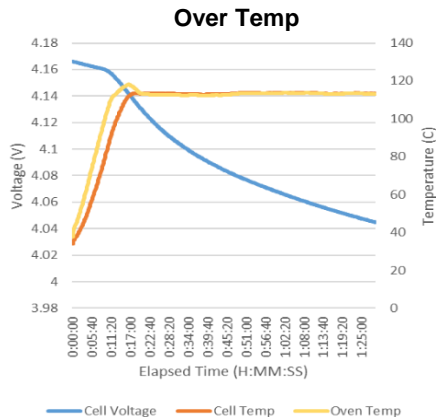
Similar to or better than comparable graphite cells with the same capacity

Application	Test	Result
Military	UL 1642	Pass
	Nail Penetration	Pass
	Drop	Pass
NASA	Hot Box (110°C/1h)	Pass
	Short Circuit	Pass
	Overcharge	Pass
	Overdischarge/Reversal	Pass
Commercial/All	UN 38.3	Pass

# Cell safety and environmental testing for NASA

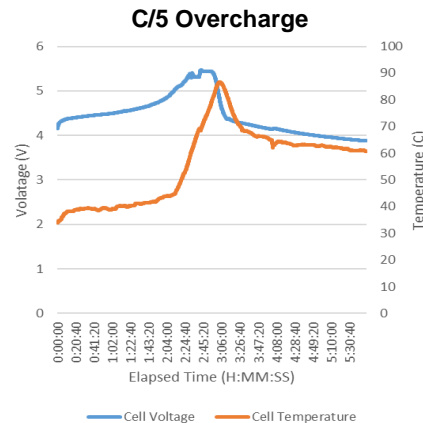
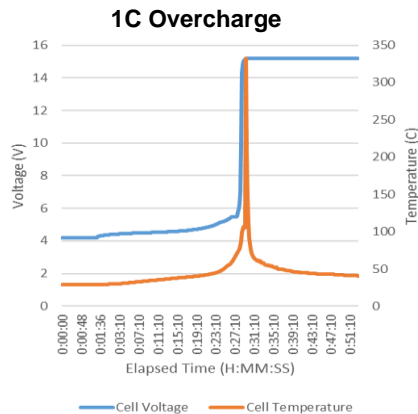


110°C for 1h –  
no fire, no  
explosion



Reversal with  
150% excess  
discharge – vent  
with no fire, no  
explosion

1C overcharge and  
thermal runaway –  
explosion above 5V,  
in about 30 minutes  
(50% overcharge)



C/5 overcharge –  
no fire, no  
explosion,  
maximum of 5.3V  
and ~85°C



# Amprius Technologies High Power Products: Span 2 Ah – 10 Ah Cells



High Power capability with highest energy density and specific energy Li-ion Cells



Product ID	Capacity Ah	Energy Wh	Wh/L	Wh/kg	Capacity Ah	Energy Wh	Wh/L	Wh/kg
	Charge-Discharge Rate: C/5-C/5				Charge-Discharge Rate: 1C-3C			
ANW3.6-405056	3.6	13.2	1000	415	3.4	11.5	870	360
ANW2.6-405056	2.8	10.1	915	365	2.65	9.0	815	325
ANW10-7550106	10.6	38.4	1000	390	10.1	34.2	885	345

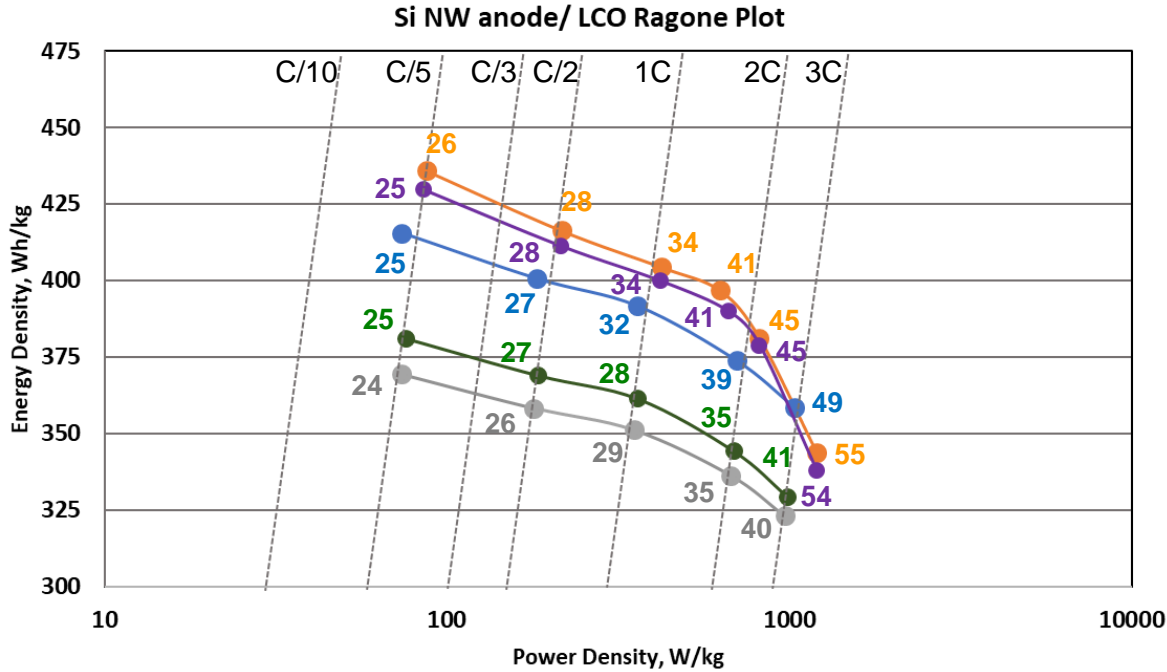


Voltage range 2.5-4.35V at 1C-3C rates

Operating temperature range: -20 °C to 55 °C

Cycle life of 150-300 cycles, depending on operating conditions

# Amprius Technologies Products: High Energy and Power Capability



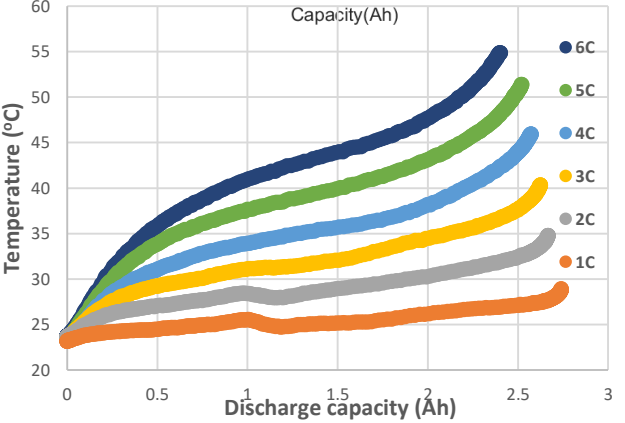
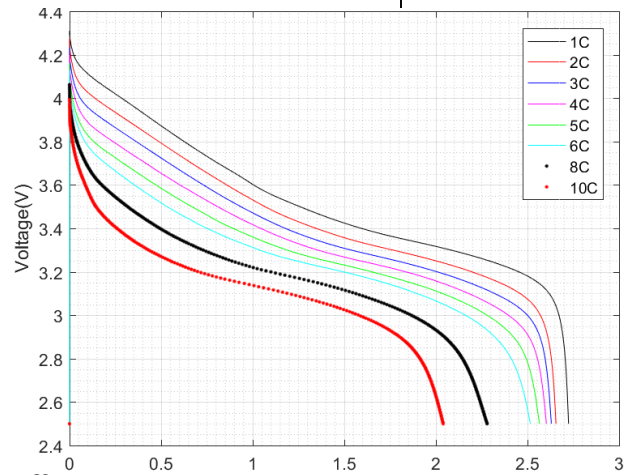
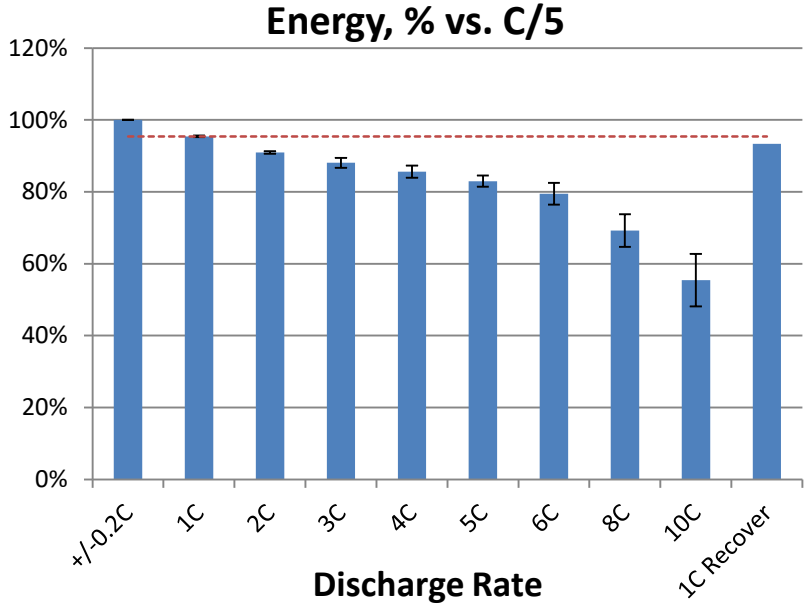
\* Numbers indicate maximum cell body temperature during discharge

It is more efficient to use high loading cathodes if the rate requirement allows it.

The curves can be extended to higher power at similar loadings if the cathode design is changed for power performance

Temperature increase during discharge is an important factor that depends on loading, foil thickness and tab design

# Amprius Technologies High Power Products: Rate Capability



>80% relative energy to 6C rate

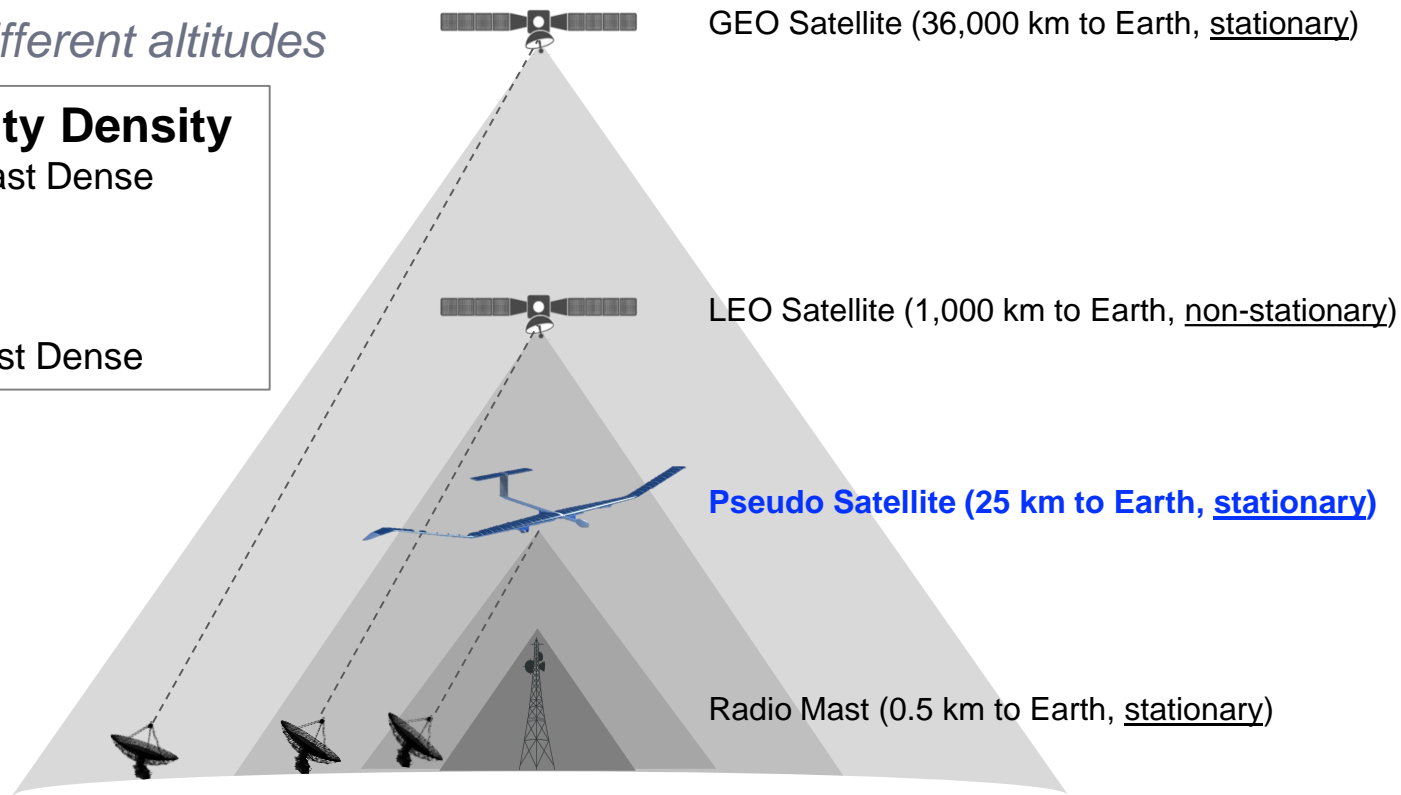
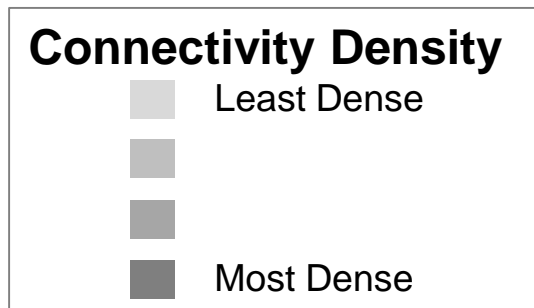
The temperature increase is small and within operating limits to 10C rate

## Applications that must have ultra-high energy density to be viable product

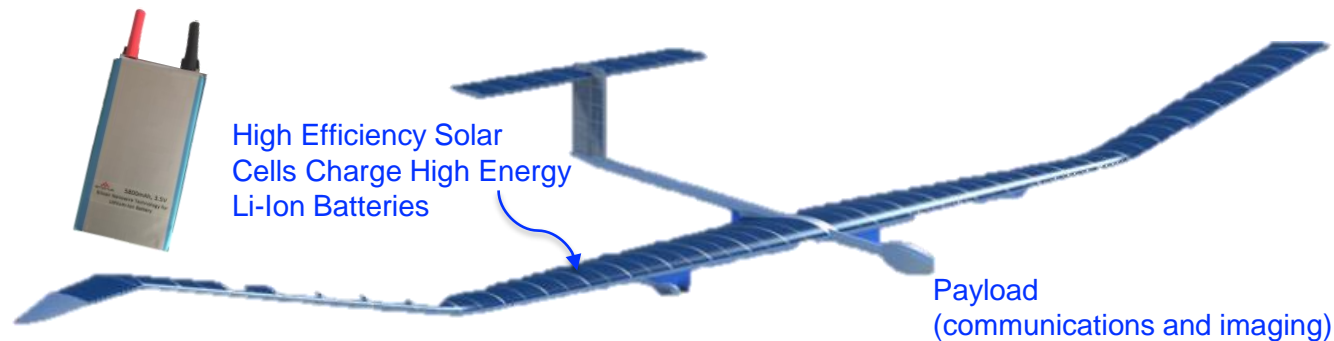
- **Aerospace (UAVs)**
  - High Altitude Pseudo Satellites (HAPS)
  - Lightweight / hand-launched / long endurance drones
  - Long Endurance Multi-rotor drones
- **Mission Critical**
  - Wearable / conformal packs
  - Autonomous systems (robotics)

# Data Communication Platforms

## Platforms at different altitudes



# High Altitude Pseudo Satellites (HAPS)



## Emerging application in Aerospace

- *Solar-Electric aircraft serves as High Altitude Pseudo Satellites (HAPS)*
- *Low launch cost & very mobile*
- *Amprius' cells enable over 12 weeks endurance (4 weeks world record set recently)*

# Very Long Endurance Batteries for UAS



Battery option for deployed drones



Amprius nanotechnology more than doubles endurance

Specification	Current - Standard Battery	Current - Long-Endurance Battery	Amprius Very Long Endurance Battery
Energy (Wh)	349	468	768
Weight (g)	1680	2048	2148
Specific Energy (Wh/kg)	208	223	346
Flight Endurance (hours)	2	3	4.5

# Mission Critical: Conformable Wearable Batteries

## Electronics Burden of War Fighter



Specification	CWB-150 (Fielded Model)	Amprius CWB (June 2017)
“Flexible” battery		
Energy	150 Wh	150 Wh
Weight	1.18 kg	0.85 kg
Dimensions	194mm x 221mm x 18mm	182mm x 221mm x 13mm
Specific Energy	127 Wh/kg	177 Wh/kg

**40% Greater Specific Energy (Wh/kg) than current model**



# EV cells that exceed USABC 2020 goals



SiNW/NCM622

ISO form factor VIFB-/99/300

Capacity: 46 Ah at C/3 rate (30°C)

Cell weight = 450.7g

Cell size = 6.0x96x288mm (body only)

Energy: 350 Wh/kg and 925 Wh/L

Peak Power: 830 W/kg and 2200 W/L

80% capacity charged in 15 minutes



# 2018-20 Si Nanowire Anode Production

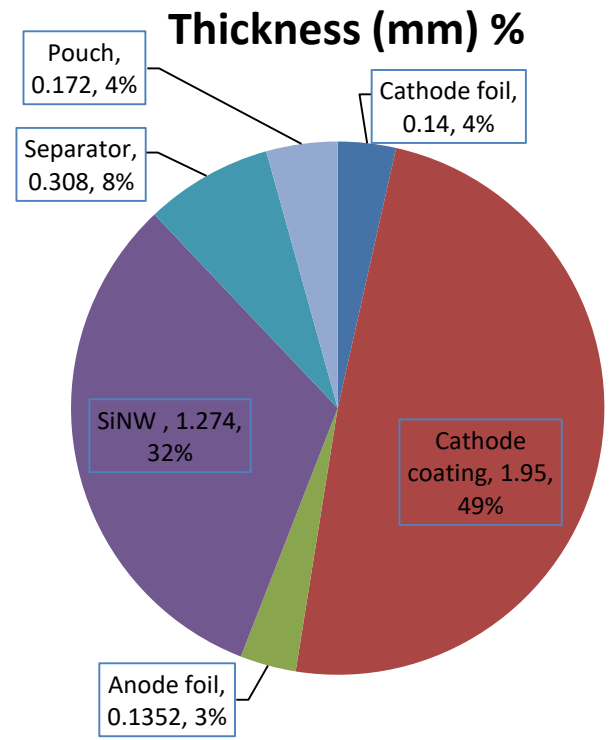
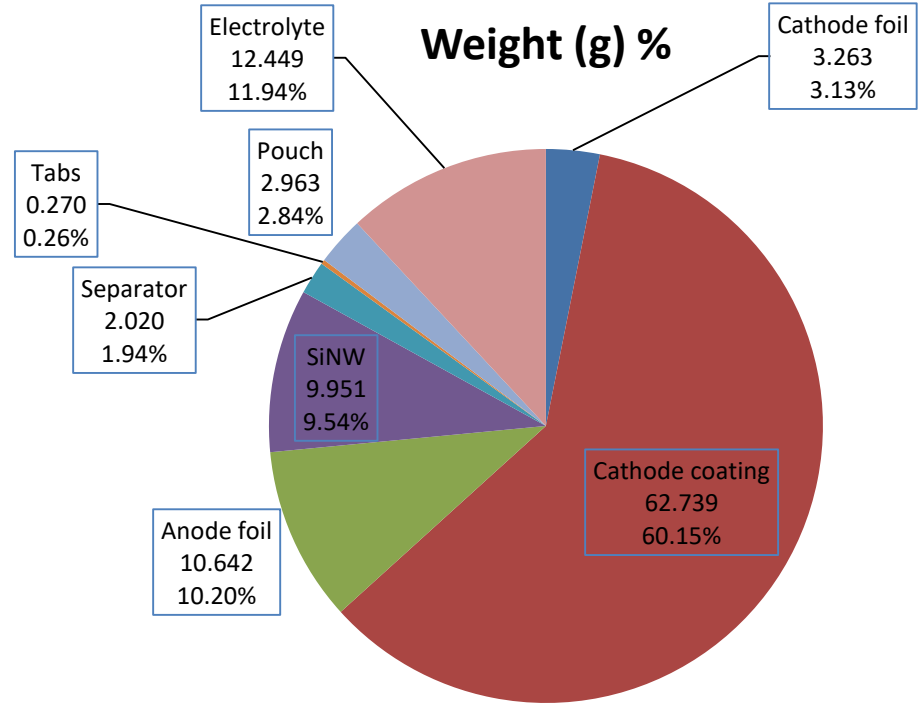


- First-of-a-kind R2R system for 100% silicon nanowire anode manufacturing
- Amprius began R2R silicon nanowire anode Pilot production this year.
- 150 kWh annual installed capacity
- Purchased a 2<sup>nd</sup> R2R tool and will take delivery in April 2019
- Beyond 2019, Amprius seeks to scale manufacturing by developing an upscaled tool (5-10x throughput increase).



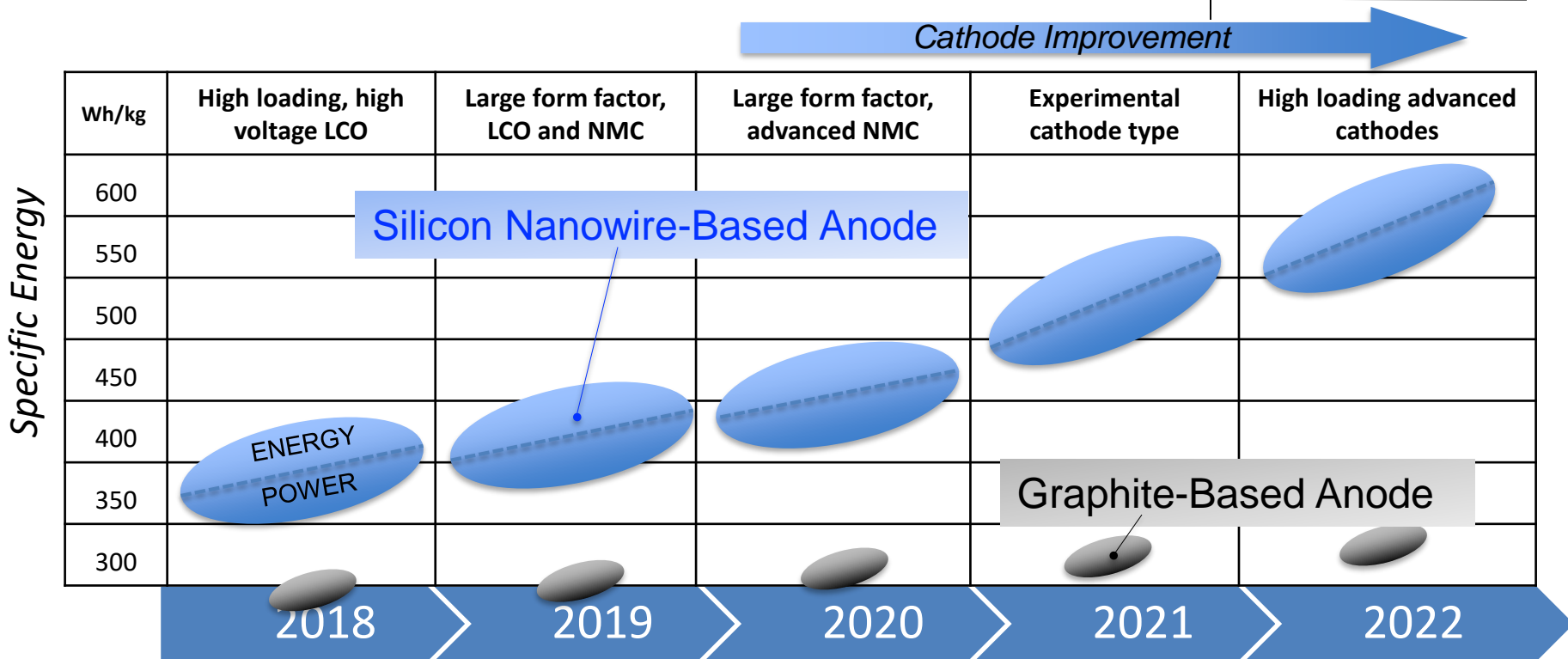
Installed in Sunnyvale.... Feb-2018  
Qualified..... Jul-2018  
Second Tool..... Q2-2019  
Upscaled Tool(s)..... 2020+

# Road Ahead: What components to improve?



The cathode material dominates both in weight and volume proportion

# Si Nanowire Anode Specific Energy Roadmap



Power/energy ratios are optimized in the design space (blue ellipses)

# Thank You

**Amprius wishes to acknowledge the funding received from US Army (Contract No. W911QY-12-C-0118), NASA (Contract No. NNC16CA10C), USABC (Project No. DE-EE0006250) and DOE (Award No. DE-EE0005474).**

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