

# **High Energy Density and Specific Energy Silicon Anode-Base Batteries for Aerospace Applications**

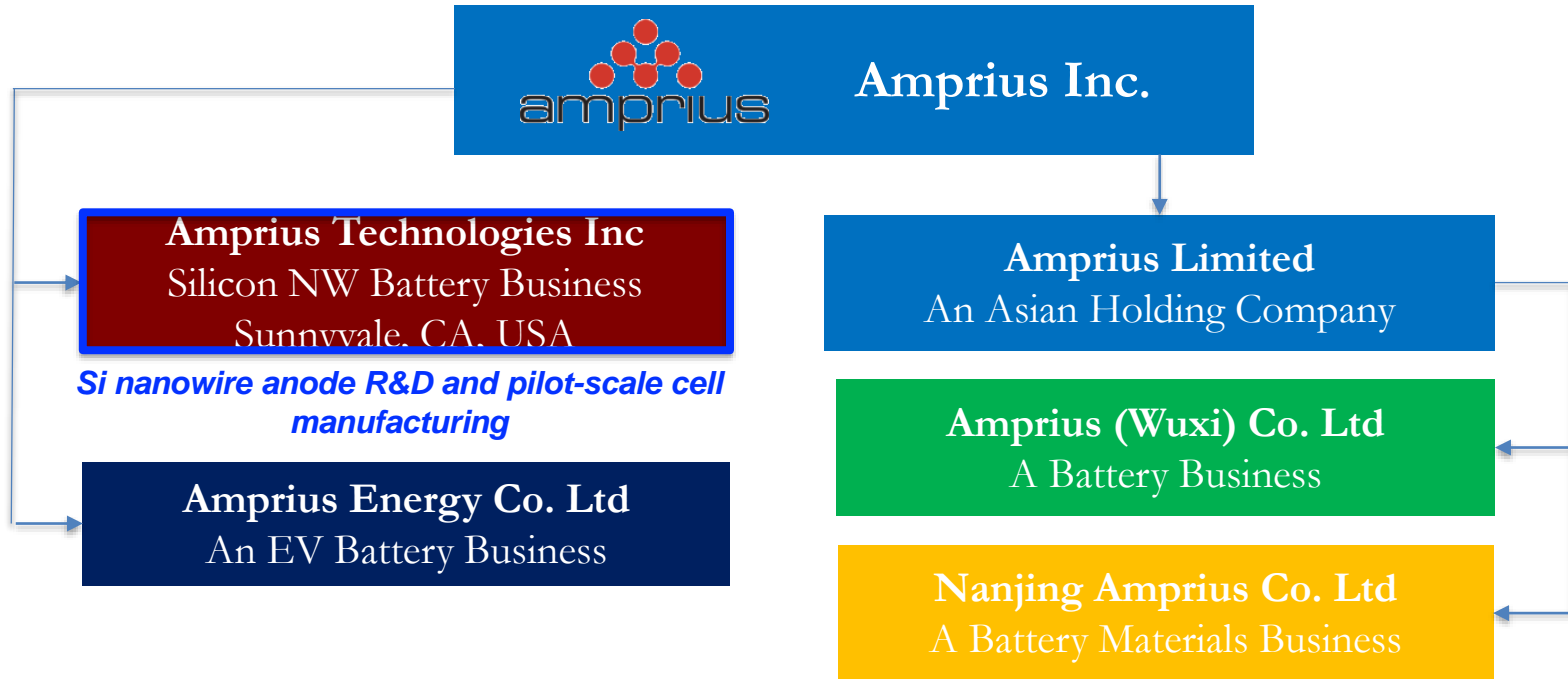
Ionel Stefan  
CTO, Amprius Technologies  
225 Humboldt Ct, Sunnyvale, CA

NASA Aerospace Battery Workshop  
Huntsville, AL, Nov 14-16, 2017



- **Venture financed startup founded in 2009 with novel silicon anode materials technologies from Stanford University**
- **50 independent patents and patent filings**
- **Silicon Nanowire Anode Platform has demonstrated over 1200 Wh/L and 400 Wh/Kg → *highest Li ion cells in the industry***
- **Pilot scale manufacturing for Silicon Nanowire anode in 2018**

# Amprius Organization



-  a JV between Amprius and Wuxi IDG
-  in progress

# Amprius R&D and Manufacturing Centers



- California R&D Center & Headquarters – focus on silicon nanowire anode and advanced materials
- Nanjing R&D Center – focus on silicon/graphite composite anode as well as lithium-rich cathode and electrolytes.
- Wuxi R&D Center and Manufacturing Lines – focus on battery technologies and manufacturing

**Materials Technologies**

**Battery Technologies**

**Manufacturing Technologies**

# Private & Public Support: Leading Investors & U.S. Gov't Agencies



## VCs & Private Equity



Trident Capital



Stanford University



Dr. Eric Schmidt



VantagePoint



## U.S. Government



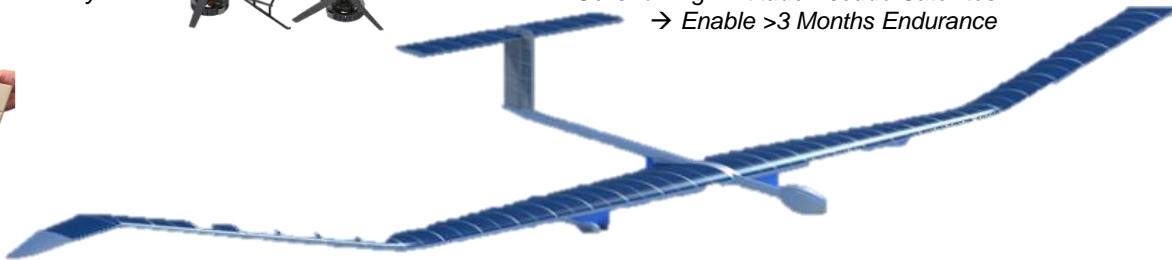
# Mission Statement

- 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 High Altitude Pseudo Satellites  
→ Enable >3 Months Endurance



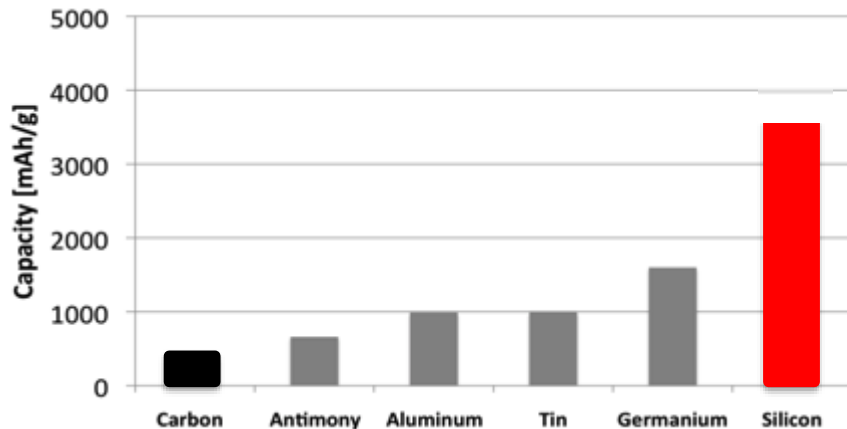
Cells for Lightweight Drones  
→ Enable >4 hr Missions  
(>2x current endurance)



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



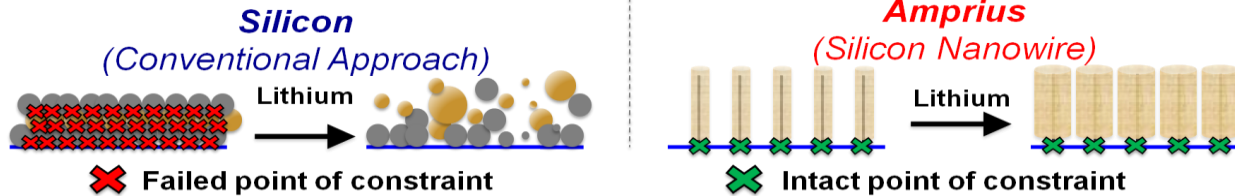
## Silicon has 10X Capacity vs. Carbon



### Amprius solutions enable:

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

*Silicon anodes are the “holy grail” for lithium ion batteries*

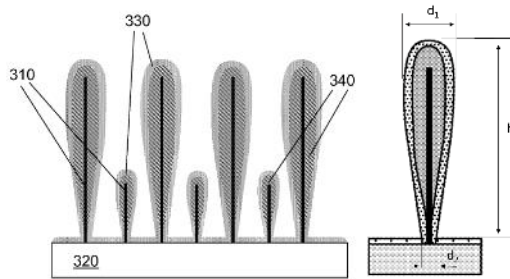


## Fundamental Problem of Silicon-Containing Anode

- *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*



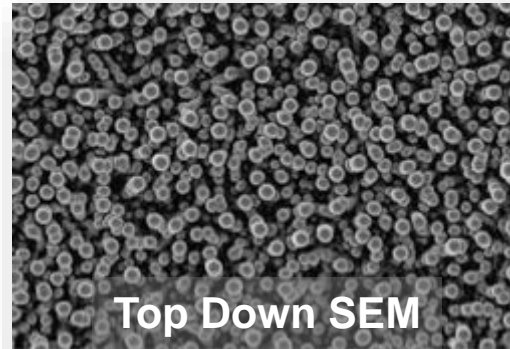
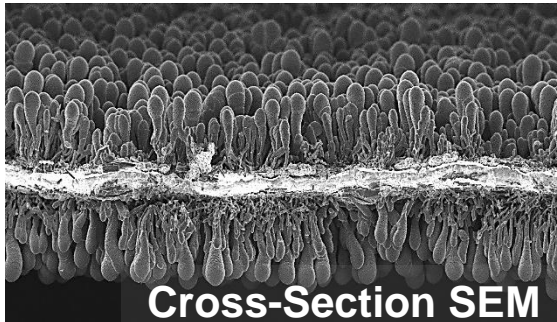
# Silicon Nanowire Structure



(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:

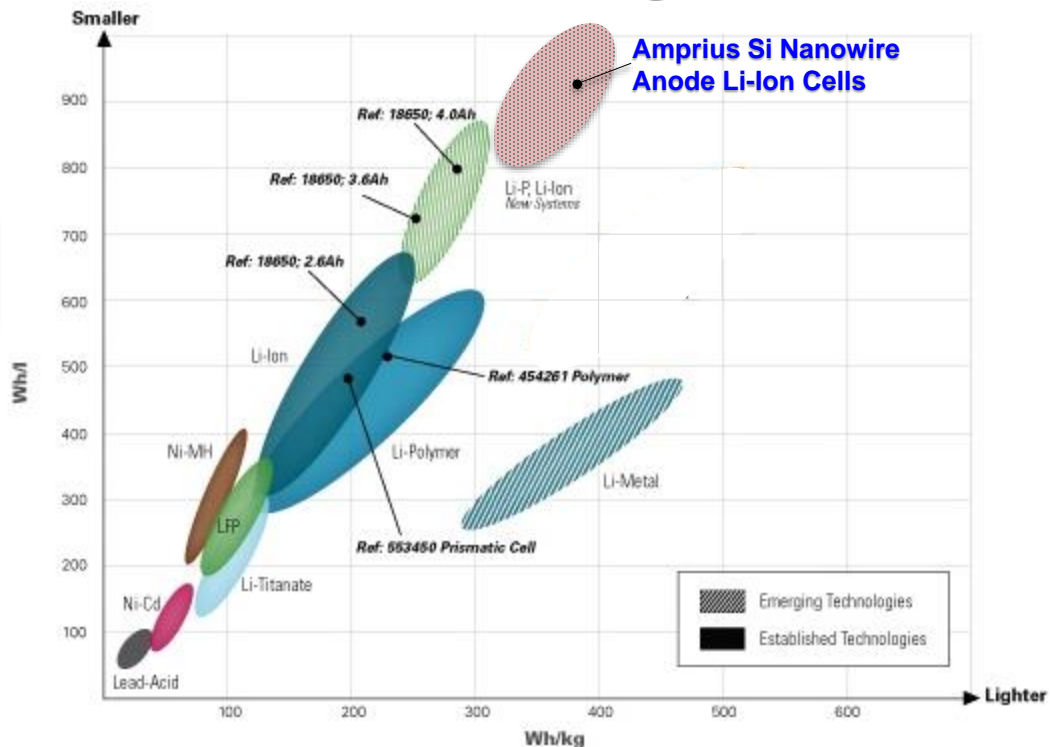
- Highest content active silicon material (100%)
- High conductivity and connectivity (rooted to substrate)
- Low tortuosity – high rate capability
- Ideal and adjustable porosity distribution
- High mass loading (2-3 mg/cm<sup>2</sup>)



# Battery Landscape

## Comparison of Energy Densities for Various Battery Chemistries

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

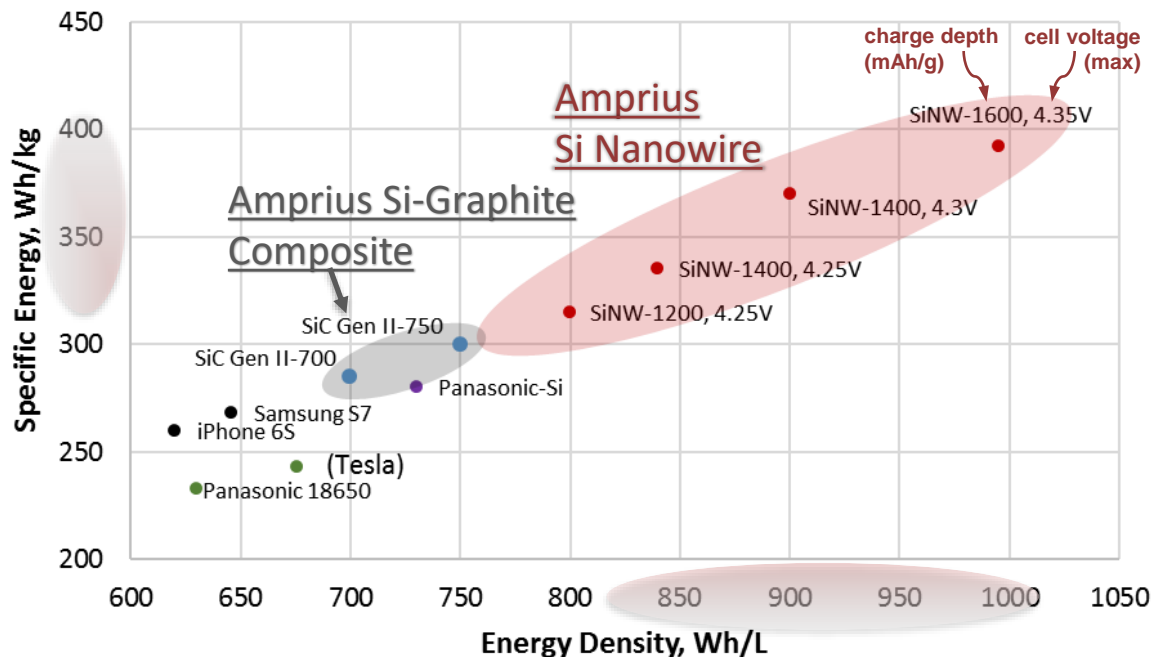


# Li-ion Battery Landscape



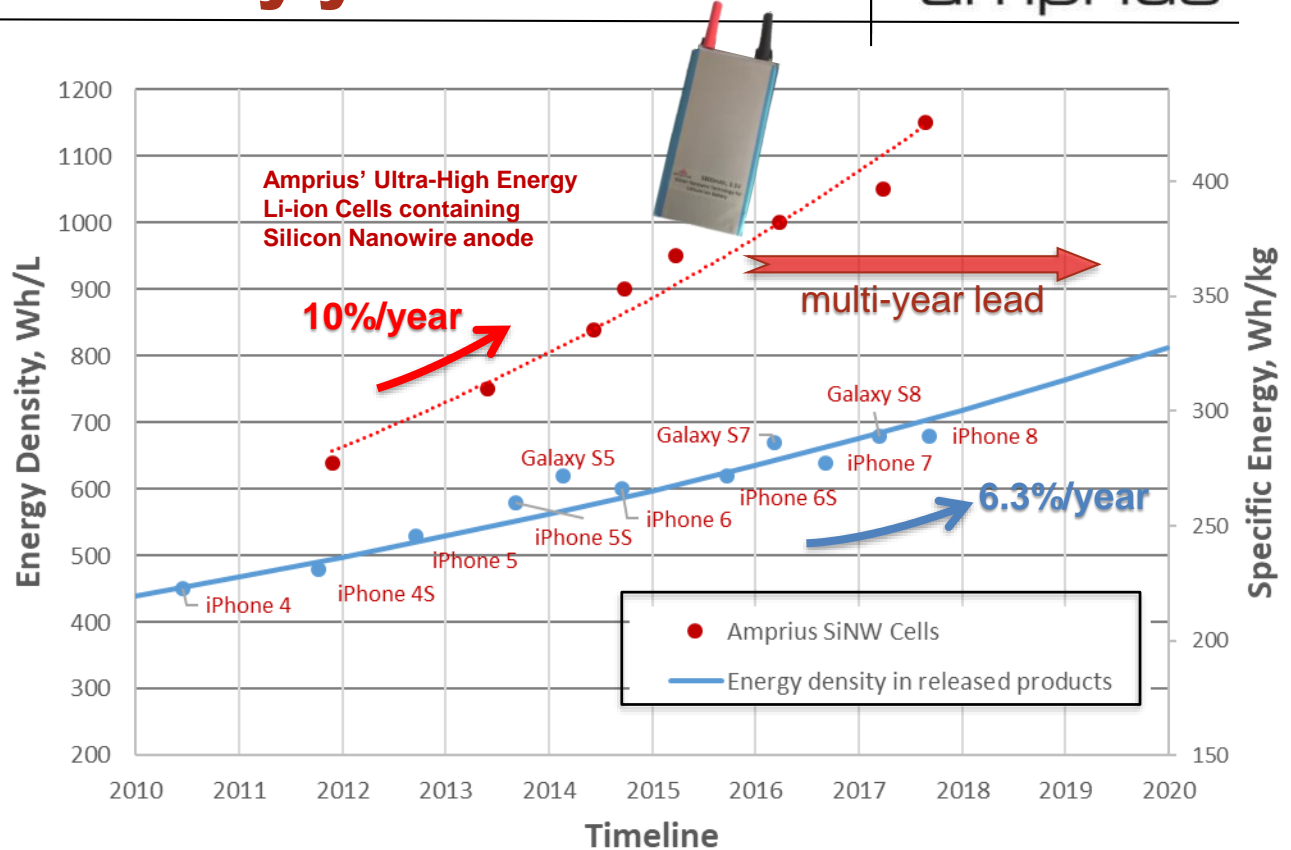
**Silicon nanowire technology** performance is adjustable by voltage & charge depth

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

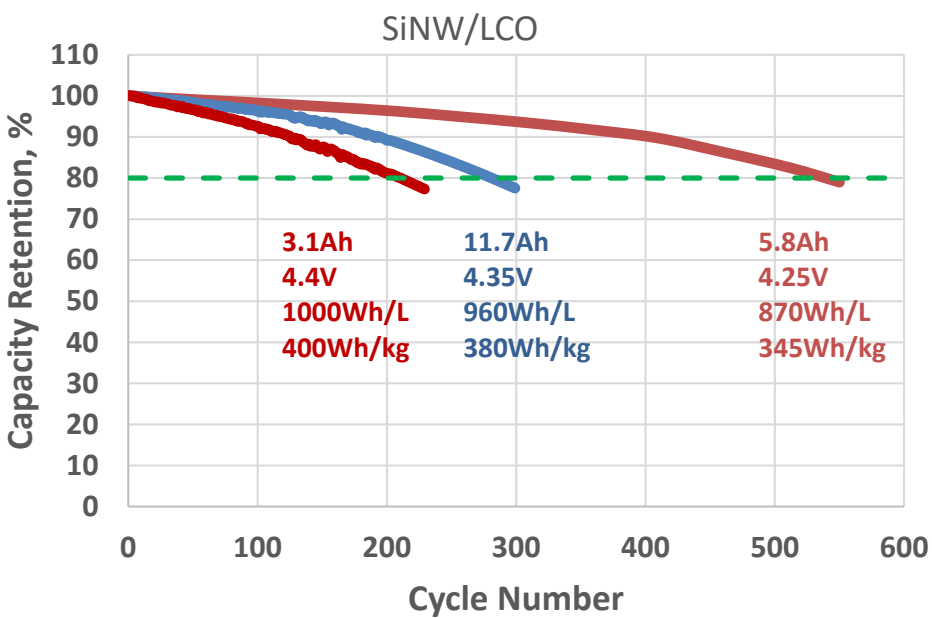


Voltage range 2.75-4.35V, measured at C/5 rate,  
Operating temperature range: -20 °C to 45 °C

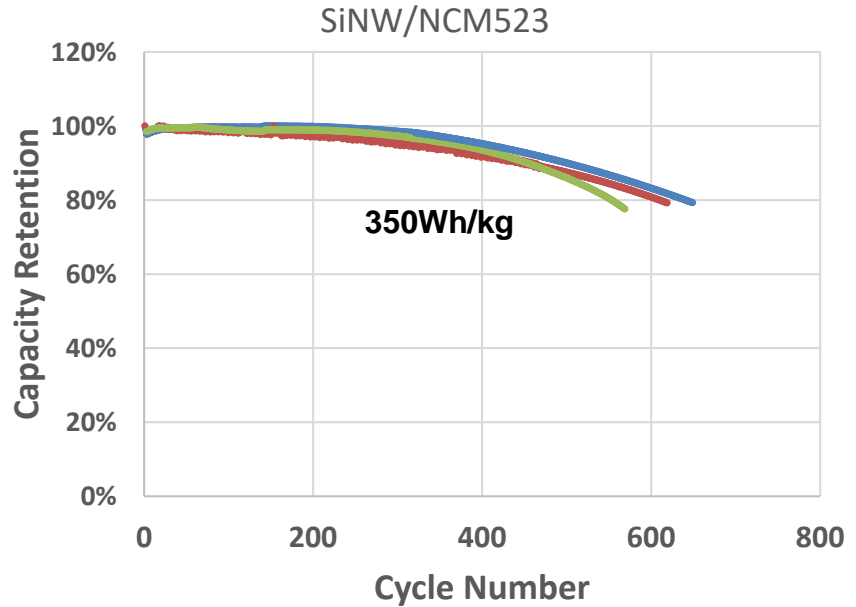
# Amprius Technologies High Energy Products: Cycle Life



Tailored to application and energy density level



C/5 to C/10 rates, for aerospace applications



C/2 rate, for EV 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

# 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			
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

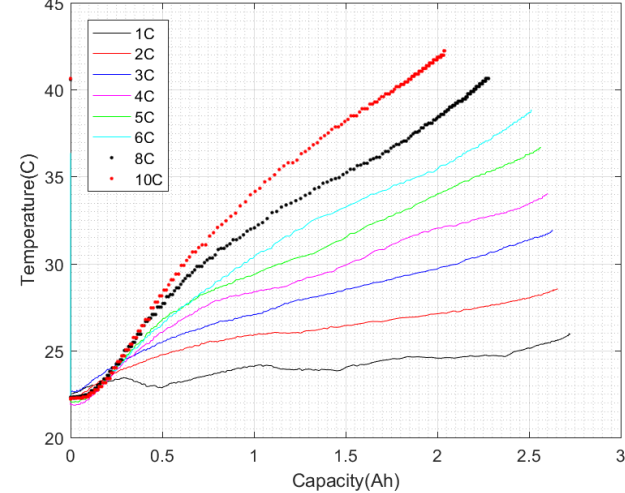
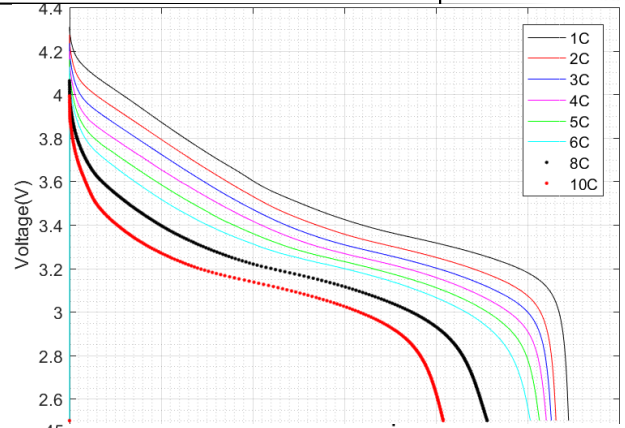
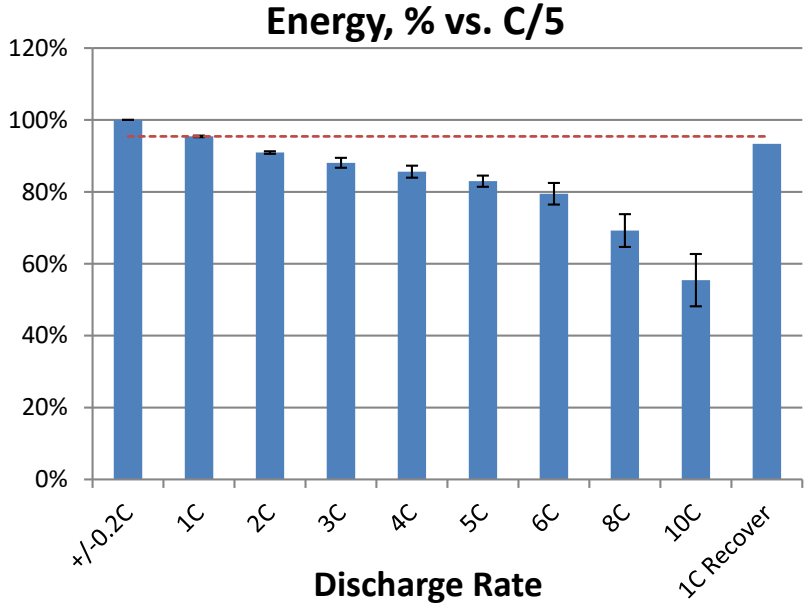
Operating temperature range: -20 °C to 55 °C

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





# Amprius Technologies High Power Products: Rate Capability



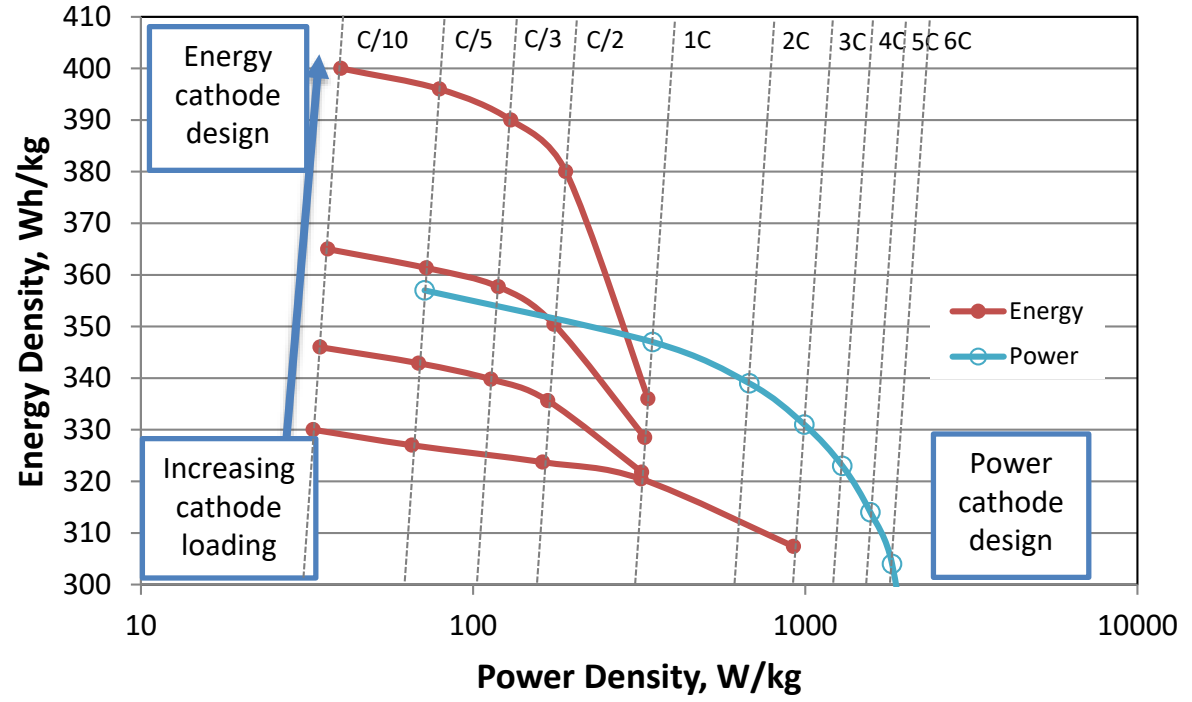
>80% relative energy to 6C rate

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

# Amprius Technologies Products: High Energy and Power Capability



### Si NW anode/LCO Ragone Plot



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

# Initial Target Markets

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

- **Aerospace (UAVs)**
  - High Altitude Pseudo Satellites (HAPS) **\$25bn Market by 2025\***
  - Lightweight / hand-launched / long endurance drones
  - Long Endurance Multi-rotor drones
- **Mission Critical**
  - Wearable / conformal packs
  - Autonomous systems (robotics)

\* 2016 PwC HAPS market analysis

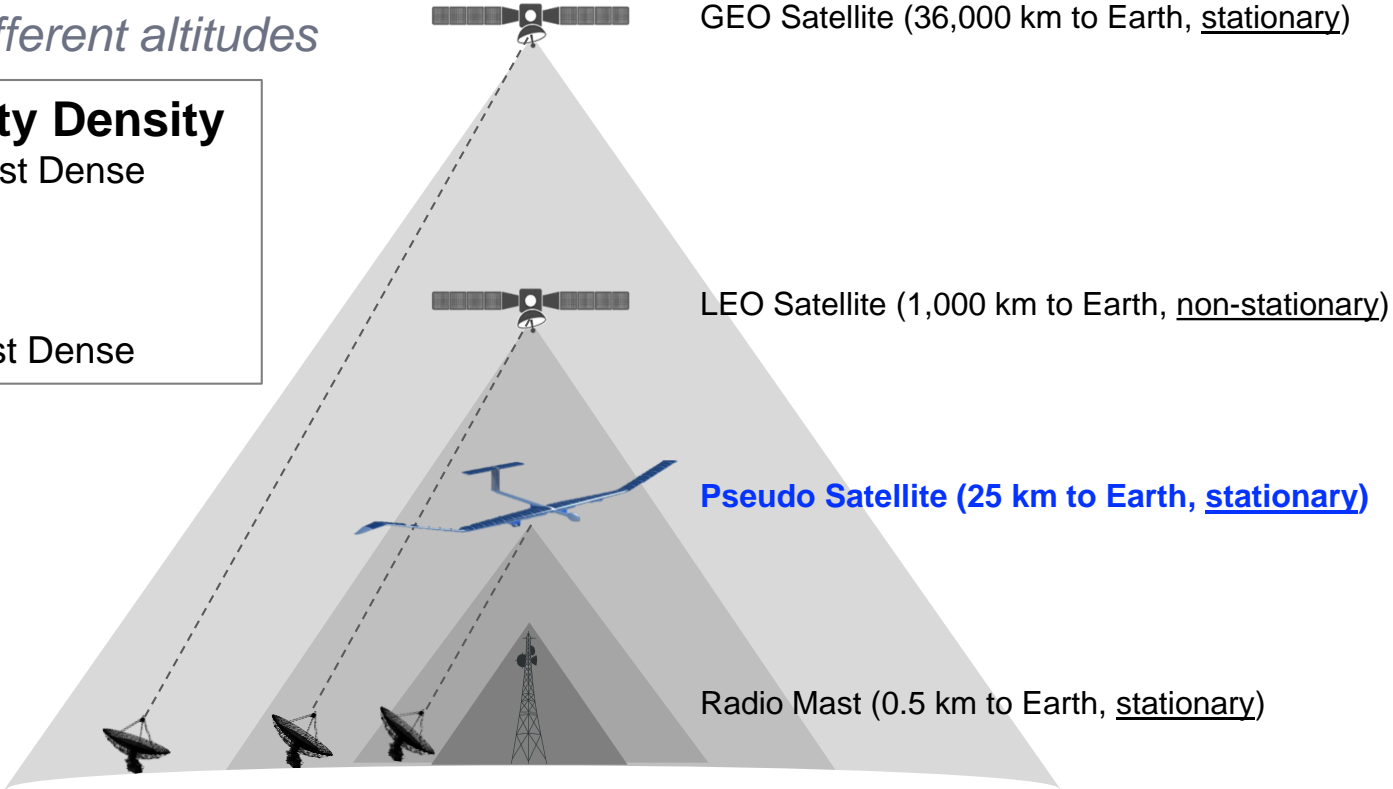
# Data Communication Platforms

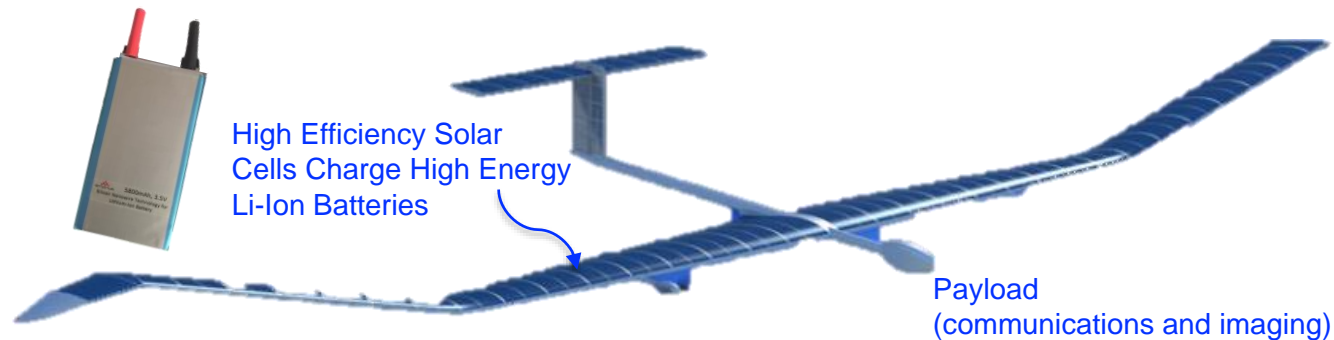


*Platforms at different altitudes*

**Connectivity Density**

- Least Dense
- Most Dense

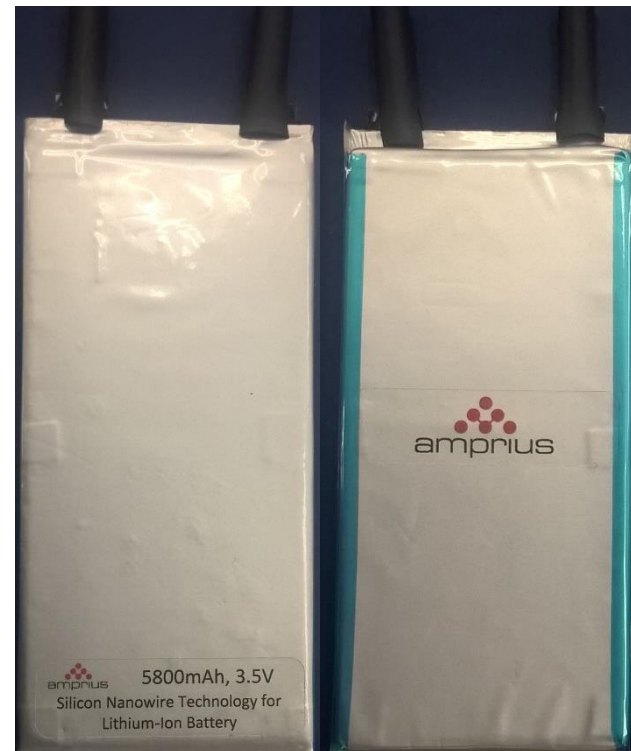




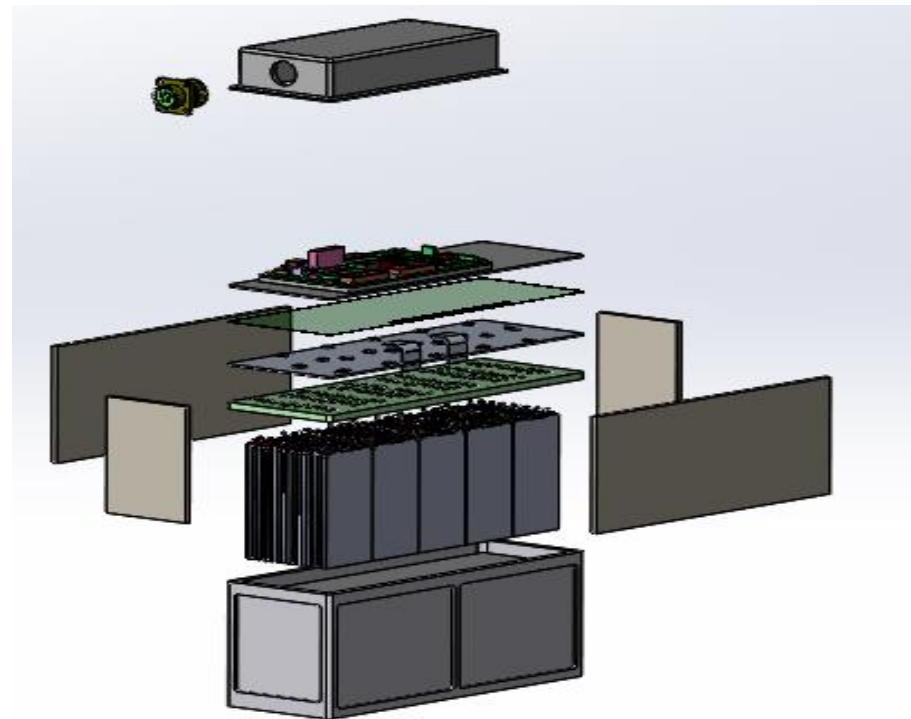
## Emerging application in Aerospace

- *Solar-Electric aircraft serves as High Altitude Pseudo Satellites (HAPS)*
- *Low launch cost & very mobile*
- *Amprius' cells will enable over 12 weeks endurance*  
(Current endurance is 2 weeks)

- NASA Cell Specifications:
  - Cell capacity: 5.8Ah
  - Cell energy: 21Wh
  - Energy density: 860 Wh/L
  - Specific energy: 340 Wh/kg
  - >200 cycles
  - 2.75-4.25V (Si/LCO)



- NASA Battery Specs:
  - Configuration: 8S10P
  - Capacity: 58Ah
  - Energy: 1625Wh
  - Nominal Voltage: 28V
  - Energy density: 400 Wh/L
  - Specific energy: 250 Wh/kg
  - >200 cycles



# Very Long Endurance Batteries for UAS



Battery proposed to Navy for development

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



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



## Replaces:

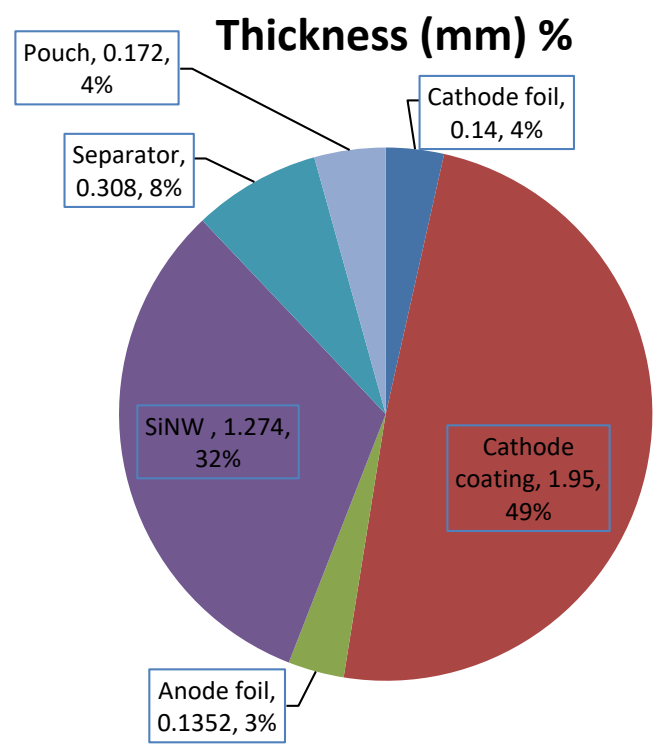
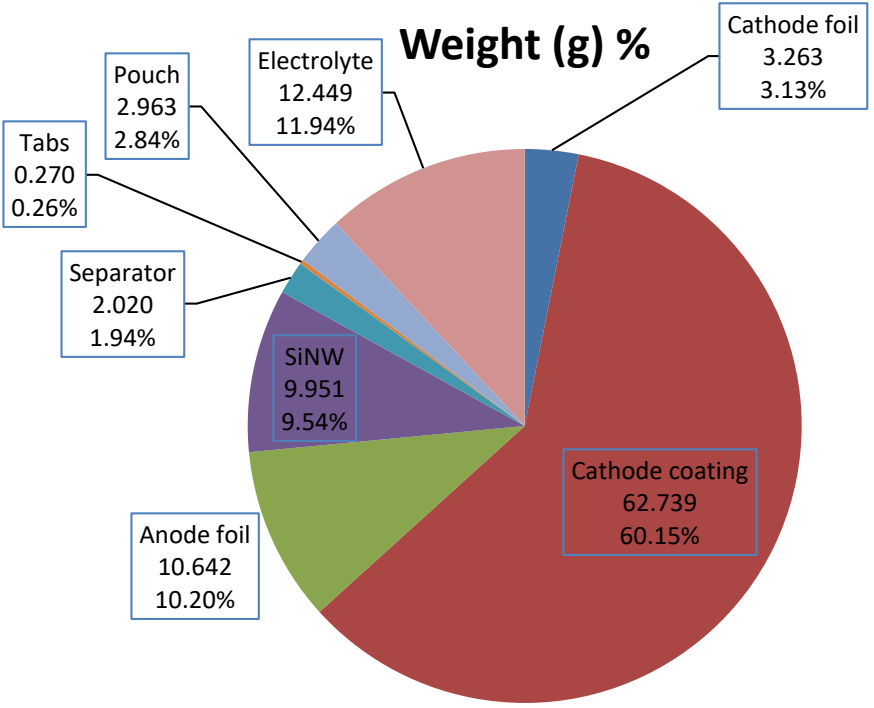
- Graphite powder mixing
- Slurry mixing
- Roll coating (2x)
- Drying
- Calendaring

## Bare Foil In → Finished Anode Out

- Pilot Tool capable of ~300 kWh/year
- At 100 MWh/year near \$/Ah parity with graphite *but* 40% higher energy density

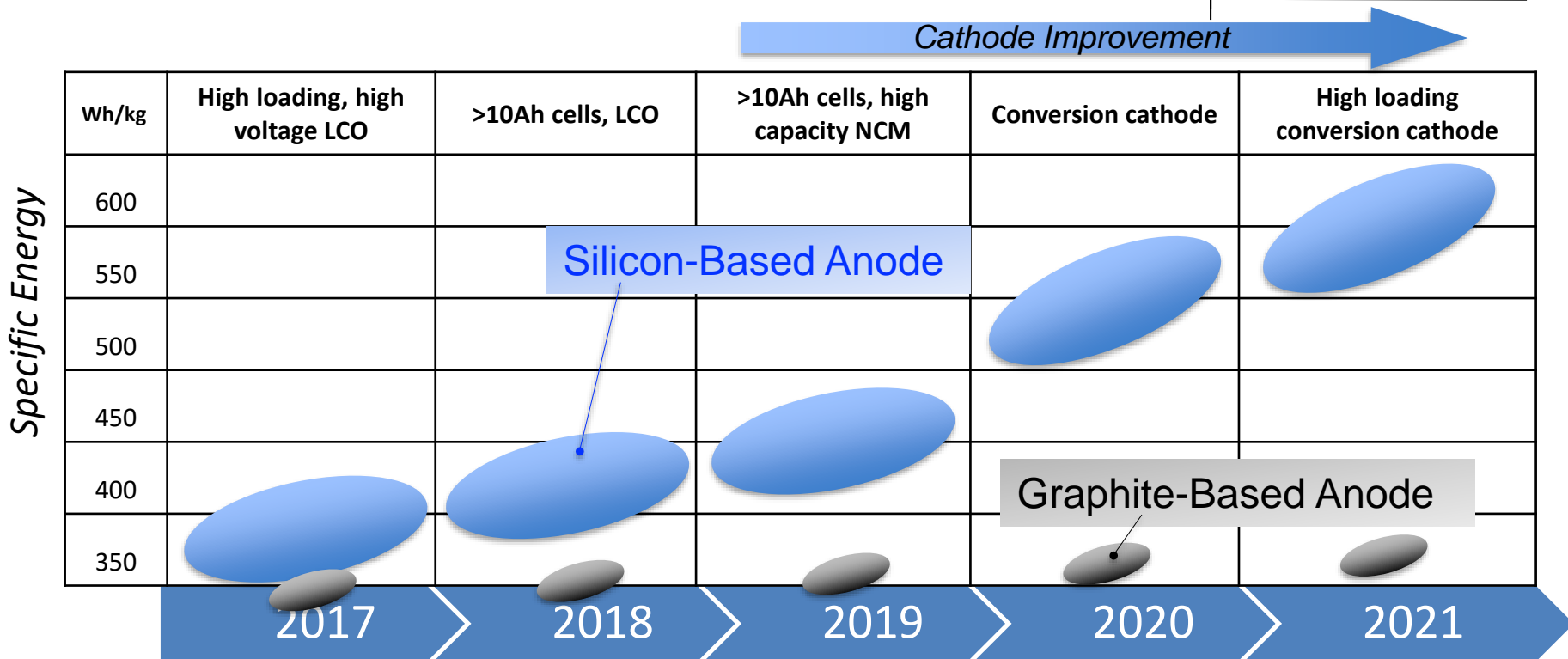


# Road Ahead: What components to improve?



The cathode material dominates both in weight and volume proportion

# Si Nanowire Anode Specific Energy Roadmap



# Amprius – a Leader in High Energy Density Batteries



Amprius is a pioneer and leader of high capacity silicon anode materials and high energy density lithium ion batteries.

Amprius was the first to introduce silicon anode polymer batteries to market in 2013 and manufactures the highest capacity silicon anodes and the highest energy density commercial batteries in industry at the present time. Amprius is the only silicon anode polymer battery manufacturer today.

Amprius technology and product platforms include high energy density silicon nanowire anode battery materials system, silicon-graphite anode battery materials system, lithium-rich cathodes, electrolytes, polymer binders and encapsulation materials.

Amprius high energy density batteries have been and can be used for smartphones, wearables, drones, robotics, aerospace devices, electrical transportation, military equipment.

Amprius has an advanced silicon-graphite anode battery manufacturing facility in Wuxi, China, a silicon anode production pilot line in Nanjing, China, a silicon nanowire anode pilot production line in Sunnyvale, California

**Thank You**