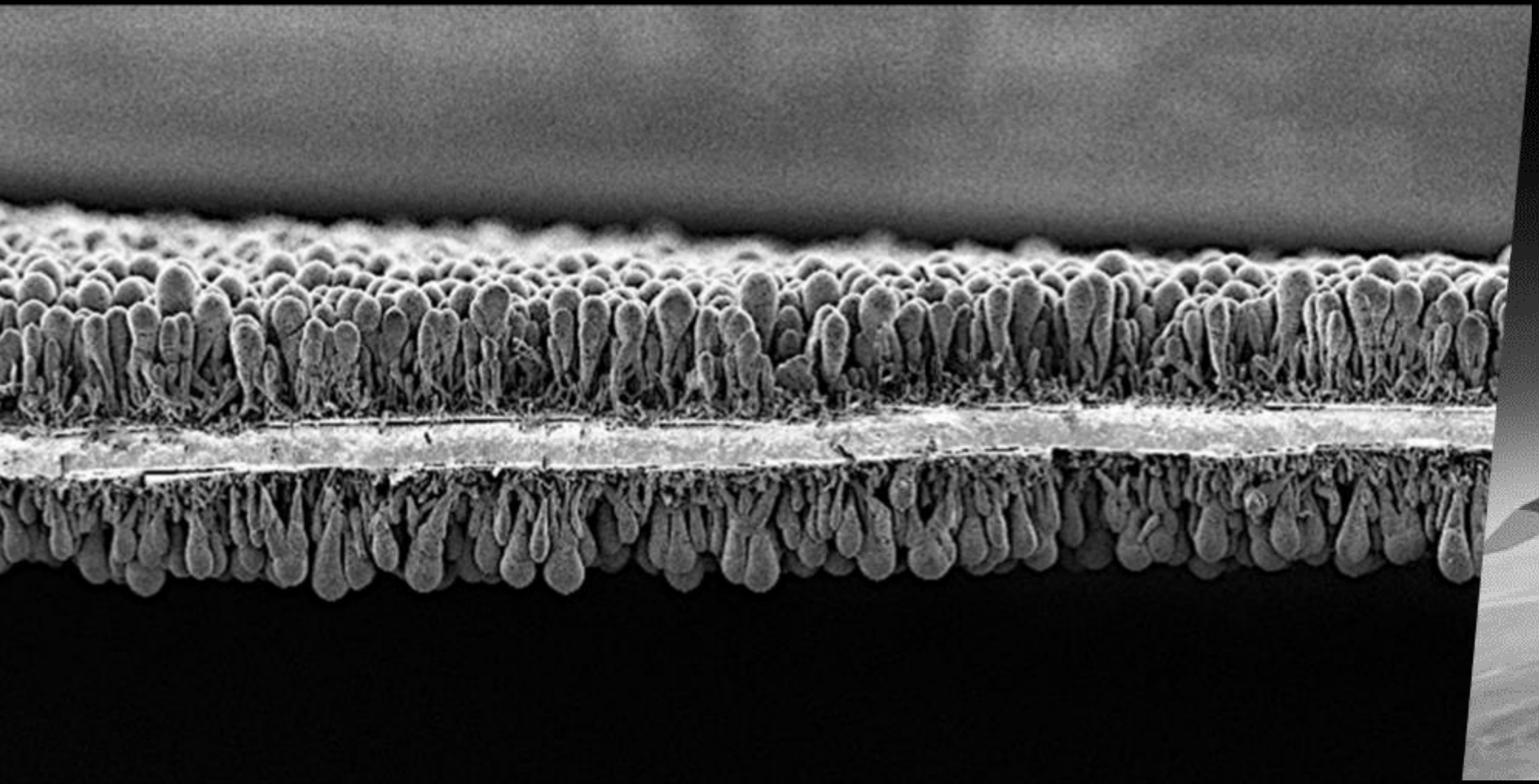
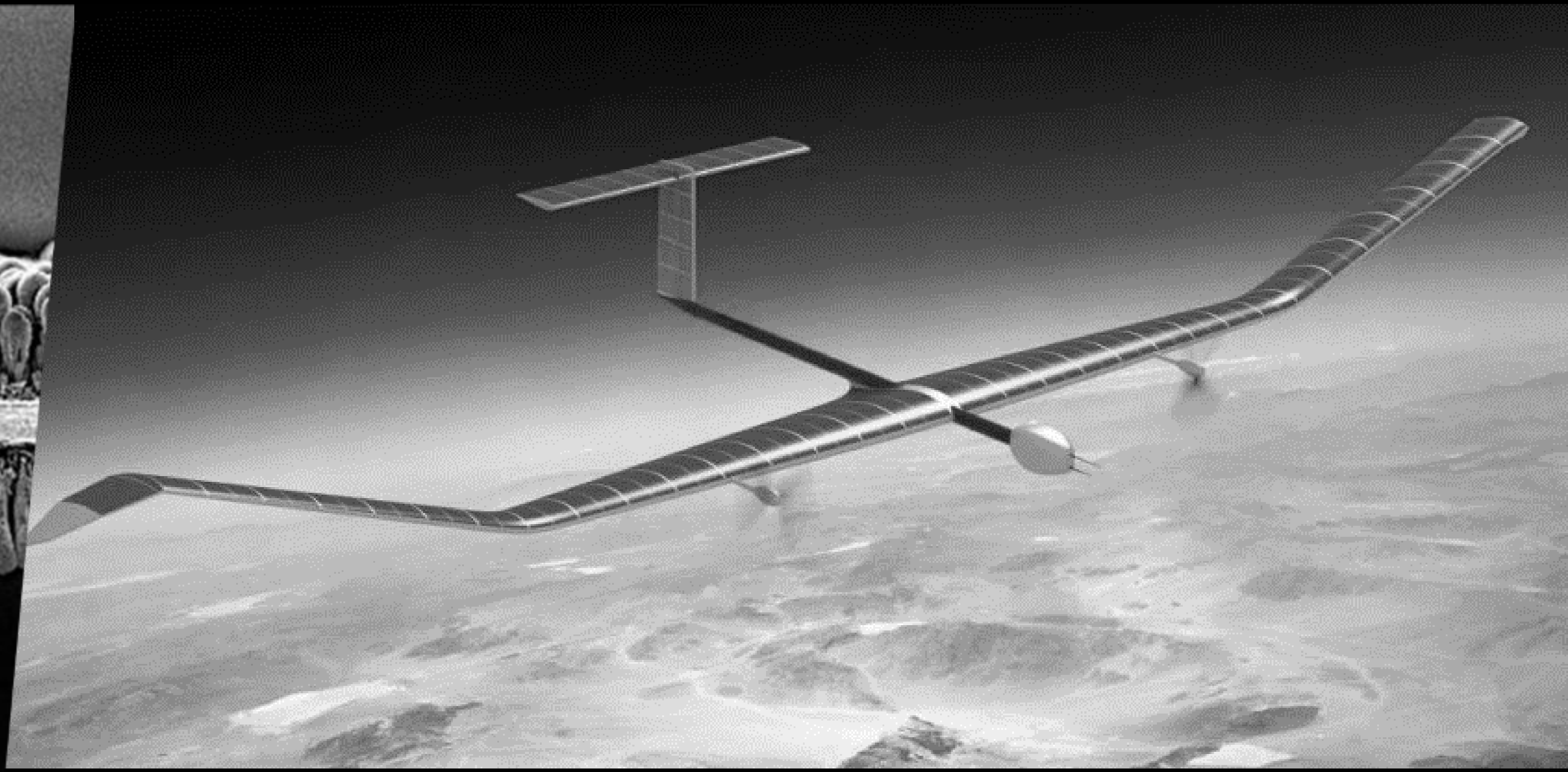
500 Wh/Kg Li-Ion Batteries for Stratospheric Applications



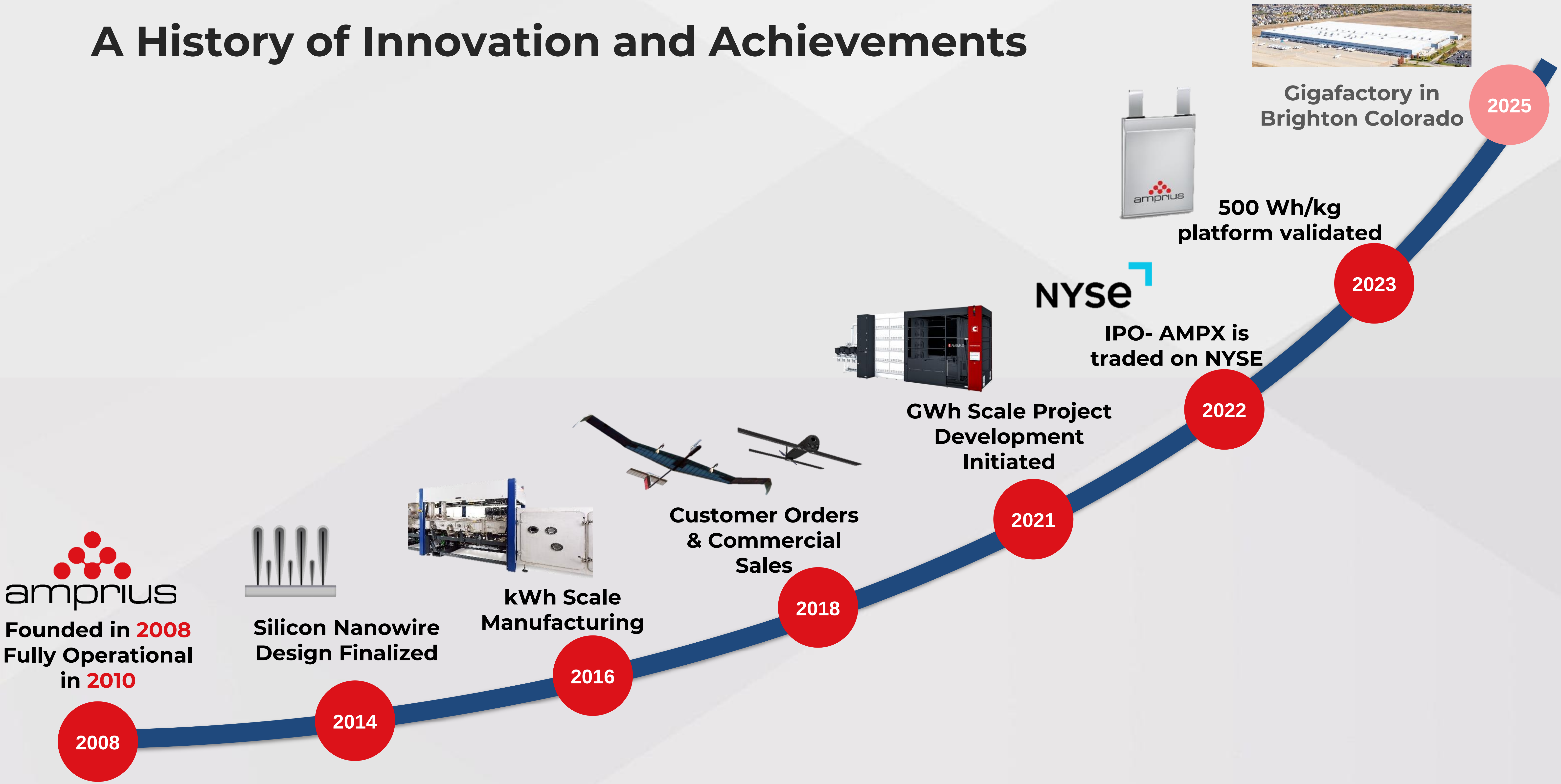


Ionel Stefan
CTO, Amprius Technologies, Inc.
1180 Page Ave., Fremont, CA

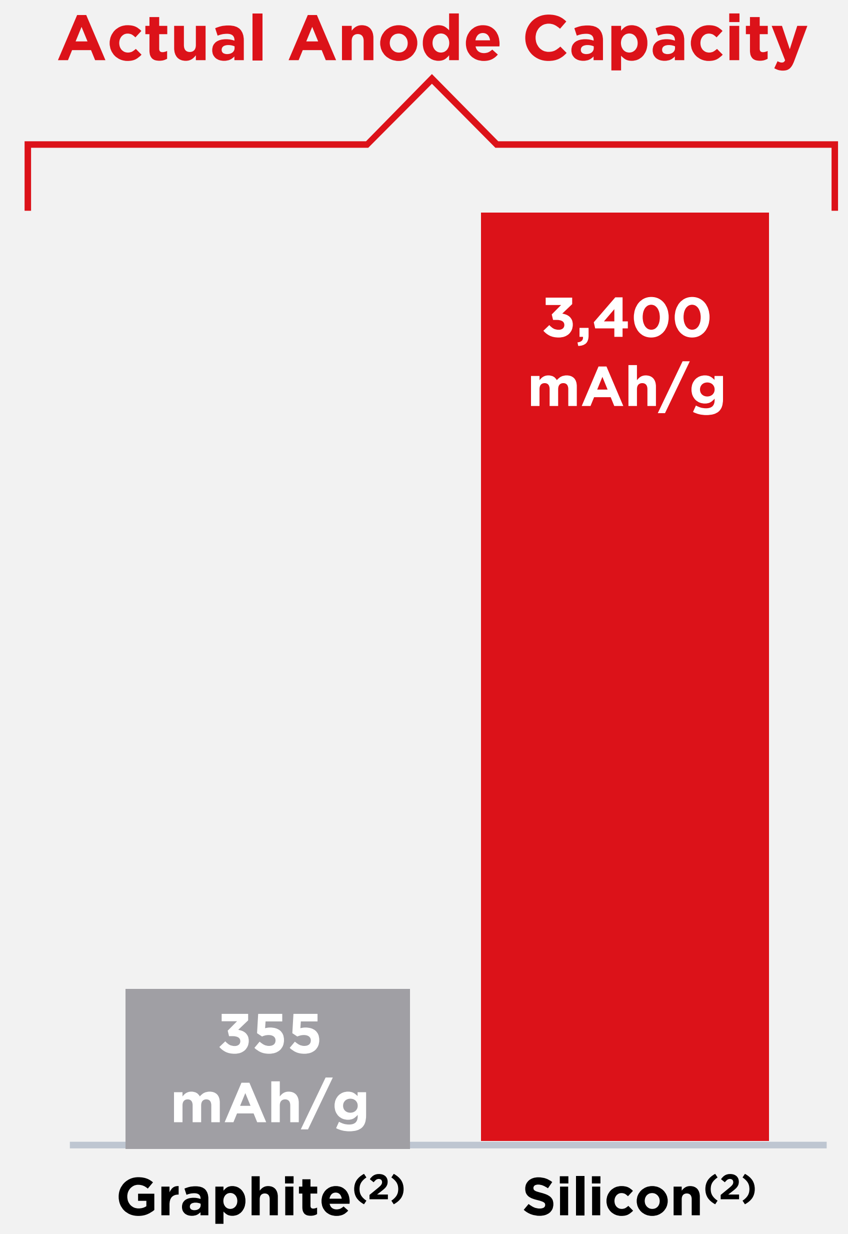
UND SOaRS Symposium

March 2024

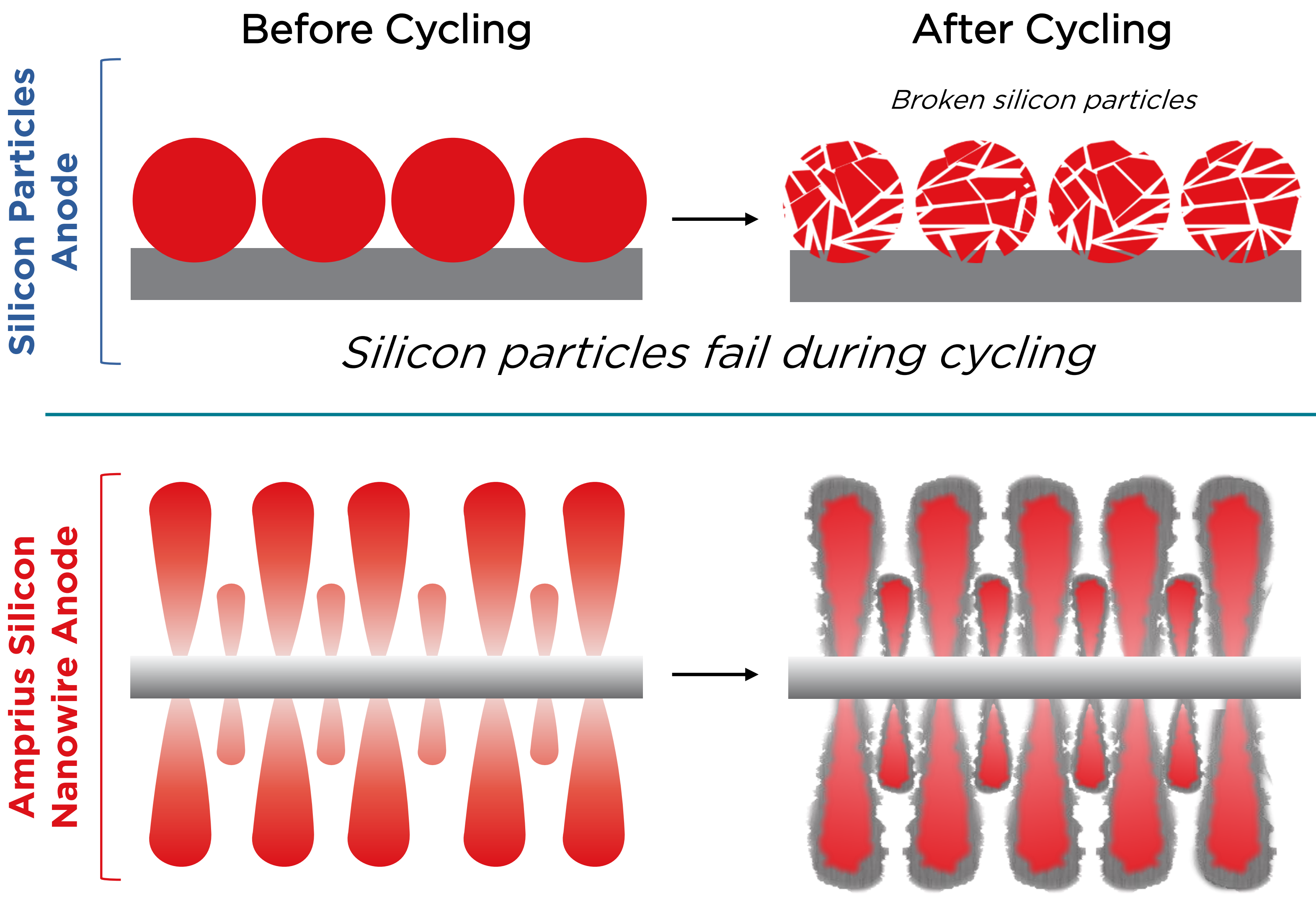
A History of Innovation and Achievements



Why Silicon? 100% Silicon Anode(1) Has ~10x Capacity vs. Graphite



Silicon anode can swell up to ~300% causing battery damage after a few cycles

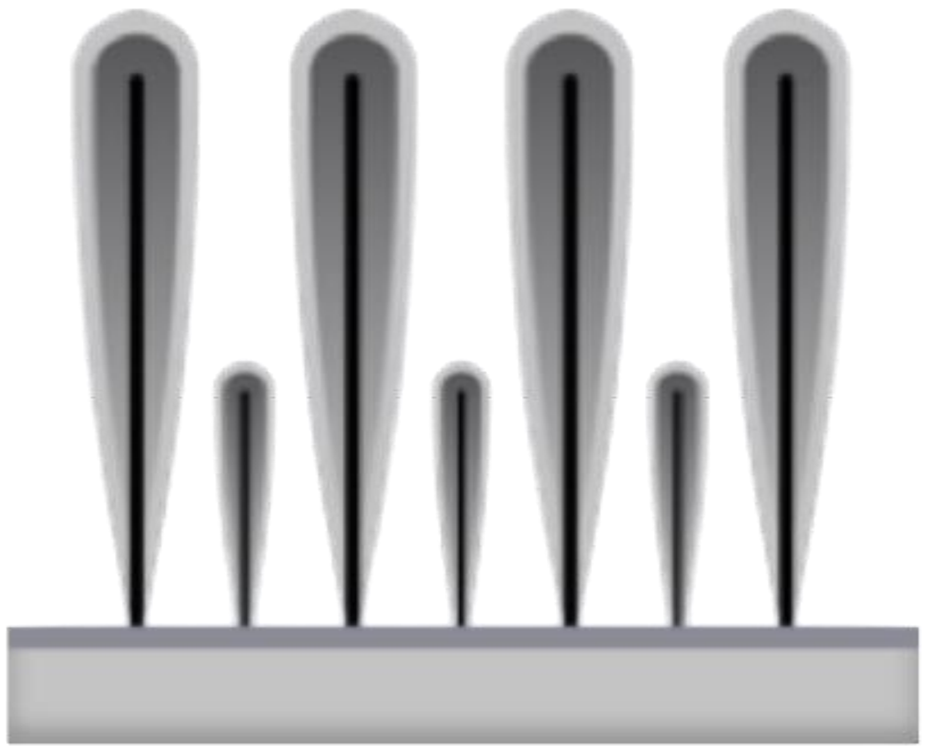


Silicon particles fail during cycling

Silicon nanowire structure maintains its form

(1) Actual percentage of silicon is 99.5-99.9% which is within the range of acceptable purity levels for materials that are considered 100%.
(2) Based on Amprius measurements in half cells.

Enable the Highest Energy and Power Batteries in Industry



SiMaxx™

100% Silicon[1] without
Other Active Anode Material
(can be coated with other active materials)

SiCore™

Up to 100% Silicon without
Other Active Anode Material
(can be mixed with other active materials)

(1) Actual percentage of silicon is 99.5-99.9% which is within the range of acceptable purity levels for materials that are considered 100%.

Amprius Utilizes Existing Commercial Manufacturing Processes

- Only Change is to the Anode Manufacturing Line
- Cathode and Assembly Lines are Unchanged

SILICON NANOWIRE ANODE

Proprietary Deposition

STANDARD CATHODE


Mixing


Coating


Calendaring

STANDARD BATTERY ASSEMBLY


Slitting


Stacking

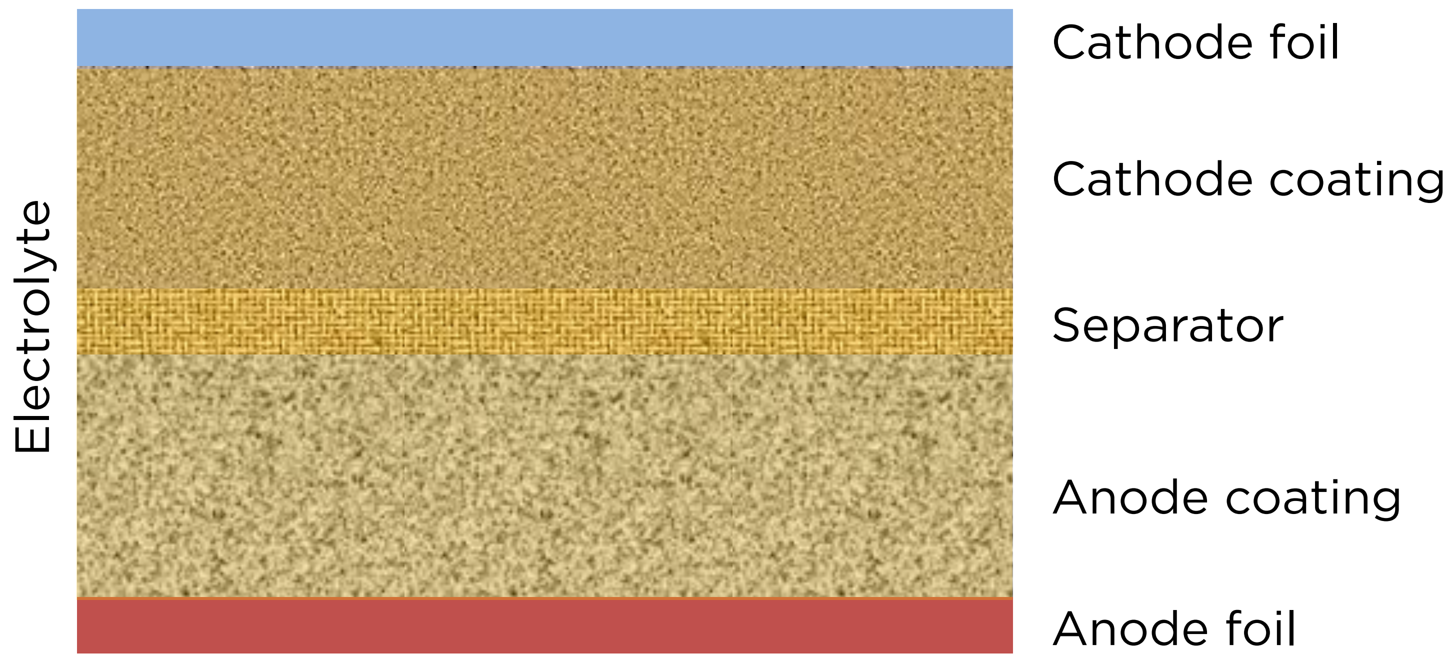

Formation

SILICON NANOWIRE ANODE MANUFACTURING LINE

STANDARD BATTERY MANUFACTURING LINE

All about Specific Energy

Unit cell specific energy (1 cm^2)



$$Specific\ Energy = \frac{Cell\ Energy}{Cell\ Mass} = \frac{Wh}{kg}$$

$$Cell\ Energy = Areal\ capacity \text{ x } Cell\ voltage$$

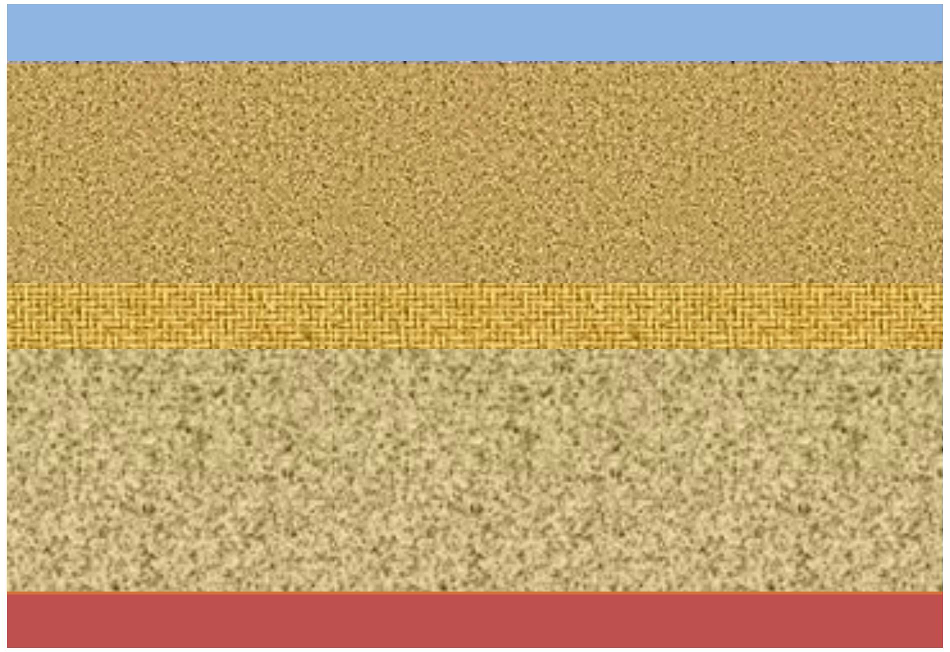
$$Cell\ Energy = M_{cat\_active} \text{ x } Capacity_{cat} \text{ x V}$$

$$Cell\ Mass = M_{an\_active} + M_{an\_inactive} + M_{cat\_active} + M_{cat\_inactive} + \\ + M_{an\_foil} + M_{cat\_foil} + M_{sep} + M_{ely} + M_{case}$$

$$M_{an\_active} = M_{cat\_active} \text{ x } \frac{Capacity_{cat}}{Capacity_{an}} \text{ x } \frac{N}{P}$$

$$Specific\ Energy = \frac{M_{cat\_active} \text{ x } Capacity_{cat} \text{ x V}}{M_{cat\_active} \text{ x } \frac{Capacity_{cat}}{Capacity_{an}} \text{ x } \frac{N}{P} + M_{an\_inactive} + M_{cat\_active} + M_{cat\_inactive} + (\rho * h)_{an\_foil} + (\rho * h)_{cat\_foil} + (\rho * h)_{sep} + M_{ely} + M_{case}}$$

Unit cell specific energy (1 cm²)



$$Specific\ Energy = \frac{Cell\ Energy}{Cell\ Mass} = \frac{Wh}{kg}$$

$$Cell\ Energy = Areal\ capacity \times Cell\ voltage$$

$$Cell\ Energy = M_{cat\_active} \times Capacity_{cat} \times V$$

$$Cell\ Mass = M_{an\_active} + M_{an\_inactive} + M_{cat\_active} + M_{cat\_inactive} + M_{an\_foil} + M_{cat\_foil} + M_{sep} + M_{ely} + M_{case}$$

$$M_{an\_active} = M_{cat\_active} \times \frac{Capacity_{cat}}{Capacity_{an}} \times \frac{N}{P}$$

$$Specific\ Energy = \frac{M_{cat\_active} \times Capacity_{cat} \times V}{M_{cat\_active} \times \frac{Capacity_{cat}}{Capacity_{an}} \times \frac{N}{P} + M_{an\_inactive} + M_{cat\_active} + M_{cat\_inactive} + (\rho * h)_{an\_foil} + (\rho * h)_{cat\_foil} + (\rho * h)_{sep} + M_{ely} + M_{case}}$$

Only two ways to increase specific energy:

- Increase the capacity of active materials
- Reduce inactive material content (higher active/inactive ratio)

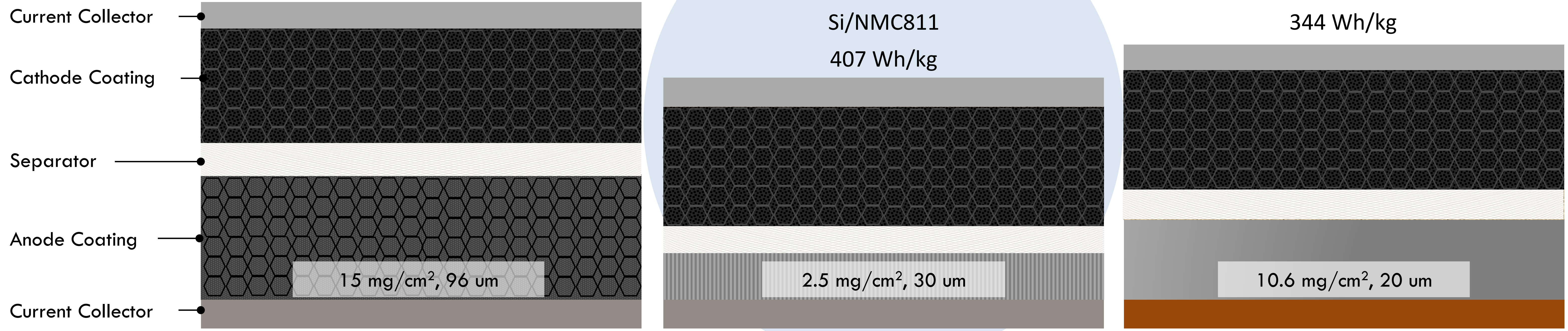
Pure Silicon Anode Mass is Lower than Alternatives

Example for 5 mAh/cm^2

Conventional Graphite
C/NMC811
301 Wh/kg

amprius
Pure Silicon
Si/NMC811
407 Wh/kg

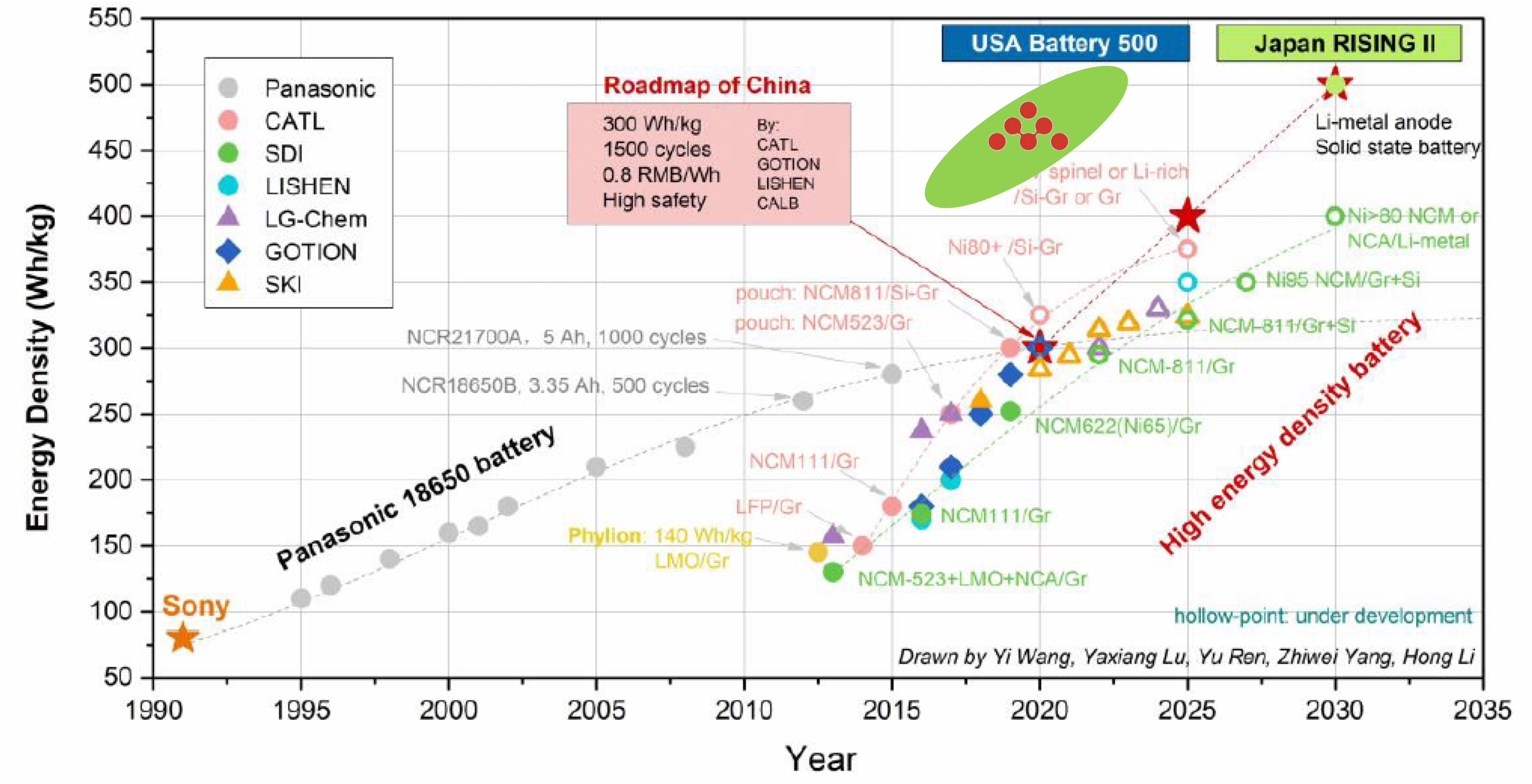
Li-Metal
Li/NMC811 (20um film Li/Cu)
344 Wh/kg



KEY TAKEAWAYS

- 2.5 mg/cm^2 Si has a reversible capacity of 9mAh/cm^2
- Lithium metal electrode has to be thinner than 5um to be equivalent in mass
- Solid-state electrolytes further increase cell mass
- First to reach 500 Wh/kg with commercial cathodes

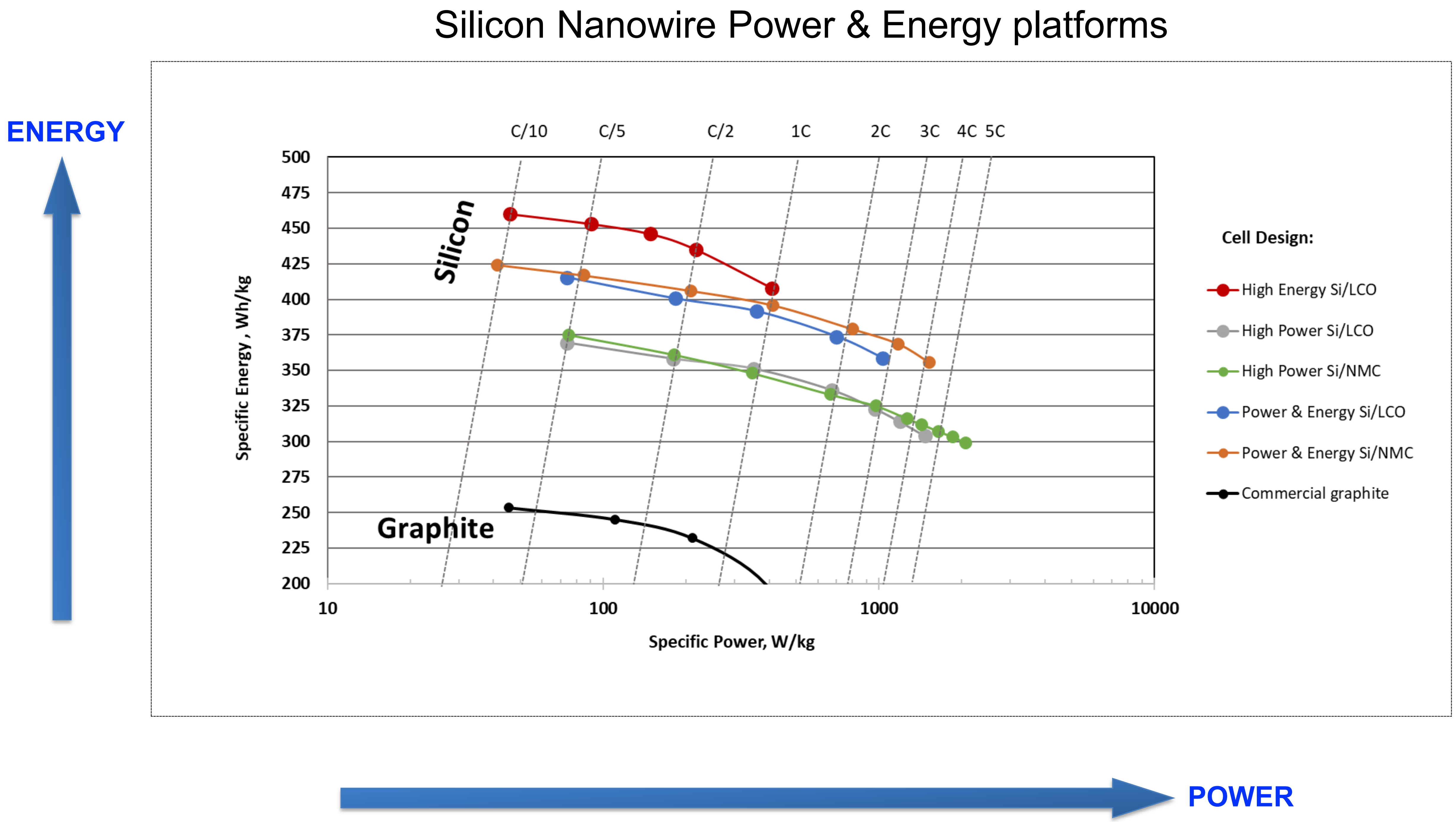
Silicon content is increasing



Source: https://battery2030.eu/wp-content/uploads/2022/07/BATTERY-2030-Roadmap_Revision_FINAL.pdf

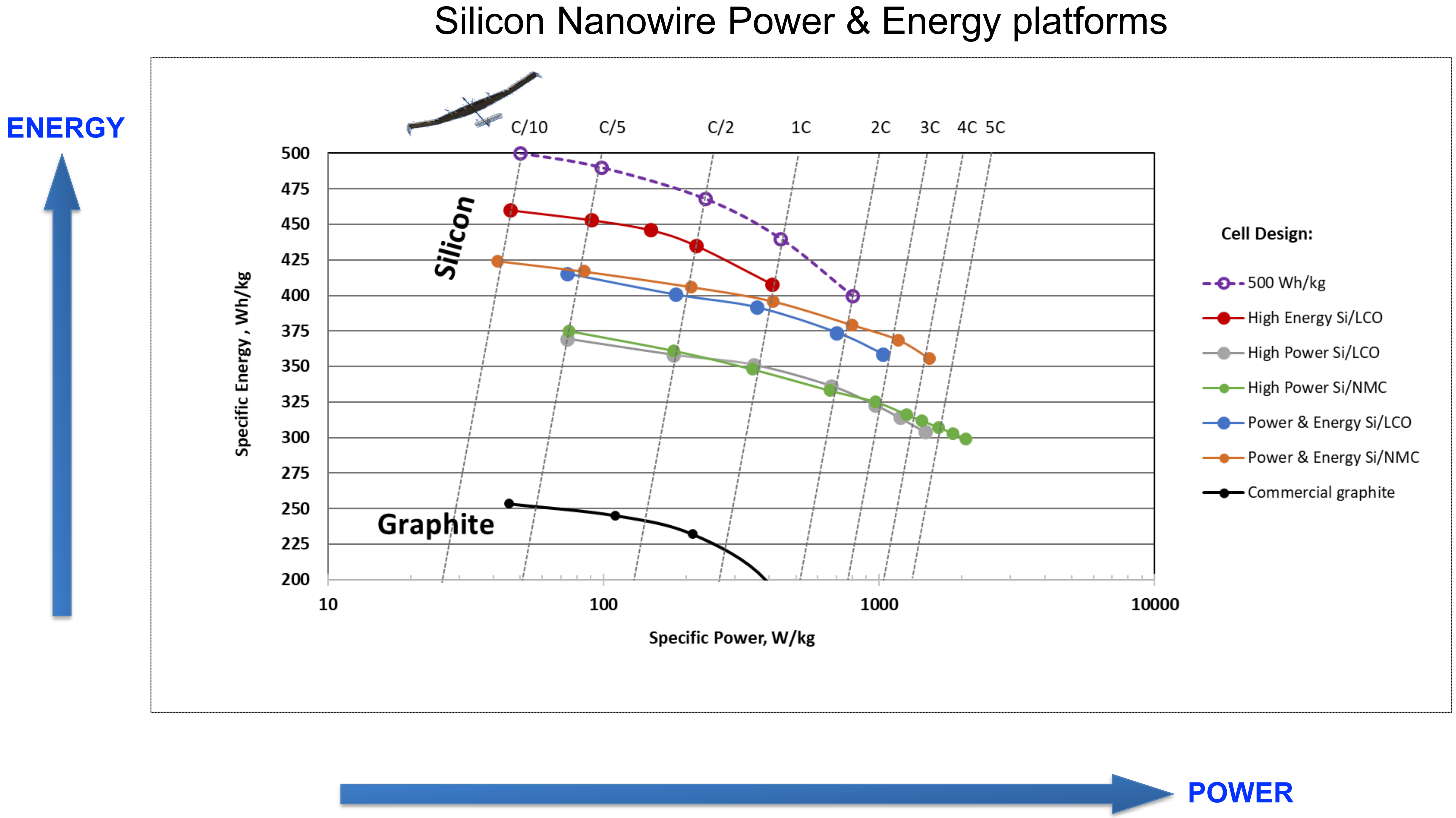
Amprius batteries

Minimal trade off between specific energy and specific power

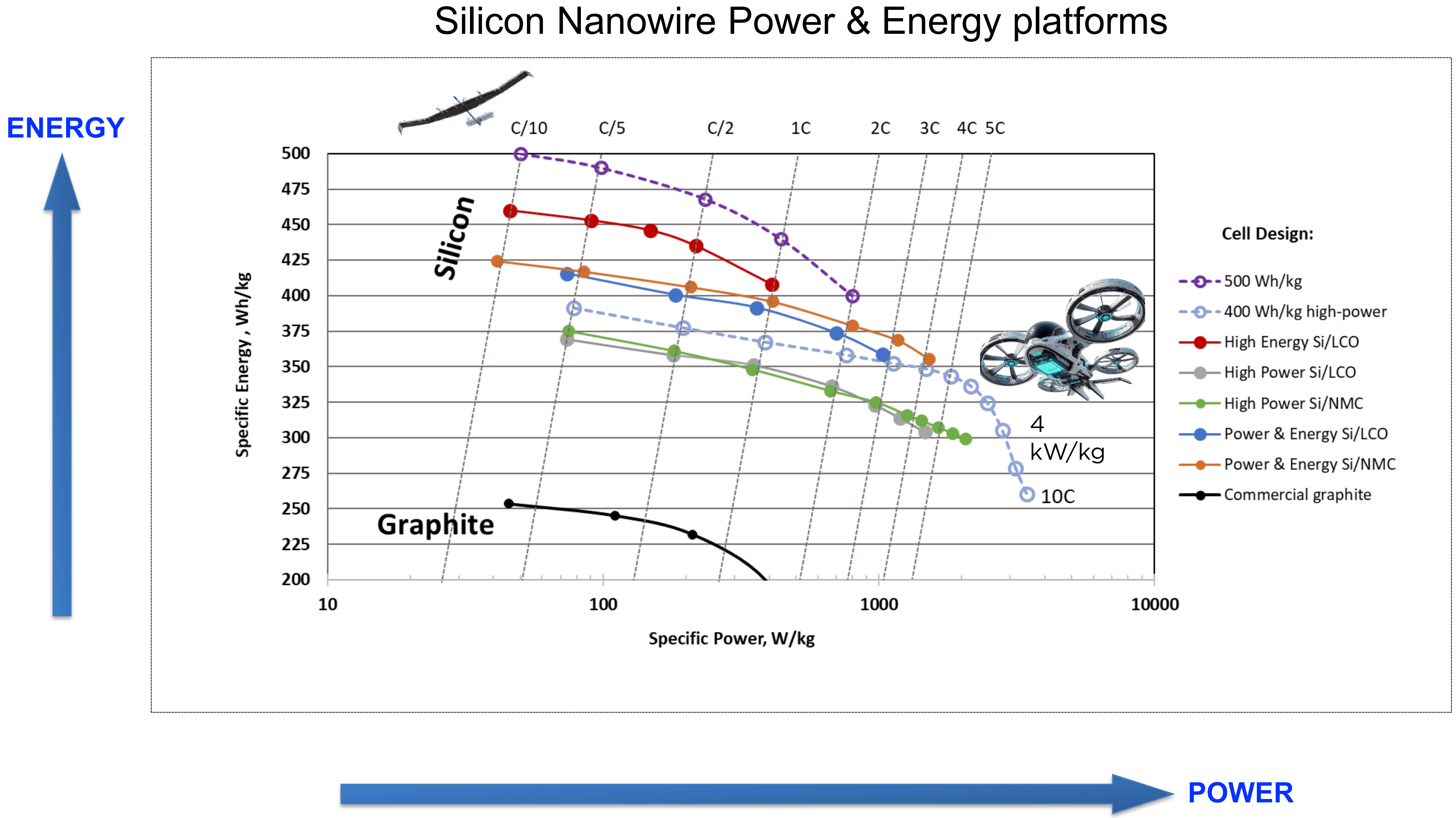


HIGH ENERGY AND POWER DENSITIES PRODUCTS

2023: New energy cell design: 500 Wh/kg cells

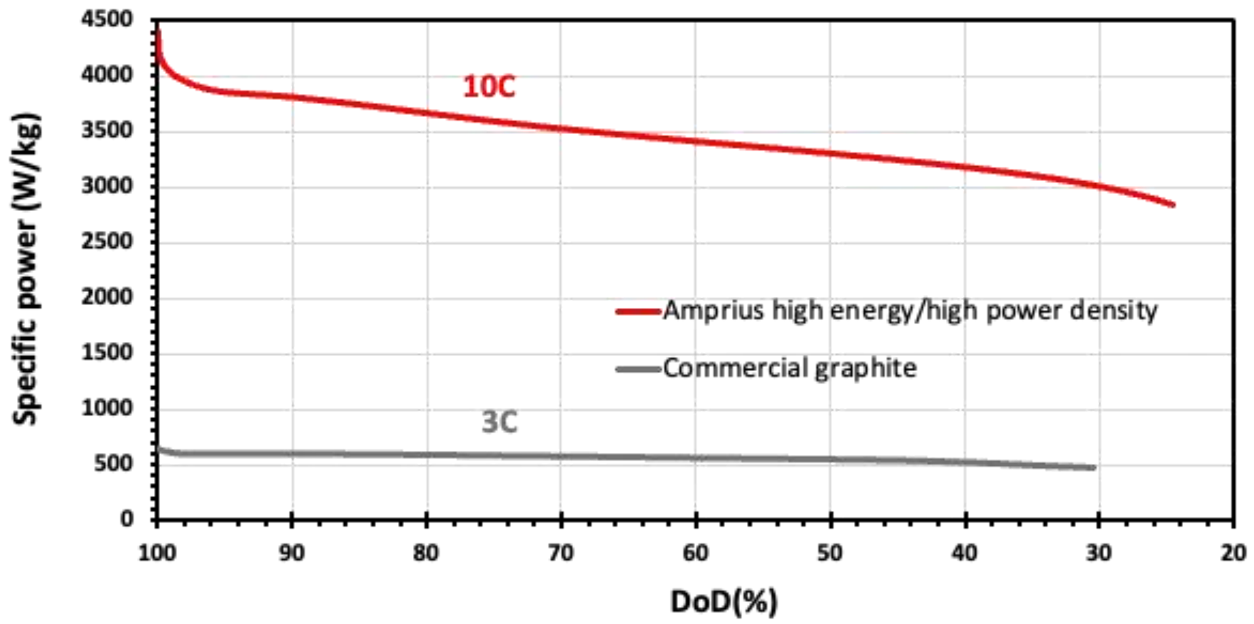


2023: New power cell design: 400 Wh/kg with 4000 W/kg power density

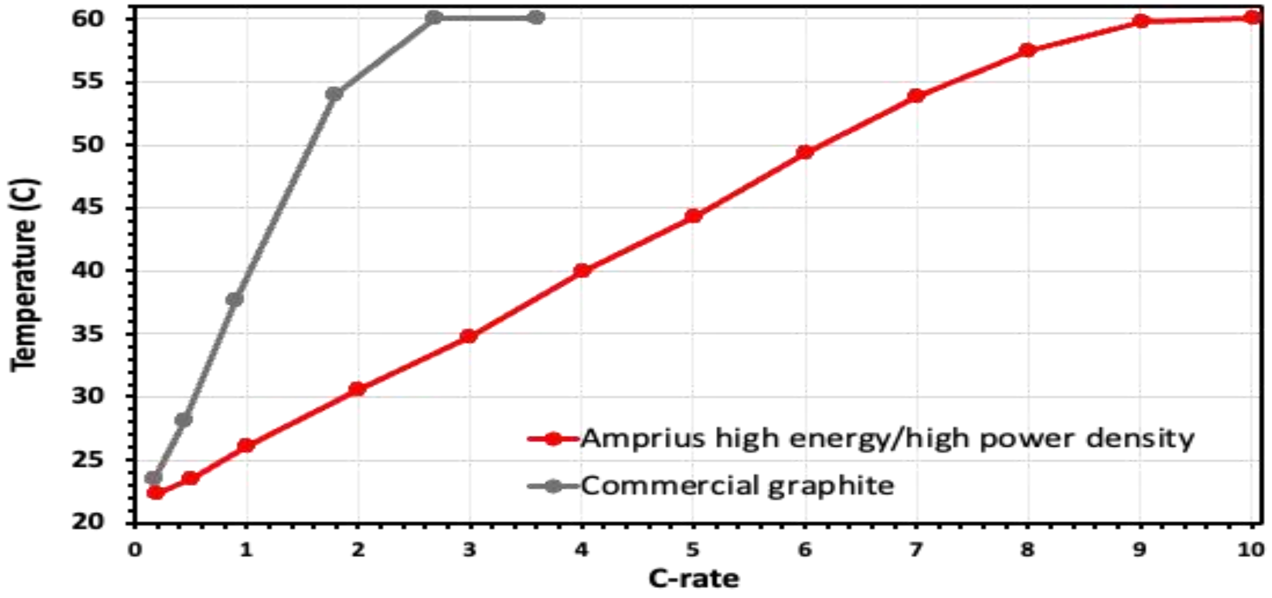


Ultra High-Power, High-Energy Cell Platform

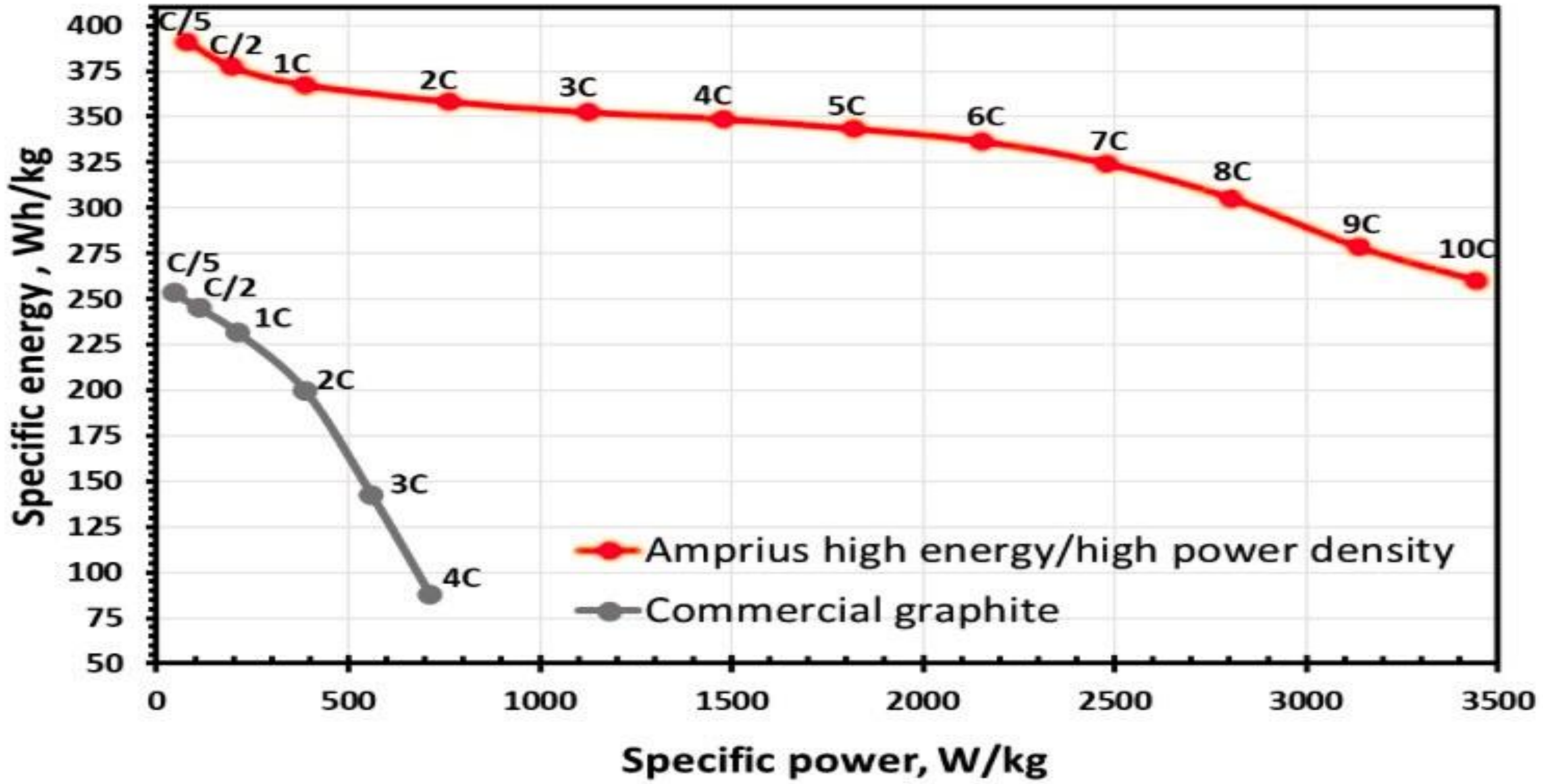
Power Density vs DoD%
Amprius Silicon Anode System vs. Commercial Graphite Anode System



Maximum Cell Temperature vs. Discharge C-Rate
Amprius Silicon Anode System vs. Commercial Graphite Anode System



Gravimetric Energy Density vs. Power Density
Amprius Silicon Anode System vs. Commercial Graphite Anode System



KEY TAKEAWAYS

- Amprius' cell is >3x the discharge rate while sustaining the power delivery at lower DoD; resulting in extended usable battery capacity.
- Amprius' cell has > 40% higher GED across a significantly wider range of discharge rates
- Amprius' cell has the ability to stay cooler at higher discharge rates allowing for fewer thermal management components

amprius

External Validation of Early Prototypes by 3rd Party

MOBILE POWER SOLUTIONS
Battery Technology Center

Prepared for: Amprius
Test report numbers: AK-1823
Report date: 3/17/2023

MPS SN:	Cell SN	1st cycle Capacity (Ah)	1st cycle Energy (Wh)	2nd cycle Capacity (Ah)	2nd cycle Energy (Wh)
AK-1823-CP-1	40546	6.8552	23.657	6.8482	23.632
AK-1823-CP-2	40544	6.8766	23.648	6.8636	23.602
AK-1823-CP-3	40574	6.8529	23.424	6.8432	23.389

MPS SN:	Cell SN	Weight (g)	L (mm)	W (mm)	T (600g plate) (mm)	Gravimetric Energy Density (Wh/kg)	Volumetric Energy Density (Wh/l)
AK-1823-CP-1	40546	46.3604	59.72	52.31	5.667	509.7	1335
AK-1823-CP-2	40544	46.3627	59.81	52.37	5.693	509.1	1324
AK-1823-CP-3	40574	46.3638	59.76	52.32	5.662	504.5	1321

Executive Summary

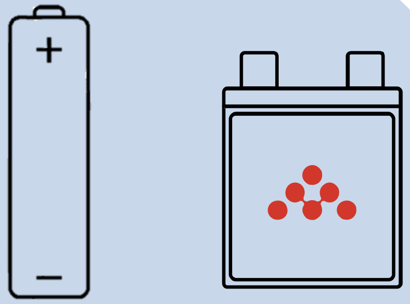
Amprius Technologies Model RD1039-R49 cells were tested at MPS using a test regimen provided by Amprius. The results indicate that this cell model provides >504 Wh/kg and >1321 Wh/l at 25°C.

Industry Leading

500 Wh/kg Battery

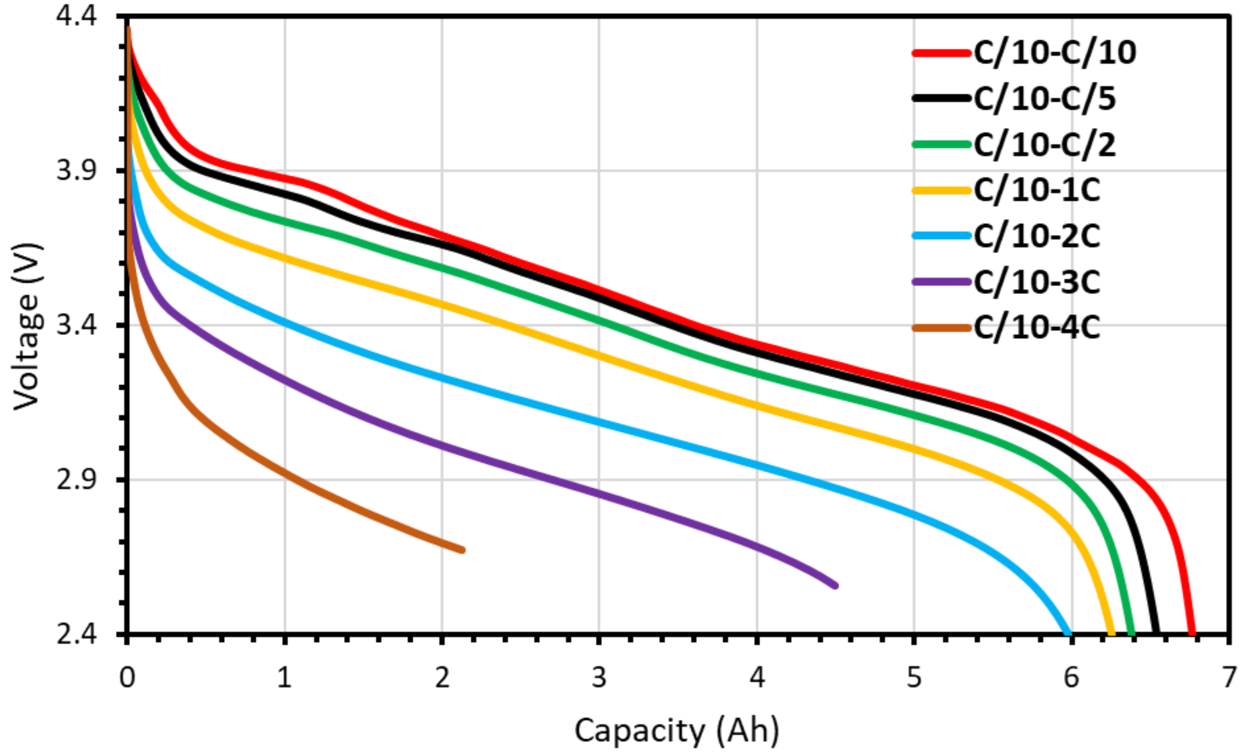
- Unprecedented Energy Density
- Unparalleled Run Time

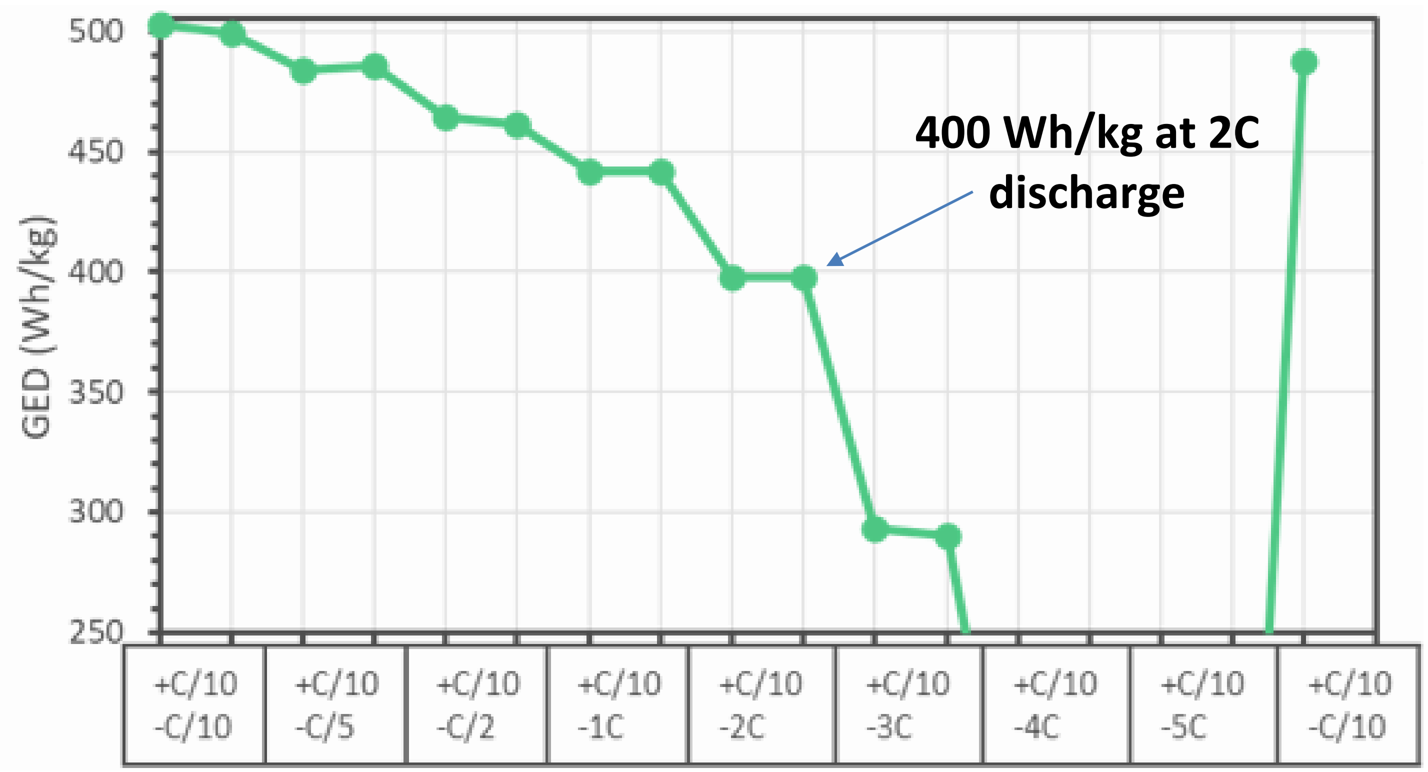
Typical 18650 Cell vs. Amprius 500Wh/kg Cell

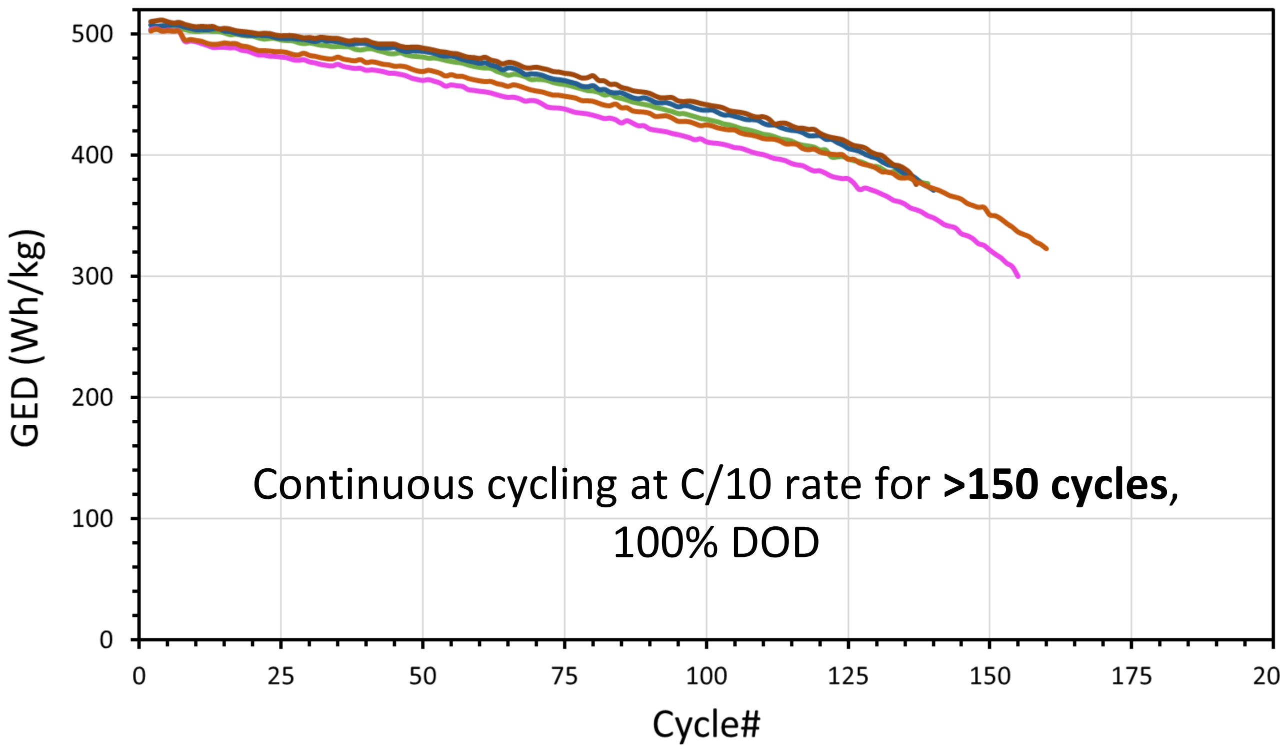


Same Weight | 2X the Capacity

Products under development







KEY TAKEAWAYS

- Potential for 6 months of operation
- 400 Wh/kg at 2C discharge
- Optimization of electrolyte formulation and amount & full electrical and safety evaluation underway for future product release

amprius

450 Wh/kg PRODUCTS RELEASED IN 2023

UN38.3 Certified

SA75

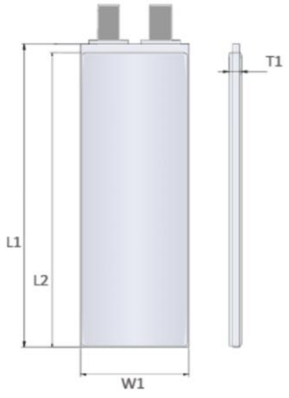
SiMaxx™ | Rechargeable Lithium-Ion Cell

amprius PRELIMINARY

11.8 Ah High Energy Cell

Specifications

Capacity	Typical @ C/10	11800 mAh
		40.7 Wh
	Minimum	11500 mAh
		40.6 Wh
Cell Voltage	Nominal	3.45 V
	Charge	4.20 V
	Discharge	2.50 V
Discharge Current	Max Continuous	11.8 A (1C)
	Max Pulse (≤ 30 seconds)	23.6 A (2C)
Charge Current	Typical	2.36A (C/5)
	Maximum (0% to 100% SOC)	11.8 A (1C)
Temperature Range Ambient	Discharge	-20 to 50°C
	Charge	10 to 45°C
	Storage	-20 to 30°C
Internal Resistance	ACIR (1 kHz @ 30% SOC)	20 mΩ
	DCIR	N/A
Cycle Life	+0.2C/-0.2C, 100% DOD to 80% SOH	150 cycles
Weight		90.0 ± 2g
Packaging		Pouch
Cathode		NMCA
Energy Density Including packaging	Gravimetric	450 Wh/kg
	Volumetric (@ 30% SOC)	1100 Wh/l
Special Note	Cell requires external clamping of 30 PSI	
Certifications	UN 38.3	



Dimensions

Size	L1	127.0 ±1.5mm
	L2	123.5 ±1.5mm
	W1	53.5 ±1.5mm
	T1 (@ 30% SOC)	5.5 ±0.40mm

SA76

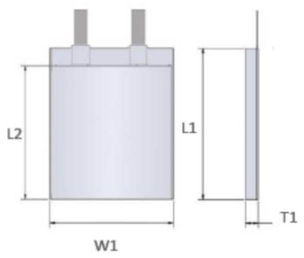
SiMaxx™ | Rechargeable Lithium-Ion Cell

amprius PRELIMINARY

4.2 Ah High Energy Cell

Specifications

Capacity	Typical @ C/10	4200 mAh
		14.5 Wh
	Minimum	4000 mAh
		14.0 Wh
Cell Voltage	Nominal	3.45 V
	Charge	4.20 V
	Discharge	2.50 V
Discharge Current	Max Continuous	4.2 A (1C)
	Max Pulse (≤ 30 seconds)	8.4 A (2C)
Charge Current	Typical	0.84 A (C/5)
	Maximum (0% to 100% SOC)	4.20 A (1C)
Temperature Range Ambient	Discharge	-20 to 50°C
	Charge	10 to 45°C
	Storage	-20 to 30°C
Internal Resistance	ACIR, 1 kHz @ 30% SOC	≤ 40 mΩ
	DCIR @ 30% SOC, 1C	≤ 36 mΩ
Cycle Life	+0.2C/-0.2C, to 80% SOH	150 cycles
Weight		32 ± 1g
Packaging		Pouch
Cathode		NMCA
Energy Density Including packaging	Gravimetric	450 Wh/kg
	Volumetric (@ 30% SOC)	990 Wh/L
Special Note	Cell requires external clamping of 30 PSI	
Certifications	UN 38.3	



Dimensions

Size	L1	56.5 ±1.5mm
	L2	52.5 ±1.5mm
	W1	49.5 ±1.5mm
	T1 (@ 30% SOC, Fresh)	5.3 ±0.4mm

SA77

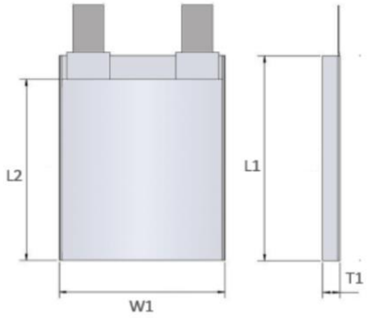
SiMaxx™ | Rechargeable Lithium-Ion Cell

amprius PRELIMINARY

5.8 Ah High Energy Cell

Specifications

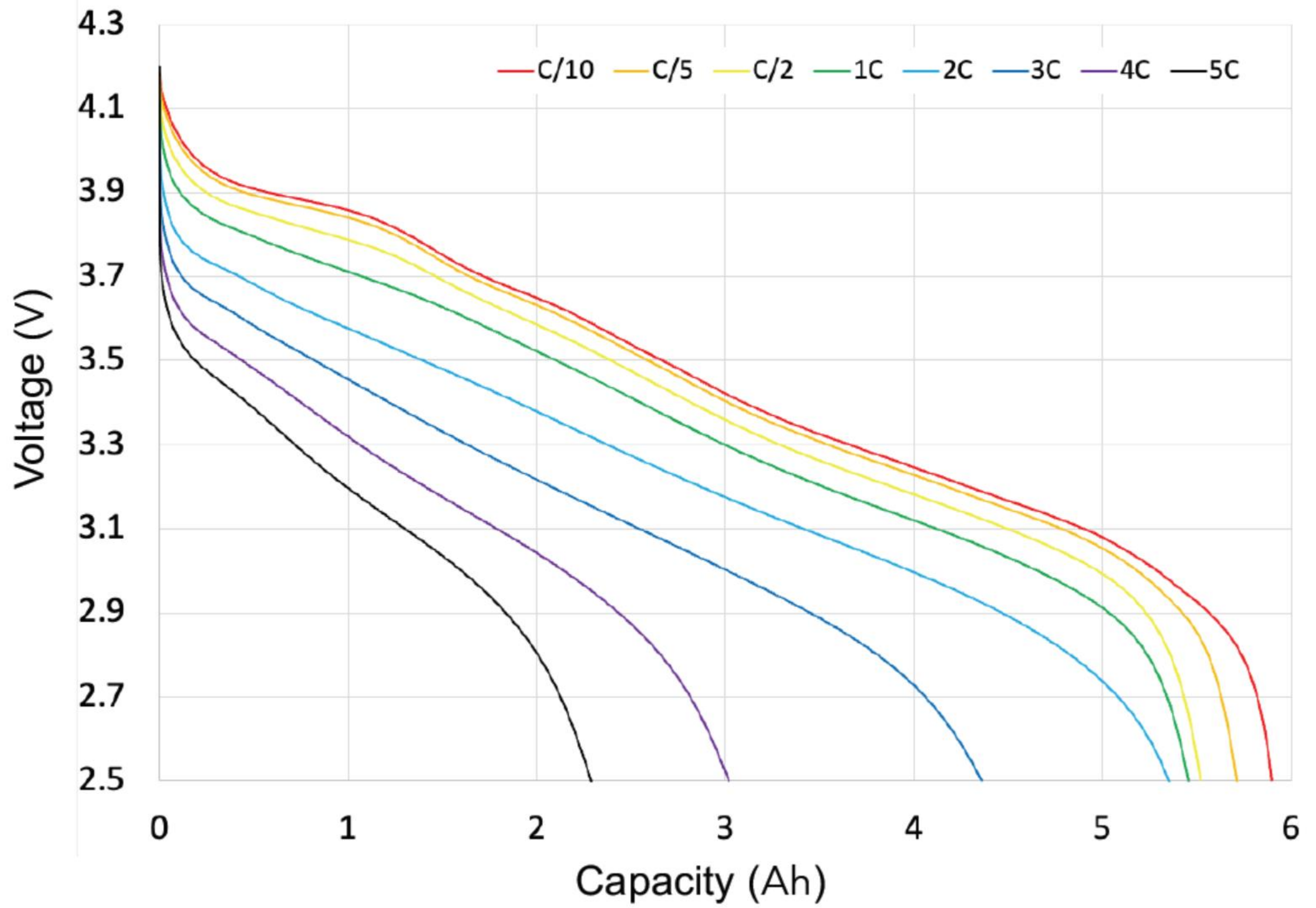
Capacity	Typical @ C/10	5800 mAh
		20.0 Wh
	Minimum	5660 mAh
		19.4 Wh
Cell Voltage	Nominal	3.46 V
	Charge	4.20 V
	Discharge	2.50 V
Discharge Current	Max Continuous	5.8 A (1C)
	Max Pulse (≤ 30 seconds)	11.6 A (2C)
Charge Current	Typical	1.16 A (C/5)
	Maximum (0% to 100% SOC)	5.8 A (1C)
Temperature Range Ambient	Discharge	-20 to 50°C
	Charge	10 to 45°C
	Storage	-20 to 30°C
Internal Resistance	ACIR (1 kHz @ 30% SOC)	≤ 22 mΩ
	DCIR	N/A
Cycle Life	+0.2C/-0.2C, to 80% SOH	150 cycles
Weight		44.5 ± 1g
Packaging		Pouch
Cathode		NMCA
Energy Density Including packaging	Gravimetric	450 Wh/kg
	Volumetric (@ 30% SOC)	1050 Wh/L
Special Note	Cell requires external clamping of 30 PSI	
Certifications	UN 38.3	

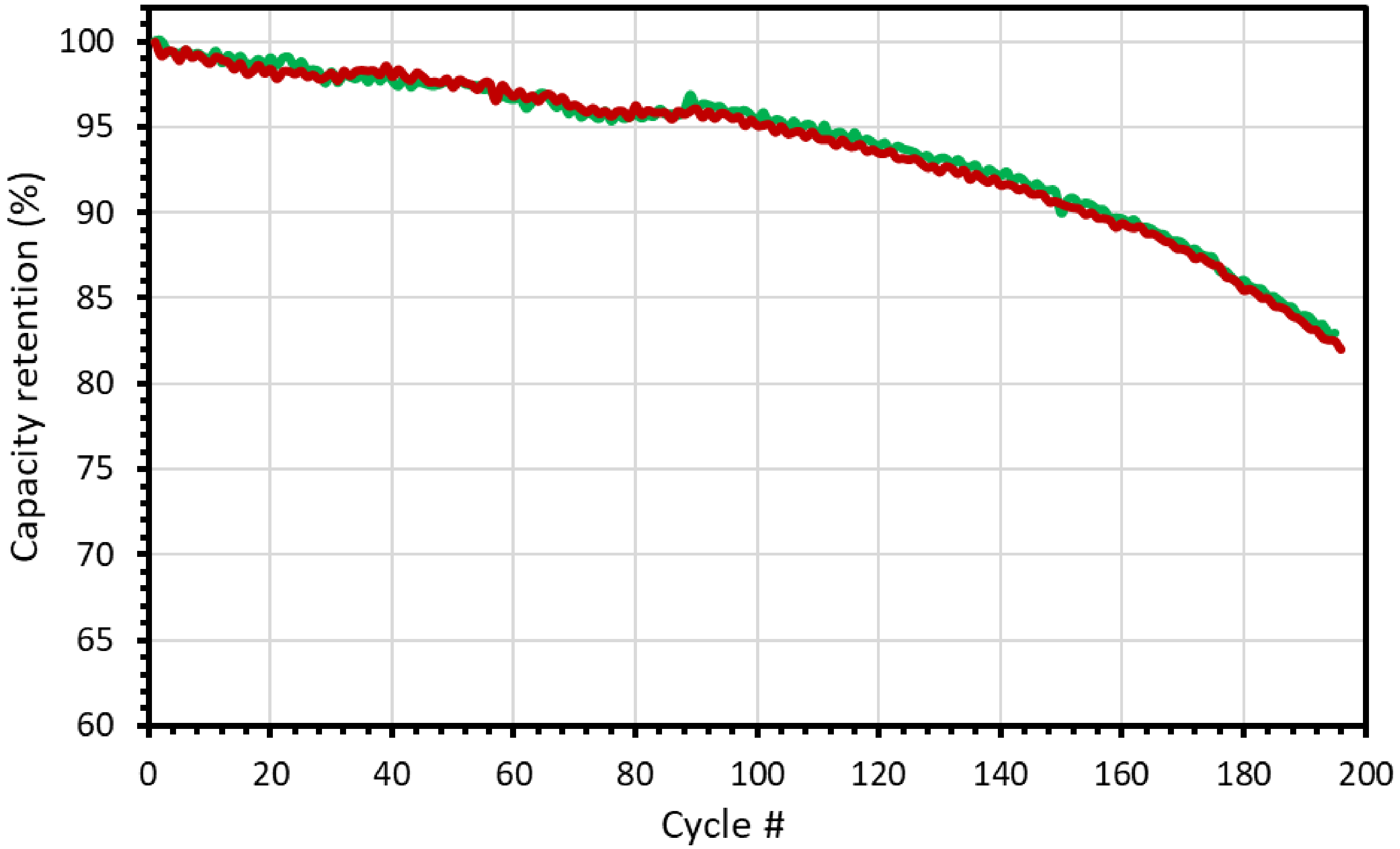


Dimensions

Size	L1	65.5 ±1.5mm
	L2	62.3 ±1.5mm
	W1	53.5 ±1.5mm
	T1 (@ 30% SOC)	5.70 ±0.40mm

Designed for HAPS platforms



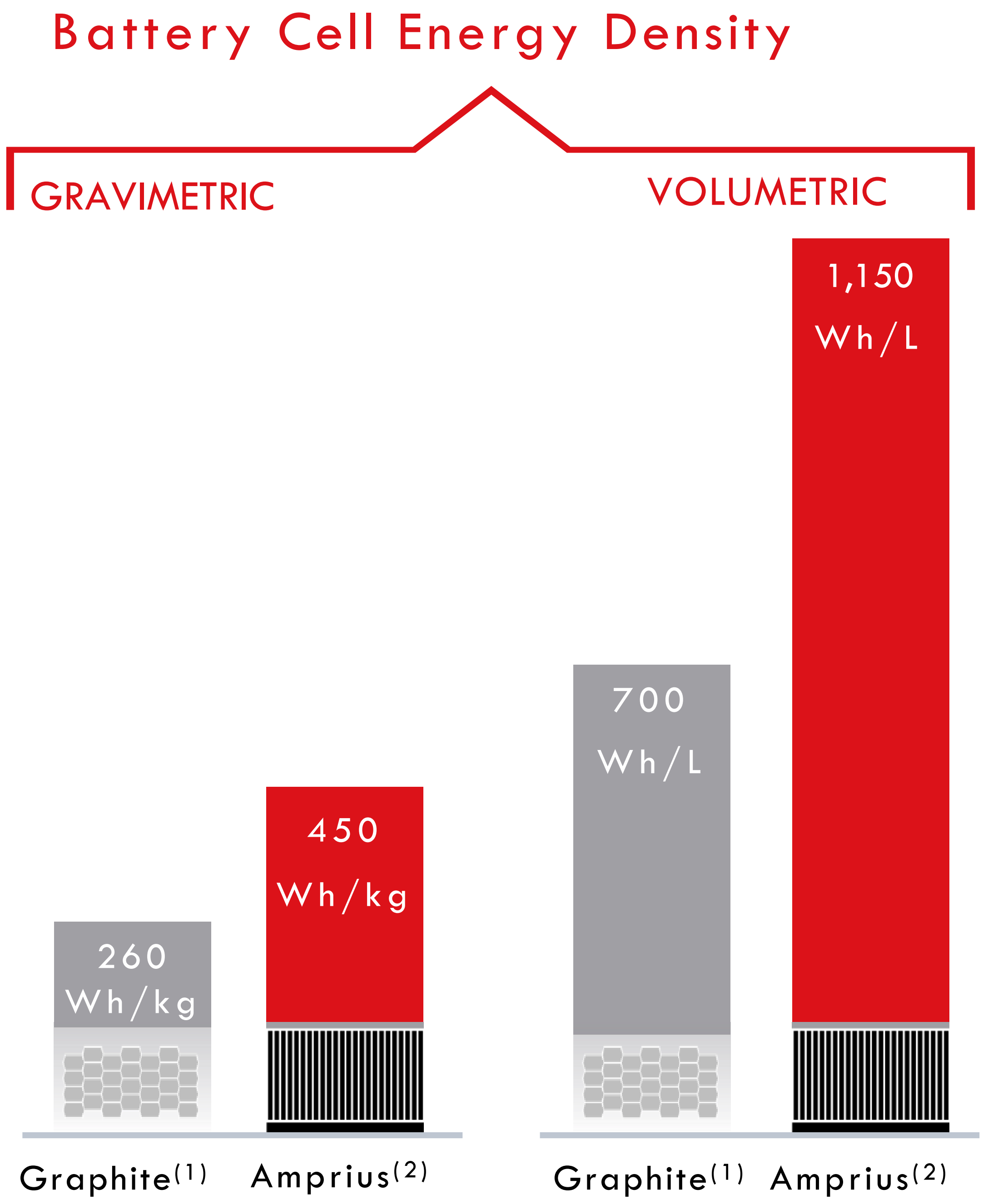


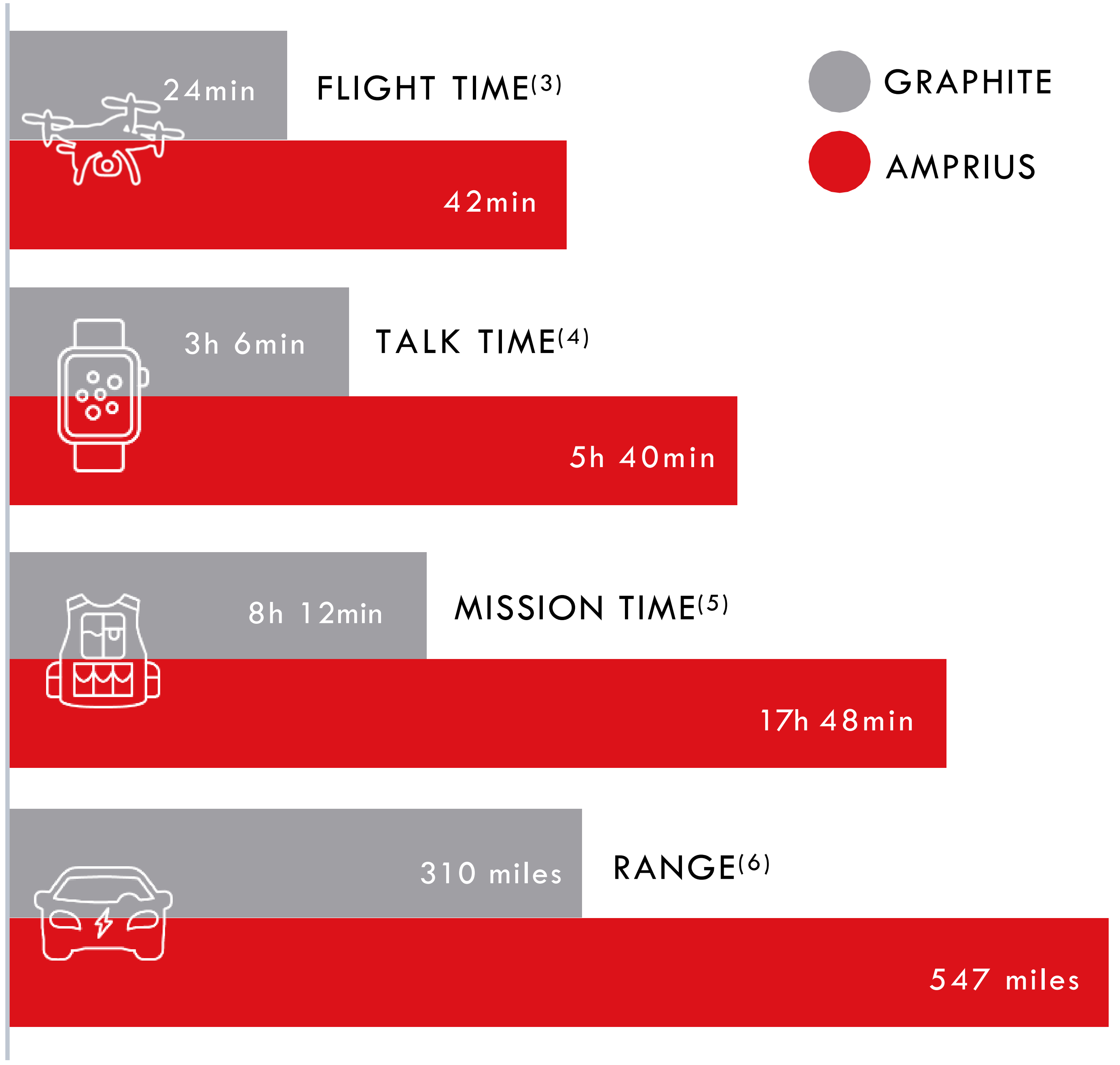
KEY TAKEAWAYS

- At least six months of operation
- > 3C discharge rate capability
- Up to 1C charge rate

RELATIVE PERFORMANCE

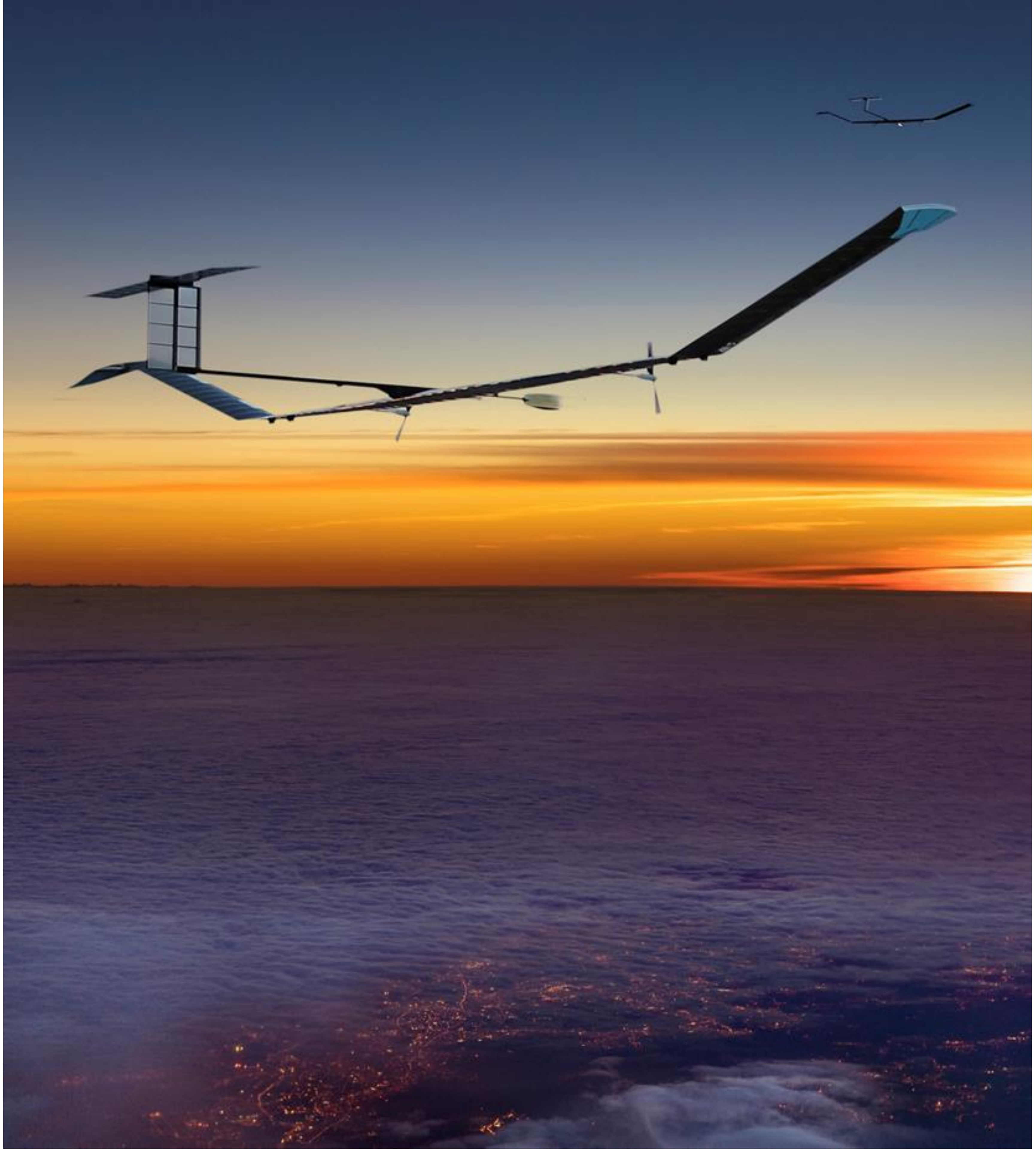
Amprius Batteries Deliver Twice the Mission Time





(1) Survey of 18650 technical datasheets (ex. Panasonic NCR18650G) and iFixit reports on iPhone and Samsung batteries.
(2) Actual battery cell energy densities measured by Amprius for an energy cell design.

(3) Flight Time – estimated based on customer-generated models for a balanced power and energy cell design
(4) Talk Time – customer-reported data for an energy cell design.
(5) Mission Time – results from Conformal Wearable Battery developed for U.S. Army for an energy cell design.
(6) Range - estimated for a Tesla Model 3 long-range battery specifications for an energy cell design.



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Amprius wishes to acknowledge the support received from
US Army, DOE, USABC, NASA, and ONR