Beyond Lithium-Ion

Next-Generation Battery Technologies: Technical Review, Data Sheet and Comparison

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23 September 2026

Covers solid-state, silicon-anode and lithium-sulfur batteries against the NMC and LFP lithium-ion baseline, with sodium-ion, LMFP, lithium-metal and LTO as context. Figures separate demonstrated values from targets.

Contents

Executive summary

Three chemistries lead the post-lithium-ion race: solid-state, silicon-anode and lithium-sulfur. Each beats today's graphite/NMC cell on a different metric, and none beats it on all of them yet.

- **Solid-state** offers the best overall package: higher energy density, longer cycle life, faster charging and a non-flammable electrolyte. Its barrier is manufacturing cost and scale.
- **Silicon-anode** is the nearest-term upgrade. It drops into existing cell lines and already ships in phones, drones and some vehicles.
- **Lithium-sulfur** has the highest theoretical energy per kilogram and the lowest weight. Short cycle life limits it to aviation, drones and defence for now.

Standard lithium-ion remains the volume and cost benchmark. Sodium-ion and LMFP are cheaper challengers at the other end of the market.

Note on figures: ranges separate **demonstrated** cell values from **targets or theoretical limits**. Headline claims such as 800 Wh/kg for solid-state are research ceilings, not shipping products.

Baseline: standard lithium-ion today

Standard lithium-ion is the moving target every challenger must beat, and it keeps getting cheaper. Global average pack prices fell 8% in 2025 to a record $108/kWh, 93% below 2010 (BNEF).

Two cathode families dominate:

- **NMC (nickel-manganese-cobalt):** about 250–300 Wh/kg at cell level, roughly 1,000–2,000 full cycles, 20–45 minutes for 10–80% charge. Average NMC pack price was $128/kWh in 2025.
- **LFP (lithium-iron-phosphate):** about 160–205 Wh/kg, but 3,000–6,000+ cycles, better thermal stability and no nickel or cobalt. Average LFP pack price was $81/kWh in 2025.

Both use a graphite anode and a flammable liquid organic electrolyte. That electrolyte is the root of lithium-ion's two hard limits: thermal-runaway risk and lithium plating during very fast charging. BNEF expects a further 3% fall to about $105/kWh in 2026.

1. Solid-state batteries — the ultimate successor

Solid-state batteries replace the liquid electrolyte with a solid ceramic, polymer, glass or sulfide layer. This enables a lithium-metal (or anode-free) anode, which is where most of the energy gain comes from.

Metric	Claimed / target	Demonstrated in 2025–26
Energy density	400–800 Wh/kg	~300–400 Wh/kg cells; QuantumScape QSE-5 B-samples at 844 Wh/L
Cycle life	3,000–5,000+ cycles	1,000+ cycles with high retention in lab and B-sample testing
Charging	80% in 10–15 min	10–80% in about 12 min (QuantumScape)
Safety	Non-flammable, near-zero thermal-runaway risk	Much improved; dendrites and interface cracking still need control

Electrolyte families:

- **Sulfide** (Toyota, Samsung SDI, Solid Power): highest ionic conductivity; moisture-sensitive, needs dry-room processing.
- **Oxide / ceramic** (QuantumScape, ProLogium): very stable; brittle and hard to make in thin, large layers.
- **Polymer** (Bolloré, Factorial in part): easy to process; usually needs warm operating temperatures.
- **Semi-solid / hybrid** (WeLion, Gotion, Factorial FEST): a gel with a little liquid; already shipping.

The catch. Manufacturing is the bottleneck, not chemistry. As of early 2026 only pilot runs of all-solid-state cells exist, while semi-solid packs such as NIO's 150 kWh WeLion pack are already on the road. IDTechEx forecasts do not show cost parity with lithium-ion before 2032–2035. The 800 Wh/kg figure comes from projections for optimized lithium-metal designs; treat it as a ceiling, not a product specification.

2. Silicon-anode batteries — the drop-in upgrade

Silicon-anode cells replace or blend graphite with silicon-carbon composites, nanowires or silicon oxide. Silicon stores roughly ten times more lithium per gram than graphite (about 4,200 vs 372 mAh/g).

- **Energy density:** 20–50% higher than graphite cells. Amprius ships cells up to 450 Wh/kg and 1,150 Wh/L, with third-party validation at 500 Wh/kg. Its second-generation SiCore reaches 500 Wh/kg on conventional equipment, with availability expected in Q4 2026.
- **Charging:** supports extreme fast charging (XFC), about 80% in 10 minutes. Amprius has demonstrated 0–80% in under six minutes.
- **Longevity:** silicon swells by up to about 300% when lithiated. Nanostructured silicon-carbon matrices, pre-lithiation and 3D cell architectures now bring cycle life close to standard lithium-ion.
- **Manufacturing:** most silicon materials are drop-in — same liquid electrolyte, separators and coating lines. This is its strategic edge over solid-state.

Main players: Sila (Titan Silicon; Mercedes G-Class), Group14 (SCC55; Porsche), Amprius (nanowire; drones and aviation), Enovix (3D cell), plus silicon-carbon phone cells from Chinese makers.

The catch. Swelling stress must be engineered around at particle, electrode and pack level. Silicon materials cost more than graphite, so today they target premium EVs, phones and drones.

3. Lithium-sulfur (Li-S) — the lightweight specialist

Li-S pairs a sulfur cathode with a lithium-metal anode. Sulfur is cheap, abundant and free of nickel and cobalt, and both elements are very light.

- **Energy density:** theoretical limit about 2,600 Wh/kg. Practical pouch cells deliver roughly 300–450 Wh/kg today; the practical target is 500–600 Wh/kg.
- **Weight:** the lightest chemistry here per kWh — suited to high-altitude pseudo-satellites, long-endurance drones, defence and future electric aircraft.
- **Safety:** the sulfur cathode releases no oxygen when heated, removing one thermal-runaway driver; the lithium-metal anode remains the risk point.

The catch. Cycle life is the main weakness. Soluble lithium polysulfides migrate between electrodes (the “polysulfide shuttle”), losing active material, and the cathode changes volume by about 80%. Lyten's own target was 500 cycles at C/3 by 2026. Fast charging is moderate and volumetric density is lower than lithium-ion.

Fixes in progress: sulfurized polyacrylonitrile (SPAN) cathodes, 3D graphene sulfur hosts, protected lithium anodes and solid-state Li-S. **Main players:** Lyten, Zeta Energy, Theion, Li-S Energy.

4. Other emerging chemistries

- **Sodium-ion (Na-ion):** CATL's Naxtra cell reaches 175 Wh/kg, comparable to LFP; CATL claims 10,000+ cycles and 90% usable power at −40 °C. CATL and Changan announced the first mass-production sodium-ion passenger car in February 2026, due on the market mid-2026. Best for low-cost EVs, cold climates and grid storage.
- **LMFP (lithium-manganese-iron-phosphate):** adds manganese to LFP, raising energy by roughly 15–20% while keeping LFP's cost and safety.
- **Lithium-metal with liquid electrolyte:** removes the graphite anode; targets 400+ Wh/kg, but dendrite growth limits cycle life.
- **Lithium-titanate (LTO):** only 60–110 Wh/kg, but 6,000 to over 45,000 cycles and very fast charging; used in buses and grid services.

5. Technical data sheet

Values are cell-level. The first figure is demonstrated or shipping; the bracket is the target or ceiling.

5.1 Performance comparison matrix

Technology	Energy density (Wh/kg)	Cycle life (cycles)	Charge time (~80%)	Main advantage
Standard Li-ion (NMC)	~250–300 (baseline)	~1,000–1,500	~30–45 min	Mature supply chain, proven reliability
Solid-state	~300–400 [target 400–800]	1,000+ [target 3,000–5,000+]	~10–15 min	Highest density potential, non-flammable
Silicon-anode	350–500	1,500+	~6–10 min	Fast charging on existing lines
Lithium-sulfur	~300–450 [target 500–600]	~500–1,000	Moderate (~1–2 h)	Ultra-light for drones and aviation

5.2 Extended data sheet

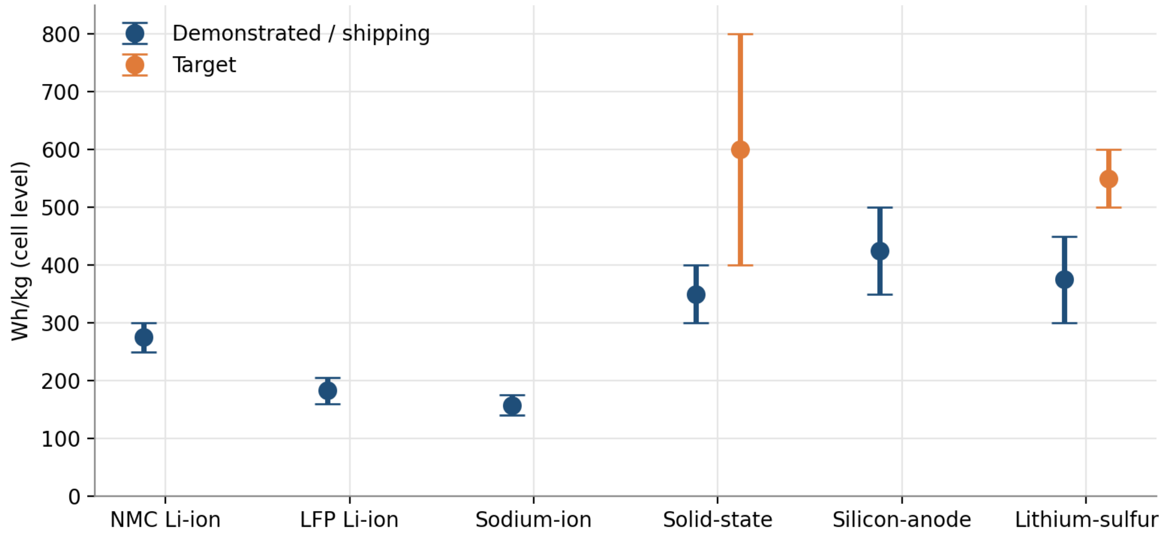
Parameter	NMC Li-ion	LFP Li-ion	Solid-state	Silicon-anode	Li-S	Sodium-ion
Anode	Graphite	Graphite	Li metal / anode-free	Si-C, Si nanowire	Li metal	Hard carbon
Cathode	NMC	$LiFePO_4$	High-Ni NMC	NMC	Sulfur	Layered oxide / Prussian blue
Electrolyte	Liquid organic	Liquid organic	Solid (sulfide, oxide, polymer)	Liquid organic	Liquid ether or solid	Liquid organic
Volumetric (Wh/L)	~600–750	~350–450	~800–1,000	~800–1,300	~300–500	~250–350
Cell voltage (V)	3.6–3.7	3.2	3.6–3.8	3.6	2.1	3.0–3.1
Operating range	−20 to 55 °C	−20 to 60 °C	Wide; some need warmth	−20 to 55 °C	Narrower	−40 to 70 °C
Thermal-runaway risk	Moderate	Low	Very low	Moderate	Low–moderate	Low
Critical minerals	Ni, Co, Li, graphite	Li, graphite	Li, Ni	Ni, Co, Li	Li only	None critical
2025 pack cost	$128/kWh	$81/kWh	High; not priced at scale	Premium over graphite	Low material, low volume	Near or below LFP
Maturity (2026)	Mass market	Mass market	Pilot; semi-solid shipping	Early commercial	Early niche	Mass production starting
Best-fit uses	Long-range EVs, electronics	Mass EVs, grid storage	Premium EVs, aviation	Phones, drones, premium EVs	HAPS, drones, defence	Budget EVs, cold climates, storage

Pack costs from BNEF 2025 survey; other cells combine cited sources with typical industry ranges and are approximate.

6. Comparison graphs

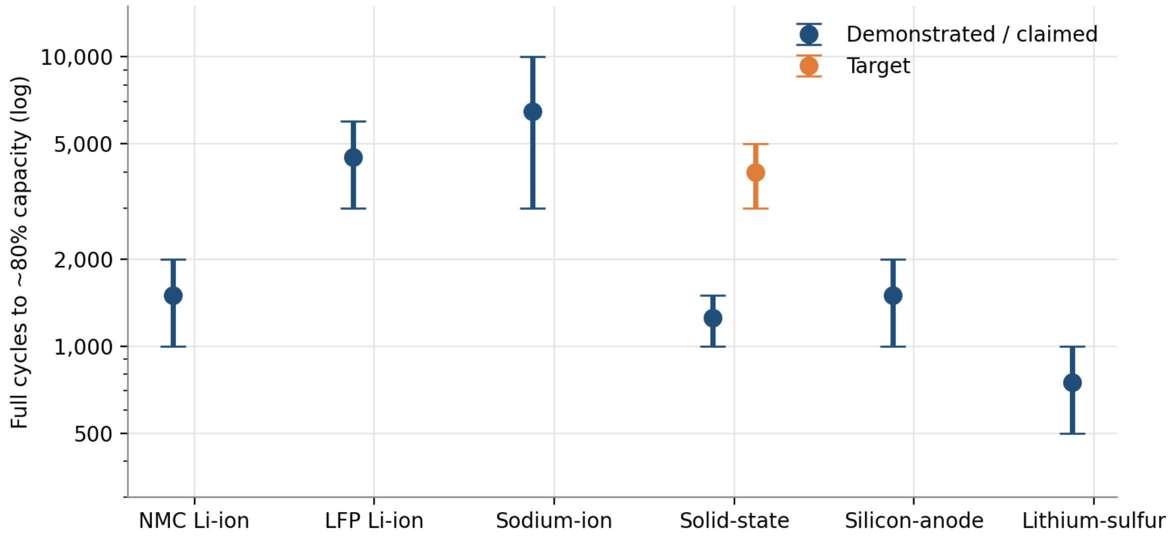
No single chemistry wins every chart: silicon-anode charges fastest, sodium-ion and LFP last longest, and solid-state and Li-S have the highest energy ceilings.

Figure 1. Gravimetric energy density

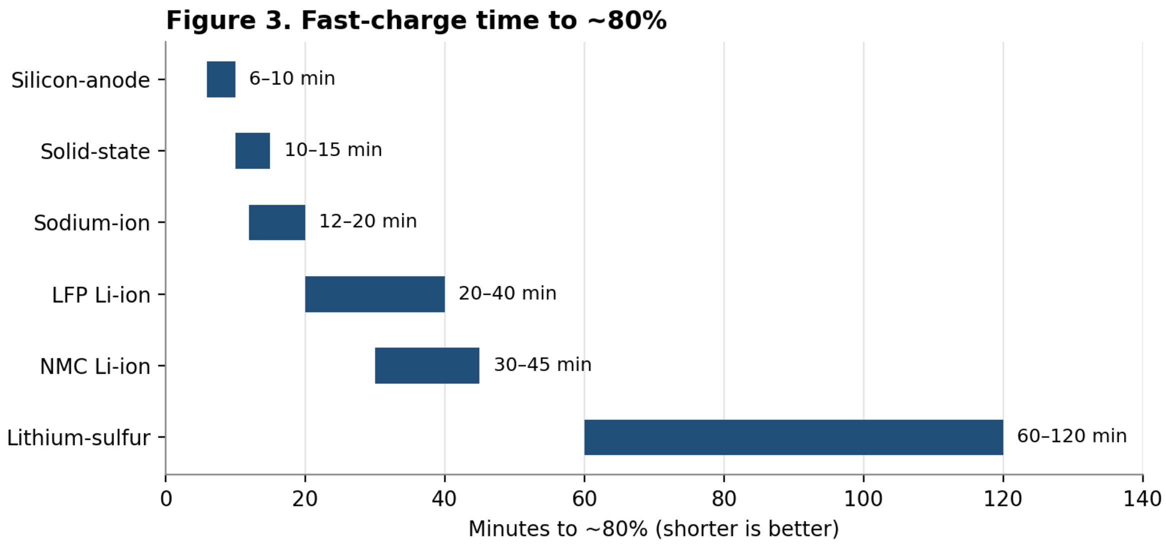


Dot = midpoint, whisker = range. Li-S theoretical limit (~2,600 Wh/kg) not shown.

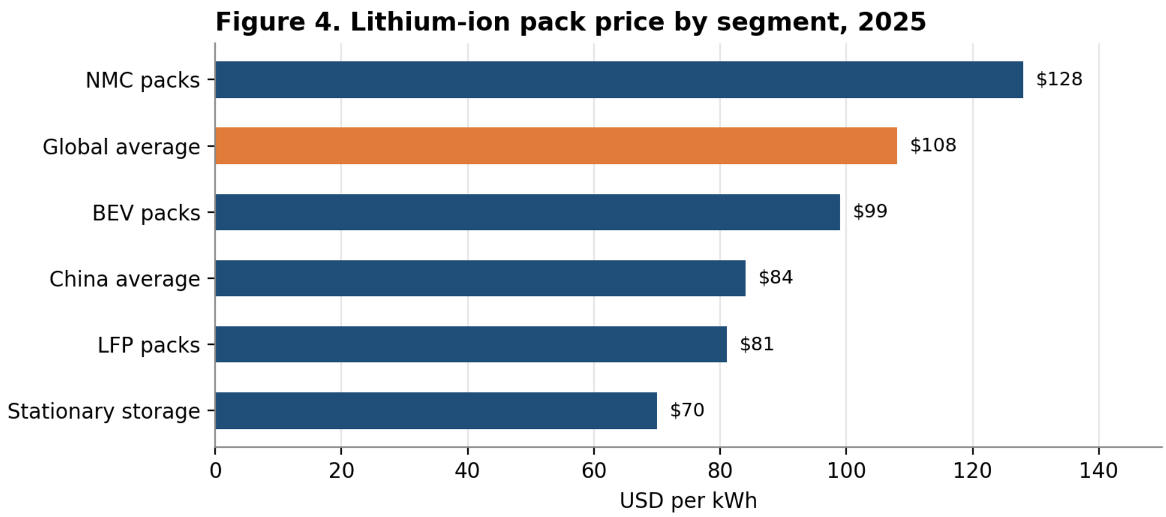
Figure 2. Cycle life



Sodium-ion upper figure (10,000+) is a CATL manufacturer claim.



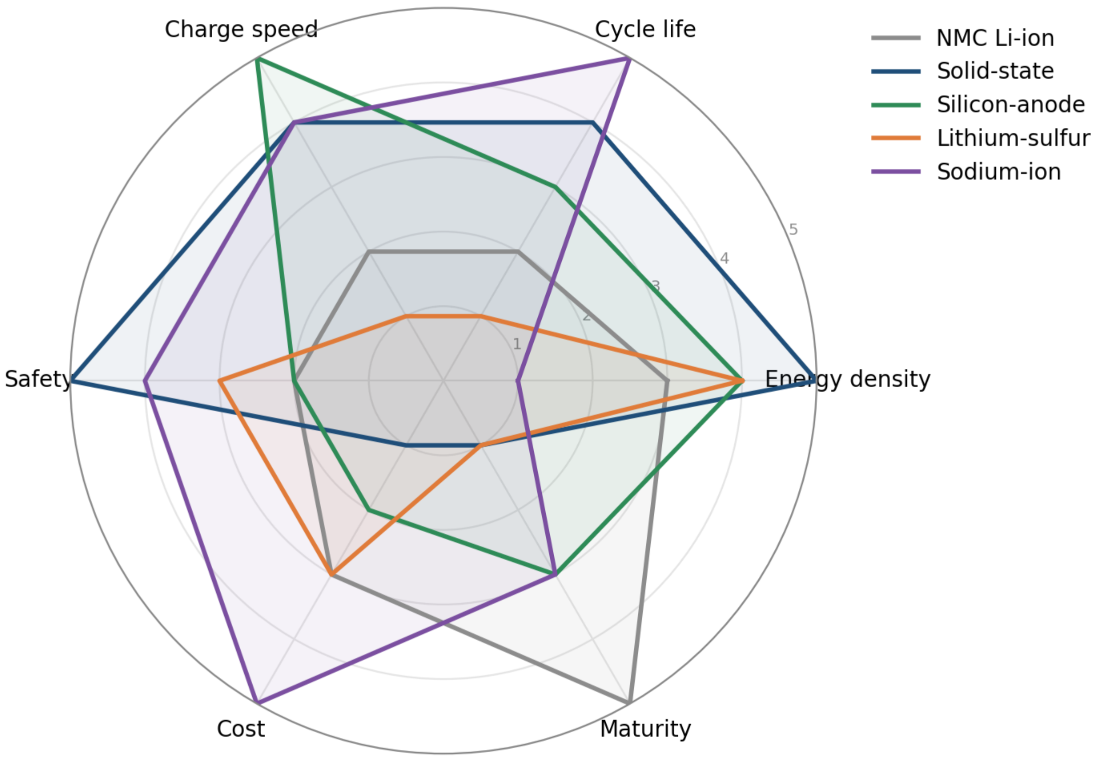
Best demonstrated fast charge; Li-S typical and approximate.



Source: BloombergNEF 2025 Lithium-Ion Battery Price Survey.

At $81–128/kWh for incumbent packs, a new chemistry must win on performance per dollar, not performance alone.

Figure 5. Relative profile (5 = best)



Qualitative author scoring from the data sheet; higher is better on every axis (cost: 5 = cheapest).

7. Commercialization status and outlook

Incremental chemistries arrive first: silicon-anode and sodium-ion are shipping now, while all-solid-state mass production is scheduled for 2027 onward.

Date	Technology	Milestone
H2 2027 (planned)	Solid-state	Samsung SDI mass production at Ulsan; CATL and BYD trial production; Toyota launch window opens
Q4 2026 (planned)	Silicon-anode	Amprius SiCore 500 Wh/kg cell commercially available
Mid-2026	Sodium-ion	Changan Nevo A06, first mass-production sodium-ion car, due on the market
Feb 2026	Solid-state	QuantumScape switches on its Eagle pilot line for QSE-5 cells
Feb 2026	Sodium-ion	CATL and Changan unveil the sodium-ion passenger car
Oct 2025	Solid-state	Toyota receives production approval in Japan
2025	Semi-solid	NIO's 150 kWh WeLion pack drives an ET7 about 1,070 km on one charge

- **Solid-state:** small-batch vehicles 2027–2028; volume and cost parity likely after 2030.
- **Silicon-anode:** rising silicon share in mainstream cells through 2030; the most likely near-term upgrade.
- **Lithium-sulfur:** stays in aviation, drones and defence until independent tests show about 2,000 deep cycles in commercial formats.
- **Sodium-ion:** grows fastest in stationary storage and budget EVs, especially when lithium prices rise.

8. Conclusions

Priority	Best choice today	Best choice after 2030
Maximum energy per kg	Silicon-anode	Solid-state (lithium-metal) or Li-S
Fastest charging	Silicon-anode	Solid-state
Longest life	LFP, sodium-ion	Solid-state
Lowest weight	Lithium-sulfur	Lithium-sulfur
Safety	LFP, sodium-ion	Solid-state
Lowest cost	LFP, sodium-ion	Sodium-ion

Lithium-ion is not standing still: silicon blending, LMFP cathodes and cell-to-pack design keep narrowing the gap. Headline figures for new chemistries should be read as ranges, with manufacturer claims checked against independent tests.

Sources

1. BNEF — Lithium-ion battery pack prices fall to $108/kWh (Dec 2025)
2. Bloomberg — Why global battery prices are expected to fall in 2026
3. MDPI Energies — Solid-state battery technology for next-generation EVs (2026)
4. Live in the Future — 2026 solid-state battery scorecard
5. Bonnen Batteries — Solid-state batteries 2026
6. Exoswan — Solid-state battery stocks 2026
7. Amprius — SiCore 500 Wh/kg announcement
8. Unmanned Systems Technology — Amprius profile
9. Internet Pros — Silicon anode batteries 2026
10. Wikipedia — Lithium–sulfur battery
11. Apricum — Lithium-sulfur batteries
12. Xnergy — Lithium-sulfur 2026 guide
13. CATL — Changan sodium-ion passenger vehicle launch
14. Carcody — CATL Naxtra specs and limits