E Source

The State of the Silicon:
Paths to Commercializing Ultra-High Energy Density Batteries

2024 update on the need for silicon anode materials and compelling pathways to near-term commercialization

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Key takeaways

- Energy density of lithium-ion batteries is primarily constrained by anode and cathode materials.

- Replacement of graphite anodes with silicon offers the most promising pathway to improvement, increasing practical energy density by 30-40% at the cell level.

- The fundamental challenge with silicon anodes is managing the material's 280% volume expansion during charging, which historically leads to particle fracture, damage to anode current collectors, and poor cycle life.

- Most current commercial solutions either limit silicon content to 15% mixed with graphite, require specialized cell designs, or use complex and expensive particle engineering approaches.

- Sionic Energy has developed a compelling solution to allow anode to flex during charging, facilitating higher silicon loadings in cells. Sionic creates a stable, porous environment that accommodates silicon's expansion while maintaining cell volume stability using novel binder, additive, and electrolyte materials.

- Sionic's technology could accommodate silicon from a variety of sources to improve battery energy density, sold at a modest $/kWh premium above graphite at the cell-level, while providing price parity with graphite at the pack level and price leadership at the vehicle level thanks to improvement in volume efficiency.

State of the art batteries today

In the past several years lithium-ion battery technology sales have skyrocketed, rising more than sevenfold over the five-year period from 2018 to 2023. Today, International sales of EVs are growing rapidly, with EVs accounting for about half of all new car sales in China, about 20% in Europe, and 9% in the US. Globally, EV sales growth is about 20% year on year.

Technological innovation in the energy density of batteries has contributed substantially to the growing acceptance of EVs. Increases in energy density lower manufacturing costs, as the same number of kilograms of material hold more kWh. Increases in energy density further reduce battery costs at the pack level by reducing materials needed to achieve a certain capacity pack, and at the vehicle level, simply by reducing the weight and volume that must be allocated to the cells.

Since the introduction of the first lithium-ion batteries by Sony in 1990, much of the improvements in cell energy density have been made by improving the battery's cathode, moving to "high nickel" compositions such as nickel cobalt aluminum (NCA) and nickel manganese cobalt (NMC) that store a large number of ions in a given space. Further improvements have come from improving general packaging efficiency, reducing the percentage of inactive materials in the cell. The improvements can be most clearly illustrated by examining the trends around in a single cell format (the 18650 cylindrical cell) by a single manufacturer, Panasonic, as shown below.

Battery capacity over time
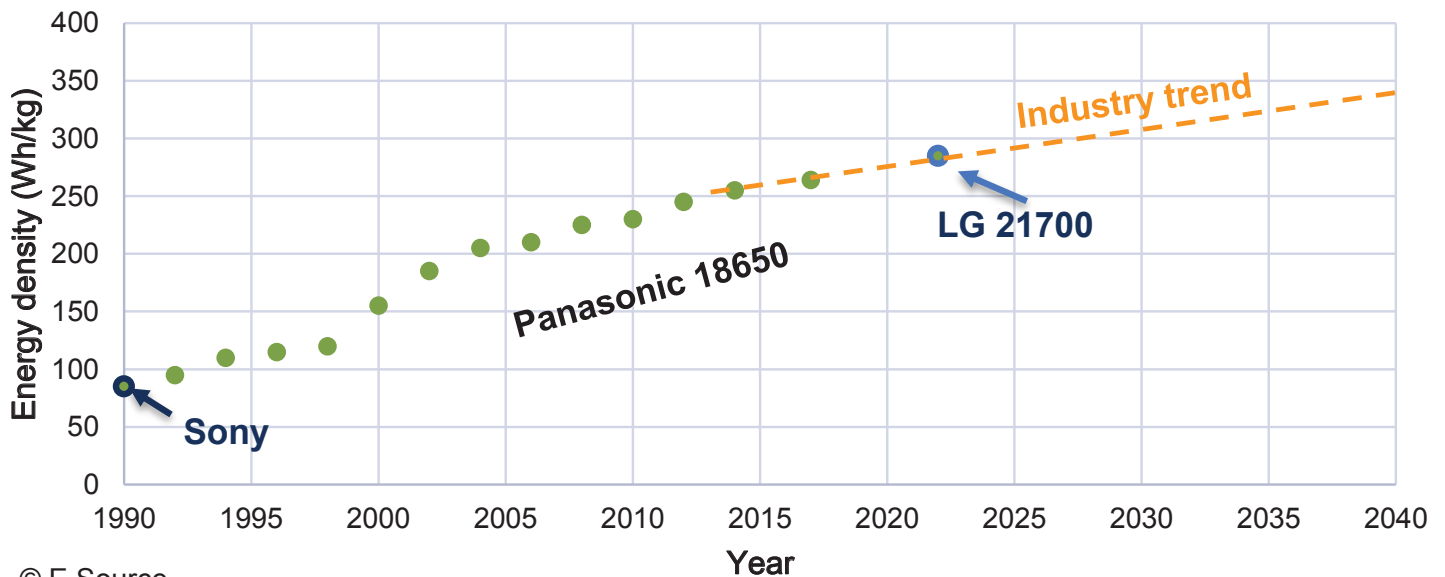
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The chemistry of the battery anode, by contrast, has remained largely stable since lithium-ion cells were first commercially introduced. Nearly every lithium-ion cell sold over the past 32 years has used graphite as the anode material, and incremental improvements in graphite manufacturing have contributed to lower costs, higher power cells, and excellent cycle lifetime. The number of ions that can be stored in the material is theoretically constrained, though, and can't increase above what's done today. To continue the industry trend of increasing capacity, new materials are needed.

Nature offers us two possibilities for improvement. The first is to deposit lithium as metal, a concept that has been attempted several times in the history of lithium cells, with unfortunately disastrous consequences. Lithium metal has a natural tendency to deposit in thin tendrils called dendrites, which will cause a short circuit—and possibly a fire—if they sneak across the separator to contact the cathode. There are several startups chasing new solutions to dendrite safety, many with promising results. But because only one cell in a million need fail to force a recall, the jury is still out on whether this approach will be effective at scale.

The second possibility for improvement is replacing graphite with silicon, which has a 10-fold higher "specific capacity" than graphite. Manufacturers recently started to augment automotive cells with a few weight percent of silicon oxide. While silicon oxide has slightly less capacity than pure silicon (only 7X relative to graphite, rather than 10X), even a small amount provides a noticeable boost to initial cell capacity.

The use of silicon creates another advantage to battery cells: improvement in power. Because the silicon is more capacious than graphite, an equivalent capacity anode will be thinner. Thinner materials create lower electrical resistance in the battery cell, so silicon anode cells charge and discharge much more rapidly than graphite cells. This reduces the all-important recharge time for EVs, and silicon cells are widely regarded as being an enabling technology to achieve EV recharge times of <10 minutes.

However, application of silicon and silicon oxide has been hampered to date by poor durability. One of the most important measures of durability is cycle life. A graphite anode cell will withstand over 800 full charges and discharges, corresponding to an EV range of about 250,000 miles, before its capacity has permanently dropped by 20%. Conventional silicon anodes fail on this metric, typically lasting only 50-200 cycles. This cycle life limitation in turn limits the amount of conventional silicon that can be added to an EV battery cell.

Returning to the graph on the previous page, the final, most recent data point (in blue) represents an LG 21700 format cylindrical cell, with an energy density of about 283 Wh/kg. Modeling at E Source shows that the improvement in this cell, as compared with the Panasonic cells before it, comes largely from the addition of 5% silicon oxide additive, without which the cell would have a capacity 5% lower, just 269 Wh/kg. Unfortunately, LG cells with silicon have relatively degraded cycle life, and the LG cell will quickly give up the 5% of capacity attributable to silicon oxide additives. By limiting additives to just a few percent, the cell will still be able to stay about the target 80% of initial capacity after 800 cycles. Cycle life requirements limit the amount of silicon that can be added beyond this level.

Extending silicon lifetime will enable the battery industry to maintain its historical trend of capacity improvement. According to the E Source model, moving to a 100% silicon oxide cell would increase the density of that LG 21700 cell to 316 Wh/kg. The use of silicon anode, coupled with a higher energy density cathode, would push the LG 21700 cell above 340 Wh/kg. Including both changes alongside moving to a large format pouch cell would push energy density above 380 Wh/kg. Enhancing the silicon content of the anode would allow the industry to maintain its current capacity trends from the previous chart to 2040 and beyond.

A new crop of startups has arisen to take on this challenge of improving the durability of silicon in lithium-ion cells. Below, we take a closer look at the materials science behind this challenge.

## The case for silicon anodes as the next critical battery innovation

Graphite's excellent reversibility as an anode stems from its mechanism of operation as an "intercalation" material. Graphite forms in two dimensional sheets, and lithium ions enter the material by sliding in between the sheets.

The volume of the graphite expands by about 10% when it's fully lithiated, and then decreases back to its original size when delithiated. Because the sheets don't travel far, they're robust, and easily find their way back to their original position. The expansion of graphite is illustrated in the image below.[1]
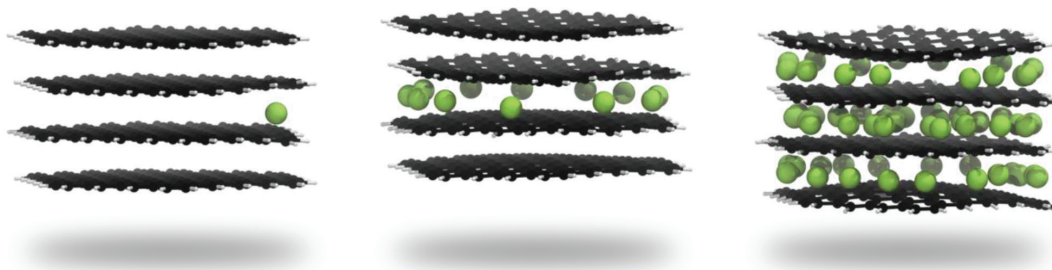
Silicon is a "conversion" material, and lithiates differently than graphite. Lithium ions will fully surround each silicon atom when the cell is charged, cutting each silicon off from its neighbors. The volume of the silicon expands by 280% during this process, and when it delithiates, not all the silicon will find its way back to its original position. This irreversibility leads to the formation of cracks in the material, resulting in "pulverization," where some of the silicon atoms lose electrical contact with the rest of the anode. Even small cracks create a path for electrolyte molecules to enter the anode and react with newly exposed silicon surfaces. Both mechanisms lead to loss of active silicon, and a rapidly fading capacity. This is illustrated in the image below.[2]
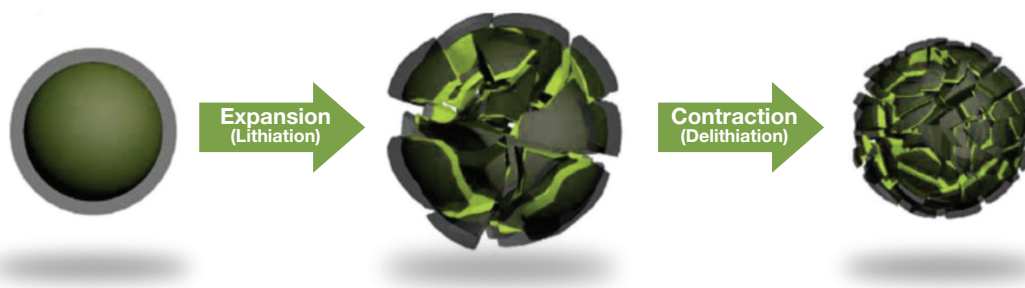
The challenge for today's battery industry is to find ways to prevent the expansion and contraction of silicon from undermining battery life. The most popular and successful approach is the simplest: Make the silicon particles smaller. Smaller particles will develop less stress on their outer surface during expansion, and thus be less prone to cracking. Most next-generation silicon companies will describe their material as "nanosilicon," meaning it has at least one cross-sectional length less than a micron, usually less than 0.1 μm, and sometimes as small as 0.01 μm.

Still, modulating the size alone isn't enough to produce reliable cells. Several other paths are being explored, including:

- Coating the silicon particles, or binding them together, to mechanically reinforce the materials such that they return to their original state after being stressed, and are shielded from electrolyte.

- Alloying silicon with oxygen in the form of silicon oxide particles (SiO_x, as used in the LG cell above), where the oxygens hold onto silicon atoms to reduce expansion.

- Nano-dispersing silicon in a carbon matrix, to help maintain electrical conductivity even in the face of pulverization.

- Including additives in the electrolyte to passive the silicon against reaction and polymerize into useful coatings or binders *in situ*.

[1] Holland, Julian, et al. "Ab initio study of lithium intercalation into a graphite nanoparticle." *Materials Advances* 3.23 (2022): 8469-8484.
[2] Zhou, Xiaozhong, et al. "Research progress of silicon suboxide-based anodes for lithium-ion batteries." *Frontiers in Materials 7* (2021): 628233.

| Cell	Example source	Specific capacity (mAh/g)	Commercialization status	Anode thickness, 80 µm thick NMC 900505 cathode	Cell capacity, 80 µm thick NMC-900505 cathode
Graphite, high quality	BTR	370	High volume	120 µm	300 Wh/kg
Silicon (theoretical)	Textbook	3600	Commercialized for high end defense applications, unacceptable for EV	15 µm	450 Wh/kg
Silicon-carbon, composite, 100%	Sionic	1600-2000	Next-generation	30 µm	390 Wh/kg
Silicon-carbon composite, 15-30%	Group14, Sila	1600-2000	Scale-up and initial commercialization underway	90 µm	335 Wh/kg

These approaches reduce the theoretical capacity of the anode, often by about 40%–50%. Yet even with this reduced capacity, modified silicon materials still outperform graphite by a factor of 5-6X. A table showing several example approaches is shown above.

One further challenge awaits developers of silicon anodes who have solved the durability challenges: the silicon expansion does more than stress the silicon particles themselves.

In battery cells, the silicon anode material is coated onto a thin copper foil, which provides electrical contact to the full cell. Lateral expansion of the silicon has the potential to shred this copper foil, undermining cell life by an entirely new mechanism. The large stretch and expansion of silicon will also stress packages, pulling apart a pouch cell, or bursting a prismatic can. One solution to thickness growth might be to pressurize packages, compressing them in a battery pack with thick walls, to push back against the volume expansion of the cell. Such pressurization plates add mass and volume, undermining much of the original benefit of the silicon.

Because of this volume expansion, the automotive industry today believes that silicon must still be mixed with graphite to make reliable cells. This limits the ability of cell manufacturers to fully utilize silicon's potential. In the graph below, we model the energy density of a 100 Ah pouch cell using NMC 900505 cathode (a next-generation cathode material which will be increasingly common in the next few years) at a variety of loadings of silicon/carbon composite. A loading of 15% silicon anode material creates a 10% improvement in cell energy density, raising it from about 303 Wh/kg to 337 Wh/kg. This is just a fraction of the total improvement potential of silicon if 100% anode could be used, with gains up to 33%, to 393 Wh/kg in the modeled configuration.[3]

NMC 900505 pouch cell, 100 Ah
Energy density vs % SiC in anode
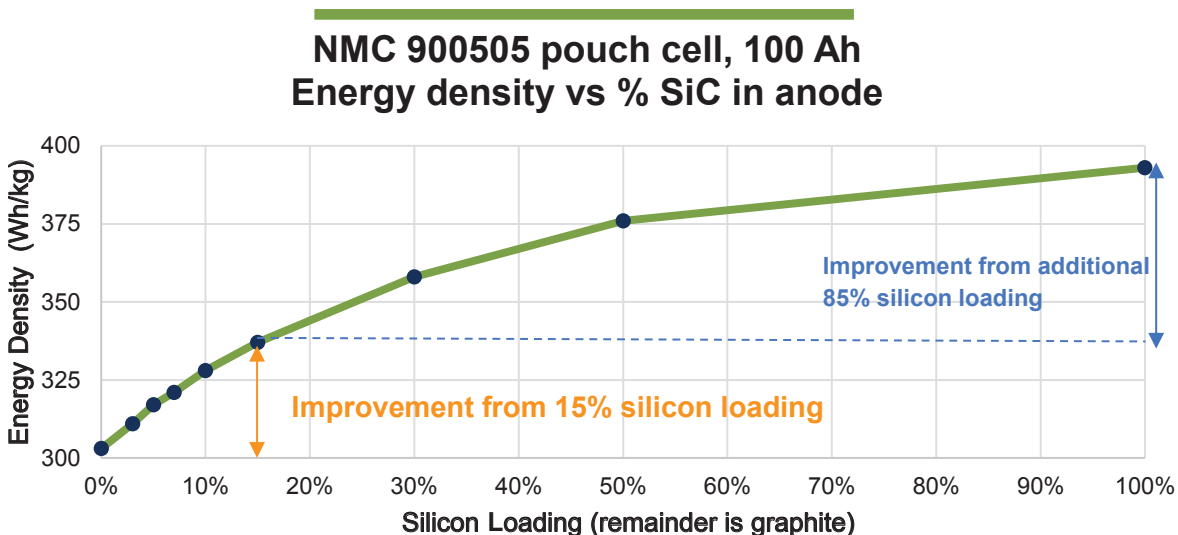
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[3] In modeled configuration, porosity linearly increases with silicon's fractional capacity. The behavior of real systems may vary depending on silicon source.

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Commercial considerations of silicon anodes

One of the compelling properties of graphite anodes is their price: Synthetic graphite today has a market price of $7.00-$7.50/kg, and accounts for 15% or less of the cost of the assembled cell.

Silicon anode materials will likely be more expensive, at least at first. This isn't because of the inherent properties of silicon—the solar and semiconductor industries have already created enough demand to stand up large sale silicon refining and purification operations, such that the cost of raw metallurgical silicon is less than $5/kg at scale. However, many of the next-generation silicon anode materials are synthesized from expensive silane gas rather than silicon metal and are combined with relatively expensive carbon scaffolding and specialized coatings.

A commonly discussed short-term market price range for silicon/carbon anode material is between $50-75/kg. Such an anode material has about 5-fold higher capacity than graphite, so this silicon price would be about 1.5-2X that of graphite on a $/kWh basis, leading to a cell increase between 6-15% per kWh. Should cell pricing be the only consideration, this would make silicon anode suitable for high end EVs, where consumers are willing to pay extra for longer range and faster charging, but not necessarily the mass market of vehicles.

However, silicon anodes create other systems-level savings, by reducing the number of cells in a battery pack, and ultimately the size and weight of those packs.

Silicon will increase the volume efficiency of cells by about 50%, when comparing the volume of fully lithiated silicon cells to that of fully lithiated graphite cells. Pack size can thus reduce by about 1/3, leading to less material, fewer electrical connections. At E Source, we estimate that at a price of $75/kg, 100% silicon anode cells will be only slightly more expensive than their graphite counterparts, and at a price of $50/kg, silicon anode packs will be cheaper.

Further savings are available at the system level of EVs, where automakers can use the extra volume afforded by smaller batteries to decrease their materials costs or increase their feature set. As a result, E Source believes a silicon materials price of about $75/kg will enable 100% silicon anodes to reach mass markets.

As a result, E Source expects silicon anode material to price at about $75/kg if demand continues to outstrip supply. Over the long-term, silicon anodes can become substantially less expensive than graphite. Our modeling suggests that even sophisticated, silane-based silicon particles can be sold for less than $40/kg if silane availability is not a bottleneck. Metallurgical sourced silicon particles may offer both higher capacity and still lower cost, assuming the cycle life limitations are overcome: At a price of $20/kg, the cost per kWh drops below the future cost of synthetic graphite. Graphite may still outperform on metrics such as cycle life, and is not expected to disappear from the market, even if outcompeted on price. However, we expect silicon to eventually dominate the future EV market, thanks to its lower systems-level cost.

Anode	Cost, $/kg, 2025	2035 projected cost, $/kg	2025 cost of anode active material, $/kWh cell (NMC 955 benchmark)	2035 projected cost of anode active material, $/kWh cell (NMC 955 benchmark)	2035 EV pack costs $/kWh
Graphite	$7.50	$5.50	$7.00	$5.10	$97
Silicon-carbon composite	$75	$40	$16.10	$8.60	$85
Engineered metallurgical silicon	—	$20	—	$3	$70

Status of commercialization of silicon

Several companies are engaged in the scale-up and integration of engineered particles, including next-generation silicon oxide, silicon-carbon composite, and coated silicon nanoparticles. These companies have business models that encompass multiple points in the value chain, including cell design, material manufacture, anode roll production, and cell manufacture. Silicon anode cells are in small scale production today, with commercially relevant quantities of material scheduled to come to market between 2027 and 2028. Notable companies include:

- Group14
- Sila
- Amprius
- Ionblox
- Enovix
- Enevate
- StoreDot

Benchmark: Group14
Group14 was the second major silicon anode company to raise substantial funds for scaling, having raised $750M to date. It's building a first manufacturing facility with a capacity of 4,000 tons per year (20 GWh/yr) and is engaged in a joint venture with SK On to stand up a second facility to produce an additional 2,000 tons/year (10 GWh/yr). Like Sila, Group14 deposits silane gas onto a conductive carbon scaffold to form silicon nanoparticles surrounded by a conductive matrix. It achieves a practical specific energy of 1800-1850 mAh/g, about 200 mAh/g of which is attributable to its carbon scaffold. Group14 is partnering with ATL for consumer electronics cells and has Porsche as a major automotive investor.

Group14's carbon is promoted as a drop-in replacement for silicon oxide additives in batteries today, without the drawbacks of irreversibility and lifetime degradation. The company intends to commercialize in automotive at >15% loadings, that still minimize problems associated with cell-level volume expansion and contraction. It claims to improve volumetric energy density by 30%, with a path to 50%, while delivering at least 1000 cycles with >80% retention of capacity.

Benchmark: Sila Nano
Sila Nanotechnologies was the first silicon anode to gather substantial investment toward scaling and has raised $1.4 billion in total. The company makes its carbon/silicon composite by depositing silicon from silane gas onto a polymer matrix. Sila claims to be able to be shipping commercial cells with 100% silicon for a consumer electronics application, though it's not clear how scalable this solution is. Sila has signed an agreement to sell anode material to Panasonic Energy and is building facilities with a claimed capacity of 150 GWh/yr (about 30,000-40,000 tonnes/yr) by the end of the decade. The anode material is slated to be used by Mercedes Benz, which is also an investor in the company.

Sila states that it expects Mercedes to use a blend of silicon and graphite, at about 50 weight percent silicon, which would correspond to 80% of capacity in silicon. The company claims specific capacity in the range of 1600-1900 mAh/g, relative to a theoretical capacity of 3,600 mAh/g for pure silicon. It claims to be able to deliver volumetric energy density improvement of 20%, with a pathway to 40%, though such improvements will require innovations at the cathode as well.

Benchmark: IonBlox
Ionblox, formerly ZenLabs, is a silicon oxide anode company that has raised over $60M. The company has developed a cyclable, reversible SiOx material by pre-lithiating silicon oxide precursors using equipment produced by Applied Materials. It's targeting eVTOL vehicles with a 100% silicon anode, starting with a claimed capacity of 340 Wh/kg and 850 Wh/L. The cells are capable of pulse discharge rates up to 12C. It has partnered with jet company Lilium.

Unlike Group14, Ionblox's anode material isn't a drop-in for existing manufacturing lines. Instead, Ionblox intends to produce anode rolls at its own facility and provide those roles to cell assembly houses. This unusual strategy derives from the uniqueness of its pre-lithiation equipment, which isn't standard in the cell manufacturing equipment set.

Benchmark: Amprius

Like Sila and Group14, Amprius deposits nanoscopic silicon structures from silane gas. Rather than deposit into a carbon framework, Amprius tunes the deposition to favor the growth of silicon rods from seed material on a surface. Amprius patents indicate that the resulting material is tethered to the current collector rather than prepared from a free-flowing powder. As a result, the Amprius process isn't compatible as a "drop-in" with existing manufacturing infrastructure and is presumed to be quite expensive (though price quotes weren't publicly available). The company has raised $300M in equity, and is publicly traded, with a market capitalization at the time of writing of about $130M. It's standing up a GWh-scale facility in Colorado to build full cells, in support of its unique production requirements.

Amprius previously owned a Chinese subsidiary, Brezelius, which developed pre-lithiated silicon oxide anode powders. The Brezelius powder is designed to be water-stable after lithiation, allowing it to be fabricated using standard battery manufacturing equipment. Brezelius was spun out as an independent company, likely to defend Amprius's sales to the defense sector in the West, but Amprius retained a license to market Brezelius cells in the US.

Amprius resells Brezelius technology under the brand name SiMaxx™, with energy density up to 400 Wh/kg. The original Amprius nanowire technology is sold under the brand SiCore™, with energy density up to 450 Wh/kg and 1,100 Wh/L. The SiMaxx™ silicon oxide cells only support 150-220 cycles. The SiCore™ silicon nanowire cells can support >500 cycles at 100% depths of discharge (DOD), while limited to about 70%

DOD when more than 1,000 cycles are required. In the aviation market, a 70% DOD cycle is normal use, since planes must maintain a power reserve in normal operation. These cells aren't compliant with EV requirements. Amprius wouldn't answer questions about the volume expansion in its SiCore™ or SiMaxx™ platforms without NDA. Given its high self-reported energy density, it's likely that these cells haven't been designed to eliminate swelling.

While the cost and performance profile of Amprius cells aren't suited for EV applications, this platform illustrates that silicon can potentially attain and even exceed 400 Wh/kg and 1,000 Wh/L in full-scale cells, if other technical hurdles can be overcome.

Benchmark: Enovix

Enovix is a publicly traded lithium-ion cell company, having raised about $500M with a market capitalization of about $2B. The company has a unique electrode stacking and package design that allows high pressures to be easily applied to cells, increasing the cycle life of cheaper, less-engineered silicon particles, and improving cell safety. At the time of writing, Enovix has just formally opened a factory in Malaysia, on a path to a proposed total investment of $1.2B. The newly opened plant's capacity hasn't been publicly disclosed. The company intends to market its product for applications in consumer electronics, military, industry, and healthcare. It's unique packaging is likely too expensive for EV use.

Enovix hasn't published specifications for its production cells. It has also publicly engaged with Group14 to use its carbon-silicon anode material, which presumably increase cycle life to match consumer electronics requirements. The higher pressure of Enovix cells will allow for a dense packing of silicon anode powder without volume change, at the cost of requiring a heavier package. This is likely a suitable trade-off for a portion of the battery market, most especially consumer electronics, but will limit its utility in sectors such as automotive that require inexpensive, large-format cells.

Benchmark: Enevate

Over the last decade, the anode company Enevate has developed a novel approach to create a flexible, glassy silicon-carbon layer directly on copper foils. Enevate's approach doesn't require a binder, but still requires copper current collectors. Because Enevate doesn't use a powder precursor for its anode, it can't be built in conventional lithium-ion cell manufacturing operations, and Enevate has partnered with Korean startup JR ES and CustomCells to create bespoke processes for manufacturing of anode jumbo rolls. These rolls would be supplied to conventional cell assembly operations, where they'll be cut to size and stacked into batteries.

Because Enevate uses a custom manufacturing process, it's not likely a viable competitor for EVs. The charge rate of Enevate cells is very high. The technology may be well-suited for other mobility applications such as e-bikes.

Benchmark: StoreDot

StoreDot is leveraging silicon to enable fast charge EVs, with charge times of less than 10 minutes. The company is in vehicle-level testing with Polestar, one of its investors. The company doesn't focus on unique anode material and is likely using silicon sourced from Group14. Instead, the company has focused on novel cathode, electrolyte, cell design, and pack design. StoreDot intends to partner with EVE Energy, a battery manufacturer with about 6% global market share.

The energy density of StoreDot's cells is about 310 Wh/kg, which places it higher than state of the art graphite cells. Most of its value arises from its cell design, which sacrifices some energy density made possible by silicon to achieve higher power.

Sionic Energy

Sionic Energy is a privately held company developing a proprietary binder, additives, and electrolyte for its silicon anode battery cells. The binder system is designed to provide a stable, porous environment that allows 100% silicon anode room for expansion, thereby eliminating cell volume change during cycling. The anode/electrolyte system is designed to allow silicon particles to expand and contract without rapid degradation. E Source has modeled the Sionic cell and found that the technology offers up to a 47% improvement in energy density over baseline cells today, while offering a 3% cost advantage at the pack level.

Sionic's cells survive up to 1,000 cycles at 100% DOD, with less than 10% volume growth, matching the current requirements for graphite anode cells for EV applications.[4] E Source performed a bottoms-up model of Sionic's chemistry at both the battery cell and pack level, using cylindrical and pouch formats consistent with EV applications. Sionic doesn't produce its own anode material, using commercially available silicon from vendors such as Group14. The specific capacity of the silicon powder in the modeled cell was 1900 mAh/g, and no graphite is used. The porosity of the cell was set to a level defined by Sionic, consistent with the need to accommodate expansion and contraction during cycling.

E Source analyzed the cost of Sionic's cells, taking into consideration the material's component and manufacturing costs. The company uses a nonstandard binder composition, made from commodity chemicals, and E Source used Sionic's pricing for this without independent sourcing. E Source considered two medium-term prices for silicon anode material, at $50/kg and $75/kg. This pricing is above the long-term cost of production of this material and does not take into consideration the potential market entry of cheaper competitors, so these estimates should be considered conservative.

Sionic's binder requires handling in organic solvents rather than water, as is traditionally used for preparation of graphite anodes. This necessitates two changes in manufacturing: the addition of solvent handling capability in anode mixing, and solvent recapture capacity must be installed at anode coating; such equipment is already installed for cathode mixing and coating, and so is not new to the factory. Sionic's silicon anode layers are thinner than those of conventional cells using graphite, so additional drying capacity shouldn't be required, despite the higher boiling point of NMP than water. Calendaring must be controlled to Sionic's requirements, but doesn't require any unique equipment, so calendaring costs were unchanged. Downstream assembly costs (including formation) for Sionic should be less than for conventional cells on a $/kWh basis, since fewer cells need be handled per kWh.

The energy density of a 2170 format NMC900505 cell with a Sionic anode models is about 350 Wh/kg, with a capacity above 27 Wh, over 40% higher than today's NMC/graphite cells. A large format pouch cell using Sionic anode and an NMC955 cathode would have a gravimetric energy density close to 400 Wh/kg, and a volumetric energy density of 1,000 Wh/L. Overall, an increase in volumetric energy density of about 50% is achievable at the cell level.

Costs for Sionic's chemistry exceed that of graphite at the cell level, but the smaller size of Sionic's more energy-dense cells makes it cost-equivalent to graphite cells at the EV pack level, even considering the high modeled price of silicon. With a price of $75/kg for silicon materials, a Sionic cell will be 15% more expensive on a kWh basis than a graphite cell, but 2% more expensive at the pack level. With a silicon price of $50/kg, the Sionic cell will be 7% more expensive at the cell level, and 3% cheaper at the pack level.

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[4] E Source has not independently validated the electrochemical performance of Sionic cells. The company has documented consistent performance on hundreds of scaled cells from 4Ah to 10Ah pouch formats, including prototypes test results from automotive OE testing.

This low pack pricing is possible because (a) Sionic cells are more energy-dense, and therefore require fewer cell connections and less pack material to achieve the same capacity; and (b) Sionic cells do not require additional compression load or any new mechanical accommodations at the pack level. The ability to drop-in effectively at the pack level is critical to the success of next-generation anode chemistries, as requirements for compliance in the pack increases cost, and reduces pack reliability. Additional savings are available to EV manufacturers thanks to the smaller size and lower weight of Sionic's 100% silicon, energy-dense cells, which would free up space at the vehicle level.

The gravimetric energy density of NMC955 cells increases from 300 Wh/kg for graphite cells, to 337 Wh/kg for 15% silicon, up to 400 Wh/kg for 100% silicon. The 100% silicon anode is only achievable thanks to Sionic's elimination of expansion and contraction. Such a requirement is necessary to exceed 15 weight % silicon anodes for EV applications.

Alternatives to eliminating cell expansion of high silicon anodes include:

- Increasing cell pressure (e.g., Enovix)

- Accommodating silicon expansion at the particle level, rather than the binder level (possibly Group14 and Sila Nanotechnologies, though the details of their solutions haven't been disclosed)

- Reducing loading of conventional silicon to 15% relative to graphite

Sionic's approach is differentiated, in that it offers both high energy density and volume stability. Since it's a replacement for binder, it's also in principle agnostic to the silicon particle, enabling supply chain flexibility for cell manufacturers as they source high-cost silicon. A comparison of Sionic's chemistry to other competing next-generation anode companies is shown below.

Company	Gravimetric energy density	Volumetric energy density	Power density	Cycle life	Volume stability	Size scalability	Commercial readiness	Cost
Sionic	+++	+++	+++	+++	+++	+++	+++	$$
Graphite	+	+	+	++++	+++	+++	++++	$
Amprius	++++	++++	+++	+	—	—	+	$$$$
Enovix	++	++	+++	+	+++	—	++	$$$
Other	—	++	+++	—	—	+	+	—

Looking beyond EVs, a table showing the qualitative importance of different battery characteristics by application is shown below.

Application	Gravimetric energy density	Volumetric energy density	Power density	Cycle life	Volume stability	Size scalability	Cost
EVs	++	+++	++	++	++	++	$
Consumer electronics	+	+++	+	++	+++	—	$$
ESS	—	—	—	+++	—	+++	$
eVTOL	+++	++	+++	+	+	+++	$$
Military/Defense	+++	++	+++	—	—	+	$$$

Outside of EV applications, Sionic's cells are a best fit for consumer electronics, where product enclosures must be designed to accommodate the maximum cell volume. Historically, graphite anode cells have expanded or contracted <4% during charge cycling, while cell volume grew slowly (by about 10%) over product life as SEI thickness increased. Minimization of the expansion/ contraction of silicon will allow high-capacity consumer electronics batteries to be backward compatible with graphite anode cells, enabling differentiation of cell price and performance without redesign of a device housing. More generally, high capacity is extremely valuable in consumer electronics, and this may represent an excellent first market for Sionic's technology.

Conclusion

Sionic fills a unique and important niche in the next-generation battery landscape. Its technology provides volume stability to silicon anodes, enabling higher energy density than alternative solutions that are forced to limit silicon loading.

Sionic's process is compatible with existing battery materials and manufacturing infrastructure. The binder is likely to be extensible to accommodate multiple sources of silicon (beyond Sionic's initial experience with Group14), including metallurgical silicon. The electrolyte would likely have to be optimized to match silicon powder of different sources. Overall, E Source's analysis is that the core technology should be able to keep up with shifts in the industry's supply of anode powder.

Implementation of Sionic's technology will improve battery energy density above silicon anode competitors, with only modest price increases above graphite at the cell-level, at price parity with graphite at the pack level, and likely cheaper than graphite at the vehicle level.

About E Source and Team

E Source has been a leader in battery technology analysis and cost modeling since acquiring Cairn ERA in 2021, building upon 30+ years of thought leadership and modeling in the energy space. E Source specializes in providing curated market intelligence, data-backed industry research, and benchmarking to inform investment decisions, technology adoption, and strategic business decisions. E Source methodology for battery industry analysis entails employing a first principles analysis to examine emerging battery technologies and model their impact on battery costs. E Source forecasts battery prices with our Battery Cost Model, which contains over 3,000 inputs and 30,000 formulas that models battery component, cell, and system production. E Source forecasts technology adoption and battery demand for over 50 different battery markets based on our analysis of the technical requirements and economics of each application. Forecasts are broken down by application and segmented into global regional distribution, energy capacity, power capacity, cathode technology, anode technology, and cell revenue. Forecasts are then stress-tested against top-down historical proxy growth curves to determine how other historical examples have grown under similar supply/demand circumstances.

Dr. Seth Miller is Director of Electrochemistry at E Source and President of Heron Scientific, a boutique consulting company specializing in R&D strategy and investment planning for companies leveraging cutting edge materials science, especially new battery chemistries. As an entrepreneur, Dr. Miller has served as founding CEO of ClearMark Systems, a developer of anti-counterfeiting software for DARPA; CSO of Fluonic, a microfluidic flow sensor for medical infusion; and CSO of EverSealed, a developer of vacuum sealed windows. He also served as CTO of Technology Reserve, an IP licensing company, and Managing Director of Xinova after its acquisition of Technology Reserve. Dr. Miller has served as an expert witness and testified at trial in several high stakes patent infringement cases, most recently in SK Innovations vs LG Energy Systems regarding battery packaging. He is author or co-author on 93 issued US patents, and received a Ph.D. in chemistry from the California Institute of Technology in 1998.

Ben Campbell has been the Manager of Battery Research at E Source since April 2023. Ben analyzes the business models, manufacturing processes, and electrochemistry of batteries for stationary energy storage and electric transportation. At E Source, he led the development of a Levelized Cost of Storage model to compare the economics of different energy storage technologies, in addition to a BTM ESS ROI Model that examines the efficacy of batteries reducing demand charges for individual customer sites. Previously, he was a Lead Analyst at Cairn Energy Research Advisors (ERA), a specialty consulting company focused on batteries that E Source acquired in October of 2021. At Cairn ERA, he helped develop an industry-leading model for battery manufacturing costs and forecasted markets for batteries and charging infrastructure, which he continues to maintain at E Source. He holds a BA in philosophy from Wake Forest University.