Electric Revolution Insights

The Electric Revolution is accelerating, but yet it has hardly just begun…
By Mark C. Newman

Introducing the inaugural *Electric Revolution Insights*, a monthly report by Mark Newman (ex-Bernstein analyst) on the Electric Revolution. Here we will cover latest news and insights on recent developments in EVs and key enabling technologies, such as batteries. For background on Mark Newman or the upcoming Electric Revolution Podcast, please visit www.electricrevolution.info

Sorting out the truth from the clutter
In the world of batteries, EVs, and electrification, there is a lot of misinformation. As the world scrambles to slow down global warming and convert transportation and energy from dirty fossil fuels to clean energy and electric vehicles, there is a new generation of innovators, each promising to have the solution to all of these challenges. Some of these emerging technologies will succeed, most will fail. We intend to sift through which technologies have the best prospects of technical and commercial success, which of them are possible, and which are either a long shot or likely to fail. Today we will take a closer look at next-generation high energy density battery technologies. In future *Insights*, we will look into longer duration batteries (to enable renewable energy) and high power or fast charge batteries (for performance needs).

The race for high energy density batteries
Why do we want high energy density? Well, quite simply put, for long range (or high energy) applications like electric cars with 500 miles range, long-distance trucks, or electric planes, we need more energy and we don't want the excess weight of heavy batteries. Lithium-ion batteries are still much lower energy density than gasoline and are not really workable for long distance (e.g. trans-Continental) air flight, and far from ideal for long-distance heavy goods trucking. This is because for longer ranges, conventional lithium-ion batteries become so big and heavy that they reduce the effective range, thus creating diminishing returns (more batteries are needed to pull more battery weight without meaningful improvement in actual range). Higher energy density batteries solve this challenge.

To improve energy density, there are four ways to do this:

1. Better anodes (higher specific capacity)
2. Better cathodes (higher specific capacity, higher voltage)
3. Less inactive materials (separator, current collector, case etc.)
4. Pack efficiency (less weight/volume loss at the pack level)

While most improvements in lithium-ion to date have been from 2, 3, and 4 above, there has been little improvement in energy density from the anode, which is still mostly graphite (a form of carbon). In this letter we will focus on improvements in the anode, which are potentially far more disruptive than the ongoing incremental innovations which continue to happen in the cathode, and other parts of the battery to improve overall efficiency.

Lithium metal is the end-game for high energy density batteries
For next gen high energy density batteries, the two types of next gen anodes are lithium metal and silicon. This is because both of these materials have a significantly higher capacity (that enables higher energy density in the full battery) than graphite used today. Lithium-metal really is the ultimate end-game for high energy density anodes because it is the lightest metal on the periodic table and there is nothing else on the anode side besides lithium. Silicon also has a very high theoretical capacity but due to its hugely problematic volume expansion during charge (~300% vs. 10% for graphite), silicon is often blended with graphite and thus doesn't

provide as much a boost to energy density compared to lithium metal. We will address silicon in more detail in a later note, today we will focus more on lithium metal anodes and how these can be enabled.

What is solid state, and is it the future?

Lithium metals (and pure silicon) anodes are notoriously tricky. Solid state batteries (using solid rather than liquid electrolytes) are often thought of as the "safest" way (or according to some the "best" way) to enable these anodes. However, solid state batteries, although they sound cool, are far from commercially viable, have major performance drawbacks and are not even 100% safe.

Firstly, on safety, there is no such thing as a 100% safe battery chemistry. Gunpowder is also solid, and nobody would call that "safe". More critically, solid state electrolytes are far harder to commercialize due to the significant changes and new complexity in the manufacturing process. Many solid state electrolytes for example use a very high temperature sintering process, which is expensive and notoriously difficult (with typically low yields). They also often exhibit far worse performance than liquid electrolytes thus defeating the objective of going to these next gen anodes. Importantly, solid state electrolytes themselves are not high-energy density. In fact, solid-state electrolytes are often far denser and heavier than liquid electrolytes and thus make gravimetric energy density worse. It is only the anode (or the cathode) that enable the high energy density that the industry yearns for.

Debunking the myth – the alternative to solid state

Although we see some potential for solid state batteries in the very long-term, and there is some interesting research in this area, there is an alternative way to enable these very high-capacity next gen anodes such as lithium metal. SES, Cuberg (acquired by Northvolt) and the US DOE funded Battery 500 program and a few other companies are enabling lithium-metal anodes with liquid electrolytes. This lithium-metal with liquid electrolyte approach is far more commercially viable than any solid state alternative due to a proven manufacturing process (as it is virtually identical to lithium-ion production). Some of the solid state approaches by comparison use exotic chemistry and manufacturing techniques which only work at lab scale. The proof is in the 100 Ah cell that SES has already shown off at its Battery World event last year (that this author hosted), vs. tiny 2 Ah cells from solid state competitors. This 100 Ah cell from SES has already demonstrated a whopping 417 Wh/kg energy density (vs. lithium ion around 200-250 Wh/kg). QuantumScape has still yet to publicly demonstrate even one commercially viable cell of >25 layers.

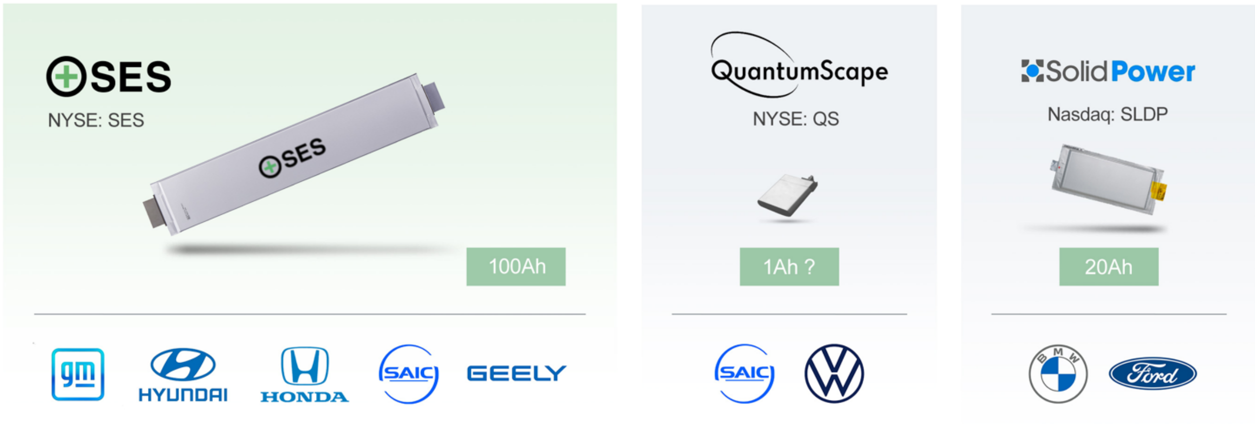
		SES	QuantumScape	Solid Power
3rd party validated		✓	Partial	Partial
Room Temperature Energy Density	*Cell type*	*4Ah (25+ layer) at 25°C (Wh/kg)*	*1, 4, 10 layer at 25-30°C*	*2Ah (10 layer) and 2 layer at 29°C (Wh/kg)*
	Low power C/20	>375*	n/a	330
	Low power C/10	375	n/a	~264
	Medium power 1C	339	n/a	~33
	High power 5C	321	n/a	n/a
0 °C Low Temperature Energy Density	Low power C/10	324	n/a	n/a
	Medium power 1C	298	n/a	n/a
	High power 5C	282	n/a	n/a
Lifetime	1-2 layer	n/a	1,000 cycles (>80% retention)**	>250 cycles (>80% retention)
	3-4 layer	800 cycles (80% retention)**	1,000 cycles (>80% retention)**	n/a
	10 layer	n/a	1,000 cycles (>80% retention)**	>32 cycles (>80% retention)
	25+ layer	550 cycles (90% retention)**	n/a	n/a
Fast Charging	1 layer	n/a	80% in <15min**	n/a
	10 layer	n/a	n/a	n/a
	25+ layer	80% in <15min	n/a	n/a
Safety	Thermal	Electrolyte is stable with Li above Li melting point	Electrolyte is stable with Li above Li melting point	n/a
	Nail	PASS TEST	n/a	PASS TEST
	Overcharge	PASS TEST	n/a	PASS TEST
	External Short Circuit	PASS TEST	n/a	PASS TEST
Manufacturability		✓ *(highly similar process to Li-ion)*	? *(unproven and complex for proprietary separator)*	? *(significant process changes vs. Li-ion)*
Commercialization Timeline		Li-Metal: 2025***	Li-Metal: 2026***	Silicon: 2026 Li-Metal: After 2026?
Source		3rd party test data (Eclipse and Exponent) and SES internal data	Investor presentations; 2021 Q3 shareholder letter. Partial 3rd party test data (Mobile Power) and QS internal data	Investor presentation (Dec 2021). Partial 3rd party test data (2Ah Abuse Test Report from SwRI)

* Estimated; ** internal test data; *** Represents at-scale post-pilot production (QS-1 Expansion for QuantumScape and Expansion 1 for SES); n/a = not available

The New Big Three – how do they stack up?

The above table prepared with the help of Dr. Billy Wu (Imperial College London) compares lithium metal batteries from the big three US listed next gen battery technology companies (though SolidPower has recently pivoted away from lithium-metal). It clearly shows far superior energy density at all power ratings for SES. In fact, on most metrics SES comes out on top, and was the first to openly share third party data.

Out of these three disrupters, SES impressively now has relationships with 5 of the top 10 car OEMs. The recent announcement that SES is now working with Honda puts SES at a clear advantage vs. QuantumScape (with two car OEMs) and SolidPower (also with two car OEMs).



Meanwhile, in other news

- Congratulations to SES on the successful listing on the NYSE (via deSPAC). As mentioned above, SES is arguably the world's leader in lithium metal batteries, with 100Ah cells shown off at the recent battery world. These cells boast a whopping 417 Wh/kg energy density (that's about twice regular lithium-ion batteries).

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