Fundamental Differences between a Hybrid Supercapacitor and LFP Battery

Hybrid Supercapacitors (HSC) are a new and unique advancement in energy storage. Because the technology is so new, it is often mistaken for being yet another Lithium Battery derivative. This is farfrom the truth.

To demonstrate the distinction of Hybrid Supercapacitors from Lithium Batteries, five different tests were conducted by independent labs to measure the advantages of Hybrid Supercapacitors over Lithium Iron Phosphate (LFP) Batteries. Before commissioning this work, we did not know whether these tests would validate the academic theories behind the HSC design or if it would provide definitive proof of the performance differences that distinguish one from the other. We believe the results speak for themselves.

The five tests performed all showed advantages of the Hybrid Supercapacitor over an LFP Battery. These tests are:

• Thermal Runaway forced by heating the cell

✓ Result HSC is more resilient than LIB

• Abnormal Charge test

✓ Result HSC passed, LIB failed

• Charge and Discharge rate test

✓ Result HSC provides faster response to power demand than LIB

• Charge and Discharge temperature test

✓ Result HSC shows higher efficiency, less heating that LIB

• Cycling Test

✓ Result HSC exceeded LIB in demonstrating less degradation as measured by change in Equivalent Series Resistance.

✓ Result HSC capacity loss was less than LIB.

While Hybrid Supercapacitors use several of the same chemical components as LFP Batteries, the performance and life cycle improvements are achieved from how these components are assembled. Some energy density is sacrificed in the HSC design, but this is not a significant issue when building reliable stationary energy storage, where space is not a primary consideration. The benefits far outweigh the energy density loss.

A good analogy when describing the differences is: synthetic oil vs regular oil. Everyone now knows synthetic is superior to regular oil. No one questions the chemistry although both are made from the same material, i.e., petroleum. How it's done doesn't really matter. Synthetic is just superior. We are certain with more observed, real-world experience of Hybrid Supercapacitors, these advantages will be commonly accepted without question as has been the superiority of synthetic oil.

Materials Analysis

Presence of Lithium Iron Phosphate: While both lithium-ion batteries (LIB) and Hybrid Supercapacitors (HSC) use lithium, they use it in different ways. Lithium-ion batteries use lithium ions that move between the anode and cathode during discharge and charge, which is an electrochemical process. HSC, on the other hand, employs lithium ions in a similar way to an electric double-layer capacitor (EDLC, sometimes referred to as a supercapacitor or ultracapacitor). The HSC uses lithium ions like a battery in an electrochemical redox (reduction oxidation) reaction, but it also uses electrostatic attraction like an EDLC.

Presence of Graphene: Graphene is a common component in supercapacitors due to its high electrical conductivity, consistency and creation of a large surface area. LFP batteries typically use the less expensive, less refined Graphite.

Chemical Make-up of test 31Ah HSC (MSDS)

Chemical Name	Concentration %	CAS Numbers
Lithium Iron Phosphate	39.05	15365-14-7
Polyvinylidene Fluoride (PVDF)	1.23	24937-79-9
Aluminum	4.17	7429-90-5
Graphene	19.57	7782-42-5
Styrene- Butadiene Rubber (SBR)	1.1	9003-55-8
Carboxymethylcellulose	0.31	9000-11-7
Copper	7.17	7440-50-8

Chemical Make-up of test LFP (MSDS)

Chemical Name	Concentration %	CAS Numbers
Lithium Iron Phosphate ($LiFePO_4$)	42.5	15365-14-7
Organic Solvent	17	N/A
Aluminum	12.5	7429-90-5
Graphite	17.5	7782-42-5
Copper	7.2	7440-50-8
Nickel	0.3	7442-02-0
Other	3	N/A

Both LFP battery and the Hybrid Supercapacitor contain many of the same materials. However, there are also some key differences.

The LFP battery also contains a couple elements indicative of an electrochemical process.

• Nickel, to increase energy density

• Graphite, a cheaper less consistent electrode surface more prone to dendrites

The Hybrid Supercapacitor, on the other hand, contains:

• Graphene rather than Graphite for an improved electrode surface area and consistency

• Significantly less Aluminum implying the use of an electrostatic electrode

These differences, along with the anode and cathode make-up, reflect the fundamentally different ways that lithium-ion batteries and Hybrid Supercapacitors store energy.

• LIBs use chemical reactions to store energy, i.e. they are purely electrochemical in nature. During charging, lithium ions move from the negative electrode (anode) to the positive electrode (cathode). When the battery discharges, the lithium ions flow back from the cathode to the anode through an electrochemical redox reaction.

• HSCs store energy electrostatically and electrochemically. They have two electrodes with graphene coated high volume surface areas that are separated by an electrolyte. Unlike the LIB, an HSC cathode contains no lithium doping. When the supercapacitor is charged, positive and negative ions accumulate on the surfaces of the electrodes. When the HSC discharges, the ions flow back together, generating a current. Introduction of the electrochemical process increases energy density of the HSC well above what is possible in a purely electrostatic EDLC.

Measurable Differences

Energy Density

• **Lithium-Ion Batteries (LIB):** High energy density. LIBs are known for their compact size and ability to store a significant amount of energy. (Test LIB – 157.4 Wh/kg)

• **Hybrid Supercapacitors:** Somewhat lower energy density. They fall between traditional EDLC (low energy density) and LIBs (high energy density), offering a balance that supports both long-term and short-term energy needs. (Test HSC – 147.7 Wh/kg)

Power Density

• **Lithium-Ion Batteries (LIB):** Moderate LIBs can provide energy at a faster rate than VRLA batteries but are not as quick as supercapacitors or Hybrid Supercapacitors. (157.4W/kg)

• **Hybrid Supercapacitors:** Very high power density. Hybrid supercapacitors excel at delivering energy almost instantaneously, which is ideal for peak shaving and demand response. (Test HSC – 857.6W/kg)

Cycle Life

• Lithium-Ion Batteries (LIB): Moderate to long cycle life which is very dependent on C-rate. LIBs have a longer lifespan compared to VRLA batteries but still experience capacity fade over time, especially under high current loads or deep discharges. (Test LIB – 4,500 @ 25°C)

• Hybrid Supercapacitors: Extremely long cycle life. They can endure hundreds of thousands to millions of charge and discharge cycles, making them highly durable for applications requiring frequent cycling. (Test HSC – 20,000 @ 25°C)

Efficiency

• Lithium-Ion Batteries (LIB): High efficiency (90-95%). LIBs are more efficient at storing and releasing energy but can lose some efficiency as they age. (Test LIB – 92%)

• Hybrid Supercapacitors: Very high efficiency (95-98%). Minimal energy loss occurs during high and low C-rate cycles, this improves overall system performance and significantly reduces degradation over cycle and time. (Test HSC – 97.5%)

Key Applications and Suitability

• Lithium-Ion Batteries (LIB) are well-suited for energy storage where high energy density and moderate power density are required, making them very useful for applications such as electric vehicles.

• Hybrid Supercapacitors are ideal for applications requiring rapid energy delivery, long duration energy delivery and frequent cycling. This makes them ideal for renewable energy applications, peak shaving. time-of-use arbitrage, and in inconsistent charge or energy applications where the load is dynamic in telecommunications, factories, hyperscale or microgrid.

Head-to-head testing of LIB vs HSC

To confirm the theoretical expectations, we performed a series of tests using both LFP batteries (LIB) and Hybrid Supercapacitors (HSC) manufactured on the same equipment by the same contract manufacturer. The LIB chosen is a 30Ah LFP. The HSC chosen is a 31Ah LFP-Graphene hybrid.

Both products were produced on the same equipment, but the application of materials differed based on the requirements and specifications of the contract customer.

Five tests were designed and applied equally.

• Thermal Runaway forced by heating the cell• Abnormal Charge test

• Charge and Discharge rate test

• Charge and Discharge temperature test

• Cycling Test

Thermal Runaway (TR) is probably the most concerning issue with lithium-ion based energy storage. The news media has hyped this issue to be virtually synonymous with LIBs and fires. Certainly, there should be concern for low quality LIBs and the existence of impurities in the coatings applied to the anode and cathode can result in dendrite growth and eventual short circuit of the cell. Heating is another way to quickly induce TR, which could occur in many parts of the United States during extreme temperature events in summer months.

CSA, a recognized UL Certification laboratory performed TR on our HSC. To expedite the comparison, we followed their procedures and had an independent party perform the same test on our selected LIB.

Thermal Runaway is not actually defined as a cell bursting into flames as the media has conditioned most people to believe. Technically speaking, it has occurred when the internal temperature of the cell begins to exceed the external temperature applied to the cell (in the case of using heaters to perform the test)

HSCs utilize a fraction of the $LiFePO_4$ as do LIBs, because they utilize a combination of electrostatic and electrochemical mechanisms to charge and discharge and their structural design is different. They are less prone to dendrite growth or to extreme temperatures. From this we would expect that TR is harder to initiate in the HSC than in the LIB. Our test results confirm this expectation.

HSC was forced into TR at 229°C

LIB was forced into TR at 183°C

✓ Difference 25% higher temperature required to initiate TR in an HSC

To put this in perspective, 229°C is equal to 444.2°F. Functionally, to induce TR by heating the HSC cell would have to be exposed to an external fire.

Abnormal Charge (AC) is a test that stresses the cell internal construction. Normally, when this test is performed on a battery it is limited to the amp rating provided by the manufacturer. Knowing that the composition of an HSC is uniquely designed to be long lasting and more stable than an LIB, we believed that the HSC could withstand an extreme version of the AC test. To prove our expectations, we contracted CSA to apply the maximum amperage their test equipment could produce to our HSC.

The test using the equipment limits resulted in 300A being applied to a cell, which was overcharged to 1.1x its rated voltage (in this case 4.0Vdc) and held at that rate for seven hours. We then applied the same test criteria to our 30Ah LIB.

LIB vs HSC Post Abnormal Charge Test

LIB Cell

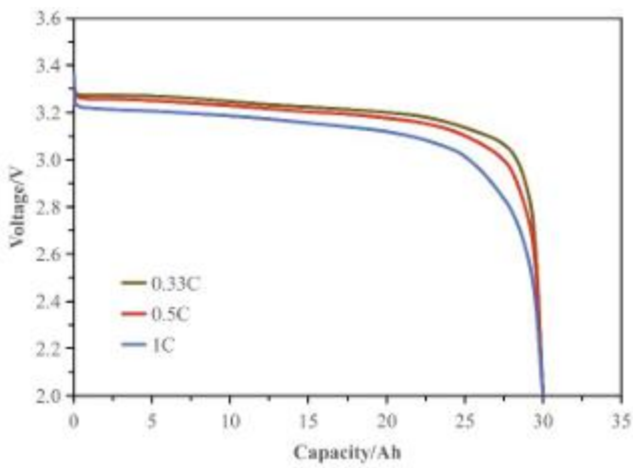
HSC Cell

HSC completed the test with no apparent damage. The cell remained functional.LIB exhibited extreme cell deformity and was damaged beyond use.

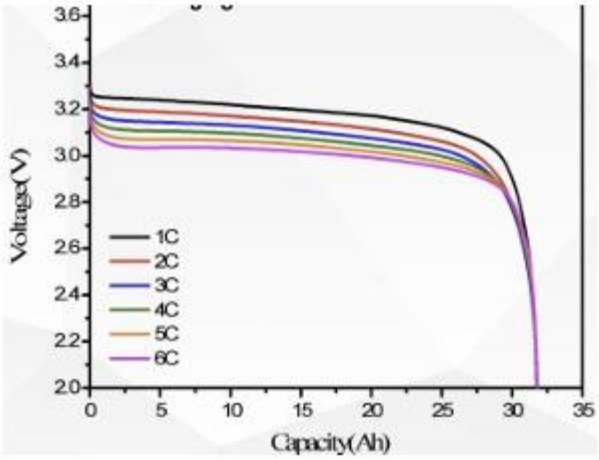
✓ Results HSC exceeded our expectations under Abnormal Charge. LIB Failed the test

Charge/Discharge Rate (C/D Rate) is a test that demonstrates the power density of the cell. Due to the electrostatic component of the charge/discharge properties of the HSC, our expectation is that the HSC has substantially higher power density than an LIB. The LIB C/D Rate is limited by the movement of electrons in an electrochemical redox reduction process whereby the electrons are forced to separate from their chemical composition (LFPO4). The reason the C/D Rate is important is that forced rapid charge or discharge of an LIB is known to cause much more rapid degradation of the battery and shorten its expected life and increase dendrite growth, a precursor to TR. The more resilient an energy storage solution is to C/D Rate, the longer it will last and the safer it will be. C/D Rate is often presented as C-Rate. To understand C-Rate, a C-Rate of one is 1-hr full discharge or charge, a C-rate of 0.5 is a 2-hr discharge or charge and a C-rate of 10 would be full discharge or charge in six minutes.

The HSC and LIB were tested at their limits. The result of the test confirms our expectations that the HSC can provide higher Power Density than an LIB.



LIB Discharge



HSC Discharge

HSC provided up to 6 C-rate discharge

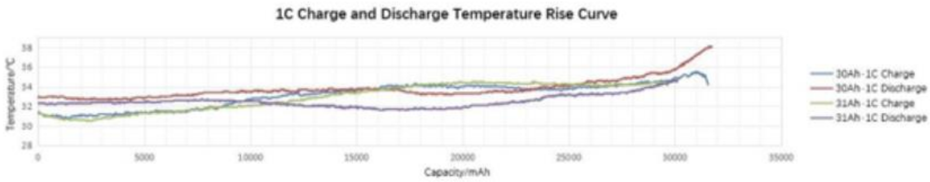
LIB provided up to 1 C-rate discharge

✓ **Result HSC exceeded LIB C/D rate as expected given its electrostatic capabilities**

Charge/Discharge Temperature (C/D Temp) is a test where we measure the rise in temperature of the cell at its different charge and discharge rates. Since these cells are symmetrical, meaning that they have equal charge and discharge rates, we can conclude that testing for either charge or discharge will provide similar temperature rise. Because HSC utilizes electrostatic electron exchange our expectation is that they provide a more efficient round-trip than does an LIB. Temperature is the result of internal resistance of the electrons and ions moving through the electrolyte. LIB utilization of a purely electrochemical exchange we expect will show greater temperature rise and therefore less efficiency.

Our test was performed at the limit of the LIB, i.e., 1 C-Rate noted in our previous test. This time, rather than charting the Voltage vs Amperage, we charted the Temperature vs Amperage. Once we compared the two products as a common C-Rate, we went on to test the HSC at its highest six C-Rate. Our expectation was that the HSC would show a lower temperature rise than the LIB confirming our theory that the use of electrostatic features of the HSC resulted in a more efficient product. This is important because temperature is a contributing factor to early energy storage degradation and further defines expected life cycles of the energy storage. In other words, lower temperature swings lead to a longer life, more efficient product.

LIB vs HSC Temperature vs Ah Capacity



HSC demonstrated a 2.5 degree increase at 1-C rate discharge

LIB demonstrated a 6.0 degree increase at 1-C rate discharge

Difference of 3.5 degrees or 140%, relative.

✓ Result HSC exceeded LIB in demonstrating higher efficiency, less losses due to internal resistance

Cycle Testing is a much longer process. We set up a test of our selected LIB and HSC at the independent test facility. The test involves continuous charge/discharge cycling with a short (< 1minute) rest between each charge and discharge event. The cells are placed in a machine, side-by side and cycled for a period of about 60 days. At a 1 C-rate this process simulates 500 full charge/discharge cycles, which when applied to a daily cycling energy storage module would be the equivalent of about two years of daily operation at 100% Depth of Discharge (DoD).

Consistent with our expectations of a longer life HSC, the HSC presented a substantially lower rate of degradation and capacity loss than the LIB. A reasonable indicator of degradation is increased Equivalent Series Resistance (ESR) over repeated cycling. The expectation was that we would see the ESR, measured in mΩ across the terminals, increase more in the LIB than in the HSC. ESR is a measure of internal resistance build-up in the cell from the electrochemical process breakdown. The breakdown is the result of trapped ions at the Solid-Electrolyte Interphase (SEI).

The shorter cycle-life LIB, which utilizes purely electrochemical ion exchange, showed a 31.4%increase in the ESR than the longer cycle-life HSC over the 500-cycle test. The LIB's ESR increased by 10.3% while the HSC ESR increased by a mere 4% over 500 cycles. The HSC is rated at 20,000life cycles at 25°C and 100% DoD, while the LIB is rated at less than 6,000 life cycles under the same criteria. The SEI breakdown further manifests itself in a reduction of cell capacity (useable energy). In this comparative test the LIB capacity loss was 4.3% greater than that of the HSC over 500 cycles.

✓ Result HSC exceeded LIB in demonstrating less degradation as measured by change in Equivalent Series Resistance.

✓ Result the HSC capacity loss was lower than seen in the LIB.

Conclusions

The Hybrid Supercapacitor has shown superiority over the LFP Battery across several comparative tests designed to demonstrate operational performance. The practical tests shown here were done in an identical manner for each product. Both products were built on the same machinery by the same manufacturer and only the composition of materials differed. Additional testing is underway, but we believe we have identified and quantified the unique and valuable characteristics that make Hybrid Supercapacitors a superior product for stationary energy storage.

Field applications continue to operate daily in real-life environments from the Mohave Desert to the mountains of Alaska. We firmly believe these daily cycled systems will continue to confirm our findings here as they have for many years in all instances already.

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