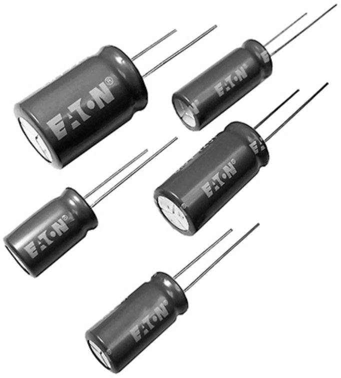
The major differences between supercapacitors and batteries

Eaton supercapacitors



Overview

Batteries are composed of electrodes, an anode, and a cathode, immersed in an electrolyte. When each electrode of the battery is brought into contact with the electrolyte, a certain electrode potential is developed. The difference in potential between the electrodes causes the current to flow and the subsequent power delivery to any connected electronics. In batteries, electric energy is stored indirectly as potentially available "chemical energy" that can be tapped into through a faradaic process, where the oxidation and reduction of the electrochemically reactive agents cause a transfer of charge between the electrodes and the electrolyte. All charge-transfer processes are governed by Faraday's laws of electrolysis, where the amount of chemical change at the electrode-electrolyte interface is proportional to the current that flows through the interface.

Supercapacitors is a blanket term for electric double-layer capacitors (EDLCs), electrochemical capacitors, electrochemical supercapacitors, and ultracapacitors. While supercapacitors also leverage an electrolytic solution, they mainly accomplish the electrical "double layer," where oppositely polarized ions are adsorbed at electrode surfaces separated only by Helmholtz layers. This molecular dielectric mimics a capacitor by storing charges electrostatically. This fundamental difference in the inner workings of these two storage technologies leads to significant functional differences in performance.

This whitepaper outlines the key differences between supercapacitors and batteries in construction, specifications, capabilities, and applications.

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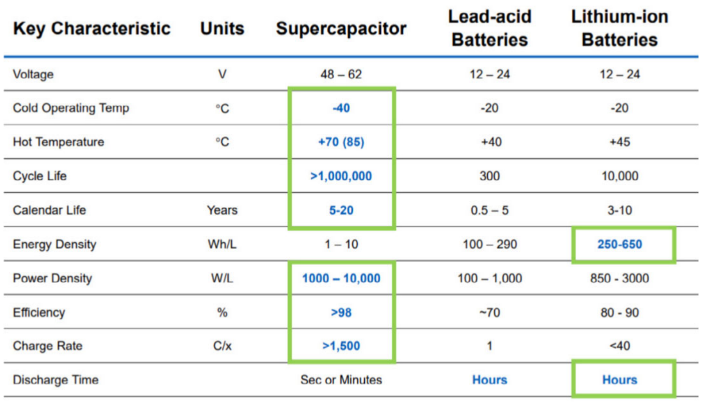
Major distinctions between supercapacitors and batteries

As shown in Table 1, there are distinct differences between batteries and supercapacitors in terms of key parameters for energy storage. This section dives into these differences to better understand the advantages and considerations of each technology.



Key Characteristic	Units	Supercapacitor	Lead-acid Batteries	Lithium-ion Batteries
Voltage	V	48 – 62	12 – 24	12 – 24
Cold Operating Temp	°C	-40	-20	-20
Hot Temperature	°C	+70 (85)	+40	+45
Cycle Life		>1,000,000	300	10,000
Calendar Life	Years	5-20	0.5 – 5	3-10
Energy Density	Wh/L	1 – 10	100 – 290	250-650
Power Density	W/L	1000 – 10,000	100 – 1,000	850 - 3000
Efficiency	%	>98	~70	80 - 90
Charge Rate	C/x	>1,500	1	<40
Discharge Time		Sec or Minutes	Hours	Hours

Table 1: Energy storage solutions comparison

Calendar and cycle life

In a battery, the act of recharging is inherently faradaic. It involves forcing the ions at the cathode electrode back to the anode to a point where there is sufficient electrochemical potential. However, the charge and discharge processes usually necessitate an irreversible interconversion of the chemical electrode reagents or ingredients. The cyclic stresses on the battery lead to the cracking of the electrode material and the decomposition of both the solvent and salt components of the electrolyte, which eventually prevents any reversible electrochemical reactions. Li-ion batteries form a permeable passivation layer called the solid-electrolyte interphase (SEI) on the electrode surface. This allows for blocks of electrons to pass while also preventing the electrolyte decomposition, therefore, extending the cycle life. However, this SEI formation and growth also consumes active Li and electrolyte materials, causing a reduction in capacity and power density. Another aging mechanism is the breakdown of the SEI layer, which leads to overheating and immediate failure.

As shown in Table 1, supercapacitors far exceed batteries in terms of cycle life. There is no hard failure point to determine end-of-life, and there are comparatively few chemical and phase changes occurring during charge and discharge since the charge storage process is non-Faradaic. In other words, minimal electron transfer occurs across the electrode interface, and instead, electrical energy is stored electrostatically. Rather than hard failure modes, there are typical deviations from nominal parameters values, such as capacitance or equivalent series resistance (ESR), that signify end-of-life. The long supercapacitor cycle life is further illuminated in Figure 1, where Li-ion batteries offer the best cycle performance with only 4 percent of the load cycles at nearly half of the depth of discharge (DOD).

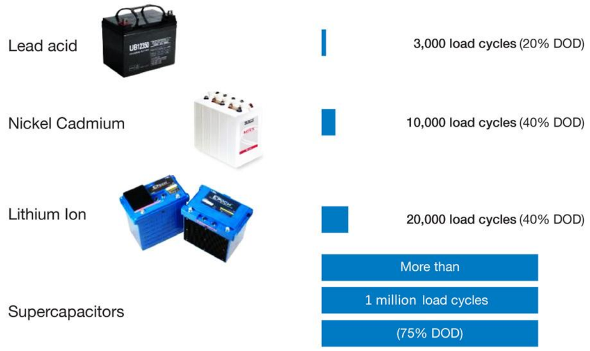


Figure 1: Comparing cycling capabilities of Lead acid, Nickel Cadmium, Lithium ion, and supercapacitors storage technologies

Operating temperature

Batteries generally have a limited temperature range that allows for nominal operation. For instance, for Lithium-Ion batteries (LIBs), the negative impact of low and high temperatures involves two different degradation modes. For these batteries, the typical operating temperature range runs from -20 °C to +40 °C. LIBs exhibit a slowed chemical-reaction activity and charge-transfer velocity at low temperatures, leading to a lower ionic conductivity and diffusion coefficient of the Li-ions. This reduces the power and energy capabilities of these components. On the other hand, high storage temperatures, straining operating conditions with high power/current loads, and internal manufacturing issues such as electrode defects can all lead to extreme heat, sudden rise in temperature, and thermal runaway.

In some cases, thermal runaway has the potential to trigger self-ignition and explosion. For this reason, temperature monitoring of batteries is of the utmost importance to ensure the user's safety. Heat generation is unavoidable in a battery during charge transfer and chemical reactions during charge and discharge. Entropic heat occurs during electrochemical reactions, while ohmic heating occurs when the resistance of the electrode and electrolyte impedes the transfer of charges. Outside of the entropic heat coefficient (EHC) and internal resistance, additional heat generation processes are leveraged in thermal models for batteries.

For supercapacitors, the operating temperature range is extended from -40 °C to +85 °C. The internal resistance of supercapacitors is typically an order of magnitude lower than batteries, and, as shown in the following equation , this minimizes the energy wasted in the form of heat.

$$Ploss,int = P_L \frac{r_{int}}{R_L}$$

In this equation, R_L is load resistance, r_{int} is internal resistance, P_L is load power, and $P_{loss'int}$ is the power wasted as heat inside an energy source. Self-accelerating reactions do not occur in supercapacitors, thus mitigating the concern of thermal runaway. Besides leveraging a non-faradaic process for charge storage and electron transfer, individual supercapacitors also operate in a lower voltage window, allowing for an even slower decomposition of the electrode and electrolyte.

Energy density

As shown in Figure 2, the energy density of fuel cells and batteries exceeds supercapacitors. Electrical energy is stored in the form of chemical energy, which happens to be more energy-dense than capacitor-based electrostatic energy storage. LIBs, in particular, accomplish some of the industry's highest energy densities at up to 650 watt-hours per liter (Wh/L). On the other hand, supercapacitors exhibit only 15 percent of this energy density, with high-end supercapacitors at 10 Wh/L. This is the main reason why batteries continue to be leveraged in applications that require higher storage capacity, such as electric cars, grid storage, and renewable energy storage. Batteries generally allow for a longer current draw in these high-power applications.

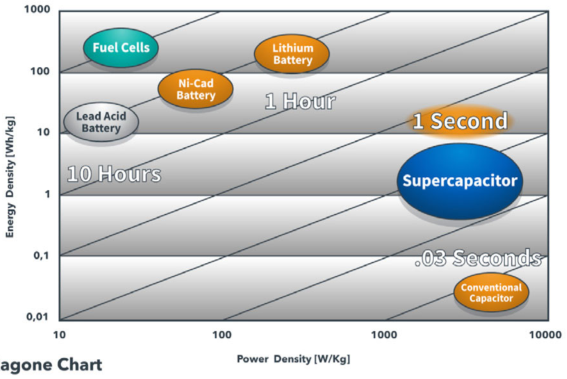


Figure 2: Ragone charge of energy density overpower density for various energy storage technologies

Power density and charge rate/discharge time

Power density relates directly to the charge rate and discharge times of the energy storage technology. Backup energy storage applications, for instance, favor power density over energy density for many applications such as computer servers, manufacturing lines, and hospitals. These applications critically rely on energy storage to deliver power immediately after power loss or a low-threshold voltage state. With power densities up to three times that of LIBs (10,000 watts per liter), the charge rate is hundreds of times that of LIB, and discharge times on the order of seconds and minutes, instead of the hours for most batteries.

This difference in power and energy can lead to other differences when the energy storage is not charged. Energy storage loses a portion of its charge (voltage) due to self-discharge and leakage current. When the charge voltage is removed, the leakage current, also known as self-discharge current, discharges the unloaded capacitor due to design optimization, impurities, and material imperfections. A trickle current, equal to the leakage current, must maintain a charge on the capacitor or a battery. Without charging, this results in a supercapacitor that could lose ~30 percent of its stored energy in a month compared to a Li-ion battery losing 10 percent. However, since there is no practical limit to the recharge capability of supercapacitors, they can be recharged just as fast as they are discharged. Supercapacitors can be charged using various methods, including constant current, constant power, constant voltage, or paralleling an energy source.

Efficiency

As shown in Table 1, supercapacitors are far more efficient under full load conditions. This is largely due to many mechanisms for heat generation in a battery that results in power loss, as described earlier. The typical round-trip efficiency for a supercapacitor is greater than 98 percent, while LIB efficiencies are typically less than 90 percent.

Management systems: supercapacitors vs. batteries

Battery management systems (BMS) are critical to ensure proper charging and discharging. The systems do this by monitoring, controlling, and optimizing battery parameters (e.g., temperature, voltage, current, overcurrent/overvoltage protection, state of charge, state of head, depth of discharge, protective relay actuation to disconnect of faulty cells, etc.). Due to the growing complexity in maintaining the nominal performance of the battery and the increasing stringency in safety measures (especially around automotive applications), BMSs often feature software architectures with multi-tasking capabilities calling for complex processing for real-time monitoring and control.

Supercapacitor module management systems do not necessarily have to be as complex due to the inherent robustness of the technology. To achieve the long lifetimes inherent with the supercapacitor cell at the module level, the cells within the module need to be voltage-balanced while charged and during charge and discharge. There are three general approaches to maintain this voltage balance: passive balancing, shunt balance, and active balancing. Supercapacitor modules can come with preinstalled balancing circuits to ensure safe and optimal operation. Unlike BMS, these balancing schemes do not require external controls or monitoring. This allows for greater simplicity in integrating this energy storage into an application while also mitigating operational expenditures (OPEX).

Management systems can also be for systems that leverage both supercapacitors and batteries in hybrid energy storage systems. Power electronics are integrated into a hybrid or combined energy storage system to provide a control strategy to charge and discharge the appropriate energy storage device based on the power requirements. These power electronics can also optimize the charging power flow between energy storage technologies. The very same control system can allow the battery to charge the supercapacitor and vice versa.

Series and parallel supercapacitor configurations

Supercapacitors can be arranged in series or parallel configurations. Typically, the voltage ratings of individual capacitors fall in the 2 V to 3 V range. As stated earlier, the working voltage can be increased by arranging the supercapacitors in series for voltage ratings up to 1500 VDC, also known as a module string. This allows supercapacitors to work efficiently in higher voltage systems. Arranging a supercapacitor in parallel allows a designer to meet current or power application needs over the desired timeframe. Both series and parallel configurations can also be employed to enjoy the benefits of both topologies.

Pairing supercapacitors with batteries in a hybrid energy storage system (HESS)

Many storage systems pair batteries with supercapacitors to get the best of both worlds. Both have an energy-dense battery in a small form factor while also allowing the power-dense supercapacitor to deliver short bursts of power. Typically, applications leverage either a passive configuration by placing the two technologies directly in parallel or in an active configuration that uses multiple input power conditioning systems (PCS).

An independent configuration can be utilized where the distinct/unconnected battery and supercapacitor are connected to their loads (Figure 3). The passive/parallel HESS effectively suppresses transient current under pulse load conditions while also increasing the peak power that the energy storage system can deliver. All this while decreasing internal losses. However, since the output voltage of the supercapacitor is directly tied to the battery voltage, the supercapacitor cannot function within its full state of charge (SOC) range and fully realize its power handling capability, resulting in less volumetric efficiency. The active system allows the battery power flow and supercapacitor to be controlled with bidirectional DC/DC converters, improving system performance, enhancing efficiency, and improving the calendar life of both storage devices.

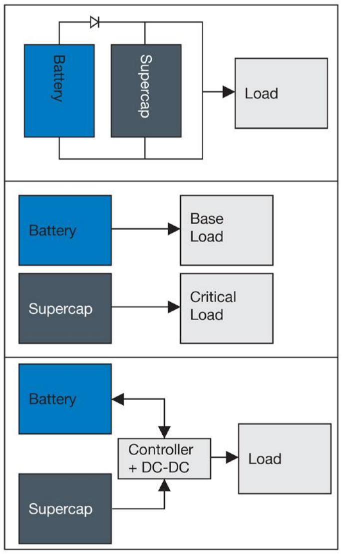


Figure 3: Battery and supercapacitor hybrid energy storage systems (HESS) in a passive, split, and active configuration (top to bottom).

Combining batteries and supercapacitor structures to create hybrid supercapacitors

Hybrid supercapacitors are used when pairing supercapacitor and battery technology in a device. In this type of energy storage, one of the carbon-based electrodes in a supercapacitor is replaced with a lithium-doped carbon electrode similar to LIB. This increases the operating voltage to 3.8 V (where standard EDLCs are rated to 3.0 V maximum) as well as the capacitance by nearly 10 times. While standard EDLCs are typically discharged in under 60 seconds, hybrid supercapacitors can go up to a few minutes. They also have much lower self-discharge and leakage current than EDLCs. All while still benefiting from the supercapacitor's inherently high power density and long cycle life.

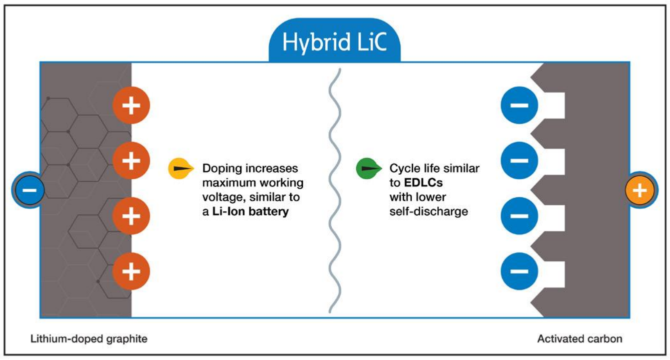


Figure 4: Hybrid LiC supercapacitor diagram.

Summary

Supercapacitors and batteries are storage technologies which have strengths for different applications. Supercapacitors are ideal where power bursts are required, long life backup power or a high number of charge/discharge cycles. The two technologies can complement each other in systems that require a combination of these as well as long discharge times requiring high energy.

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