Ultrafast charging for different applications with SuperBatteries and Supercapacitors

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ABSTRACT: Supercapacitors and SuperBatteries have experienced an evolution over the last years. Supercapacitors reach up to 16 Wh/kg and 60 kW/kg whereas SuperBatteries reach 65 Wh/kg and 4 kW/kg, outperforming every lithium-ion battery and lithium capacitor in terms of power but also cycle life (1,000,000 cycles for supercapacitors and 50,000 cycles for SuperBatteries). These unique properties are only achievable by utilizing a unique active material called curved graphene. Skeleton achieves superior power density and durability while eliminating the need for cobalt, copper, nickel, or graphite. This unique technology allows a variety of automotive applications, which were not possible before: power backup units for trucks providing 600A for six minutes out of a 24V battery; ultra-fast charging energy recovery in racecars allowing to recharge the whole system in just 4 s; emission reduction in vocational trucks with opportunity charging with 300kW in less than 6 minutes; on-board net stabilization for safer and longer-lasting primary batteries through supercapacitor support. Supercapacitors and SuperBatteries are poised to drive innovation in energy storage, offering safer, more efficient, and environmentally friendly alternatives to conventional lithium-ion batteries.

KEY WORDS: supercapacitors, high-power, superbattery, energy storage, graphene

1. INTRODUCTION

One of the most significant advancements in the field of supercapacitors and SuperBatteries is the development of curved graphene. The advanced porous carbon material, invented by Skeleton Technologies' founders, provides a substantial improvement in energy density and positioned the company as a global leader in the manufacturing of supercapacitors for industrial applications. Curved graphene powered products focus on high-power and short duration applications where conventional lithium-ion batteries are not suitable. Rather than competing with Li-ion batteries, these products serve a specialized niche, addressing energy storage needs that require rapid charge and discharge cycles, high power density, and extended cycle life. This makes them particularly well-suited for a variety of industrial applications, ranging from grid stabilization to peak shaving in data centers.

The use of curved graphene in supercapacitors provides a significant advantage over competing technologies that rely on conventional activated carbon. Considering a D60 cell, competitors typically achieve energy densities around 9 Wh/L, whereas supercapacitors incorporating the porous carbon can reach up to 26.90 Wh/L. Even in products specifically designed to minimize ESR and maximize power density, curved graphene enables an energy density of 12.8 Wh/L, still surpassing that of competing technologies.

Besides focusing on supercapacitors, Skeleton has developed and is currently industrializing SuperBattery, a novel energy storage product that combines the characteristics of supercapacitors and batteries and further expands the curved graphene products' application range. The following table gives an overview of the main characteristics of Skeleton's Supercapacitors and SuperBatteries, comparing them to lithium-ion batteries.

	Li-ion Batteries	SuperCapacitors	SuperBatteries
Power Density	Limited 0.5 kW/g	High Up to 60 kW/kg	High 4kW/kg
Energy Density	High 250 Wh/kg	Limited Up to 16 Wh/kg	Increased 65 Wh/kg
Cycle Life	Limited < 6000 cycles	Extreme > 1 million cycles	Long 50,000 cycles
Charge Rate	Slow 3 C	Extremely fast 2000 C	Fast charge < 60s
Safety	Safety concerns	High inherent safety	High inherent safety
Raw Materials	Critical raw materials (Li, Graphite, Co)	No rare metals	No Graphite, no Co, <5% Li

Table 1: Comparison between Li-ion batteries, Skeleton Supercapacitors and SuperBatteries.[(1)]

High inherent safety means that cells do not experience thermal runway after being fully charged and heated to 250°C. Additionally, cells survive nail penetration and crushing tests without safety risks, and no fire or explosion occurs upon cell overcharging.

2. TECHNOLOGICAL FOUNDATIONS

This section will focus on the first two phases of Skeleton's vertical integration, namely the raw material and the single cells, which form the foundation for the industrial modules and systems.

2.1. Curved Graphene: Material Innovation

Curved Graphene is the commercial name of Skeleton's proprietary active material. The inventors of curved graphene and co-founders of Skeleton, Dr. Anti Perkson, Dr. Jaan Leis and Dr. Mati Arulepp, were awarded the European Inventor Award (2022) by the European Patent office.(1) The material contains free-standing hexagonal single-atom layers, with pore sizes precisely engineered to match the dimensions of electrolyte ions. While the influence of surface area and electrode density on the electrical double layer capacitance is well established, studies have demonstrated that pore size distribution also plays a crucial role in enhancing electrochemical performance.(2)

Figure 1 illustrates the relationship between pore width and pore area in both curved graphene and commercially available activated carbon, providing insight into the distribution of available surface area across different pore sizes. The pore area represents the contribution of each pore width to the total accessible surface area for charge storage. This distribution is critical in determining the electrochemical performance of the material, as optimal pore sizes—particularly those matching the dimensions of electrolyte ions—maximize double-layer capacitance and ion transport efficiency.

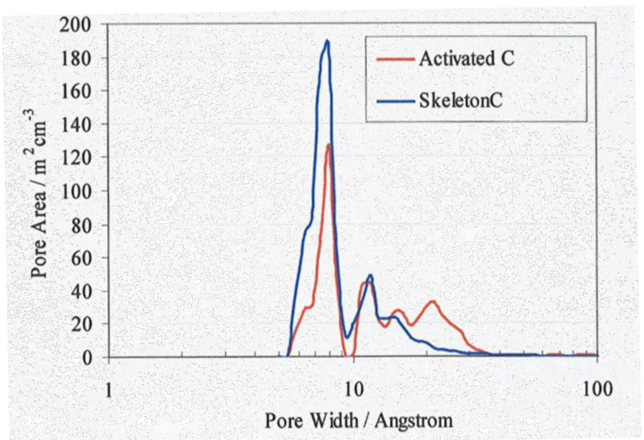

Figure 1 Comparison between Skeleton's Curved Graphene and Activated carbon - Pore size distribution.(3)

A well-defined pore structure with a high surface area in the appropriate size range enhances charge storage capability, distinguishing advanced materials such as curved graphene from conventional activated carbon electrodes.

These unique structural characteristics directly translate into enhanced electrochemical performance. This is evident in the following comparison of volumetric capacitance and electrical conductivity between curved graphene and commercially available activated carbon (Figure 2). Curved graphene achieves a volumetric capacitance of 90 F/cm³,(4) significantly outperforming activated carbon at 67 F/cm³. This improvement is attributed to its optimized pore architecture, which enhances ion accessibility and charge storage efficiency, particularly in applications requiring high energy density. In addition, Curved Graphene exhibits an electrical conductivity of 18.9 S/cm, compared to 12.3 S/cm for activated carbon. This superior conductivity is likely influenced by the intrinsic properties of curved graphene, such as its optimized carbon structure and reduced defects compared to conventional activated carbon. These characteristics facilitate more efficient electron transport and enable faster charge/discharge cycles.

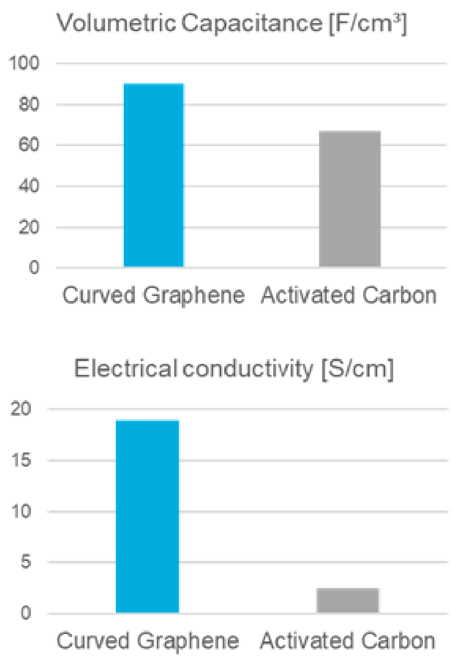

Figure 2 Comparison between Skeleton's Curved Graphene(4) and Activated carbon - Volumetric capacitance and electrical conductivity.

Finally, curved graphene is also advantageous from a production point of view: it is based on a widely available low-cost material

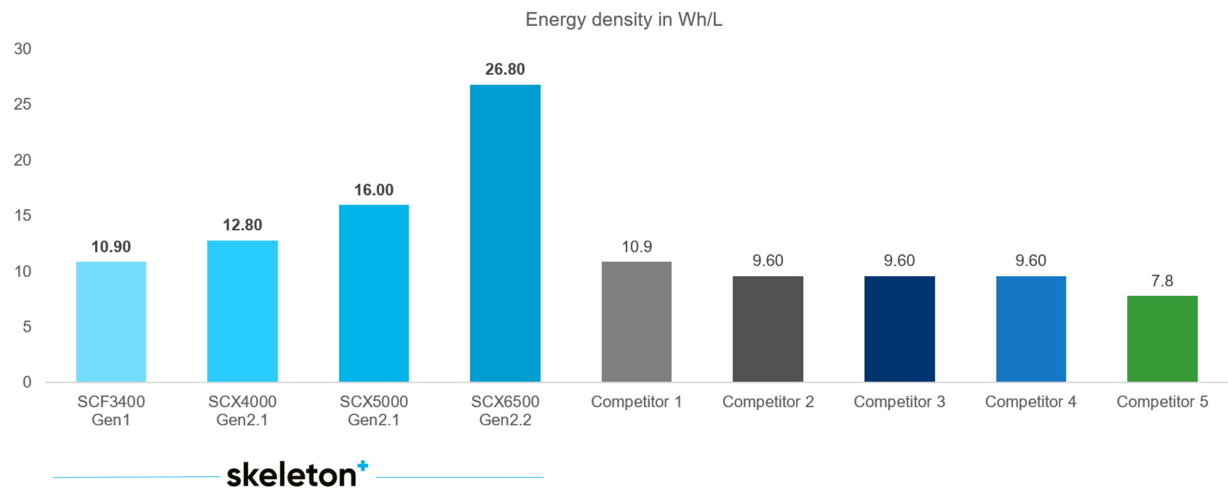

Figure 3 Energy Density comparison between different D60 supercapacitors cells.

and does therefore not require any rare earth material;(5) and it is usable as a direct replacement of activated carbon, with no novel coating techniques required.

2.2. Supercapacitors: Performance Enhancement with Curved Graphene

As discussed in the previous section, supercapacitors benefit greatly from the incorporation of curved graphene. This improvement is particularly evident in energy density, as depicted in Figure 3. This plot compares different supercapacitors cells from Skeleton Technologies as well as from competitors: while competing D60 cells typically achieve around 9 Wh/L, supercapacitors utilizing curved graphene-based porous carbon can reach up to 26.90 Wh/L. Notably, Skeleton Technologies' Gen1 supercapacitors also utilize activated carbon, whereas Gen2 incorporates Curved Graphene, enabling the substantial energy density improvement. Importantly, despite this material shift, the lifetime of the cells remains unchanged, demonstrating that the enhanced energy storage does not come at the cost of durability.

In terms of power density, the impact of curved graphene depends on the specific product. While the 5000F cell (SCX5000) exhibits a slightly lower power density (41.2 kW/L) compared to the Gen1 cell (SCF3400, with 47.9 kW/L), both the 4000F and 6500F cells show a significant increase, reaching 72.1 kW/L and 92.6 kW/L, respectively. This confirms that Curved Graphene not only enhances energy density but can also outperform activated carbon in power density.

2.3. SuperBattery: Advanced Energy Storage

While the first and main Curved Graphene application are supercapacitors, Skeleton has also developed a new energy storage product called SuperBattery.

Classical electric double-layer capacitors (EDLCs) rely on capacitance-based energy storage, where energy is limited by the available surface charge at the electrode-electrolyte interface. In lithium-ion batteries (LIBs), energy storage is driven by the combination of active and conductive materials, with intercalation and redox reactions occurring within the electrodes. However, the

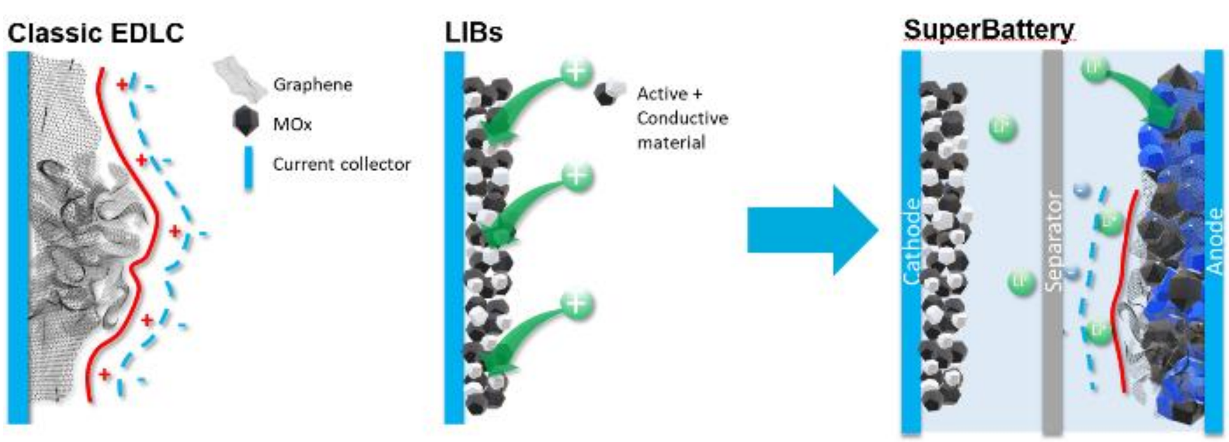

Figure 4 SuperBattery's hybrid charge-storage capabilities, which combine classic Electric Double Layer Capacitors (EDLC) and Li-ion Batteries.

power output of LIBs is constrained by the rate at which charge can intercalate through the bulk material of the electrodes. The SuperBattery, on the other hand, was developed to combine the benefits of both technologies. It utilizes faradaic intercalation through the anode's active materials for energy storage, while the addition of Curved Graphene on the anode also enhances the capacity storage through its high surface area. This combination results in an increased energy density compared to traditional supercapacitors, while maintaining a significantly higher power density than in conventional Li-ion batteries (Table 2). Figure 4 provides a visual comparison of the core charge-storage mechanisms of the SuperBattery, highlighting its distinctions from both Supercapacitors and Li-ion Batteries.

3. PRODUCT APPLICATIONS IN THE AUTOMOTIVE INDUSTRY

3.1. "Push to pass" system for race cars

Supercapacitors are used in IndyCar Racecars to recover kinetic energy upon braking and provide extra power via the "push-to-pass" system.[6] Supercapacitors are perfectly suited for this application thanks to their fast charge time, ideal for racing circuits where braking is minimal: only 4 seconds are needed to recharge the push-to-pass system. Compared to lithium-ion batteries, Supercapacitors deliver the necessary power with reduced weight and space requirements, while also enhancing the racecar's safety.

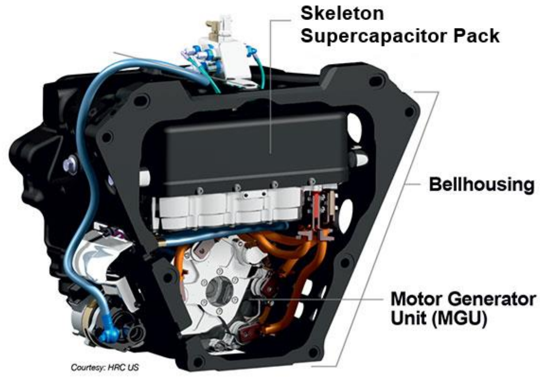

Figure 5 Schematics of the push-to-pass system.

As shown in Figure 5, this hybrid system consists of a Supercapacitor Pack, a Motor Generator Unit (MGU) and a Bellhousing. When the drivers push the button, the energy stored in the supercapacitors is transferred to the MGU, where it is converted into torque and eventually provides the drivers with an additional 60 horsepower. This not only creates more overtaking opportunities, but it also enables racecars to re-start without external help, thereby reducing the number of full course yellows during a race.

3.2. Vocational trucks

Hybrid Systems employing SuperBatteries are better suited for vocational trucks. A key advantage of the SuperBattery technology is its ability to support ultra-fast charging with standard 300 kW fast chargers. This makes hybrid and fully electric vocational trucks highly efficient and practical for demanding applications. The hybrid truck configuration, equipped with a 15 kWh SuperBattery, achieves a 37% fuel reduction and can be fully recharged in just 3 minutes using a 300 kW charger.

In this case, a SuperBattery Powerpack is combined with an electric power takeoff (ePTO) which electrifies the truck equipment to operate when the engine is off, thus reducing emissions. Depending on the availability of opportunity charging in a certain area, the electric motor generator can be replaced by an electric traction motor, which leads to a zero-emission vehicle. The fully electric version with a 30 kWh SuperBattery can be fully charged in just 6 minutes. These ultra-fast charging capabilities allow the vehicle to seamlessly integrate into existing operational cycles, ensuring minimal downtime and maximizing fleet efficiency. As SuperBatteries can be recharged more frequently than Li-ion batteries, the systems can be smaller in size thus resulting in significant weight reduction, as well as lower acquisition costs and lower total cost of ownership.

3.3. On-board net stabilization

Supercapacitors play a crucial role in low-voltage on-board net stabilization: with a power density 100 times higher than lithium-ion batteries and rapid charge-discharge capabilities, they optimize power management and support primary lithium-ion traction batteries. The growing complexity of modern on-board power networks is driving a shift away from single-channel DC architectures toward dual- or multi-channel low-voltage DC systems. This approach separates loads based on power demand and safety criticality, with slower, less critical functions (e.g., hotel loads) powered by lithium-ion or lead-acid batteries, while fast, high-power safety-critical systems (e.g. engine starting, regenerative braking, power steering) are supplied by supercapacitors.

The integration of supercapacitors reduces the energy throughput and the peak load of the primary battery, ultimately extending the battery lifespan and improving efficiency. The exact reduction depends on the usage profile and environmental temperature; for in the steering ripple application the peak load is reduced by 50%. Additionally, supercapacitors contribute to a reduction in the Depth of Discharge (DOD), further enhancing the longevity of lithium-ion batteries.

The supercapacitor-based 12V boardnet is now increasingly adopted by American and European OEMs. The instantaneous power delivery backups the primary lithium-ion battery during malfunction and peak power demands, with the rapid response securing the function of critical vehicle systems like Electronic Control Units and active safety features at any time without interruption. Furthermore, by smoothing voltage fluctuations, they protect sensitive electronics from damage and enhance overall system reliability. As the supercapacitors have a life span of 1 million charging/discharging cycles, the 12V system stays reliable over the actual vehicle's lifespan.

4. CONCLUSIONS

By integrating proprietary curved graphene materials, supercapacitors and SuperBatteries address unique industrial and automotive challenges, achieving power solutions that are safer, more efficient, and longer-lasting than traditional lithium-ion batteries. From stabilizing vehicle power systems to enhancing performance in racecars and vocational trucks, this technology proves its adaptability and effectiveness.

Beyond these established applications, further potential uses for supercapacitors are on the horizon. Emerging concepts such as post-crash backup systems, where supercapacitors provide critical functionality even after parts of the vehicle's electrical network are severed. Thanks to the reduced size and robustness, supercapacitors can easily be integrated across the vehicles sub-components – e.g. an electrically operated door lock can be supplied with individually fitted small back-up supercapacitors inside the door, to ensure there is always enough energy to unlock the door in a post-crash scenario, even when all other connections to the door severed.

As industries seek scalable and sustainable energy solutions, supercapacitors and SuperBatteries are set to play an increasingly pivotal role in transforming power management across mobility, grid storage, and beyond.

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