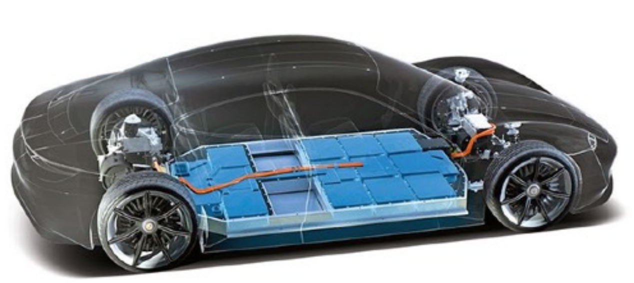
Batteries are dead, long live Carbon based Power Capacitors!

Anyone who is involved in electric mobility must admit that batteries are still the problem. Well, actually it is the combination of the batteries and the capability to charge them. So, why did Tesla buy a supercapacitor company?

What's the issue with batteries?

The best batteries we have today are based on Lithium and some other chemical elements. Lithium Iron Phosphate batteries are relatively safe but offer a lower energy density (typically around 100 Wh/kg) and are often used in smaller applications because they can be used with no active thermal management, at least when the outside temperature is above freezing point and moderate. In cars, range and performance are dominating requirements and hence often Lithium Nickel Manganese Cobalt batteries are used. They offer up to about 200 Wh/kg without the additional battery and thermal management system that easily can take up 30% of the weight and volume. Such batteries still make up a large part of the cost price and weight of vehicles.



Moreover, battery powered vehicles are not yet as easy to use as vehicles based on fuel powered engines. As was made evident again this winter, they loose a lot of capacity when it gets cold. Just like a lead-acid car battery, when it is freezing, the battery might loose a significant part of its energy and current capacity. Therefore most electric vehicles use some of their own energy to keep warm enough and it is actually recommended not to park a car outside when the polar vortex strikes. A completely drained battery can even become a so-called "brick", expensive to replace, impossible to repair. Another issue is the thermal risk, especially when charging. At that moment the current in the battery and the internal heat generation is at its highest and a single defective cell can result in the whole battery experiencing a so-called thermal run-away. Such a fire is impossible to extinguish and often the whole vehicle becomes a total-loss.

Now, to be honest, battery technology has improved a lot. The safety risks are a lot less than with an exploding fuel tank. But the economic risks remain and electric vehicle drivers must be prepared for some planning and long stops. Finding a charging station is not always trivial when not at home. The last issue is therefore the charging process. Lithium-ion batteries for vehicles range from a few 10's of KWh to above 100's of KWh, yet they can only charge at their nominal current. At a standard power connection (like at home) it can take up to half a day. With a fast charger, half an hour might be sufficient but such chargers are small power plants on themselves and require a dedicated connection to the power grid. In addition, charging at these high currents is not without risks. It will also have an impact on the lifetime of the battery. The issue here is scalability. Unless massive buffering is used, the current system is not scalable in an economic way and hence today not sustainable.

The hunt is on

There is not a single day or week without an announcement about a breakthrough in battery technology. Finding a better battery is crucial for the real switch to electric energy to happen. And hence, many materials are being researched: lithium-ion based, different types of electrolytes, graphene, sodium or even aluminium, zinc and salt water. However, there is a wide gap between a small scale experiment and real industrial deployment in volume. What are the properties of a better battery?

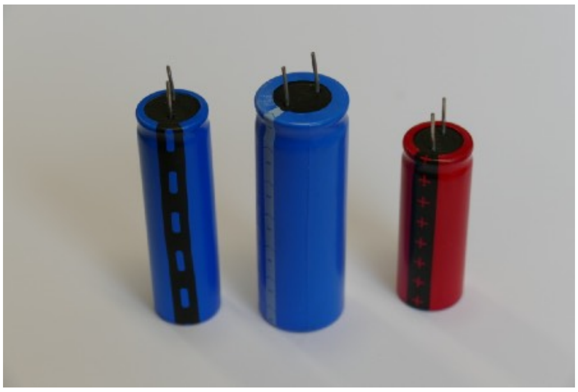
We list them here:

- Energy density: the more energy can be stored in a given weight or volume, the better.

- Power density: the higher the peak current that a battery can generate the easier it is to operate it across a wide range of applications.
- Charging speed: the faster a battery can be charged, the more practical it becomes to use it.
- Thermal behaviour: batteries operate on chemical reactions and these depend on the temperature. The ideal battery offers as much energy and capacity from polar freezing cold temperatures to dessert like baking temperatures.
- Thermal risk: the lower the internal resistance the less internal heat will be generated by internal currents and the lower the risk that a thermal runaway can happen. The thermal risks and behaviour are a major reason why higher performance batteries need a complex battery and thermal management system. This has a direct impact on the practical energy density and cost-price.
- Life-time: many of the above properties have a damaging effect on the lifetime of a battery, the latter often being measured in charge-discharge cycles. Good batteries should outlive the system in which they are used and when that point is reached, they should still be powerful and safe enough for a second life in a less demanding application.
- Economical: in the end, all above properties have to be met at an affordable and competitive price. The latter implies that the batteries can be easily manufactured in high volume and without using toxic or rare materials. Unless for specific applications, what counts is the life-time of the system.

The best of both worlds: power capacitors that behave like safe batteries

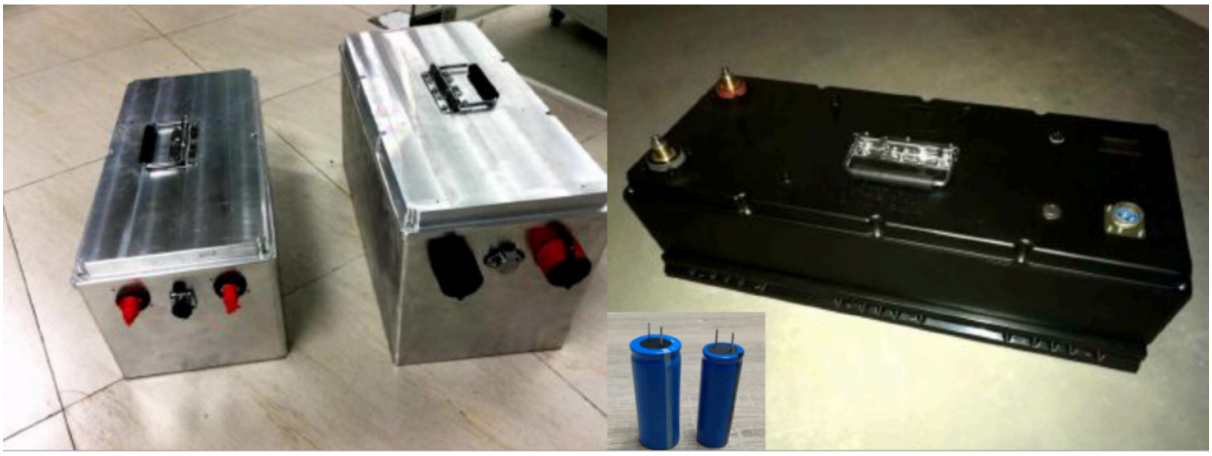
Needless to say, the road towards the ideal battery is a long one and while constant progress is being made, the progress is relatively slow for the fundamental reason that one can't change the law of physics. To make progress, a different approach will be needed. One such approach is to use super capacitors. Contrary to batteries, supercapacitors store directly the electric energy upon charging, whereas batteries rely on a chemical reaction. A major result is that supercapacitors have many of the ideal properties like a very low internal resistance, making it a very safe device that operates across a wide range of temperatures, voltage and currents. When they fail (after many years), most often it is due to improper use. So why are we still not using supercapacitors everywhere? The reason is that they have a much lower energy density than the best battery cells. Leading lithium based supercapacitors typically have 5 to 6 Wh/kg, a factor 20 to 40 less than typical lithium based battery cells. Nevertheless, in many applications where short power bursts are needed (and that can't be delivered by batteries), they dominate in the market.



This is about to change with the introduction of a novel type of carbon based power capacitor based on carbon nano-materials. The cell actually combines the power density and thermal safety of supercapacitors with the energy density benefits of Lithium-ion battery cells. These carbon based power capacitors come in two flavours. Tune for power types can deliver a sustained current of 10 or 20 times their nominal current at an energy density of 80 to 100 Wh/kg. The energy tuned ones delivers 200 to 230 Wh/kg with the capability to deliver a sustained current at the nominal value or slightly above. The latter matches the energy density of NMC type batteries but can deliver twice as high current without any need for battery or thermal management and this from -40°C to +80°C. Note that these power capacitors can safely operate outside these conditions. This can have an impact on the lifetime, but will never result in a safety risk.

These carbon based power capacitors look like the normal battery cells we all use. To reach a required voltage and current capability they are simply connected in a matrix-like mesh. This has many benefits. First of all, for a regular NxN matrix the internal resistance remains as low as if only a single cell would have been used. Hence, the heat dissipation is negligible and as the cells are relative small, any heat is quickly evacuated to the housing. Secondly, such a mesh is resilient. Even if several cells short circuit, the mesh will still be able to reach more or less its specified design specifications. Cells can even be taken out. Except small monitoring circuits, maximum space is available for the cells themselves. No heavy cooling or heating equipment is needed.

Combined with the capability to be charged fast and to deliver high peak currents this can drastically reduce the system cost and weight.



These carbon based power capacitors were developed and brought into production by Toomen based in Shenzhen, China. In a Joint Venture agreement, Altreonic brings them as complete customer specific solutions to the market in Europe.

What is the impact?

The novel carbon based power capacitors have a first obvious application: replacing the lithium based supercapacitors already in use with a smaller and more cost efficient package. Moreover, in the same volume the new power capacitors can deliver more power and more energy. Typical applications are pitch control in wind turbines, regenerative braking in electric vehicles or replacing the batteries in electric buses that quickly charge at every stop.

Another less expected application is to replace lead-acid based car batteries. Whereas a lead-acid needs a serious over-capacity to compensate for lower temperature and ageing loss, a 20 Ah C-based supercapacitor battery can replace a 80 Ah battery and still deliver 800 Ah for starting the engine (even when it is freezing cold). Hence, such a battery facilitates the start-stop function. It recharges much faster once the engine is running and even lowers the fuel consumption (5% or more as measured) for spark-plug based combustion engines. Moreover the battery will last much longer.

Carbon based power capacitors also allow to make more efficient electric vehicles. Current electric vehicles have an oversized lithium-ion battery on board (up to 1 ton for some brands) to meet high speed performance and acceleration demands but also to deliver an acceptable driving range, especially as freezing temperatures can reduce the available range with up to 40%. This has multiple negative consequences. It increases the energy consumption (even an empty battery keeps its weight), it increases the cost-price (batteries typically account for 1/3 of the vehicle price and it increases charging times. Moreover, it implies more powerful charging stations and hence a corresponding power grid and electricity generation. Carbon based power capacitors however can charge 10 to 20 times faster. We can install smaller battery packs in the vehicle provided we change the charging process. For

example if a battery can be charged in 5 to 10 minutes, then a range of 2 hours driving will be sufficient. This means that with a 20 kWh battery, one could cover about 200 km and recharge it in the same time one needs to fill up a conventional car with fuel. What is needed is not so much a few superchargers requiring a power-station next to it, but a more widespread network of less powerful fast chargers. The latter should be equipped with large buffer batteries that continuously charge from the grid or from a local field of solar panels or windmills if the weather permits. Power capacitors are better at picking up every little energy that they generate.

Game changing from small power-banks to megawatt energy buffers

Carbon based power capacitors with an energy density comparable to the best of batteries have an impact beyond their technical specifications. They provide not only energy and power, they also provide us with more time, safety and convenience. Just imagine you have a power bank for your mobile phone and you only need to plug it in for 5 to 10 minutes and there you go again. Or what about all these nice power tools. Now you need two battery packs so that when one is depleted, you can charge it while using the second one. With supercapacitors, you just take a coffee break while charging.

It is not difficult to image that this can also apply to systems that need more energy than a power tool. Often, smaller battery packs wil do the job because the peak loads are not continuous and with short charging stops one gets further with less time lost and less energy needed. This also applies to megawatt grid stabilisation systems and large energy storage stations. While electric energy storage improves everyday, it might still take a 100 years before we can match the energy density of classical fuels. But by being able to high power peaks and enabling fast and safe charging, electric systems become a lot more convenient and economical. The potential is enormous and it brings real competition to fossil fuels. Carbon based power capacitors are here to stay.

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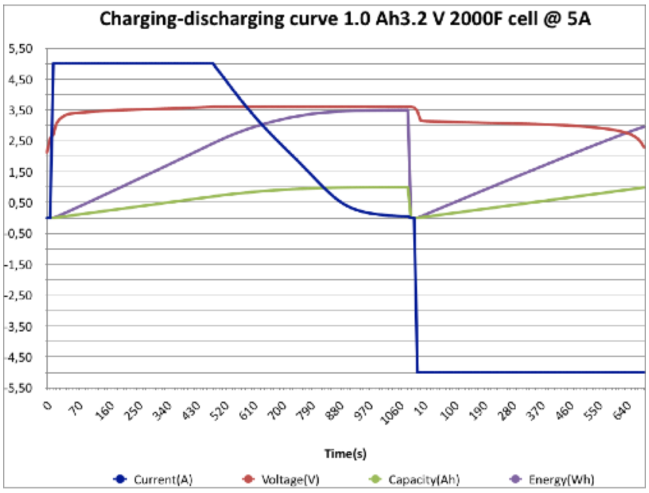
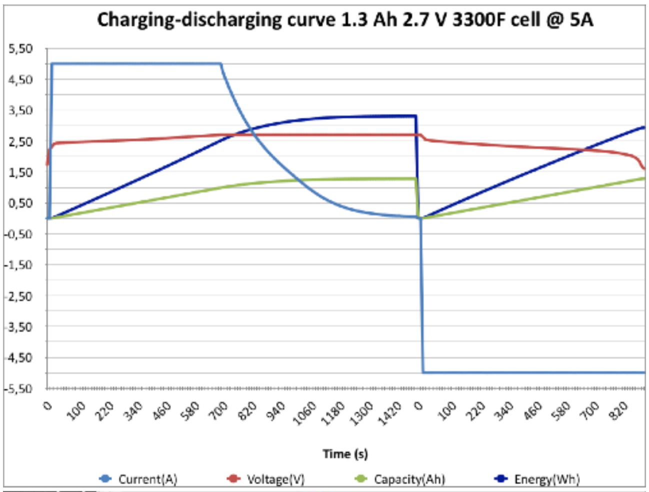
Appendix:

1. Charging and discharging curves for carbon based power capacitors

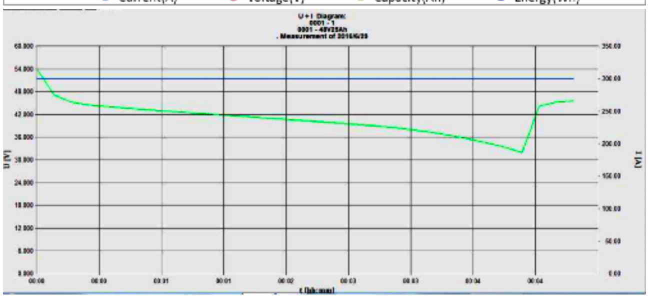


The 18500 power capacitor cell can contain about 3.4 Wh at 3.2 V. (80 Wh/kg). Charged in about 10 minutes to 80% capacity or to 100% in 20 minutes at 5 A. However, this power capacitor can also be charged and discharged at 20 A without any significant heat generation. Higher short bursts of up to 100 A are permitted. It has an estimated lifetime of 20000 cycles.

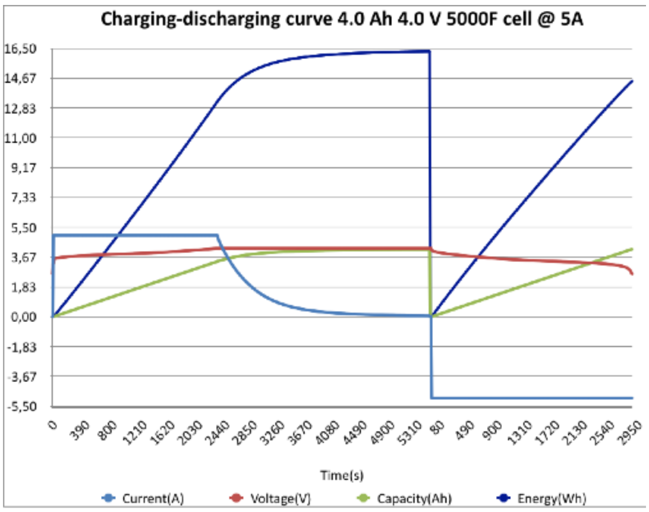


The 18650 power capacitor cell can contain about 3.2 Wh at 2.7 V. (100 Wh/kg). Charged in about 12 minutes to 80% capacity or to 100% in 25 minutes at 5A. However, this power capacitor can also be charged and discharged at 10 A without any significant heat generation. Higher short bursts of up to 100 A are permitted.

It has an estimated lifetime of 50000 cycles.



The diagram on the left shows a battery pack configuration of 48V/25 Ah discharging at 300 A in about 4 minutes, immediately followed by a recharging at 300 A.



This 23680 power capacitor cell can contain about 16 Wh at 4.0 V. (200 Wh/kg). Charged in about 60 minutes to 80% capacity or to 100% in 120 minutes at 5A. Higher short bursts of up to 8 A are permitted.

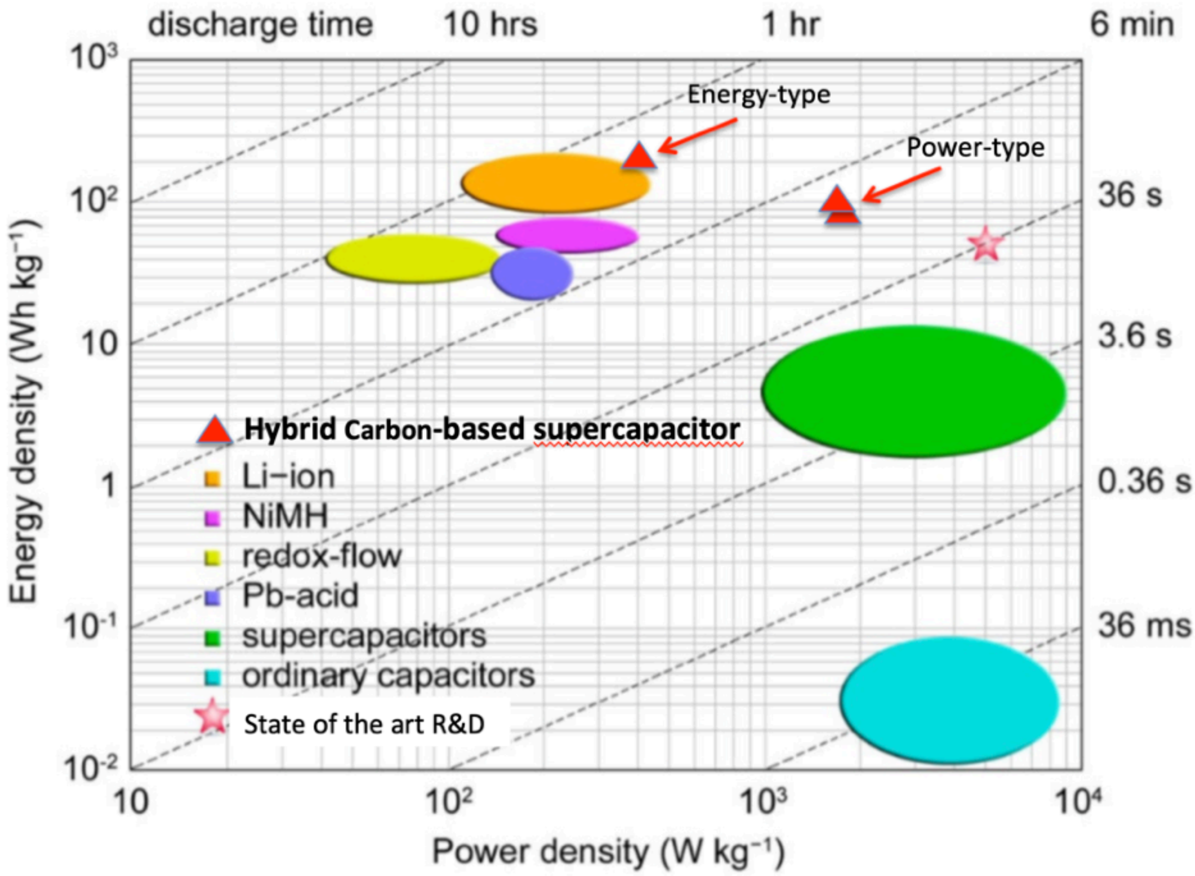
It has an estimated lifetime of 10000 cycles.

2. Comparative tables

	Lithium iron phosphate battery	NMC lithium battery	Lithium titanate battery	Lithium based super capacitor	Power-type carbon power capacitor	Energy-type carbon power capacitor
Energy density (Wh/kg)	90 - 150	180 - 250	70 - 95	4 - 6	80 / 100	200 - 230
Power density (kW/kg)	0.1 - 0.2	0.1 - 0.5	0.5 - 1	5 - 7	1 / 1.5	0.3 - 0.5
Typical charging/ discharging rates	1.0 C	0.7 - 1.0 C	1.0 - 5.0 C	100.0 - 200.0 C	10.0 C / 20.0 C	1.0 - 1.25 C
Working temperature (℃)	-10 ~ 55	-20 ~ 45	-40 ~ 60	-40 ~ 65	-20 - +80 / -40 ~ +80	--40 ~ +80
Cycle life (times)	2000	2000	5000	> 500000	20000 / 50000	> 10000
Safety	acceptable	not good	good	excellent	excellent	excellent
Complexity	Medium: BMS needed	High: BMS needed + thermal mgt	Medium: BMS	Low: no BMS, passive cooling	Low: no BMS, passive cooling	Low: no BMS, passive cooling

2. Comparative Ragone Chart

Note: this chart is using the previous name "hybrid carbon-based supercapacitor".
The two red triangles are the carbon based power capacitor (cylindrical ones).



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