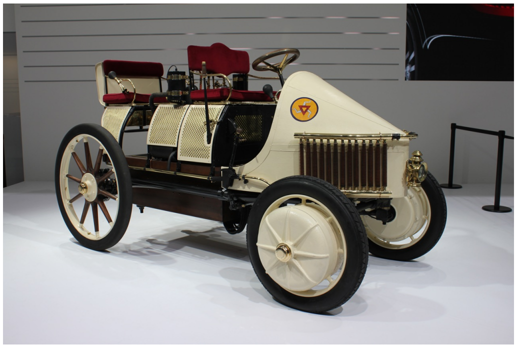
Hybrid power capacitors:
the step beyond Lithium-ion

Introduction

In its quest for a cleaner environment, electric energy plays a prominent role. Besides the fact that electric devices barely produce pollutants, electric energy is convenient and relatively easy to put at work. With just two wires it can be delivered to the device that operates on it. For this reason, electric devices are with us already for more than 100 years. The first electric car was invented in 1832 and on in the early 1900's, they had a 30% market share. Moreover the first hybrid electric car was invented in 1901 by Porsche (see picture). But barely 20 years later most of them had disappeared. The introduction of the affordable gasoline powered Ford-T and the subsequent dropping oil prices were no match for the expensive and not that practical battery powered vehicles. Mobile electric vehicles require a battery and 100 years later, this is the reason that electric vehicles still have a hard time competing with the established vehicles using a combustion engine. Nevertheless, technology is making progress. It's a story of cost-efficiency, energy density, power density and safety.



Lithium-ion batteries provides the proof of concept

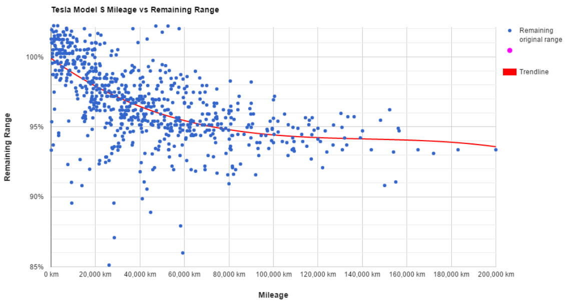
Fast forward: the oil crisis of the 1970's prompted a renewed interest in electric vehicles, but as conventional engines improved and remained more practical to use, interest faded quickly. However, improvement in battery technology, now mainly lithium-ion based prompted Egon Musk in 2006 to try to deliver the Ford-T of electric vehicles. Today, with the Tesla-3 at a market competitive price, this goal seems to be reached. But will it last? While fuel-burning engines are getting cleaner by the day, competing technologies like hydrogen are making progress as well. The main problem remains the battery. While it has more energy than ever before, it has many practical issues.

- Energy density: today we can reach about 230 Wh/kg but that is still a factor 100 less than gasoline. Even if electric drive trains are much more efficient, simpler and more reliable than conventional ones, it still means that electric vehicles are essentially massive batteries on wheels. This means that the energy needed to move the payload (passenger or cargo) is often a fraction of the energy needed to move the whole. A typical car battery can weigh as much as 8 passengers on board.
- Charging times: charging and driving an electric vehicle requires planning and patience. While superchargers reduce the waiting, they require a dedicated high power grid. The latter is also a luxury for less developed countries. Electricity is cheapest when delivered in a continuous stream whereas liquid fuel can be conveniently stored when not needed.
- Power density: certainly for e-vehicles, a battery also needs to deliver power on demand. E.g. when driving uphill or when accelerating, energy consumption can increase tenfold. Lithium-ion batteries cannot handle the high current very well. It cannot only destroy the battery but it also impacts on the lifetime.
- Lifetime: while current, especially liquid cooled batteries have a very respectful lifetime, the statistical spread and variability is also substantial. Thermal

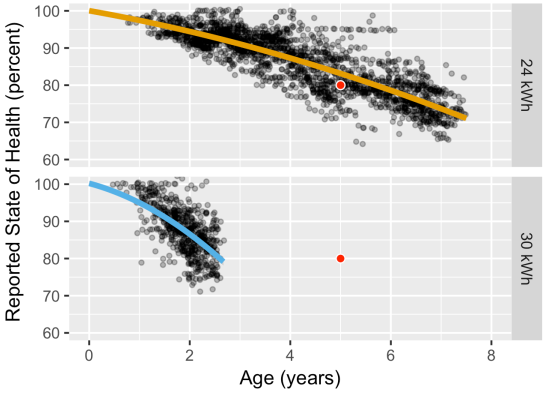
management and strict quality control reduce the problem, but is expensive. And replacing a battery can cost more than the market value of the vehicle.

- Complexity: as lithium-ion cells are very sensitive to high current peaks and don't work well in very cold or warm temperatures, they need a complex Battery Management System and active temperature control. This adds not only to the complexity but it also to the cost, weight and volume.
- Safety: this is perhaps the most controversial issue. While not all Lithium-ion chemistries are the same, all have two major safety risks. The first on is that lithium dendrites grow between the electrodes. Sooner or later, they can create a short circuit resulting in an unannounced catastrophic heating of the cell. The other major risk is that the cells get damaged (e.g. during an accident); the internal very inflammable electrolyte escapes after which it ignites. The combination of these two and other factors are the reason that a battery fire is often total and often cannot be extinguished.

All factors combined means that while lithium-ion batteries have allowed a re-emergency of electric vehicles and have given us a convincing proof of concept, for wide-scale adoption it needs to be as cost-efficient and practical as the proven technology of fuel based vehicles.



https://electrek.co/2016/11/01/tesla-battery-degradation/



On the left:
Remaining range capacity over time for a Tesla-S and Nissan Leaf as recorded by its owners. Notice the statistical spread.
On the right:
A 3 year old Tesla-S who started to burn spontaneously on a parking lot.

What are the alternatives?

Of course, people are aware of these issues and research is constantly trying to find better solutions. The problem is that any new technology must score well on all fronts. Safer and higher energy density batteries exist, but don't score well in terms of power density (hence can't be charged fast either) or score badly in terms of lifetime. Other technologies like super capacitors score well on most fronts, except on energy density and cost. Hydrogen fuel cells, which are often put forward as the future, score relatively well, but have a low power density. As none of the technologies seems to be able to meet all requirements, what of we combine them? It was done before. Even Porsche's e-vehicle was a hybrid.

Hybrid carbon based supercapacitors

We go in two steps. Firstly we eliminate the safety risks of lithium-ion and inherit the benefits of supercapacitors. The result is called a hybrid or asymmetric supercapacitor. While one electrode has a similar chemistry as a lithium-ion technology, although by binding the lithium in a metal oxide, the other electrode is based on an activated carbon material. What is the result?

- The cell works as a capacitor and has a relatively low internal resistance; hence it keeps cool when current is flowing through the cell.
- As a capacitor it can work from -40°C up to 80°C with no active thermal management.
- As things keep cool, the cells have a lifetime 10 to 20x longer than lithium-ion.
- Power capacitor battery packs are configured in a mesh and are resilient as a failing cell creates an open circuit (not a short-circuit).
- No dendrites can form and the carbon material soaks up the small amount of electrolyte.
- While the energy density if comparable with Lithium-ion cells (from 80 to 230 Wh/kg), the power density is much better (10 to 20 times).
- As no BMS and active thermal management are needed, battery assemblies are simple, very reliable and the resulting use of space is more efficient.

Practically speaking, we now have a battery in more or less the same volume as with lithium-ion ones, but we can use it safely over the lifetime of the vehicle and it can operate at a power level that is 10 times higher. In other words, a 15 kWh battery has the capability to deliver the power of a 150 kWh lithium-ion battery.

This brings us to the next step. Why not drive around with a 15 kWh battery as it can still deliver 150 kW? In addition, we can safely charge it in 10 minutes. Of course, a smaller and lighter battery saves energy but will provide less range. This can be adequate in many circumstances as charging can be fast. Another option is to link the power capacitor battery with a steady energy source. Let's explore the scenarios.

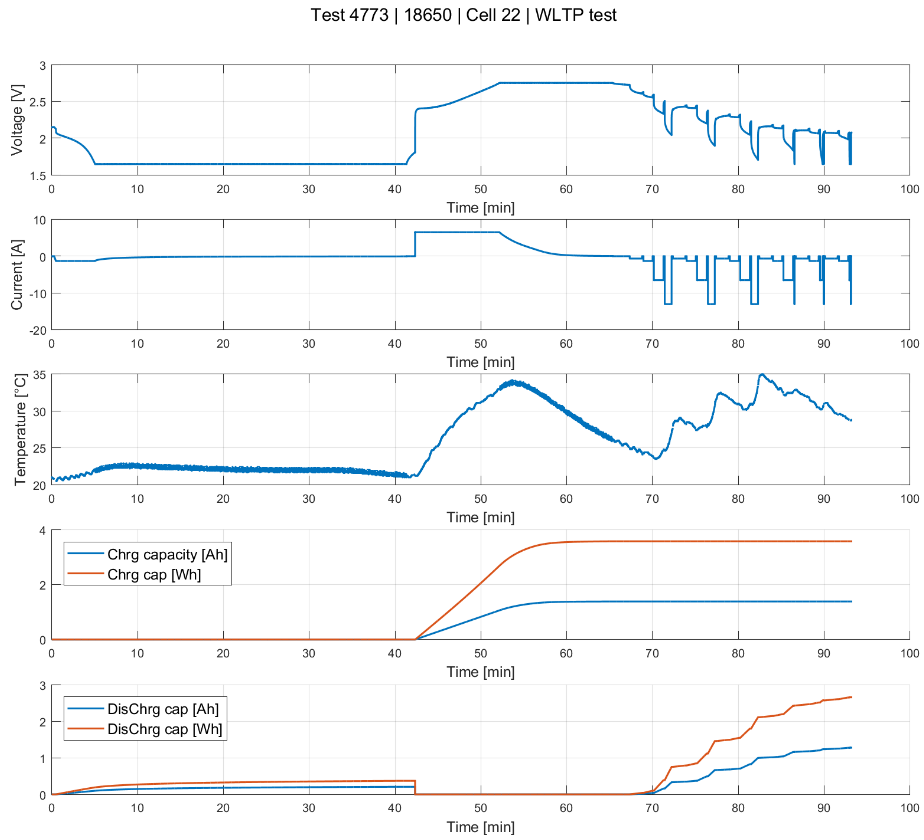
WLTP stress testing the power capacitor cells.

Our starting point is to verify our premises using the power capacitor cells. Previous tests like charging and discharging at 10C have already revealed that the capacitor cells could handle it. Tests at room temperature showed an acceptable temperature increase (even with no cooling). We now try to test a more realistic scenario by using the WLTP driving profile. As the test equipment cannot be programmed to follow a curve, we program the test as a series of steps with or 0,5, 1,0 , 5,0 and 10,0 C with 1C being the nominal capacity of the cell. Any regenerative braking is ignored. This gives the following table:

WLTP-like testing profile:

Step	1	2	3	4
C-rate	0,5	1,0	5,0	10,0
Duration (sec.)	87,0	64,0	67,0	48,0
Ah for C-18500 cell	0,5	1,0	5,0	10,0
Ah for C-18650 cell	0,7	1,3	6,5	13,0
Rest between steps (sec.)	6,0	6,0	6,0	6,0

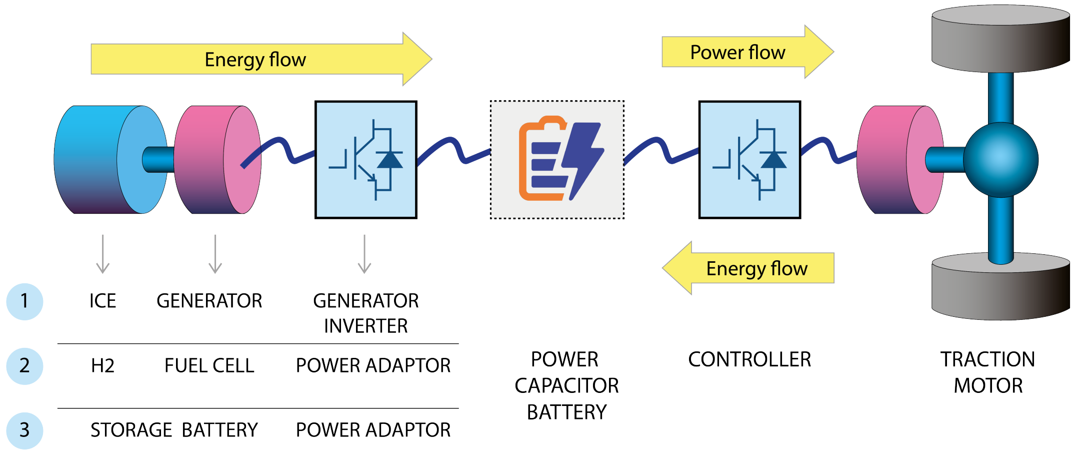
This gives us an average C rate of 3,05. The test is done in a room at 22 °C with no active cooling. Hence the only cooling is by conduction to the surrounding air. The test trace (given for the C-18650 cell) starts by charging fully at 5C, followed by the test sequence, until the cell becomes depleted. Of course, the WLTP profile was taken as an example. Real-life driving conditions can be less or more demanding.



What are the conclusions? The cell charges at a constant current of 5C in about 10 minutes to reach 75%. The test sequence can be fully repeated 3 times and partly a 4th and 5th and 6th time with the temperature never reaching more than 35°C. Hence, no need for cooling. The first three runs take about 75% of the cell's capacity.

What does this mean for our electric vehicle? We assume that the e-vehicle consumes 15 kWh/100 km (a good average for a modern e-car) while the average WLTP speed is about 50 km/hr. We need a solution that can provide 15 kWh for a 200 km range. As a power capacitor cell provides 3 Wh this results in a power capacitor battery pack of about 5000 cells. Such a battery will weight about 200 kg and can deliver 265 kW sustained (in our test we only use half of that). Such a battery can be recharged in 10 minutes to 75% at a 90 kWh charger. A 200 kg battery is what small e-vehicles have on board. It is a fraction of what high-end e-vehicles need in lithium-ion batteries. But it delivers more than twice the power output. The only drawback is the range. Every 200 km, we need to recharge but this can be done in 10 minutes if the charging point allows it. Can we do better?

We now consider three hybrid scenarios. Until today, the most widely known hybrid drive train is a parallel hybrid. An internal combustion engine is still the primary propulsion source but a small electric motor with a small battery takes over when the speed is low enough. A good solution for urban driving that still allows going on the highway with a full tank. Drawbacks of the system are the complexity and the extra weight even if the energy efficiency is quite good. Hence, we focus on serial hybrid propulsions. Hereby, a primary energy source charges the power capacitor battery. The solution exploits that we can operate the power capacitor battery at a 10 times higher power while the average power consumption is more or less 3 times its nominal value. Hence we can reduce the power capacitor battery to e.g. 5 kWh if we keep it charging at its nominal 3C rate. Such a weight reduction is not possible with a typical Lithium-ion battery.



What can we use as primary energy source?
1. We use a small combustion engine. As there are energy losses and the engine operates at about 30% efficiency, a small 15 to 20 kW engine running at it highest efficiency point will suffice. While this is not a zero emission solution, fuel consumption will be low and pollution minimal. This hybrid solution is likely better for heavier vehicles operating in urban settings. The power capacitor battery absorbs the power peak demands.
2. We use a hydrogen fuel cell. Similarly as above but the fuel cell efficiency is higher than that of a combustion engine. The power capacitor battery absorbs the power peak demands. Given the advances made in hydrogen charging stations and production, hydrogen fuel cells might well an option for the future. A benefit is that the range can be extended by simply placing a larger hydrogen tank that still fills up relatively quickly.
3. The last solution is to use a high energy battery (e.g. lithium-ion). In above scheme if we are happy with a 2 hours charging interval we just need a 10 kWh battery provided it can deliver 3C continuously. As lithium-ion batteries are practically limited to 1C or less, we would need a 30 kWh, which adds range, but no power. Alas, we now need more time to fully charge it. Hence it looks like we better stick to a 100% power capacitor battery. If the usage profile requires a longer range, we can double the battery and still charge it in about 20 minutes.
Postscript: Mazda's upcoming e-TPV vehicle is a perfect example of applying above principles. Only using a 37 kWh battery, it comes with a small rotary engine that charges the battery. The rotary engine weights 9 kg and is dual fuel. It can run on gasoline or on hydrogen.

Conclusions

The ideal battery not only has to provide sufficient energy but also sufficient power. Its operating conditions can be very demanding in terms of safety and temperature while the system should require few maintenance interventions and last a long time before its needs to be replaced. A better lifetime cost and assured reliability is what carbon based power capacitors deliver. The combination of energy and power density also enables new applications that before were not really feasible or cost-efficient. There are many more applications that will benefit. Kurt.energy is enabling such solutions with as main goal to deliver practical and long-term reliable clean energy. Contact us for your specific project.

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