Sustained extreme performance becomes sustainable with hybrid powercapacitors.

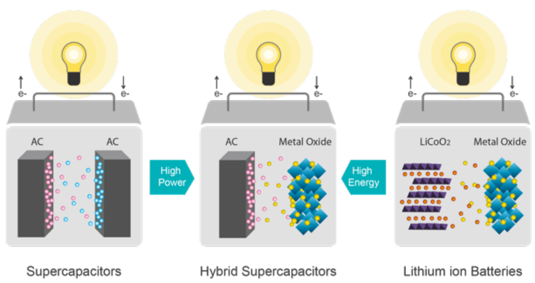
Most people consider batteries as energy storage devices. The more energy they contain, the better. In a car this translates into range. But range isn't everything. A battery becomes useful when the energy can be charged and discharged rapidly. This is what we call "power". Often energy and power capabilities are not compatible with each other. The more energy, the less power and vice versa. We examine this further using 3 real-world applications, some rather extreme but they highlight the issues. All examples are based on real-world scenarios.

What are extreme battery load scenarios?

Let's first take the extreme driving profile of a race car. The race will last only 30 minutes, consuming about 130 kWh but as the race car has 4 motors of 400 kW each, it's the equivalent of 1.6 MW on the wheels. Peak demand is 2 MW. If we use a 130 kWh lithium-ion battery, then about 60 to 80 % of the energy will be available but unless special precautions are taken, the maximum power output will be around 390 kW. We need 5 times more power. The reason is that a lithium-ion battery is limited in current and hence it will heat up too much and likely destroy itself. In order to meet the requirements we would need a battery with more than 500 kWh. Such a battery would weigh more than 6 tons.

How to overcome this challenge? Let's use hybrid powercapacitors. These cells combine a reasonable energy density with excellent power capabilities.

What are hybrid power capacitors?

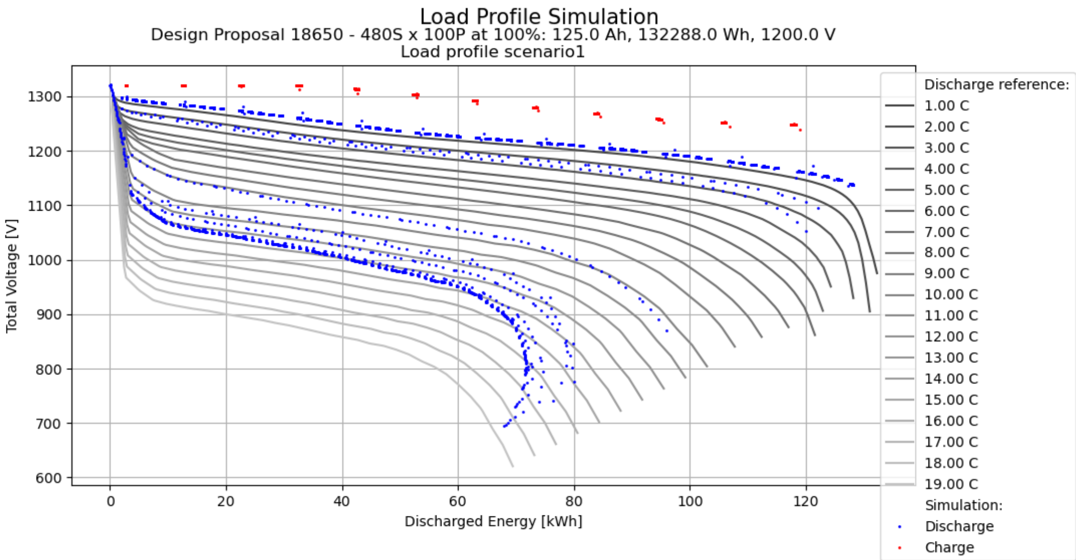


A typical lithium-ion battery operates based on a redox-reaction. The energy is stored by an oxidation-reduction chemical reaction using electron charges between cathode and anode of the battery cells. Discharging reverses this redox reaction. A capacitor on the other hand does not involve a chemical reaction but stores the energy statically (like when rubbing your sleeve). The absence of a chemical reaction offers many advantages like safety (capacitors cannot short-circuit), long lifetime, capability to operate at extreme temperature and the capability to charge and discharge fast. The drawback is that less energy can be stored. Supercapacitors typically store 10 to 20 less energy than a battery cell of similar dimensions. Hybrid supercapacitors combine the two mechanisms by building an asymmetric device. The energy is still stored statically but one of the electrodes has a local Faradaic reaction that gives it a serious energy boost. The result is a device that inherits most of the properties of a capacitor with a less extreme power capability but with a reasonable energy density that allows it be used like a classical battery. We call these powercapacitors. Another benefit of powercapacitor batteries is that they remain a lot cooler, can be assembled without a BMS and have a close to 100% DoD, so almost all the charged energy can be used. For the rest of this article, the reader will see that the we often use the term C-rate. This is the ratio between the current charged or discharged vs. the nominal current.

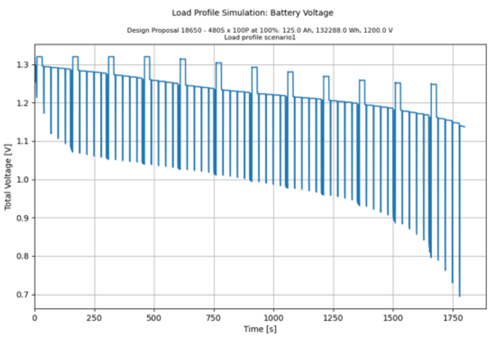
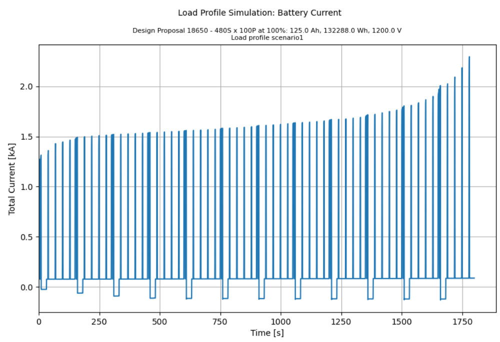
Scenario 1: the race car

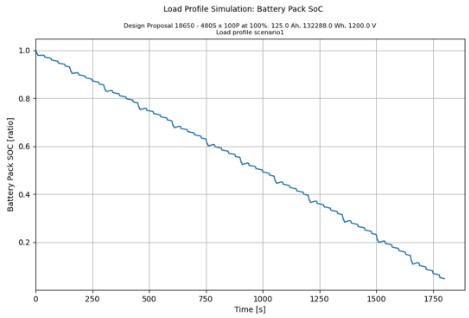
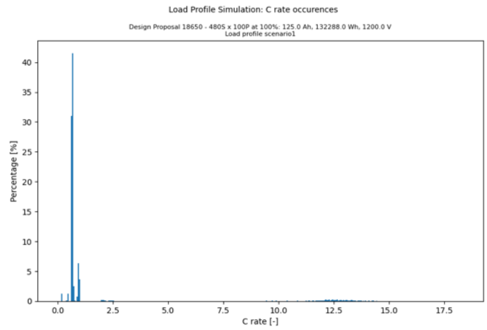
With a 130 kWh powercapacitor battery having a C-rate of 20, we can reach 2.6 MW sustained power and still have some margin. This is desirable because the efficiency is of course lower at these high currents. This brings us to the next challenge. How high should this current be? At 600V, this would translate into 3000 to 4000 A. Hence we adopt a 1200V design, cutting the current in half. How will the battery behave in reality? While above calulations were back of the envelope ones, we need to take into account that a battery and this applies also to hybrid powercapacitors are not linear devices. The energy that can be drained depends on the SoC (State of Charge) and on the current resulting in different voltages for a constant power. For this, we use a battery load simulator with a load profile and the battery parameters as input.

Below is the scatter diagram shown of the above-described system. It gives the operating points (Voltage, Energy, current) over the load profile.



Other interesting simulation results are:

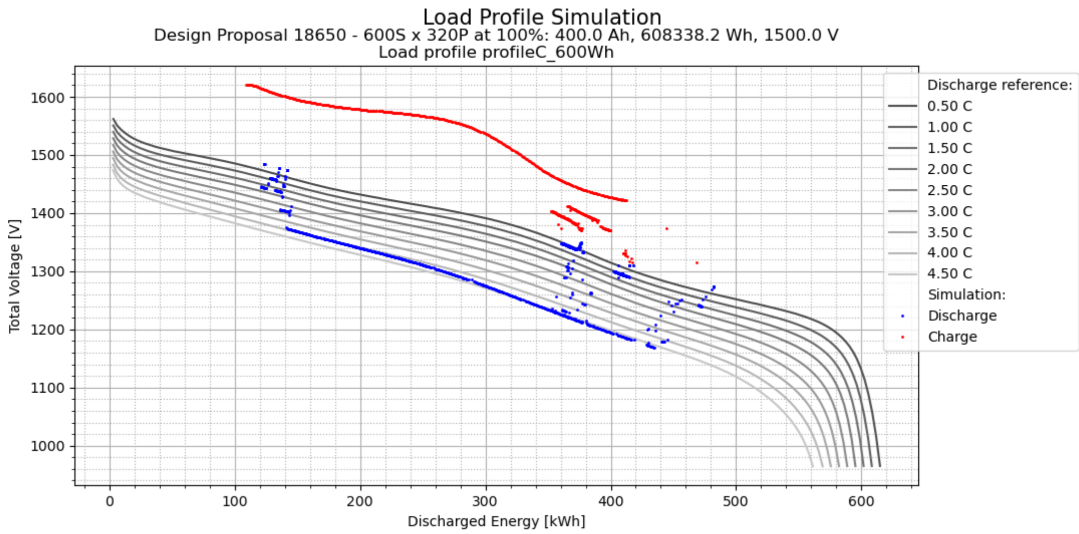
Voltage (t)	Current (t)
	

SoC (t)	C-rate histogram
	

Scenario 2: Heavy duty transport with fast charging

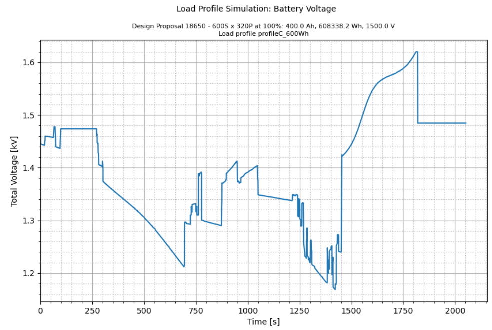
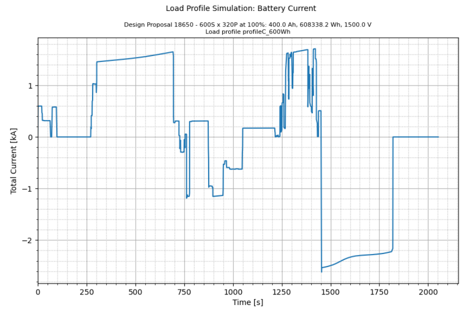
Next we take on the challenge of transport vehicles like the ones used for mining operations or e.g. trains. These vehicles are very heavy and can transport hundreds of tons. They need powerful motors of 2 MW to pull the loads op the hills. Another important factor is fast charging, as charging times are dead times whereas the heavy diesel equivalent only needs 15 minutes/24 hours to be refilled. We take one driving profile as example, where the total energy used, including regenerative braking and overhead line charging requires almost 500 kWh per trip. During the trip we charge at 3C and at the end of each trip at 6C to reduce the downtime. To keep the currents at a reasonable level, we operate at 1500V.

The resulting (V, Wh) scatter diagram is as follows:



Notice that this driving scenario minimizes the charging time. The powercapacitor battery is operated at a lower SoC level allowing for faster charging. Hence, we use a 600 kWh battery. This also gives additional margins for non-scheduled extra loads or trip extensions.

The resulting graphs are as follows:

<table>
<tr><td>Voltage (t)</td><td>Current (t)</td></tr>
<tr><td>
</td><td>
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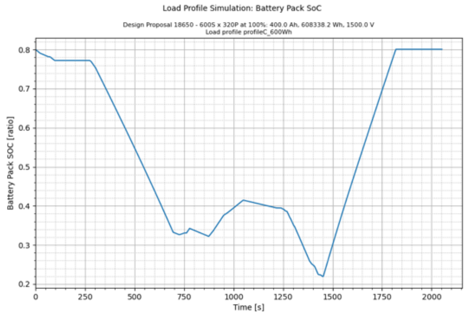
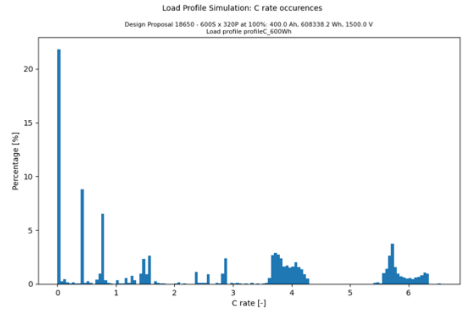
<tr><td>
</td><td>
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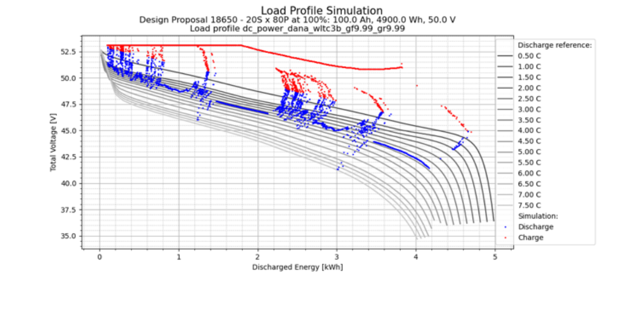
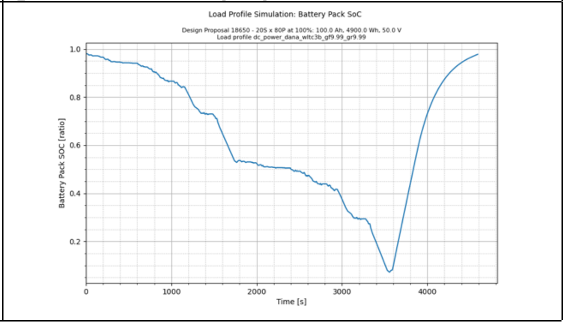
Interesting is to note that such a configuration results in only short times that the vehicle is not available. In this case we charge for about 350 at 3C seconds while driving and for about 425 seconds at 6C at the end of a half hour trip. Note that this is below the maximum C-rating (20C) of the battery. The reasons for staying lower are lifetime and system level considerations such as maximum current (that must be handled by the connectors, contactors and cabling), the operational margin and capacity degradation. It also allows to operate without a complex cooling solution, only a forced air circulation is suggested.

Scenario 3: a small electric vehicle

Above scenarios might give the impression that hybrid powercapacitors can only be used for heavy or racing vehicles. In the EU Multi-Moby project we look into small (900 kg) electric urban vehicles operating a 48V. Still, these can reach 100 km/hr. A traditional LFP battery would have a capacity of 30 kWh and requires more than 10 hours to charge at home. We use a powercapacitor battery of only 5 kWh that can charge at upto 12C. The simulations shows it can be not only handle the 30 kW power needed for the WLTC driving profile (reaching peaks of 7.5C), we can also charge the battery at 6C from 10 to 80% SoC in 205 seconds or 500 seconds to reach 100%. We could charge faster at 12C (180 seconds to 80%, 400 seconds to 100%) but actually the benefits in time are not worth it. Note that this will also apply to any other battery technology that could match the C-rates.

Below the (V, Wh) scatter diagrams and SoC(t) diagrams

<table>
<tr><td>Voltage-energy diagram for a WLTC load</td><td>SoC(t) diagram with 2 runs of the WLTP profile + recharging at 6C</td></tr>
<tr><td>
</td><td>
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It should be noted that the trade-off to be made is the initial investment in battery capacity (range) vs. the charging time (convenience). This has a direct impact on the usage profile. Large energy type batteries provide more range but often need long hours of overnight charging. Small power type batteries provide less range but translate in less weight, a lower energy consumption and lower initial cost while allowing to charge fast. The latter scenario is in particular important for logistic operations that often have to operate 24/7.

Comparison with other cell technologies

Needless to say. A 600 kWh battery delivering power levels like in scenario 2 is a heavy one. In this case in the order of 7.5 ton (cells only).
How would this compare using more traditional battery technologies? We have taken some representative cells available on the market. Simplifying the comparison, we have assumed a 100% DoD for all devices, although in practice it can be as low as 60%, especially at high currents. The results are as follows:

CELL PROPERTIES (Typical)	***LFP LIPO***	***LFP***	***NMC***	***NMC***	***TESLA-3***	***Power-capacitor 18650***
Weight [g]	80	86	46	95	68.5	39
Nom. capacity [Ah]	2.3	3.2	2.6	5	4.8	1.25
Nom. voltage [V]	3.2	3.2	3.7	3.6	3.6	2.5
Est. Max. cycles	500	2000	300	1000	1500	20000
Max. discharging current [A]	46	9.6	1.3	10	7	25
Max charging current [A]	6.5	1.6	1.3	5	7	15
C-rate (max. current / nom. current)	20	3	0.5	2	1.5	20

Scenario 1 : 1200V-125Ah-2000A peak sustained						
S (number of cells in Series)	375	375	325	334	334	480
P (number of cells in parallel)	55	209	1539	200	286	100
Total mass [kg]	1650	6740	23008	6346	6543	1872
Scenario 2. 1500V-400Ah-3200A peak sustained						
S (number of cells in Series)	469	469	406	417	417	600
P (number of cells in parallel)	493	2000	2462	640	458	320
Total mass [kg]	18497	80668	45980	25354	13083	7488

Conclusion:

The more extreme an application is in terms of requiring both energy and power in a sustained way, the better hybrid powercapacitors deliver. The only technology that comes close is Lithium-polymer but at the cost of a much lower lifetime, safety and higher complexity. Hybrid powercapacitors vs. traditional Lithium-ion batteries have another benefit. When they age (because of calendar time, higher temperatures, high current, …) all batteries lose their capacity. Once they lost 20 to 25% of their initial capacity, batteries are considered end-of-life mainly because the currents will start to increase, which will increase the temperature and increase the safety risk. Hybrid power capacitor batteries will also see increased currents but can still deliver the required power because the maximum current is still not reached. Hence, one can continue to use them at the expense of some range or continue to use them for second-life applications without any risk.

Download at: https://kurt.energy/sustained-extreme-performance-with-powercaps/

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