Supercapacitors take charge in Germany

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The yellow-and-white Stadtbahn trams criss-crossing the streets of Mannheim in southern Germany look unremarkable, but some of them are literally carrying what could be the key to greener public transportation. The electrically powered vehicles use 30% less energy than their equivalents in most other cities because they contain onboard systems for capturing the energy that would otherwise be squandered when the trams brake. This energy is converted into electricity, which is then stored in devices called supercapacitors mounted on the tram roof.

Supercapacitors are power-storage devices that can supply onboard electrical power in hybrid vehicles. Unlike batteries, supercapacitors can be charged and discharged in seconds and can withstand many hundreds of thousands of such charging cycles. This makes them ideal for energy-saving applications that capitalize on transient opportunities for recharging, such as energy capture during braking, and that require power to be delivered in short bursts of perhaps half a minute or less. They can, for example, help with acceleration or can restart engines that cut out to reduce fuel use and pollution in stop-and-go traffic.

Whereas batteries store energy in chemical form—in substances that can react to release electrical energy—capacitors store it by simply piling up electrical charge on two electrodes. The larger the electrodes and the closer they are, the more energy that can be stored. An ordinary capacitor consists of two conductive plates separated by an insulating (dielectric) layer. But a supercapacitor (sometimes called an ultracapacitor) holds its charge a little differently. Typically it contains two conductive porous electrodes—usually made of carbon—immersed in a liquid electrolyte and separated by a very thin insulating film, usually made of a porous polymer. The charge is stored by adsorption of ions onto the high-surface-area electrodes. When the electrodes are charged, this produces a layer of oppositely charged ions on their surfaces: a so-called electrical double-layer, which is why this type of supercapacitor is often called a double-layer capacitor.

The potential of supercapacitors to assist in powering vehicles was displayed in dramatic fashion in the 24-hour speed race at Le Mans this June, when Toyota fielded a hybrid TS030 that used them for energy-capture during braking. The devices performed perfectly, but a crash scuppered the vehicle's bid for glory.

The Mannheim trams are rather more sedate, but with their own onboard power, they can keep running across short gaps or disruptions in the electricity line, for example due to ice or where overhead power lines cannot be deployed for aesthetic or technical reasons. The energy source can also be tapped to drive air conditioning, automatic windows, or passenger doors.

These trams have been reaping the benefits of supercapacitors since 2003 and are now joined by a host of other public-transportation systems in Germany and beyond. Supercapacitor technology is deployed, for example, on Spanish and French trains and hybrid buses all over the world, on construction equipment such as cranes, and on garbage-collection trucks. On buses, it can reduce the effective carbon-dioxide emissions by around 30%, while the Munich-based heavy-vehicle manufacturer MAN estimated that their supercapacitor-fitted coaches each save around $4,500 a year on fuel costs.

Reducing fuel consumption and emissions during the "dead time" of standing at stops, intersections, and traffic lights is a particularly pressing concern for buses. Since 2001, MAN has been developing hybrid supercapacitor buses called the Lion's City Hybrid. The current commercial model, available since 2010, cuts diesel consumption by up to 30%, and is now being used on a small scale in Paris and some other European cities. In principle, buses can recharge their supercapacitors not just during braking, but also at every bus stop by making contact with overhead charging lines for just a few seconds.

So far the take-up of the technology has been relatively modest. But it looks set to expand both as energy-saving and low-emission technologies become more imperative and as the technical capabilities of supercapacitors improve. Supercapacitors are not by any means a panacea for green transportation: they have a lower total energy density than batteries by one or two orders of magnitude, for example. But they have a higher power density, delivering much more power over a short period of time.

"There is no single perfect energy-storage solution, no 'one size fits all,'" said materials scientist Yury Gogotsi at Drexel University in Philadelphia. "A 'battery of the future' may be a battery-supercapacitor hybrid having the long lifetime, fast charging, and high power of a supercapacitor combined with a high energy density of a battery."

The main producers of supercapacitors worldwide are Nesscap Energy, based in South Korea, and the California-based company Maxwell Technologies. These and other manufacturers supply the basic

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cells to companies such as Siemens and the Belgian firm 4Esys, which incorporate them into modules that can be added directly into vehicle designs. In Germany, the electrical-component manufacturer WIMA in Mannheim, which specializes in capacitors and supercapacitors, manufactures both individual cells and modules. Siemens has developed two energy-storage supercapacitor modules called Sibac and Sitrac, which are incorporated into the vehicles or the power-supply lines respectively to capture energy during braking. Sitras can also be used to maintain the voltage of the network during peaks of high power demand or temporary outages.

Trams in Germany powered by supercapacitors use 30% less energy than their equivalents in other regions. *Credit:* RNV

Despite the promise of supercapacitors in transportation, their uptake has been rather slow and cautious over the past decade. "There have been a lot of projects where prototypes are tested over a considerable time," said Frank Herrmann, an engineer at WIMA. The market has, however, been picking up speed over the past two or three years, partly because of rising fuel costs. "The economics are driving it," said Juergen Auer of Nesscap's division in Schondorf, Germany. "It's very sensitive to what happens to diesel prices."

And although Germany is noted for its commitment to green energy policies, the kind of support from central government that has been enjoyed by, say, photovoltaic energy (where subsidies and guarantees of competitive rates have boosted production and use) has not been extended to the supercapacitor market. "German authorities are pretty conservative," Auer feels. There are also no coherent plans for how and where the technology might be introduced. "Each energy or transport company has a hybrid solution, whether with supercapacitors or batteries," he said, "but the final customers like cities aren't ready to buy it or implement it into their fleets. That makes it a very difficult product to market." Auer contrasts this ruefully with China, where efforts to use supercapacitors in transport began only about four years ago but have resulted already in tens of thousands of "supercap" buses on the road, especially in Shanghai. "Right now the biggest market is in China," Herrmann agreed.

However, Herrmann thinks that Germany's energy policy to use renewable rather than nuclear energy will indirectly help the technology. Offshore wind farms, for example, need regular maintenance using ships and helicopters, and supercapacitors should help to reduce the running costs of these fleets.

Germany's federal system offers scope for regional projects, and individual cities such as Mannheim have sometimes launched their own initiatives. Siemens' Combino trams, which use the Sibac system, have been deployed in several German cities, including Augsburg, Düsseldorf, Ulm, and Potsdam, as well as outside Germany in Amsterdam, Basel, and Budapest for example. The company unveiled a second-generation tram system, called Avenio, last year. Meanwhile, the Mannheim trams use the Mitrac supercapacitor system produced by the Berlin-based company Bombardier Transportation. Last year, the German transport operator RNV, which serves the Rhein-Neckar region and includes Mannheim, Heidelberg, and Ludwigshafen, ordered 11 more Bombardier trams for its 200-km network.

In part, the obstacles to wider use are matters of infrastructure and design: engineers are more used to thinking in terms of hybrid vehicles with batteries that require charging cycles of several hours, rather than the several seconds needed by supercapacitors. But as their use hinges mostly on economics, it is vital to improve performance while reducing costs. Supercapacitors can have an impressive lifetime—15 to 20 years—but the initial outlay is still rather high.

A key problem is that the individual cells develop relatively low voltages—typically less than 3 V—because of the limited electrolyte stability. This means that to obtain the 24 V typically needed for vehicle systems, several cells must be connected in series, making for relatively costly and bulky modules. "We need to increase voltage per cell in order to have higher energy density and fewer cells," said Herrmann.

Auer said that some of the raw materials, such as the porous carbon electrodes, are also somewhat costly, and so is the manufacturing process. However, Gogotsi insists that "there is no fundamental reason for supercapacitors to be expensive, because they use just carbon, polymer film, an inexpensive aluminum foil, and an organic electrolyte, with no rare or expensive elements." Costs should fall, for example, simply as the scale of production increases and manufacturing methods improve. That would not only boost current uses but enable new applications to emerge.

This all leaves Auer optimistic about the prospects. "There's still a lot of room for future growth," he said. "There are potential uses everywhere." He said that supercapacitors are one of the few electronic components that have had a steadily growing market over recent years.

"It takes time," he said. □

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