ULTRA CAPACITORS ELECTROSTATIC ENERGY STORAGE

4/1/2020

INTRODUCTION

Ultra capacitors are an alternative as well as a complement to chemical batteries. They are energy storage devices characterized by fast charge and discharge rates, absorbing and releasing electrostatic charge within minutes, and could be used as a rapid-charging, cheaper, and safer alternative to batteries for electric cars. However, ultra capacitors can hold just 5 percent of the energy of lithium-ion chemical batteries, providing short power bursts that limit them so far to uses in specialized applications. With ultra-capacitors, a canister the size of a soda can, could in theory, store more than a million times as much charge per volt as common capacitors.

Electrochemical battery technology has not delivered the performance improvements observed with other technologies. Electric vehicle ranges are lacking, and the time required to recharge a battery is inconvenient compared with filling up a gas tank with gasoline. Moreover battery-powered vehicles have a safety issue. Some electric car models are notorious for catching on fire and batteries are suspect. The entire fleet of Boeing's new Dreamliner 787 jets has been grounded because of a lithium-ion battery fire hazard. It appears we are hitting the physical limits to what is possible with electrochemically stored energy.

Ultra capacitors store energy electrostatically in an electric field instead of chemically in a chemical compound, as in chemical batteries. During the charging process, electrons come to the surface of one electrode, and electron "holes" form on the surface of the other electrode. This draws positive ions in an electrolyte to the first electrode and negative ions to the second.

Figure 1. Ultra capacitor used to capture the brakes energy in hybrid buses. Photo: Maxwell technologies.

In comparison, the chemical reactions used to charge batteries limit the speed with which they can be charged and eventually cause the electrode materials to break down. Ultra-capacitors can be charged and discharged very rapidly, in seconds rather than minutes, and can be recharged millions of times before wearing out.

Ultra capacitors electrostatic energy storage could ease the integration of renewable energy sources such as solar and wind power, which by their nature are intermittent. Without a way of instantaneously buffering energy from these sources, they could cause region-wide blackouts and will never be reliable enough to rely on exclusively.

As capacitors store energy by creating, and then strengthening electric fields, they are better than batteries, is that you can get back nearly 100 percent of the stored energy, as long as this is not done too quickly. That is why in battery powered electric cars, there are large capacitors on the DC bus to store energy from regenerative braking, for the next acceleration cycle.

COMPARISON OF CHEMICAL AND ELECTROSTATIC ENERGY STORAGE

The performance of an energy-storage device is assessed according to four main figures of merit: efficiency, energy density, specific energy and power.

$$\eta_{battery} = \frac{\text{Discharged energy}}{\text{Stored energy}} \tag{1}$$

$$\text{Energy density}=\frac{\text{Stored Energy}}{\text{volume}},[\frac{\text{Joule}}{\text{cm}^3}],[\frac{\text{Watt.sec}}{\text{cm}^3}] \tag{2}$$

$$\text{Specific Energy}=\frac{\text{Stored Energy}}{\text{mass}},[\frac{\text{Joule}}{\text{kg}}],[\frac{\text{Watt.sec}}{\text{kg}}] \tag{3}$$

$$\text{Power}=\frac{\text{Discharged energy}}{\text{unit time}},[\frac{\text{Joule}}{\text{sec}}],[\text{Watt}] \tag{4}$$

Consider the analog of a bucket of water. The energy density is a measure about how much water the bucket can hold. On the other hand, the power tells about how fast it can be filled and emptied.

Chemical batteries have higher specific energy and energy density than ultra-capacitors: they can store more total energy per unit mass and per unit volume. Capacitors, on the other hand, tend to be more powerful than batteries: they can take in and release energy much quicker. The two technologies operate in different ways and could operate optimally in a combined configuration.

In batteries, positive and negative electrodes are immersed in the conductive medium of an electrolyte. Chemical reactions at the electrodes cause ions and electrons to circulate between them. The process frees electrons that flow through an external circuit to power electrical devices. Batteries can store a lot of energy for release through these reactions, which in some cases can also be reversed to recharge them.

As an example, the lithium-ion battery in a laptop computer can power it for about five to seven hours. In contrast, an ultra-capacitor the size of a D cell battery could not power a flashlight for more than two minutes. But batteries wear out: the reactions change the structure of the electrodes, causing them to degrade over time, requiring them to be replaced after a specified number of charging and discharging cycles. They have historically not been good at releasing or absorbing large bursts of power in a short time period, since the speed at which the charged particles can move is limited by the rate of the chemical reaction. In cold weather that reaction rate is significantly degraded.

An ultra-capacitor, on the other hand, is made up of two porous electrodes immersed in an electrolyte and divided by a separator. These electrodes never react with the electrolyte to generate ions. Instead, applying an electrical current separates positive and negative ions in the electrolyte, causing the positive ions to accumulate on the surface of the negative electrode while the negative ions accumulate on the positive electrode.

The physical separation of charges stores the energy in the current. Reversing the polarity of the electrodes, so that the positive side becomes negative, causes the ions to rapidly switch sides, allowing the energy to be released again.

In summary, ultra capacitors can store only about 5 percent as much energy as a conventional lithium-ion battery. But they can take up and release that energy in a matter of seconds, since the process does not rely on a chemical reaction. And they can do it hundreds of thousands of times without degradation.

ULTRA CAPACITORS APPLICATIONS

There is no contest for dominance between batteries and ultra-capacitors. Chemical batteries dominate everywhere: in mobile devices, in automobiles as well as in the giant storage banks that back up computer servers data centers.

Ultra-capacitors are used for limited applications, often supplementing chemical batteries by providing or absorbing quick bursts of power. In digital cameras they provide fast zooming.

Ultra-capacitors have been used to power gantry cranes to lift shipping crates in Japanese ports, and then reabsorb the energy generated when this cargo is set down.

They perform a similar function in city buses, capturing energy released during braking. But they lack the energy density to run a cell phone or a car on their own.

The more surface area in an ultra-capacitor's electrode, the higher the energy density it can achieve, because charged particles have more places to lodge.

The reason that ultra-capacitors are able to store so much more energy than conventional capacitors is that their electrodes are usually fashioned from activated carbon, or graphite that has been treated so that it is full of holes and can suck up charge the way a sponge soaks water.

ACTIVATED CARBON ULTRA CAPACITORS

Existing ultra-capacitors use electrodes made from activated carbon, which is a porous, charcoal-like material that has a very high surface area. Activated carbon stores charge in tunnel-like pores, and it takes about one second for it to travel in and out. This is very fast compared with the fastest batteries, but activated carbon has a limited power output.

The existing ultra-capacitors cannot match batteries for energy density, so they are mostly used in hybrid systems alongside batteries or for niche applications. Because these devices can handle a rapid influx of large amounts of energy, they are often used to recover energy, for instance, when a city bus brakes or a gantry crane lowers its cargo. Ultra capacitors employed in this way have reduced by 40 percent the energy needed by some cranes used in Japanese ports. A few power tools, including electric drills, take advantage of the rapid recharging ability of ultra-capacitors.

Chemical batteries are typically operated in the middle range of their full charge cycle, often using only about 20-50 percent of their total charge capacity. This implies that an ultra-capacitor with about 20 percent of the energy density of a rechargeable battery, but with a rapid recharge time and almost unlimited lifetime, should be competitive for some electric vehicles.

In addition, while the chemical reactions that charge a battery take hours and degrade the electrodes after a few thousand cycles, ultra capacitors charge in minutes and can last millions of recharge cycles because they store charge electrostatically with ions from an electrolyte in the capacitor cling to the electrodes' surfaces.

GRAPHENE

Since it was first created in the laboratory in 2004, graphene has been hailed as a wonder material: the two-dimensional sheets of carbon atoms are the strongest material ever tested under tension.

Graphene's electrical properties make it a potential replacement for silicon in faster computer chips. Synthesizing pristine graphene of the quality needed to make transistors, though, remains a painstaking process that, as yet, cannot be done on an industrial scale.

A method for manufacturing crumpled graphene begins by oxidizing the graphite with acids, then separating it into atom-thin sheets.

The expanded graphite is then rapidly heated, creating carbon dioxide gas that builds up pressure, forcing the graphene sheets apart. Methods were developed to improve the yield and ensure that the graphene sheets completely separate.

The sheets are then heated to remove the oxygen groups. The conductivity nears that of pristine graphene, but the sheets are crumpled so they do not stack together again.

The resulting powder can be added to a solvent to make inks or added to polymers to make composites such as tough tire rubber.

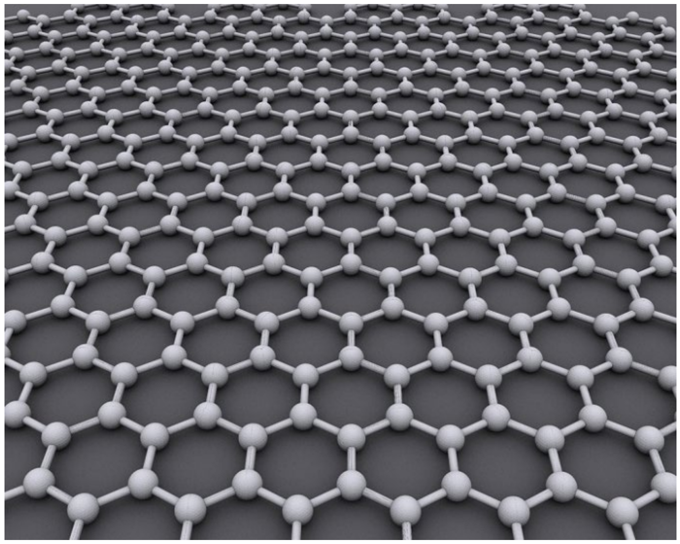

Figure 2. Graphine hexagonal cell structure.

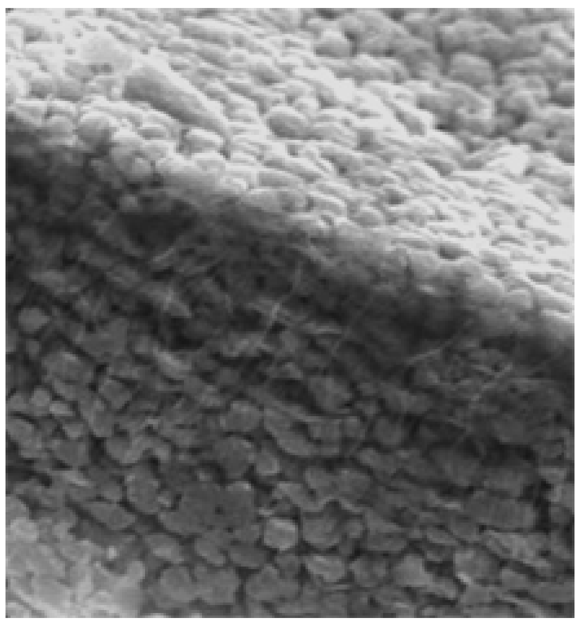

Figure 3. Scanning Electron Microscope, SEM, photo of a graphene-covered electrode.
Photo: Meryl Stoller.

ULTRA CAPACITORS WITH GRAPHENE ELECTRODES

Graphene is composed of sheets of carbon that are an atom thick. Ultra capacitors with electrodes made of grapheme could be used in ultra-capacitors. The storage capacity of an ultra-capacitor is limited only by the surface area of its electrodes, and graphene offers a way to greatly increase the area available.

Commercial ultra-capacitors have electrodes made of activated carbon, a highly porous material that stores ions in its pores. Graphene could store much more charge because ions can form a layer on the carbon sheets; the charges should also be easier to get on and off the surfaces. However, current methods to make graphene result in flat graphene flakes that overlap, so the surfaces get covered.

To make the graphene for ultra-capacitor electrodes, graphite oxide is placed in a water solution. This causes the material to flake into atom-thin sheets of graphene oxide. The oxygen atoms are next removed, leaving the graphene behind.

Graphene ultra-capacitors that match the performance of those made using activated carbon have been made. With further refinements they should outperform activated carbon.

The graphene electrodes could store 85.6 Watt-hours of energy per kilogram. Since an electrode typically weighs about one-third of a full-size ultra-capacitor, a practical device would have a specific energy of around 28 Watt-hours per kilogram.

In comparison, activated carbon ultra-capacitors have energy densities of 5 to 10 Watt-hours per kilogram, while nickel metal hydride batteries and lithium-ion batteries boast 40-100 Watt-hours per kilogram and over 120 Watt-hours per kilogram respectively.

CRUMPLED GRAPHINE ULTRA CAPACITORS

Ultra-capacitors can use flat and overlapping sheets of graphene as electrodes. Crumpled sheets of grapheme expose a larger area of carbon atoms for storing electrical charges on the electrodes of an ultra-capacitor. One approach is to use crumpled graphene wadded into a ball like a piece of paper, exposing much more of the surfaces.

Coin-sized test cells lose less than 10 percent of their charge storage capacity after being recharged 500 times. Improving the electrode materials should increase the cycle life.

Other cells lose 3 percent of their charge storage after 10,000 cycles. They have reached the range of lead-acid batteries with a charge-discharge every second.

If the electrodes can be grown in vertical arrays, like a row of perfectly flat sheets of paper standing on edge, the power output could be increased dramatically. In this arrangement, every single carbon atom would be exposed and able to store energy, with virtually no waiting time for the charge to travel down the tunnels found in activated carbon.

In addition to improving the performance of ultra-capacitors, a method must be developed for making them at larger scales.

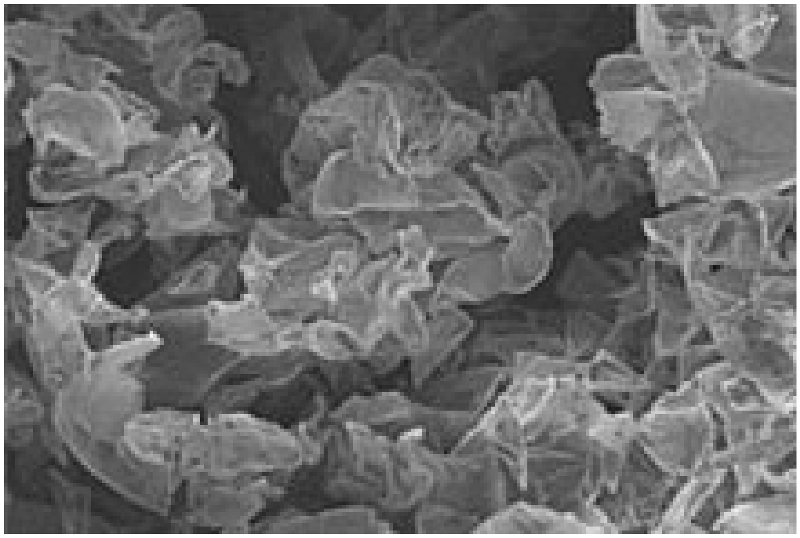

Figure 4. Crumpled graphine offer a large surface area for electrical charge storage in ultra-capacitors.

Figure 5. Crumpled grapheme is mixed with plastic and rubber making as flexible and electricity conducting as muscle.

ALTERNATE GRAPHENE MANUFACTURE METHOD

Researchers at the University of California, led by Richard Kaner, produce graphene using a simple approach. A solution of graphite oxide in a water solution is coated onto a sheet of plastic in the form of a compact disc. It is then inserted into a common, off-the-shelf optical disk drive and exposed to the drive's laser. The process yields flexible graphene.

The produced graphene is then fashioned into tiny super-capacitors. The graphene super-capacitors enjoy an energy density far higher than standard capacitors and lithium-ion batteries.

Graphene super-capacitors can be charged and discharged over thousands of cycles without degradation. A future laptop computer could run for days on a single charge, instead of just hours.

CARBON NANOTUBES ULTA CAPACITORS

Carbon nanotubes are atom-thick sheets of carbon, rolled up into straws only about 5 nanometers in diameter. They have the same chemical makeup as the graphite used to make the activated carbon ultra-capacitors, but they pack much more surface area into a given volume.

CHEMICAL VAPOR DEPOSITION

A forest of carbon nanotubes can be grown using a process called chemical-vapor deposition. An iron-coated sliver of silica is placed inside a vacuum chamber, the temperature is raised to 650 °C, and hydrocarbon gases such as methane are pumped in.

The heat causes the iron to ball up into tiny droplets, each of which begins snatching carbon from the surrounding gaseous atmosphere. The captured carbon atoms self-assemble into straw-like nanotubes that shoot up rapidly, resulting in a dense nanotube carpet.

These nanotube carpets can store a lot of charge but there is one small problem: The silica substrate is an electrical insulator, and to deliver energy effectively, an ultra-capacitor must be based on a conductor substrate. It is harder to grow carbon nanotubes at the same density on a conductive substrate. They grow so sparsely that the result looks like a shag carpet instead of an oriental rug.

LAYER BY LAYER ASSEMBLY

A technique called layer-by-layer assembly is a way of building high-performance devices by repeatedly dipping a thin substrate, often a flexible polymer sheet, into water solutions containing a mix of positively and negatively charged materials, in this case nanotubes.

Using this technique, one can make layers of nanotube carpets at room temperature in the open air, a process that is more manufacturing friendly than vapor deposition.

With the incorporation of lithium ions into the films, the resulting device could hold as much energy as a lithium-ion battery but charge and discharge as rapidly as a carbon-nanotube capacitor.

BIO-NANOTECHNOLOGY PROGRAMMED VIRUSES

Layer-by-layer assembly and chemical-vapor deposition are not the only ways to make nano-structured materials that could improve energy storage. Programming viruses have been investigated to make electrodes for more powerful batteries.

Viral genomes are blueprints for building highly ordered, reproducible molecular structures from the bottom up. This is the same thing materials scientists try to do in the laboratory. Viruses are made up of proteins, which bind their targets very selectively, so they are reliable building blocks.

Viral replication can be used to build battery materials. A very simple virus called M13 is easy to work with because it has only a few genes, all of which had been sequenced. One takes its DNA, cut certain genes, and put in random DNA. If this is repeated a few billion times, one gets viruses whose proteins differ by a few amino acids. This is akin to producing induced fast-forward artificial evolution.

To make a battery electrode, there is a need to screen for viruses with two specific proteins. The first makes up M13's outer coat by accumulating iron phosphate. The second is a single protein, on the tip of each virus that is selected for its ability to bind carbon nanotubes. M13 was also a good virus for the purpose because it is long, thin, and uniform in size. Coating the engineered viruses with iron phosphate turns them into nanowires. When researchers add these M13 nanowires to a water solution of carbon nanotubes, they bind tightly to the nanotubes, which are also long and thin.

The networks of viral nanowires and carbon nanotubes look like a jumble of pickup sticks but are orderly. They form highways for electrons, speeding them along so that a battery can charge and discharge faster.

The batteries based on the virus electrodes are presented as good as lithium- ion batteries currently on the market.

NANOTUBES AND NANORIBBONS FOR ULTRA CAPACITORS

An approach to make better ultra-capacitor electrodes is to replace activated carbon with vertically oriented carbon nanotubes which are rolled-up tubes of graphene that have many of the same properties.

This significantly increases the surface area and voltage of an ultra-capacitor electrode, which in turn boosts the amount of energy that an ultra-capacitor can store.

Because ultra-capacitors can be charged and discharged thousands of times more than a rechargeable battery, a goal that would make ultra-capacitors a viable and cost-effective solution for hybrid vehicles.

Ultra capacitor electrodes with vertically grown arrays of carbon nanotubes achieved energy densities of 20 to 25 watt-hours per kilogram. The target is a specific energy of 25 to 30 Watt.hour /kg.

To compete with chemical batteries, all of the carbon nano material technologies for ultra-capacitors face the challenge not only of improving energy densities but also of making electrodes that perform well consistently on a large scale.

Exposing carbon nanotubes to sulfuric acid and potassium permanganate, a strong oxidizing agent leads to a reaction in which a bond between two carbon atoms in the nanotube is broken, and each carbon atom bonded with an oxygen atom instead.

The oxygen atoms created a strain that caused the nanotubes to unzip into ribbons. This reaction slices each nanotube layer open in one clean cut because it is more favorable for the reaction to propagate along the length of the tube than for distant bonds to be oxidized. The width of the ribbons is determined by the diameter of the nanotubes used to make them. Nanoribbons are easy to process because they are graphene oxide, which is soluble in water.

We suggest that the use of boron nitride nanotubes may offer an even better alternative, since they are better electrical conductors than carbon nanotubes.

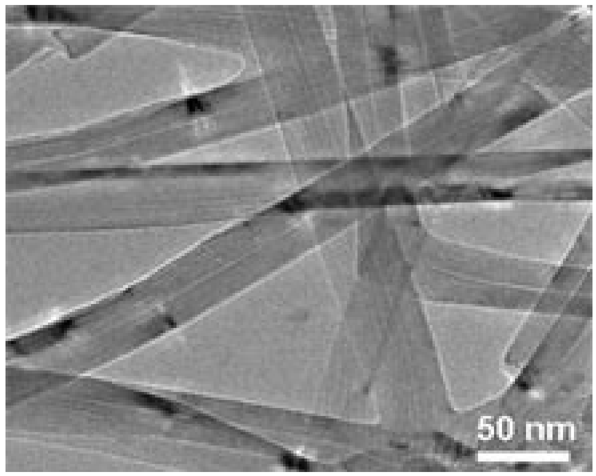

Figure 6. Carbon nanotubes. Photo: Rice University.

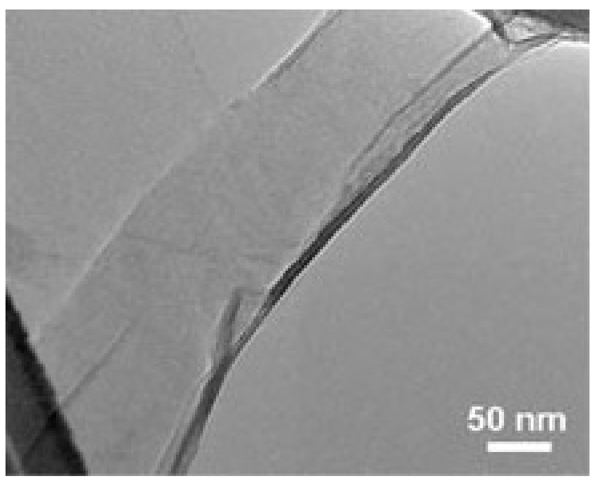

Figure 7. Carbon nanoribbons produced from unzipped carbon nanotubes. Photo: Rice University.

ULTRA CAPACITORS IN PLUGIN VEHICLES

Figure 8. Bus running on ultra capacitors charges up at a bus stop every 3-5 miles for fast recharging. Photo: Sinautec Automobile Technologies.

Ultra-capacitors could lower the cost of the battery packs in plug-in hybrid vehicles by hundreds or even thousands of dollars by cutting the size of the packs in half.

Ultra-capacitors could also dramatically improve the efficiency of another class of hybrid vehicle that uses small electric motors, called micro hybrids.

The use of ultra-capacitors in hybrids is not a new idea. But the falling cost of making these devices and improvements to the electronics needed to regulate their power output and coordinate their interaction with batteries could soon make them more practical.

Although batteries have improved significantly in recent years, the cost of making them is the main the reason why hybrids cost thousands of dollars more than conventional vehicles. This is especially true of plug-in hybrids, which rely on large battery packs to supply all or most of the power during short trips. Battery packs are expensive in part because they degrade over time and, to compensate for this, automakers oversize them to ensure that they can provide enough power even after 10 years of use in a vehicle.

Ultra-capacitors offer a way to extend the life of a hybrid vehicle's power source, reducing the need to oversize its battery packs. Unlike batteries, ultra-capacitors do not rely on chemical reactions to store energy, and they do not degrade significantly over the life of a car, even when they are charged and discharged in very intense bursts that can damage batteries.

The drawback is that they store much less energy than batteries, typically, an order of magnitude less. If, however, ultra-capacitors were paired with batteries, they could protect batteries from intense bursts of power, such as those needed for acceleration, thereby extending the life of the batteries.

Ultra-capacitors could also ensure that the car can accelerate just as well at the end of its life as at the beginning.

Reducing the size of a vehicle's battery pack by 25 percent could save about $2,500. The ultra-capacitors and electronics needed to coordinate them with the batteries could cost between $500 and $1,000, resulting in hundreds of dollars of net savings.

PAIRING OF ULTRA CAPACITORS AND CHEMICAL BATTERIES

Ultra-capacitors would also make it possible to redesign batteries to hold more energy. There is typically a tradeoff between how fast batteries can be charged and discharged and how much is the total energy they can store. That is true in part because designing a battery to discharge quickly requires using very thin electrodes stacked in many layers. Each layer must be separated by supporting materials that take up space in the battery but do not store any energy. The more layers used, the more supporting materials are needed and the less energy can be stored in the battery. Paired with ultra-capacitors, batteries would not need to deliver bursts of power and so could be made with just a few layers of very thick electrodes, reducing the amount of supporting material needed. That could make it possible to store twice as much energy in the same space.

Ultra-capacitors could also be useful in a very different type of hybrid vehicle called a micro hybrid. These vehicles use small electric motors and batteries to augment a gasoline engine, allowing the engine to switch off every time the car comes to a stop and restart when the driver hits the accelerator. A micro hybrid's batteries can also capture a small part of the energy that is typically wasted as heat during braking. Because ultra-capacitors can quickly charge and discharge without being damaged, it would be possible to design micro hybrids to make much greater use of an electric motor, providing short bursts of power whenever needed for acceleration. They could also collect more energy from braking. Such a system would improve the efficiency of a conventional engine by 40 percent during city driving. Conventional micro hybrids only improve efficiency by 10 to 20 percent.

COLD WEATHER PERFORMANCE

In both plug-in hybrids and micro hybrids, ultra capacitors would offer improved cold weather performance, since they do not rely on chemical reactions that slow down in the cold. In very cold weather, you have to heat the battery, or you cannot drive very fast, you would have very low acceleration. In contrast, ultra capacitors could provide fast acceleration even in cold temperatures.

In micro hybrids ultra-capacitors could simply replace batteries, since they store enough energy to augment the gasoline engine without the help of batteries. In plug-in hybrids, which require much more energy, ultra capacitors would need to be paired with batteries, and this would require complex electronics to coordinate between the two energy storage devices.

By and large, you never want to add parts to a car. You want the simplest system possible so that there are fewer things to go wrong.

For ultra-capacitors to be practical in micro hybrids, the cost of making them has to decrease by about half, which may be possible because many parts of the manufacturing process for large ultra-capacitors are not yet automated. But to justify the added complexity in plug-in hybrids, the entire system would have to cost significantly less than using batteries alone.

USE IN MUNICIPAL TRANSPORTATION

Municipal transit agencies have tried to reduce the carbon footprint of their bus fleets using a range of options over the years, from biofuels and hydrogen to batteries and hybrid-electric diesel.

The best ultra-capacitors can only store about 5 percent of the energy that lithium-ion batteries hold, limiting them to a couple of miles per charge. This makes them ineffective as an energy storage medium for passenger vehicles. But what ultra-capacitors lack in range they make up in their ability to rapidly charge and discharge. So in vehicles that have to stop frequently and predictably as part of normal operation, energy storage based exclusively on ultra-capacitors begins to make sense.

The trick is to turn some bus stops along the route into charge stations. Unlike a conventional trolley bus that has to continually touch an overhead power line, ultra capacitor buses take big sips of electricity every two or three miles at designated charging stations, which double as bus stops. When at these stations, a collector on the top of the bus rises a few feet and touches an overhead charging line. Within a couple of minutes, the ultra-capacitor banks stored under the bus seats are fully charged.

The buses can also capture energy from braking. The recharging stations can be equipped with solar panels.

The buses use 40 percent less electricity compared to an electric trolley bus, mainly because they are lighter and have the regenerative braking benefits. They are also competitive with conventional buses based on fuel savings over the vehicle's 12-year life, based on current oil and electricity prices.

The bus ultra-capacitors are made of activated carbon and have a specific energy of 6-10 watt-hours per kilogram. For comparison, a high-performance lithium-ion battery can achieve 200 watt-hours per kilogram.

The buses, based on current technology, lose 35 percent of their range when air conditioning is turned on from about 5 miles to about 3 miles, and have weak acceleration. But even under these conditions, they could still prove practical for municipal, campus, airport, and tourist buses.

ELECTRICAL GRID INTEGRATION

New ultra-capacitor applications are developing devices with far higher power output. These ultra capacitors offer the potential to be used to regulate surges in the electrical grid or to power hybrid transportation vehicles.

Integrating intermittent sources of renewable energy, such as wind and solar into the electrical grid, while keeping the power output steady, is a big challenge. Energy storage devices such as ultra-capacitors could help by storing sudden surges of power for later fast delivery, smoothing out the power output. Much will depend on developing a new generation of ultra-capacitors with enough storage capacity to meet the likely demand.

Currently, utility companies are required to maintain what are known as "spinning reserves," which are turbines that are already running, so that when there are sudden surges in demand--say, on a hot summer day, the turbines can provide the extra electricity almost instantaneously.

Ultra-capacitors distributed throughout the network could provide a few minutes of reserve capability locally, without requiring utilities to burn fuel in a turbine to keep it spinning. That would not only decrease fuel requirements and carbon-dioxide emissions, but also allow companies to use the grid closer to capacity. If the grid could be used just 5 percent closer to capacity, it would save billions of dollars in infrastructure investment.

USE IN MICRO DEVICES

Higher energy density is important for tiny batteries like the ones that power pacemakers and other implantable medical devices; the more total energy they can hold, the longer they last and the less frequently they need to be replaced.

Achieving this goal is challenging, because the smaller a battery gets, the less energy per unit volume it can store.

Seeking energy-dense batteries for microdevices, the USA Defense Advanced Research Projects Agency, DARPA, put out a call for a battery 10 cubic millimeters in volume with an energy density comparable to that of early lithium-ion batteries: 200 watt-hours per liter.

Getting a density comparable to that of today's lithium-ion technology in a micro battery is extremely difficult. Part of the problem is that as size decreases, the packaging and electrical connections account for an increasingly large portion of the battery. By redesigning the electrodes and packaging, a 5 mm^3 battery that holds 650 watt-hours per liter, or half the size and more than three times the energy density that is targeted.

In plug-in or hybrid electric vehicles, the more energy their batteries can store, the farther they can travel without needing to recharge or dip into the gas tank.

That is not the only environmental benefit that might flow from developing batteries with greater energy density. The smaller a battery that stores a given amount of energy, the cheaper it will be. The cheaper the technology, the more of the batteries utility companies will be able to buy and use to incorporate renewable energy into the electrical grid. If you need less battery for a given application, you can drive down the cost, which means wider adoption of these technologies, and that means we can at last start relying on green power sources to meet a significant fraction of our energy needs.

DISCUSSION

Finding better technologies for energy storage will be crucial as we work to switch from fossil fuels to more environmentally friendly power sources. When we reach the point where renewables are the main forms of energy, we are stuck if we do not have a place to store it for when it is needed.

Unlike coal and gasoline, which can be burned whenever they are needed, renewable energy sources are intermittent. Solar power can be captured only when the sun is shining. Wind power peaks at night in most locations, whereas energy demand typically peaks in the afternoon. If energy from these sources cannot be stored, it will be lost. It must be integrated into the electrical grid, where it can help even-out discrepancies between supply and demand. Better energy storage is also needed to make clean electricity a more widely useful power source for transportation.

Existing energy-storage devices would not work for these purposes, because they are too expensive, too cumbersome, or too limited in capacity. Considering chemical batteries, the best-known storage technology, sodium-sulfur batteries have the capacity to store wind power that cannot be used immediately, but adding them to a wind farm would quintuple the price of electricity per kilowatt-hour. State-of-the-art rechargeable lithium-ion batteries, which are used in laptop computers and plug-in hybrid cars, are likewise too expensive to be incorporated into the grid in bulk. They wear out and need to be replaced every few years, they are too expensive for widespread use in cars. Lead-acid batteries--the kind used in ordinary gas-fueled cars, are cheaper but too heavy, and too short-lived, to serve as a vehicle's power source.

Ultra capacitors can improve efficiency when used in tandem with batteries, but they do not yet have the capacity to solve the storage problem.