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Some electric cars are already using solid-state batteries, but a battery for the mass market is years away.

TECHNOLOGY

A solid future

Swapping the liquid electrolyte in batteries for a safer solid-state interior is bringing electric cars to the mass market.

BY JIM MOTAVALLI

During the first eight months of 2015, a row of five electric vehicles sat parked in Indianapolis, Indiana, available for test drives. The compact vehicles are part of the first US wave of the ambitious BlueIndy electric car-sharing programme from the Bolloré Group, headquartered in Paris, which is already running similar large-scale schemes in London and the French capital.

These Bluecars are a technological milestone: with unique 30-kilowatt-hour battery packs designed by Bolloré, they are the first plug-in vehicles on the road to have solid-state batteries, rather than the liquid-electrolyte batteries that many other electric vehicles use.

BlueIndy president Hervé Muller says that the plug-in vehicles' batteries have been performing well. And the safety record for Bolloré's batteries is good. "We haven't had an issue in Indianapolis, nor in Paris with the 3,000 cars in service there that have driven more than 10 million miles," Muller says. Bolloré's BlueIndy batteries, although groundbreaking, are an early iteration of solid-state technology and not yet ready for the mass market. Scientists, however, are working on more advanced cells.

PROMISES AND CHALLENGES

The lithium-ion batteries in most electric cars consist of a negative — usually graphite — anode, a positive cathode and a liquid electrolyte. When these batteries release power, lithium ions move from the anode, through the electrolyte, to the cathode. The more conductive the electrolyte, the better the battery performs.

The promise of lithium-ion solid-state batteries is that they will replace the heavy and sometimes dangerous liquid electrolyte — which in car batteries can be volatile at high temperatures when the battery is charged or discharged quickly or when packs are damaged in accidents — with a lighter, more versatile solid alternative.

Although finding a solid electrolyte with conductivity that is comparable with liquids has been a challenge, the advantages are many. The batteries are safer because flammable components have been removed. They deliver more power because solid electrolytes mean that the carbon-based anodes can be replaced with lithium metal, which has a higher energy density and cycle life, with less weight and cost. And without the need to package the liquid electrolyte safely, solid-state batteries can be made in more versatile shapes (even thin films), reducing manufacturing costs. This could make electric cars a more enticing proposition, with longer ranges and a lower purchase price.

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"Imagine batteries that do not catch fire and do not lose storage capacity. That is the promise of solid-state batteries," says Gerbrand Ceder, a materials scientist at the Massachusetts Institute of Technology (MIT) in Cambridge.

Solid-state batteries are not quite ready for mass-market vehicles yet — the Bluecars' batteries need to be warmed up and can power a very small car for 240 kilometres. Scientists are struggling to find solid materials with conductivity similar to that of liquids, as well as working to increase cycle life and longevity, and to improve the solid electrolyte's ability to operate at ambient temperatures.

Yan Eric Wang, a materials scientist who worked with Ceder at MIT, and his team may have found the ideal solid electrolyte (Y. Wang *et al. Nature Mater.* **14,** 1026–1031; 2015). "We found a framework that could lead to identifying electrolyte materials with high ionic conductivity," says Wang. The research, in partnership with electronics firm Samsung, pointed to a class of compounds of lithium, phosphorus, germanium and sulfur called super-ionic conductors.

A solid electrolyte allows batteries to switch to lithium metal anodes, says Jeff Chamberlain, a battery researcher at the Joint Center for Energy Storage Research at Argonne National Laboratory in Illinois. "With a solid-state battery you open up the field of metallic anodes, and make possible a big jump in energy density. That would be a game changer."

To be commercially viable, solid-state batteries need to work reliably for years in a tough automotive environment. And durability is an issue for researchers. Lithium metal, although excellent at storing large amounts of energy at low volume, is very reactive. And it is prone to forming 'dendrites' — tiny lithium spurs that degrade battery performance and can cause a short circuit if they reach the cathode. With conventional lithium-ion batteries, a chemical separation layer guards against dendrites.

Sam Jaffe, managing director of Cairn Energy Research Advisors in Boulder, Colorado, says that solid-state researchers are working with additives in the electrolyte carrier, as well as ceramic shields, in an attempt to block dendrite formation.

PHONES FIRST

In the short term, as solid-state science is evolving, the durability issue may not matter as much in applications such as mobile phones, because consumers tend to switch to newer technology in a year or two — whereas cars are kept for a decade or more. "People turn over portable electronics very quickly," Chamberlain says, "so the ability to inject new technology is higher."

SolidEnergy Systems, headquartered in Waltham, Massachusetts, uses technology developed at MIT and is targeting smartphones. The firm developed an improved electrode material for solid-state batteries that replaces the usual graphite with a very thin film of lithium-metal foil. The electrode's ability to store lithium seems promising (go.nature.com/b3xkhh), and the higher the storage capacity, the more energy the battery can deliver.

Something of a hybrid, SolidEnergy's cell maximizes efficiency by using both a solid and an ionic liquid electrolyte — and works at room temperature. A high-performance car battery is promised within the next four years.

INTERNATIONAL INVESTORS

Commercial solid-state cells for mass-market electric cars are at least a decade away, but they are coming, researchers say. Solving the significant technical hurdles has become a central focus for a group of start-up companies and research labs. Most companies, even those that have generated interest from vehicle manufacturers, are still in the developmental stage. Cosmin Laslau at Lux Research, headquartered in Boston, Massachusetts, says that today's best lithium-ion batteries are approaching 250 watt-hours per kilogram (the early Nissan Leaf had only 140 watt-hours), an impressive measure of energy density, but they will struggle to reach 350 — a performance goal set by the US Battery Consortium. If solid-state batteries can reach 350 "that's a pretty good sustainable advantage over traditional lithium-ion", he says.

This could be good news for the electric vehicle industry. Donald Sadoway, a materials chemist at MIT, says that achieving such high energy densities is key to widespread adoption of electric vehicles. "If we had batteries with 350 watt-hours per kilogram we'd have EVs with 350 miles of range, and that's the end of petroleum," he says.

But scaling up from a cell that generates results in a bench test to a durable, roadworthy battery pack will be a long road. Menahem Anderman, a physical chemist and chief executive of Total Battery Consulting in Oregon House, California, authored the California Air Resources Board's 2000 report on battery technology. "I have not seen any indications of a significant breakthrough or signs that they have a technology likely to find its way into the mass-produced vehicle inside the next ten years," he says. "A new development often shows improvement in one or two areas but experiences difficulties in others."

Chamberlain agrees, and he stretches the timeline a bit further. "To be in showroom cars ten years from now, the solid-state cells would essentially have to be leaving the laboratory now, and I don't think that's happening," he says.

Still, vehicle manufacturers are interested, whatever the timeframe, as evidenced by a rash of investment and acquisitions over the past few years. In 2014, Volkswagen bought a 5% stake in QuantumScape, an electronics firm in San Jose, California, that is hoping to benefit from developing solid-state technology that could triple the range of its forthcoming electric cars.

Car manufacturer Toyota says that cells that it has developed with double the energy density of today's alternatives could provide electric vehicles with a range of 480 kilometres on one charge. It has built prototype cells and even a small scooter powered by the batteries. Positive results have been reported for solid super-ionic electrolytes (N. Kamaya *et al.* *Nature Mater.* **10,** 682–686; 2011). But the company says that cell-energy density is still far below the potential, and production of the batteries is not expected to start until the early 2020s.

Battery-development firm Seeo, based in Hayward, California, which was acquired in August by German auto supplier Bosch, is also making solid-state cells.

Ulrik Grape, a vice-president at Seeo, says that the company's cells represent "a very durable technology with good cycle life. They're as good or better than current lithium-ion." He adds that Seeo packs could be half the weight of those in the current Nissan Leaf — the leading battery electric car worldwide in terms of sales. The company also says its cells achieve 350 watt-hours per kilogram in the lab, but the real-world performance could be less.

One more player, Solid Power, which is based in the Colorado Technology Center in Louisville and is a spin-off from the University of Colorado at Boulder, says it has made lab-scale cells that have reached 400 to 500 watt-hours per kilogram, and up to 500 charging–discharging cycles of durability. Company founder Doug Campbell says that Solid Power is targeting the automotive sector, although its first market may be the armed forces, for use in communications equipment. "Troops in the field can carry 60 pounds of batteries, and if we can cut that in half, it's a strong value proposition for the US military," he says.

"Everything that we have done to date can in principle be done at scale."

For competitive reasons, many of the lab-stage battery companies are keen to emphasize the positive aspects of their research, but not all are forthcoming with sample cells or technical details. Sakti3, based in Ann Arbor, Michigan, and headed by former University of Michigan engineer Ann Marie Sastry, is promising greatly improved energy density and an improved manufacturing process, with weight and cost savings, from its thin-film cells that operate at ambient temperatures. Sastry says that the company, with investments from General Motors and UK-based Dyson, has demonstrated that it can double the density of conventional lithium-ion at the lab scale.

But Sakti3 has released little information about its chemistry or its results, so its claims are difficult to verify. Laslau estimates that Sakti3 has reached a fairly impressive 300 watt-hours per kilogram, but Sastry says that the company is not disclosing energy-density results just yet.

Cost to manufacture is another important factor. "We do think that solid-state technology will enable much better performance, at lower cost, than the incumbents," Sastry says. Her company is aiming for cells that cost just $100 per kilowatt-hour, which means around $2,400 for an average-sized electric-vehicle pack, plus costs for packaging, transportation and other factors. Nissan currently sells its lithium-ion packs for $5,499 in the United States, although it may be losing money on every sale. Asked if her cells could enable the goal of a 450-km, $25,000 electric car, Sastry says: "At least."

Scaling up to that level, Sastry admits, will be challenging because of the need to invent manufacturing processes. But "everything we have done to date can in principle be done at scale".

The 30-kilowatt-hour solid-state lithium metal polymer battery packs in the Bluecars are here now, but the 240-km range is not a huge improvement on current technology. BlueIndy's packs require heating above ambient temperature, and that uses some of the battery's energy and reduces range.

Solid-state-battery researchers will surely hit some as-yet unforeseen roadblocks on the way to a commercially durable cell. For cars, conventional lithium-ion probably has at least a decade of dominance remaining, although Sadoway believes that "the rush to deployment would be very, very fast" if stable, high-density solid-state cells were developed.

Solid-state batteries, Sadoway adds, "would be preferable, because they're a lot safer". The lithium-ion fires that have occurred on some aircraft show what can happen when you rush to scale up battery technology without doing your homework first. ■

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Lithium-ion batteries have led to fires in some aircraft.

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