IN DEPTH

In 2014, Airbus's Zephyr 7 drone relied on lithium-sulfur batteries for an 11-day nonstop flight.

ELECTROCHEMISTRY

Lithium-sulfur batteries poised for leap

Promising chemistry is starting to compete commercially with lithium-ion

By **Robert F. Service**

Take that, Tesla. Researchers at Oxis Energy, a startup company in Abingdon, U.K., are building batteries with a combination of lithium and sulfur that store nearly twice as much energy per kilogram as the lithium-ion batteries in electric cars today. The batteries don't last very long, conking out after 100 or so charging cycles. But the company hopes that for applications such as aerial drones, submersibles, and power packs that could be shouldered by soldiers, weight will matter more than price or longevity. Oxis's small pilot factory aims for an annual production of 10,000 to 20,000 batteries, which sit in thin pouches the size of cellphones.

The Gigafactory this is not—at least not yet. But Chief Technology Officer David Ainsworth says the company has its eye on a far bigger prize: the $100 billion electric vehicle market. "The next few years will be critical," Ainsworth says. He and others see lithium-sulfur as the heir apparent to lithium-ion as the dominant battery technology.

They are encouraged by a spate of recent reports suggesting that many of the technology's performance and durability challenges can be overcome. "You're seeing advances on a number of fronts," says Brett Helms, a chemist at Lawrence Berkeley National Laboratory in California. Others, like Linda Nazar, a chemist and lithium-sulfur pioneer at the University of Waterloo in Canada, remain cautious. "It's a really tall order" to create high-capacity lithium-sulfur batteries that are also cheap, lightweight, small, and safe, she says. Improving one factor, she adds, often comes at the expense of others. "You can't optimize all of them simultaneously."

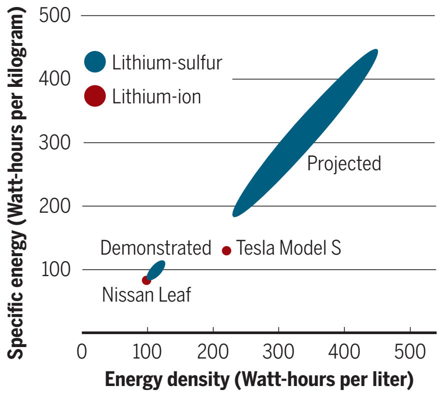
Lithium-ion batteries contain two electrodes—an anode and a cathode—separated by a liquid electrolyte that allows lithium ions to move back and forth during charging cycles. At the anode, lithium atoms are wedged between layers of graphite, a highly conductive type of carbon. As the battery discharges, the lithium atoms give up electrons and generate a current. The resulting positively charged lithium ions move into the electrolyte. After powering anything from a cellphone to a Tesla, the electrons wind up back at the cathode, which is typically made from a mix of different metal oxides. Here, the positive lithium ions in the electrolyte snuggle up next to metal atoms that have taken up the traveling electrons. Charging reverses this molecular shuffle as an external voltage pushes the lithium ions to ditch their metallic hosts and return to the anode.

Metal oxide cathodes are reliable. But the metals—typically a combination of cobalt, nickel, and manganese—are expensive. And because it takes two metal atoms working together to hold a single electron, these cathodes are heavy, which limits the capacity of these cells to about 200 watt-hours per kilogram (Wh/kg). Sulfur is much cheaper, and each sulfur atom can hold two electrons. Theoretically, a battery with a sulfur cathode can store 500 Wh/kg or more.

But sulfur is anything but an ideal material for an electrode. For starters, it's insulating: It won't pass electrons to lithium ions crossing over from the anode. That was a deal breaker until 2009, when researchers led by Nazar showed that the sulfur could be embedded within a cathode that, like the anode, was made of conductive carbon. It worked, but it brought other problems. Forms of carbon like graphite are highly porous. That adds to the overall size of the battery without boosting its storage capacity, and it means that more of the expensive liquid electrolytes are needed to fill the pores. Even worse, when lithium ions bind to sulfur atoms at the cathode, they react to form soluble molecules called polysulfides that float away, degrading the cathode and limiting the number of charging cycles. Polysulfides can also migrate to the

Powering up

Lithium-sulfur batteries have the potential to be both smaller and lighter than lithium-ion batteries.



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anode, where they can wreak further havoc.

Now, advances are coming on all fronts. Three groups have made strides in solving problems at the cathode. Last year, for example, researchers led by Helms reported in *Nature Communications* that they added a polymer layer to a carbon-sulfur cathode, sealing in the polysulfides and enabling the battery to survive 100 charging cycles. Another group, led by Arumugam Manthiram at the University of Texas in Austin, replaced the graphite in a cathode with highly conductive graphene—graphite in sheets just a single atom thick. As they reported in the 12 January issue of *ACS Energy Letters*, the graphene cathodes held five times as much sulfur as traditional graphite ones, thereby boosting energy storage. And 2 weeks ago researchers led by Nanfeng Zheng, a chemist at Xiamen University in China, reported in *Joule* that they had created an ultrathin "separator" by topping a thin sheet of polypropylene with nitrogen-doped carbon particles. The separator sits atop the cathode, traps polysulfides, and converts them to harmless lithium-sulfide particles. That increased the energy output of the cells and helped them survive 500 charging cycles.

Others are working to fix the polysulfide problem by tweaking the electrolyte. In the 25 May 2017 issue of *ACS Central Science*, Nazar and her colleagues reported that they had made an electrolyte that permits the passage of lithium ions but inhibits the creation of soluble polysulfides.

Many teams are also targeting the anode, aiming to replace the lithium and graphite combination with pure lithium metal. That could boost the capacity of lithium-ion batteries to 500 Wh/kg—enough to drive a car nearly 500 kilometers between charges—and yield even bigger gains for lithium-sulfur batteries. To date, however, pure lithium anodes have been stymied by problems during charging, when lithium atoms migrate back from the cathode. They tend to pile up in one spot, creating spiky growths that can pierce the battery and cause shorts and even fires. Oxis Energy and another battery startup, Sion Power in Tucson, Arizona, say they have developed proprietary barriers around the anode that prevent the spiky growths. And this week in *Nature Energy*, researchers at Cornell University reported stabilizing their lithium anode with a tin alloy.

All of these advances will help push lithium-sulfur batteries forward, says George Crabtree, who directs the Joint Center for Energy Storage Research at Argonne National Laboratory in Lemont, Illinois. "It's hard to tell whether these are the final breakthroughs that are going to make it," he says. "But I'm optimistic." Electric car drivers everywhere hope he's right. ■

EUROPE

Germany's new government makes big promises

Coalition says it will hike research spending to 3.5% of gross domestic product—but is that feasible?

By **Gretchen Vogel**, *in Berlin*

Nearly 6 months after it held federal elections, Germany finally has a new government—and some welcome news for scientists. The new coalition, the fourth led by Chancellor Angela Merkel, has pledged to boost overall R&D spending from 2.9% to 3.5% of the country's gross domestic product (GDP) by 2025. That would make Germany a world leader in research spending, behind only South Korea and Israel. "The signs … are really quite promising," says Wilhelm Krull, secretary general of the Volkswagen Foundation in Hanover, Germany, a large private research funder.

But whether the government can deliver remains to be seen; it's not clear where the extra billions would come from. Meanwhile, researchers are wondering what to expect from the new research and education minister, Anja Karliczek, who trained as a banker and spent 2 decades running her family's hotel. And some chafe at the new government's positions on agricultural technology and climate.

The new German research and education minister, Anja Karliczek.

Germany's center-left Social Democratic Party voted to approve the coalition with Merkel's center-right Christian Democratic Union and its Bavarian sister party on 4 March. The three parties, which made up the previous government, all lost seats in the elections, leaving them reluctant to continue their collaboration. But after talks about a different coalition fell apart last November, the remaining options—a minority government or new elections—were even less appealing.

The three parties say a sharp rise in R&D budgets is necessary to keep Germany's edge in innovation, but don't detail how to get there. The agreement promises a yearly 3% increase in federal funding for research organizations such as the Max Planck Society and the Helmholtz Association of German Research Centres, but much more would be needed to reach the promised 3.5% of GDP. The government would also have to entice the private sector, which accounts for two-thirds of current research spending, to spend more freely, Krull says, for instance through tax breaks and matching funds. Still, says Jörg Hacker, president of the German national academy of sciences, the Leopoldina, in Halle, the target is welcome. "One has to have ambitious goals, or you don't get anywhere," he says.

In a stance that may be less popular among researchers, the new government favors a nationwide ban on planting genetically modified crops. No such crops are currently grown in Germany, but a complete ban would be very restrictive, Hacker says. He says research leaders will continue to lobby for gene technology regulations that focus on the benefits or drawbacks of the end product, rather than on the technique used to make it.

Meanwhile, climate activists say the coalition's goals aren't nearly ambitious enough. During the election campaign, Merkel said Germany would meet its target of reducing carbon emissions by 40% (from 1990 levels) by 2020, but the parties now admit that won't happen; current projections predict a 32% decrease. The government promises to redouble efforts to meet the 2030 goal of cutting emissions by 55%, but it has not named a deadline for phasing out coal. Environmental groups say the parties are too protective of Germany's auto and coal industries.

The biggest surprise was Merkel's choice of the little-known Karliczek, who has mostly worked on finance issues since her election to the German Bundestag in 2013. (Observers think the fact that she is young, female, and conservative played a role.) Karliczek told German media that research leaders should expect her to ask lots of questions. Her background in finance and management could be good preparation for many of her tasks as minister, Hacker says. "We look forward to meeting with her as soon as possible." ■

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