as a source. "You can just burn away the organics, and what's remaining is this silicon oxide nanoparticle," he explains. A silicon anode can store more lithium, hence considerably more energy, than batteries commonly used today.

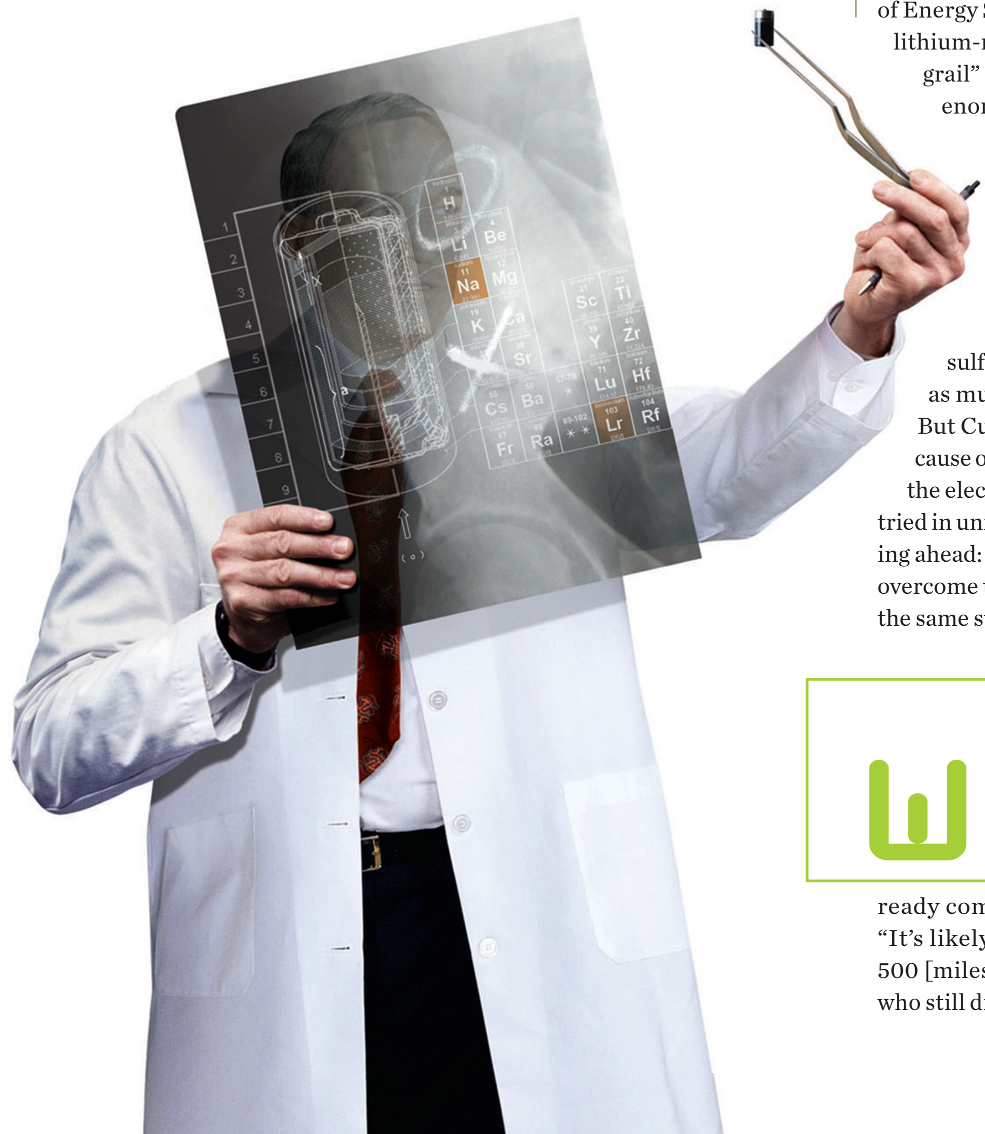
To build cheaper anodes and cathodes, researchers in Cui's group have also been trying to extract tiny carbon fibers from materials as simple as crab shells. Once, some of them bought stone crabs at a Chinese grocery store in California. They burned them so that just the calcium-carbonate shell remained, then made a powder from it. After more tinkering, they emerged with hollow carbon nanofibers.

For most of the past decade, Cui and his large team of graduate students and postdocs (35 currently work at the Moore lab) have built different silicon structures to incorporate into batteries. The goal is to keep the silicon together: It's a brittle material, prone to stretching when it reacts with lithium and then breaking as the battery charges. It also has a bad habit of reacting with the electrolyte in the battery, which creates "gunk" and harms performance.

To prevent the silicon from breaking, Cui and his team tried different configurations, including silicon nanowires and silicon particles that were too small to break. They developed an "egg" structure that gave the silicon, encased loosely like a yolk in a carbon shell, some room to bulge without cracking the coating. In February, they announced the development of a "pomegranate" structure, in which the seed-like "eggs" are gathered up into clusters within a larger carbon "rind," thus reducing the contact between silicon particles and the electrolyte. "With the seventh generation of this design, we finally feel like silicon is getting there," Cui told the energy seminar audience. The next steps are to reduce the work required to make the pomegranate structures on a large scale, and find a way to cheaply extract silicon nanoparticles from rice husks or another source. (Amprius, Cui's company, is already using silicon anodes commercially.)

Batteries are a tough and expensive field to crack, and several high-profile companies have gone bankrupt in the last few years. But Cui is undaunted, and last year he began working with former U.S. Secretary of Energy Steven Chu on another battery, featuring a lithium-metal anode that Cui describes as the "holy grail" of energy storage technology because of its enormous capacity. Chu, a professor of physics and of molecular and cellular physiology, doesn't work in the lab but provides advice; he has, says Cui, "a lot of ideas about batteries."

Cui is also focusing on sulfur for a battery cathode. Sulfur is widely available and has a high capacity, so a lithium-sulfur combination could pack four to six times as much energy as existing battery technology. But Cui says sulfur is also "very challenging" because of conductivity problems. It can dissolve into the electrolyte. Lithium-sulfur batteries have been tried in unmanned vehicles but little else. Cui is pressing ahead: Having tried different shapes and forms to overcome the shortcomings of silicon, he wants to use the same strategy for sulfur.



VIKTOR KOEN

With automakers and electronics companies clamoring for the next generation of lightweight lithium batteries, improvements may come quickly. Amprius, which recently added Chu to its board, has already commercialized its lithium-silicon battery. "It's likely in 10 years we can have the Tesla drive 500 [miles]"—about double its range now, says Cui, who still drives a 12-year-old car but says his next will probably be an EV. The trick will be keeping the battery cheap and lightweight.

Reshaping the electric grid represents another huge challenge, with enormous stakes. Renewable energy, especially solar power, is touted as a key part of the solution to climate change and energy independence. Solar growth has been rapid as prices for the Chinese-made panels have plunged. Always drawn to the cutting edge, Cui has put plenty of time into the solar problem, in addition to batteries. One second-year PhD student in his lab, Thomas Hymel, demonstrated a high-efficiency solar cell so thin and flexible it can be rolled "like a carpet," in Cui's description, allowing it to more easily adhere to a bumpy surface, among other advantages. "If you can convert just .01 percent of the energy coming to the earth every day," says Cui, "that can power the whole world."

But if solar power is going to get big, the ability to store energy for use in non-sunny periods will become of paramount concern. Right now, incredibly, the most common large-scale energy storage systems in the United States are hydroelectric plants. Water is pumped uphill during times of excess energy and then released through hydropower turbines when the electricity is needed. It's a cumbersome process, and it's not possible in places without dams. In the lab, Cui is testing semi-liquid batteries—lithium metal in a polysulfide solution, in which the liquid reacts with the lithium during charging. Any applications for the grid need to be "very low-cost and highly scalable," he says.

Down the line, Cui has an even bigger vision for batteries, even the common ones that power phones and toys. "I think it would be really cool to do wireless charging in the future," he says dreamily. However, "I haven't worked on anything like that yet." ■

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BATTERIES: AN INSIDE STORY

If Cui succeeds in making the new materials work, it will be partly because he can see inside the experimental batteries while they are operating. This "in situ" technology, providing extraordinary black-and-white images, has become readily available only in the past several years and is improving all the time. High-energy, extra-bright X-rays generated at the SLAC National Accelerator Laboratory can capture a material expanding and breaking, helping researchers probe batteries closely. The X-rays travel through helium-filled pipes so that they are not absorbed too soon, and then get focused through a condenser lens on the tiny battery sample that had been prepared in an argon-filled box, away from moisture and oxygen.

Johanna Nelson Weker, an associate staff scientist at the Stanford Synchrotron Lightsource within SLAC, has been x-raying batteries for Cui and others for more than three years. She has seen some fascinating things. One battery, made from the element germanium, expanded and contracted before her eyes, as the lithium ions moved between the cathode and anode while the battery charged and discharged. "We can watch them essentially breathe," she says. "As you lithiate them, they expand, and as you de-lithiate them, they contract." A recent X-ray image showed one of Cui's new experiments with silicon particles in a self-healing polymer—the silicon expands and breaks the polymer, which mends itself. The image was black-and-white and appeared to a lay viewer the way clouds do from a plane. Soon, Weker hopes to add another dimension to the images, so that they will appear in color, reflecting their chemical state.

With that ability, researchers could "see where the lithium is going, really," she says. "And that's what everybody wants to know. We can't actually see the lithium, but we can see this interact with the metal." The goal is to "see the lithium basically changing a particle from red to green as it lithiates, and then green to red as it de-lithiates."

The trick is "getting the information you want without damaging your sample," Weker says. That means making sure the batteries are not overexposed to radiation through too frequent X-rays. Some samples stay in the X-ray booth for more than a day, with X-rays running every half-hour.

Electron microscopy, available at Stanford rather than SLAC, produces even higher-resolution images of atoms. However, in order to absorb the electrons, the batteries must be so thin that they are "not close to a normal operating battery," Weker says. Still, she says, the technique is good for very thin materials such as the silicon nanowires Cui has used as a building block.

Cui is bullish on imaging technology. "It can further improve," he says, but "even with the current capability, there's a lot of battery problems we can study."