Corrected 13 November 2018. See full text.

been mapped in detail with modern sonar technology, Wigley says, and only 18% of the world's ocean bottom has been surveyed at all, often at resolution so coarse that jumbo jets—and volcanoes—would have no trouble hiding. The rest—four-fifths of the two-thirds of the planet covered by water—is virtually unknown. As usual, the limitations are money and time. The research vessels that do high-resolution mapping cost up to $100,000 a day to operate. And they move so slowly that it would take centuries for them to chart the world's oceans, Virmani says.

Satellites can also map the sea floor, by measuring slight variations in the ocean surface caused by the gravitational pull of massive seafloor features. But the resolution is crude. In recent years, researchers have turned to autonomous underwater vehicles (AUVs). They follow preprogrammed paths using inertial navigation systems that precisely track their speed and direction, and carry miniature multibeam sonars. By cruising close to the ocean bottom, they can detect contours in the seabed smaller than a centimeter—a vast improvement over the 50-meter resolution of a typical ship-based system working in the deep ocean, says Clague, who is not involved in the XPRIZE contest. But the AUVs are still slow. "You cover an area about the size of a football field in a 12-hour survey," he says. Efforts to add batteries and extend diving time only bulk up the AUV, requiring bigger ships to launch them, "which kind of defeats the purpose," Clague says.

XPRIZE hopes its competition will spark faster, cheaper autonomous systems. Starting from shore, the eight finalists must map between 250 and 500 square kilometers in 24 hours, at depths down to 4000 meters and resolutions of 5 meters or better. They must also carry instruments to collect images of 10 interesting features and find a trophy stashed on the sea floor. The technical challenges include building instruments to withstand enormous pressure, balancing battery life against speed, and making the robots smart enough to carry out the whole operation without human guidance. "Everything is hard," says Martin Brooke, an engineer at Duke University in Durham, North Carolina, and leader of its XPRIZE team.

Brooke's group—mostly engineering students—will try to gain time by using heavy-lift aerial drones to carry buoys that will lower tethered mapping pods into the ocean. Most teams use an autonomous surface vessel to save their AUV's precious power and to serve as a communication hub. The Swiss CFIS team, led by Toby Jackson, a financial trader–turned–inventor, will send 20 lightweight, 3D-printed AUVs directly from shore. Instead of sonar, they will use lasers, which can bounce light off the sea floor because they are at such close range.

Team Tao will also use a swarm approach, launching five custom-built AUVs from an autonomous catamaran it calls the "vending machine." Eventually, the system will carry two dozen subsea drones, says team leader Hua Khee Chan, an engineer at Newcastle University in the United Kingdom, allowing half to work while the others charge. Each AUV will follow a simple vertical path, enabling it to sample the temperature and salinity of the water column as it descends. Chan says it's "extra data that we get for free while it's traveling." Both Chan and Jackson say they aim to produce their AUVs for less than $25,000 a pop—a bargain compared with the sophisticated models used today, which can cost $1 million or more.

Cheaper, more flexible systems could help researchers rapidly fill the gaps in seafloor maps—and enable repeat surveys to monitor changes over time. Clague would like to measure how much lava is produced during a single eruption on a midocean ridge, which gives clues about magma generation in the mantle. Repeat mapping could also track movement along offshore faults that generate earthquakes, and in seafloor sediments after major weather events.

"... you go into the ocean and things are not like math."
Nuno Cruz, University of Porto

As XPRIZE's sponsor, Shell reserves first rights to negotiate with each team for use of its technology, which it could use for oil and gas exploration or to monitor production wells and pipelines. Companies hoping to mine the sea floor for minerals are also eager to get a better look. But Wigley says mapping could also aid in marine protection. "If we understand the sea floor better, we can manage where it's happening better and understand the impacts better."

For now, that's a long way off, and most teams are just scrambling to prepare for the competition in Greece. A Portuguese team still hasn't tested its acoustic positioning system, which relies on a constellation of floating beacons, in deep water. "From the math, it should work," says team leader Nuno Cruz, an engineer at the University of Porto in Portugal. "But you go into the ocean and things are not like math." Some teams already know they won't win, but they are fine with that. Most entered for the challenge, not the purse, and XPRIZE is pleased with the progress they've made, Virmani says. "We've already shifted the field." ■

Julia Rosen is a journalist based in Portland, Oregon.

ENERGY

Advances in flow batteries promise cheap backup power

Upstart technology could enable widespread adoption of renewables

By **Robert F. Service**

Batteries already power electronics, tools, and cars; soon, they could help sustain the entire electric grid. With the rise of wind and solar power, energy companies are looking for ways to keep electrons flowing when the sun doesn't shine and the wind ebbs. Giant devices called flow batteries, using tanks of electrolytes capable of storing enough electricity to power thousands of homes for many hours, could be the answer. But most flow batteries rely on vanadium, a somewhat rare and expensive metal, and alternatives are short-lived and toxic.

Last week, researchers reported overcoming many of these drawbacks with a potentially cheap, long-lived, and safe flow battery. The work is part of a wave of advances generating optimism that a new generation of flow batteries will soon serve as a backstop for the deployment of wind and solar power on a grand scale. "There is lots of progress in this field right now," says Ulrich Schubert, a chemist at Friedrich Schiller University in Jena, Germany.

Lithium-ion batteries—the sort in laptops and Teslas—have a head start in grid-scale applications. Lithium batteries already bank backup power for hospitals, office parks, and even towns. But they don't scale up well to the larger sizes needed to provide backup power for cities, says Michael Perry, associate director for electrochemical energy systems at United Technologies Research Center in East Hartford, Connecticut.

That's where flow batteries come in. They store electrical charge in tanks of liquid electrolyte that is pumped through electrodes to extract the electrons; the spent electrolyte returns to the tank. When a solar panel or turbine provides electrons, the pumps push spent electrolyte back through the electrodes, where the electrolyte is recharged and returned to the holding tank (see graphic, right). Scaling up the batteries to store more power simply requires bigger tanks of electrolytes.

Vanadium has become a popular electrolyte component because the metal charges and discharges reliably for thousands of cycles. Rongke Power, in Dalian, China, for example, is building the world's largest vanadium flow battery, which should come online in 2020. The battery will store 800 megawatt-hours of energy, enough to power thousands of homes. The market for flow batteries—led by vanadium cells and zinc-bromine, another variety—could grow to nearly $1 billion annually over the next 5 years, according to the market research firm MarketsandMarkets.

But the price of vanadium has risen in recent years, and experts worry that if vanadium demand skyrockets, prices will, too. A leading alternative replaces vanadium with organic compounds that also grab and release electrons. Organic molecules can be precisely tailored to meet designers' needs, says Tianbiao Liu, a flow battery expert at Utah State University in Logan. But organics tend to degrade and need replacement after a few months, and some compounds work only with powerful acidic or basic electrolytes that can eat away at the pumps and prove dangerous if their tanks leak.

Researchers are now in the midst of "a second wave of progress" in organic flow batteries, Schubert says. In July, a group led by Harvard University materials scientist Michael Aziz reported in *Joule* that they had devised a long-lived organic molecule that loses only 3% of its charge-carrying capacity per year. Although that's still not stable enough, it was a big jump from previous organic flow cell batteries that lost a similar amount every day, Liu says.

Iron, which is cheap and good at grabbing and giving up electrons, is another promising alternative. A Portland, Oregon, company called ESS, for example, sells such batteries. But ESS's batteries require electrolytes operating at a pH between one and four, with acidity similar to vinegar's.

Now, Liu and his colleagues have come up with a flow battery that operates at neutral pH. They started with an iron-containing electrolyte, ferrocyanide, that has been studied in the past. But in previous ferrocyanide batteries, the electrolyte was dissolved in water containing sodium or potassium salts, which provide positively charged ions that move through the cell to balance the electron movement during charging and discharging. Ferrocyanide isn't very soluble in those salt solutions, limiting the electrical storage capacity of the battery.

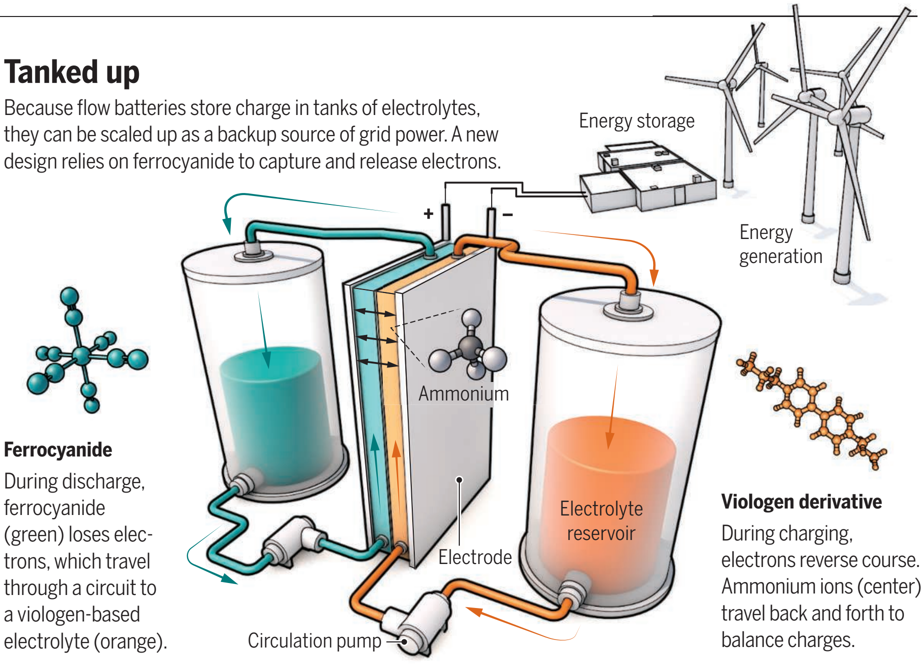
So Liu and his colleagues replaced the salts with a nitrogen-based compound called ammonium that allows at least twice as much ferrocyanide to dissolve, doubling the battery's capacity. The resulting battery is not as energy-dense as a vanadium flow battery. But in last week's issue of *Joule*, Liu and his colleagues reported that their iron-based organic flow battery shows no signs of degradation after 1000 charge-discharge cycles, equivalent to about 3 years of operation. And because the electrolytes are neutral pH and water-based, a leak likely wouldn't produce environmental damage.

"Overall, that's an excellent piece of work," says Qing Wang, a materials scientist at the National University of Singapore. Still, he and others caution that the battery is sluggish to charge and discharge. Liu says he and his colleagues plan to test other electrolyte additives, among other fixes, to boost conductivity.

It's too early to say which flow battery chemistry—if any—will support the renewable grid of the future. Another contender uses electrolytes made from metal-containing organic compounds called polyoxometalates, which store far more energy in the same volume than the competition. In the 10 October issue of *Nature Chemistry*, for example, researchers led by Leroy Cronin, a chemist at the University of Glasgow in the United Kingdom, reported a polyoxometalate flow battery that stores up to 40 times as much charge as vanadium cells of the same volume. The downside for now is that these electrolytes are highly viscous and thus more challenging to pump through the battery, Cronin says. "Today, no one flow battery fills all the needs," Schubert says. That means there's still plenty of room for innovation. ■

Tanked up

Because flow batteries store charge in tanks of electrolytes, they can be scaled up as a backup source of grid power. A new design relies on ferrocyanide to capture and release electrons.



Commercial flow batteries, such as this zinc-bromine system from Redflow, are helping back up renewables.

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Science

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