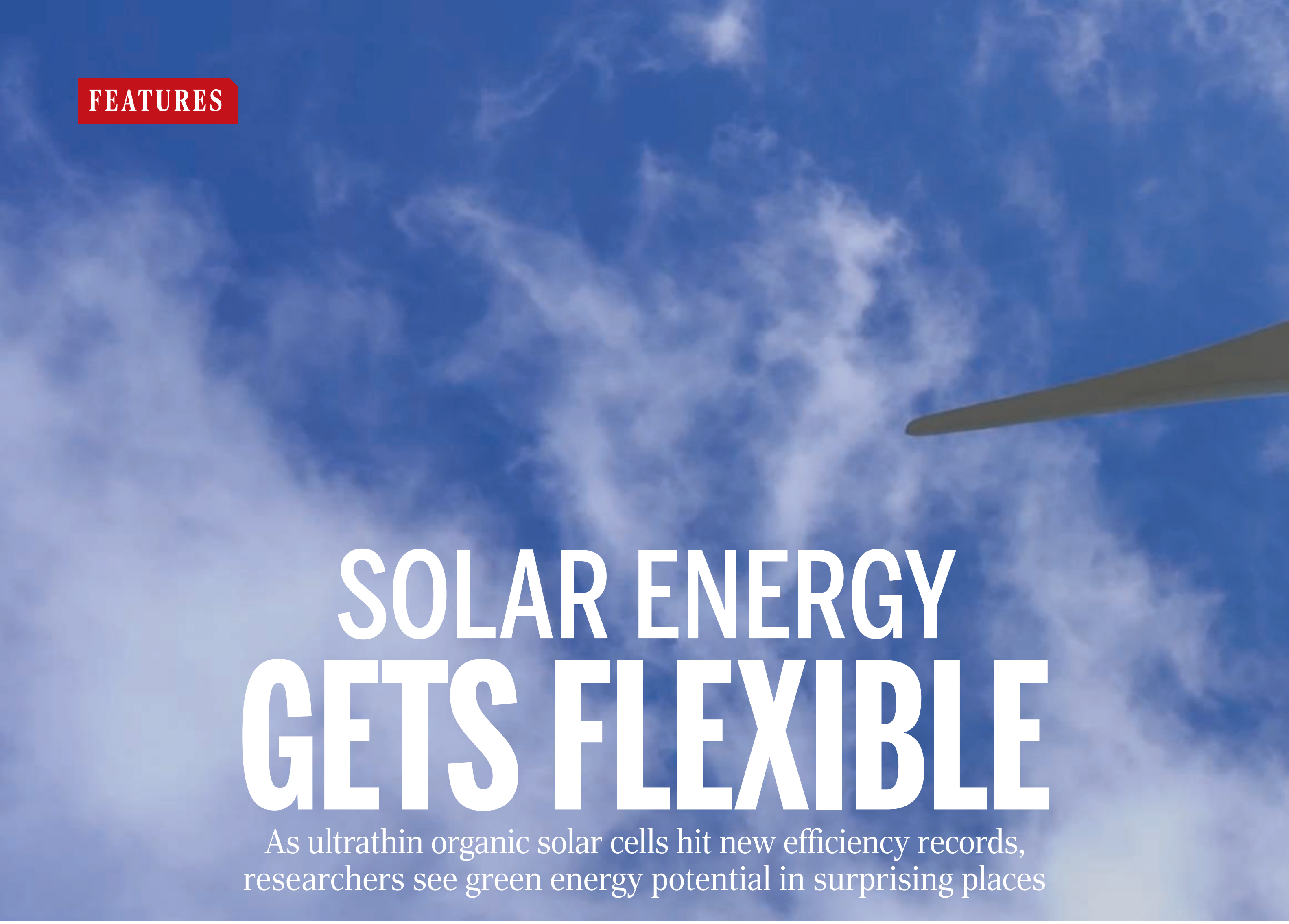

FEATURES

SOLAR ENERGY GETS FLEXIBLE

As ultrathin organic solar cells hit new efficiency records, researchers see green energy potential in surprising places

By **Robert F. Service**

In November 2021, while the municipal utility in Marburg, Germany, was performing scheduled maintenance on a hot water storage facility, engineers glued 18 solar panels to the outside of the main 10-meter-high cylindrical tank. It's not the typical home for solar panels, most of which are flat, rigid silicon and glass rectangles arrayed on rooftops or in solar parks. The Marburg facility's panels, by contrast, are ultrathin organic films made by Heliatek, a German solar company. In the past few years, Heliatek has mounted its flexible panels on the sides of office towers, the curved roofs of bus stops, and even the cylindrical shaft of an 80-meter-tall windmill. The goal: expanding solar power's reach beyond flat land. "There is a huge market where classical photovoltaics do not work," says Jan Birnstock, Heliatek's chief technical officer.

Organic photovoltaics (OPVs) such as Heliatek's are more than 10 times lighter than silicon panels and in some cases cost just half as much to produce. Some are even transparent, which has architects envisioning solar panels not just on rooftops, but incorporated into building facades, windows, and even indoor spaces. "We want to change every building into an electricity-generating building," Birnstock says.

Heliatek's panels are among the few OPVs in practical use, and they convert about 9% of the energy in sunlight to electricity. But in recent years, researchers around the globe have come up with new materials and designs that, in small, labmade prototypes, have reached efficiencies of nearly 20%, approaching silicon and alternative inorganic thin-film solar cells, such as those made from a mix of copper, indium, gallium, and selenium (CIGS). Unlike silicon crystals and CIGS, where researchers are mostly limited to the few chemical options nature gives them, OPVs allow them to tweak bonds, rearrange atoms, and mix in elements from across the periodic table. Those changes represent knobs chemists can adjust to improve their materials' ability to absorb sunlight, conduct charges, and resist degradation. OPVs still fall short on those measures. But, "There is an enormous white space for exploration," says Stephen Forrest, an OPV chemist at the University of Michigan, Ann Arbor.

Even when labmade OPVs look promising, scaling them to create full-size panels remains a challenge, but the potential is enormous. "Right now is a really exciting time in OPVs because the field has made huge leaps in performance, stability, and cost," says Bryon Larson, an OPV expert at the National Renewable Energy Laboratory.

CONVENTIONAL SOLAR POWER—mostly based on silicon—is already a green energy success, supplying roughly 3% of all electricity on the planet. It's the biggest new source of power being added to the grid, with more than 200 gigawatts coming online annually, enough to power 150 million homes. Backed by decades of engineering improvements and a global supply chain, its price continues to drop.

But solar and other green energy sources aren't growing nearly fast enough to meet growing demand and forestall catastrophic climate change. Between the march of

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Curved thin-film panels made by Heliatek, a German solar company, cover a wind turbine in Spain.

global economic development, population growth, and the expected shift of much of the world's cars and trucks from petroleum to electricity, the world's electricity demand is expected to double by 2050. According to the latest estimates from the International Energy Agency, to achieve global net zero carbon emissions by 2050, countries must install renewables at four times the current pace, a challenge the agency calls "formidable." The world needs new sources of renewable power, and fast.

OPV advocates don't see the technology replacing conventional silicon panels for most uses. Rather, they see it helping usher in a wave of new applications and ultimately putting solar in places silicon panels won't work. The field got its start in 1986 when plastic film experts at the Eastman Kodak Company produced the first OPV, which was only 1% efficient at converting the energy in sunlight to electricity. But by the early 2000s, fiddling with the chemical knobs had pushed OPV efficiencies up to about 5%, enough for several companies to try to commercialize them. Their hope was that printing panels on roll-to-roll machines such as newspaper presses would make devices cheap enough to be useful despite their shortcomings. But poor efficiency and degradation under relentless sunlight doomed the early models. "The excitement was there but it was a little too early," Larson says.

Part of the difficulty in raising OPV efficiencies—then as now—is that they work differently from cells made from inorganic materials, such as silicon. All solar cells are sandwichlike devices, with semiconductors in the middle that absorb photons and convert that energy to electrical charges, which then migrate to metallic electrodes layered above and below. When sunlight strikes silicon cells, the added energy kicks electrons out of their orbits around individual silicon atoms, freeing them to flow through the material. Each excited electron leaves behind an electron vacancy, also known as a "hole," which carries a positive charge. The positive charges flow to a negatively charged electrode (the cathode), whereas the electrons flow to a positively charged electrode (the anode), creating an electric current.

By contrast, the molecules in organic semiconductors tend to hold onto their charges more tightly. When OPVs absorb sunlight, there's enough energy to kick an electron out of its atomic orbit, but not enough for the positive and negative charges to split up and move their separate ways. Rather, these opposite charges stick to each other, creating what is known as an exciton. To generate electricity, the excitons must be separated into positive and negative charges that can travel to their respective electrodes.

The moment of separation comes when excitons move and encounter an interface between two semiconducting components, called donor and acceptor materials. The acceptor attracts electrons, and the donor attracts the positive holes, pulling the exciton apart. It needs to happen quickly: If the excited electron and hole happen to combine with each other before they can reach that interface, they often release their original jolt of excitation as heat, wasting it.

Over the decades, OPV researchers have sought to improve the performance of their devices by coming up with improved

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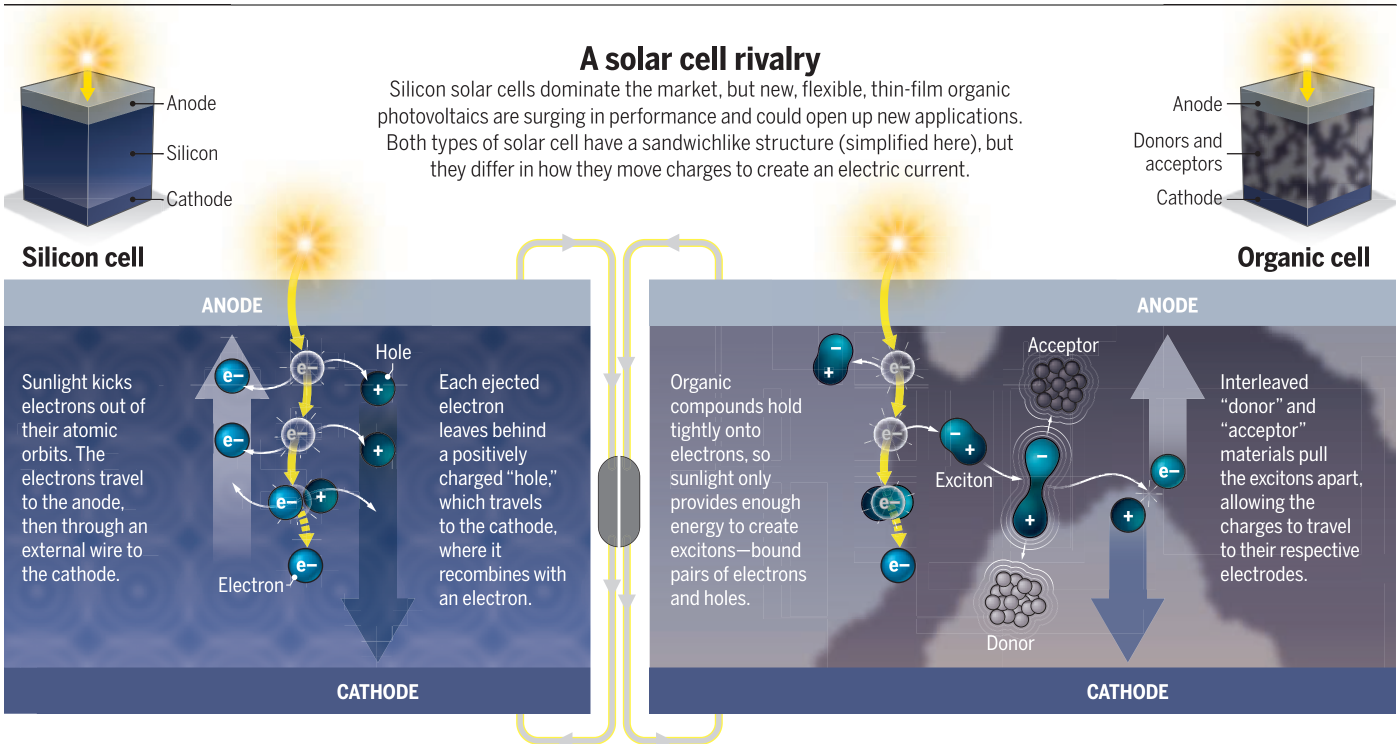


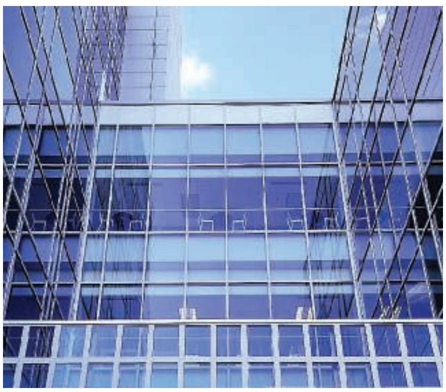
donors and acceptors. Work through the mid-2000s pushed the efficiency above 5%, mainly by incorporating soccer ball–shaped carbon compounds called fullerenes into the materials. The fullerenes' hunger for electrons makes them powerful acceptors. For the next decade, the action shifted to the donors. By 2012, a series of novel semiconducting polymers used as donors propelled efficiencies to 12%.

Then the field suffered a double blow. First, progress plateaued as researchers struggled to find the next breakthrough material. Then a rival thin-film solar technology, called perovskites, burst on the scene. Perovskites are blends of organic and inorganic compounds that are cheap to make, easy to process, and great at capturing sunlight and turning it into electricity. While OPV progress stalled, the efficiency of perovskites skyrocketed from about 6.5% in 2012 to about 24% in 2020. "Perovskites were a stick of dynamite dropped into the OPV world," Larson says. Funding agencies bailed on OPVs and researchers flocked to the hot upstart. "Perovskites were a bandwagon you simply had to be on," says Karl Leo, an OPV researcher at the Technical University of Dresden.

Today, perovskites remain hot. But challenges with long-term stability and their reliance on toxic elements have sapped some enthusiasm. Meanwhile, OPVs soon got a burst of innovation of their own.

In 2015, researchers led by Xiaowei Zhan, a materials scientist at Peking University, reported the first of a new class of nonfullerene acceptors (NFAs). Although fullerenes were good at grabbing and transporting electrons, they were lousy at absorbing sunlight. On a molecular level, Zhan's new compound, dubbed ITIC, looked like an extended Olympic symbol with extra rings, and it did both jobs well, first absorbing red and infrared light and then transporting electrons once excitons split.

Zhan's first NFA device was only about 7% efficient. But chemists around the globe quickly began to tweak ITIC's structure, producing improved versions. By 2016, new NFAs pushed OPV efficiency to 11.5%. By 2018, they hit 16%. And the records keep coming. Last year, Larson and his colleagues reported in *Nature Communications* that by combining multiple donors, an NFA, and a fullerene in a single layer, they created a material that enabled excitons to live longer, and whisked holes more quickly to their electrode, which pushed its efficiency up to 18.4%. And in August, Zhan Lingling at Hangzhou Normal University and her colleagues reported in *Advanced Energy Materials* that an OPV based on a similar multicomponent strategy achieved 19.3% efficiency. "The progress has been really impressive," says Jean-Luc Brédas, an OPV expert at the University of Arizona. "Twenty percent will be reached soon."


Transparent organic photovoltaics are incorporated into the glass facade of the Biomedical and Physical Sciences Building at Michigan State University.

THAT WOULD BRING OPV cells within a few percentage points of their CIGS and silicon rivals. Still, few market watchers believe OPVs will compete head-to-head with silicon anytime soon. Silicon solar cells already command an $85-billion-a-year market, with a 30-year track record and proven durability.

In contrast, OPVs remain niche products. Cheaper OPVs, such as the Heliatek devices, are hampered by low efficiencies, and more efficient ones are still experimental and costly. So, for now, Forrest says, it's best for OPV manufacturers to target new markets where silicon isn't suitable. "If you're competing against silicon, go home, you've already lost," he says.

One fast-growing use is plastering the energy-generating films on the sides of buildings. CIGS and other inorganic thin films can be used the same way. But demand for Heliatek's panels is brisk enough that even though the company only began to sell them last year, it is already building a factory capable of producing 2 million square meters (m²) annually, enough to provide roughly 200 megawatts of power. Meanwhile, a Swedish company called Epishine sells OPVs that work indoors and can replace

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disposable batteries in everything from temperature sensors to automated lighting controls; it has built its own high-speed production line. U.S. startups Ubiquitous Energy and NextEnergy are developing energy-generating OPV windows that primarily capture infrared photons while allowing visible light to pass through, something CIGS and other opaque thin films can't do. And the U.S. Office of Naval Research (ONR) has its eye on using OPVs as power-producing fabrics for tents, backpacks, and other equipment for soldiers on the move. "We want something we can carry to the front," says Paul Armistead, who oversees OPV funding at ONR.

For OPVs to become a significant source of green energy, however, they will need to compete with their rivals on efficiency and durability—and that requires not only new materials, but also manufacturing finesse. The most efficient devices currently exist only as postage stamp–size prototypes in the lab. In theory, scaling up production from 1-square-centimeter cells to 1-m^2 panels is simple. Organics such as polymers and NFAs can be dissolved in solvents and machine-coated over large areas. But each layer in the sandwichlike device must be completely smooth, with few or no imperfections, which can trap moving charges and reduce the overall efficiency. "To get decent efficiencies everything has to work just right," Armistead says.

Even more challenging is controlling the makeup of the central layer of the sandwich containing the donors and acceptors. This combination of materials is initially laid down as a liquid with donors, acceptors, sometimes other additives, and solvents all mixed together. As the solvent evaporates, the donors and acceptors segregate, creating two intertwining, continuous networks. The result is a large surface area at the interface between the donor and acceptor regions to separate the charges. The continuous networks also allow the opposite charges to flow along their own paths to the electrodes, with electrons cruising through the network of acceptors and holes moving through the donors.

The intertwining ribbons of donors and acceptors must be extremely thin, because excitons created when photons strike the material can only migrate about 20 nanometers before the charges recombine and the opportunity to generate electricity is lost, says Zhenan Bao, a chemist at Stanford University. "You have to get the morphology right," Armistead says. Doing so reliably, on a large scale, remains a challenge.

He and others are encouraged by a study published on 27 October in *Nature Energy* by Jie Min, an OPV expert at Wuhan University, and his colleagues. Min's team tailored a popular approach for manufacturing thin films at high speed called blade coating. The conventional approach, which mixes donors and acceptors together and spreads the liquid across a moving film and evens it out with what looks like a long squeegee, can produce such films at about 2 m per minute. But by squeegeeing the layers separately one right after the other, the researchers laid down a better network of donors and acceptors at up to 30 m per minute. The resulting cells had efficiencies up to nearly 18%. Min's team also calculates that the faster manufacturing rate could drop OPV costs more than 10-fold and make the price per kilowatt-hour (kWh) competitive with silicon.

"It's a three-legged stool and you have to have all three legs," Forrest says. Under intense exposure to the ultraviolet (UV) in sunlight, the organics in solar cells can degrade, much as our skin burns during a day at the beach.

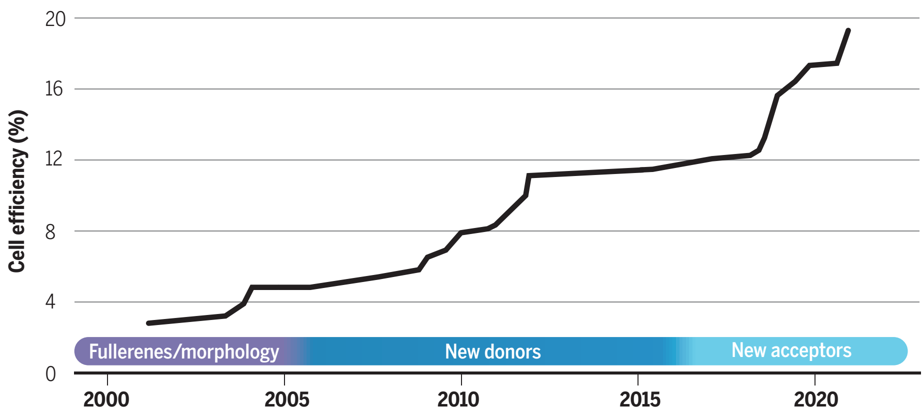
In the 14 September 2021 issue of *Nature Communications*, Forrest and his colleagues reported adding a thin layer of UV-absorbing zinc oxide—the same material in some sunscreens—to their OPV, which extended its life up to 30 years in accelerated aging tests. "It's sunscreen for solar cells," Forrest says. Larson, who was not part of Forrest's team, calls it "a huge result."

On one score, OPVs already have a clear advantage over just about every other energy-generating technology: a strikingly low carbon footprint. In evaluating Heliatek's panels, the German testing institute TÜV Rheinland certified that for every kWh of electricity the company's panels produce, at most 15 grams (g) of carbon dioxide (CO_2) would be emitted in making, operating, and eventually disposing of them. That's compared with 49 g of CO_2/kWh for silicon panels, and a whopping 1008 g of CO_2/kWh for mining and burning coal. Even with their low efficiencies, Heliatek's panels will generate more than 100 times the energy it takes to make and deal with them over their life span.

OPVs' carbon footprint is sure to lighten further as their efficiency continues to set new records, lifetimes climb, and production methods advance. Those trends are buoying hopes of a world where solar power spreads not only across rooftops and desert scrubland, but also along the curved facades of skyscrapers, the windows of the world, and just about anywhere else people are looking for a bit of juice. That could make prospects for addressing climate change just a little bit brighter. ■

Brightening prospects

A 2-decade rise in the efficiency with which organic photovoltaics turn sunlight into electricity was driven at first by molecules called fullerenes and changes to the films' structure, then by better "donor" and "acceptor" materials to separate positive and negative charges.



What remains to be seen, however, is whether such cells will retain the internal structure needed for high efficiency over decades. "In some of the record-breaking cells, the morphology changes over time and the performance doesn't hold up," Armistead says. NFAs are especially susceptible, because the best ones consist of small molecules that can easily shift through the material.

Replacing the NFAs with acceptors woven into long polymers to help keep them in place could help. "They have the chance to be very robust," Armistead says. Progress is on the march here as well. In the 18 August issue of *Advanced Materials*, researchers led by Alex Jen, a materials scientist at the University of Hong Kong, reported all-polymer solar cells that had an efficiency of 17% and retained 90% of their efficiency under accelerated aging tests. "That is quite notable," says Bao, whose team also works on all-polymer cells.

Yet, stability and high efficiency still won't be enough. To make it in the market, solar cells also need to prove reliable for decades.

CREDITS: (GRAPHIC) V. ALTOUNIAN/SCIENCE; (DATA) ZHANG ET AL., CHEM. REV. 18, 14180 (2022)

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