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ENERGY

Reinventing the Leaf

The ultimate fuel may come not from corn or algae but directly from the sun itself

By Antonio Regalado

LIKE A FIRE-AND-BRIMSTONE PREACHER, Nathan Lewis has been giving a lecture on the energy crisis that is both terrifying and exhilarating. To avoid potentially debilitating global warming, the chemist from the California Institute of Technology says civilization must be able to generate more than 10 trillion watts of clean, carbon-free energy by 2050. That level is three times the U.S.'s average energy demand of 3.2 trillion watts. Damming up every lake, stream and river on the planet, Lewis notes, would provide only five trillion watts of hydroelectricity. Nuclear power could manage the feat, but the world would have to build a new reactor every two days for the next 50 years.

Before Lewis's crowds get too depressed, he tells them there is one source of salvation: the sun pours more energy onto the earth every hour than humankind uses in a year. But to be saved, Lewis says, humankind needs a radical breakthrough in solar-fuel technology: artificial leaves that will capture solar rays and churn out chemical fuel on the spot, much as plants do. We can burn the fuel, as we do oil or natural gas, to power cars, create heat or generate

electricity, and we can store the fuel for use when the sun is down.

Lewis's lab is one of several that are crafting prototype leaves, not much larger than computer chips, designed to produce hydrogen fuel from water, rather than the glucose fuel that natural leaves create. Unlike fossil fuels, hydrogen burns clean. Other researchers are working on competing ideas for capturing the sun's energy, such as algae that has been genetically altered to pump out biofuels, or on new biological organisms engineered to excrete oil. All these approaches are intended to turn sunlight into chemical energy that can be stored, shipped and easily consumed. Lewis argues, however, that the man-made leaf option is the most likely to scale up to the industrial levels needed to power civilization.

FUEL FROM PHOTONS

ALTHOUGH A FEW LAB PROTOTYPES have produced small amounts of direct solar fuel—or electrofuel, as the chemicals are sometimes called—the technology has to be improved so the fuel can be manufactured on a massive scale, very inexpensively. To power the U.S., Lewis estimates the country would need to manufac-

IN BRIEF

Natural energy: Plants produce their own chemical fuel—sugar—from sunlight, air and water, without producing harmful emissions.

Man-made leaf: Researchers are devising artificial leaves that could similarly convert sunlight and water into hydrogen fuel, which could be burned to power

cars, create heat or generate electricity, ending dependence on fossil fuels.

Nano solution: To be practical, this solar-fuel technology would have to be

made cheaply in thin, flexible sheets, perhaps from silicon nanowires, and use inexpensive catalysts that help to generate hydrogen efficiently.

Artificial leaves could use sunlight to produce hydrogen fuel for cars and power plants.



ture thin, flexible solar-fuel films, instead of discrete chiplike devices, that roll off high-speed production lines the way newspaper does. The films would have to be as cheap as wall-to-wall carpeting and eventually cover an area the size of South Carolina.

Far from being a wild dream, direct solar fuel technology has been advancing in fits and starts ever since President Jimmy Carter's push for alternative energy sources during the 1970s oil shocks. Now, with a new energy and climate crunch looming, solar fuel is suddenly gaining attention. Researcher Stenbjörn Styring of Uppsala University in Sweden, who is developing artificial systems that mimic photosynthesis, says the number of consortiums working on the challenge has ballooned from just two in 2001 to 29 today. "There are so many we may not be counting correctly," he adds.

In July, the Department of Energy awarded \$122 million over five years to a team of scientists at several labs, led by Lewis, to develop solar fuel technology, one of the energy department's three research priorities. Solar fuels "would solve the two big problems, energy security and carbon emissions," says Steven E. Koonin, the top science administrator at the DOE. Koonin thinks sun-to-fuel schemes face "formidable" practical hurdles, but says the technology is worth investing in because "the prize is great enough."

In photosynthesis, green leaves use the energy in sunlight to rearrange the chemical bonds of water and carbon dioxide, producing and storing fuel in the form of sugars. "We want to make something as close to a leaf as possible," Lewis says, meaning devices that work as simply, albeit producing a different chemical output. The artificial leaf Lewis is designing requires two principal elements: a collector that converts solar energy (photons) into electrical energy (electrons) and an electrolyzer that uses the electron energy to split water into oxygen and hydrogen. A catalyst—a chemical or metal—is added to help achieve the splitting. Existing photovoltaic cells already create electricity from sunlight, and electrolyzers are used in various commercial processes, so the trick is marrying the two into cheap, efficient solar films.

Bulky prototypes have been developed just to demonstrate how the marriage would work. Engineers at Japanese automaker Honda, for example, have built a box that stands taller than a refrigerator and is covered with photovoltaic cells. An electrolyzer, inside, uses the solar electricity to break water molecules. The box releases the resulting oxygen to the ambient air and compresses and stores the remaining hydrogen, which Honda would like to use to recharge fuel-cell cars.

In principle, the scheme could solve global warming: only sunlight and water are needed to create energy, the by-product is oxygen, and the exhaust from burning the hydrogen later in a fuel cell is water. The problem is that commercial solar cells contain expensive silicon crystals. And electrolyzers are packed with the noble metal platinum, to date the best material for catalyzing the water-splitting reaction, but it costs \$1,500 an ounce.

That means Honda's solar-hydrogen station will never power the world. Lewis calculates that to meet global energy demand, future solar fuel devices would have to cost less than \$1 per square foot of sun-collecting surface and be able to convert 10 percent of that light energy into chemical fuel. Fundamentally new, massively scalable technology such as films or carpets made from inexpensive materials are needed. As Lewis's Caltech colleague Harry A. Atwater, Jr., puts it, "We need to think potato chips, not silicon chips."

FINDING A CATALYST

THE SEARCH FOR SUCH TECHNOLOGY remains at an early stage, despite several decades of on-again, off-again work. One pioneering experiment shows why. In 1998 John Turner of the National Renewable Energy Laboratory in Golden, Colo., built a device about the size of a matchbook that when placed in water and exposed to sunlight kicked out hydrogen and oxygen at a prodigious rate and was 12 times as efficient as a leaf. But Turner's creation depended on rare and expensive materials, including platinum as the catalyst. By one estimate, Turner's solar-fuel cell cost \$10,000 per square centimeter. That might do for military or satellite applications, but not to power civilization.

Noble metals, often the best catalysts, are in short supply. "That's the big catch in this game," Styring says. "If we want to save the planet, we have to get rid of all those noble metals and work with cheap minerals like iron, cobalt or manganese." Another difficulty is that the water-splitting reaction is highly corrosive. Plants handle that by constantly rebuilding their photosynthetic machinery. Turner's solar-fuel cell lasted just 20 hours.

Today Turner's research is consumed with devising successive generations of catalysts that each are a bit cheaper and of solar collectors that each last a little longer. At times the search is agonizingly hit or miss. "I am wandering through the forest looking for a material that does what I want," Turner says. "Progress has been minimal."

Other teams are also chasing catalysts, including one led by Daniel G. Nocera of the Massachusetts Institute of Technology. In 2008 Nocera and a colleague hit on an inexpensive combination of phosphate and cobalt that can catalyze the production of oxygen—one necessary part of the water-splitting reaction.

Even though the prototype device was just a piece of the puzzle—the researchers did not find a better catalyst for creating hydrogen, the actual fuel—M.I.T. touted it as a "major leap" toward "artificial photosynthesis." Nocera began predicting that Americans would soon be cooking up hydrogen for their cars using affordable backyard equipment. Those bold claims have not sat well with some solar-fuel experts, who maintain that research has decades to go. Others are more bullish: the DOE and the venture capital firm Polaris Venture Partners are supporting Nocera's ongoing work at Sun Catalytix, a company he created in Cambridge, Mass.

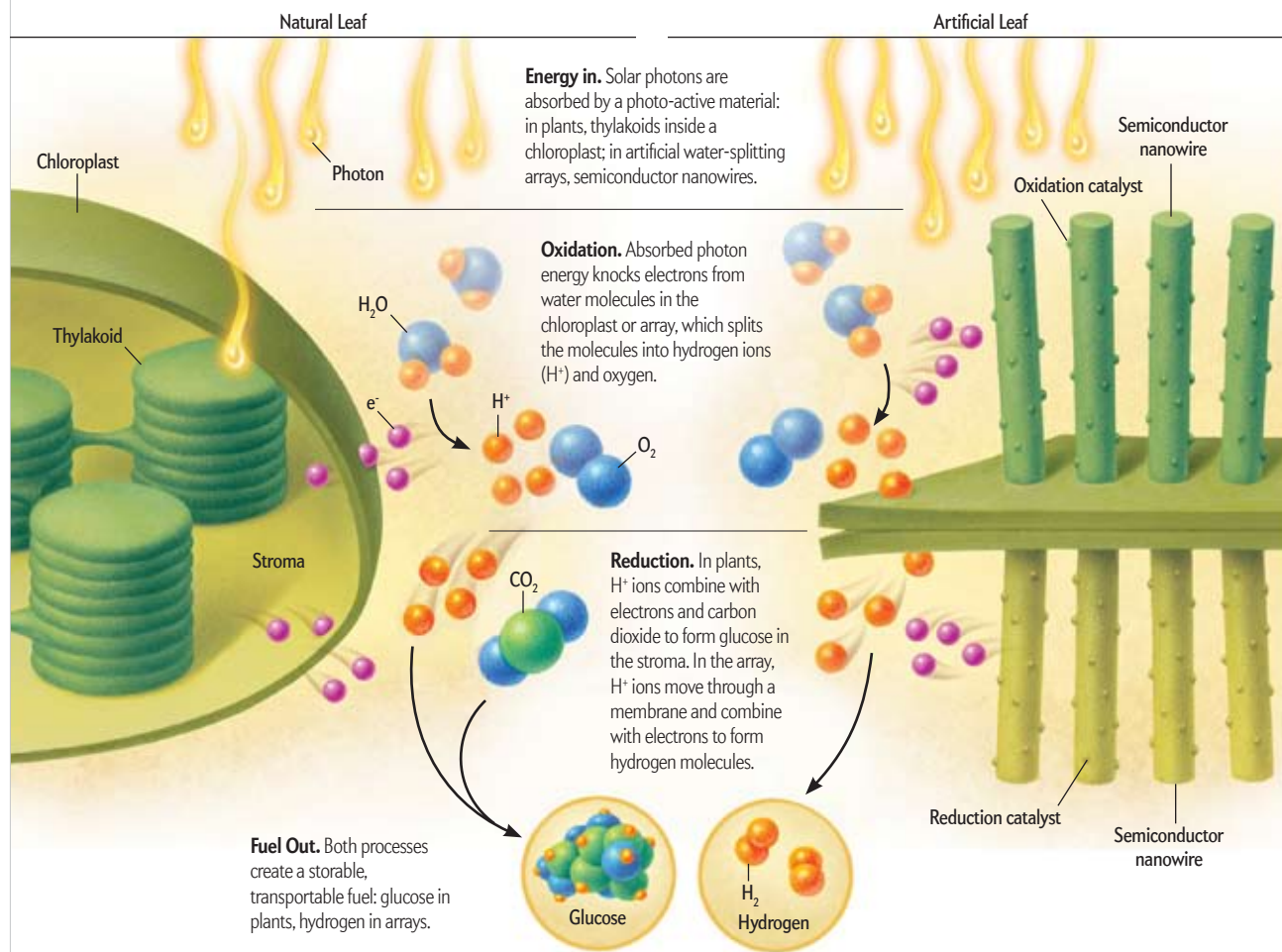
At Caltech, meanwhile, Lewis has been working on a way to collect and convert the sun's photons—the first step in any solar-fuel device—that is much cheaper than conventional, crystalline silicon solar cells. He has designed and fabricated a collector made of silicon nanowires embedded in a transparent plastic film that, when made larger, could be "rolled and unrolled like a blanket," he says [*see illustration on opposite page*]. His nanowires can convert light into electric energy with 3 percent efficiency. That pales in comparison to commercial solar cells,

If we want to save the planet, we have to get rid of all those noble metals and work with cheap minerals like iron to catalyze reactions.

Solar Nanowires Mimic Nature

Plants harness the sun's energy to convert carbon dioxide and water into glucose—chemical fuel that can be used or stored (*left*). Researchers are devising artificial leaves that use sunlight to split water

molecules, creating hydrogen fuel. Nathan Lewis's group at the California Institute of Technology is designing a small leaf with arrays of silicon nanowires that could produce hydrogen (*right*).



which are up to 20 percent efficient. But if the material could be made inexpensively enough—those sheets rolling off a press like newsprint—lower efficiency could be acceptable.

Researchers also debate whether hydrogen is the best choice for solar fuel. Teams working with biological organisms that produce liquid biofuels say these fuels are easier to store and transport than hydrogen. But hydrogen gas is flexible, too: it can be used in fuel-cell cars, burned in power plants to generate electricity, and even serve as a feedstock in producing synthetic diesel. Nevertheless, “the key is to make an energy-dense chemical fuel!” with minimal carbon emissions, Lewis says. “Let’s not get hung up on which one.”

Real-life leaves prove that sunlight can be converted into fuel using only common elements. Can humankind imitate this process to rescue the planet from global warming? The prognosis is not clear. “The fact that we can’t solve the problem with off-the-shelf components is why it’s an exciting time to be working in this area,” Lewis says. But he is worried that society—including

policy makers, government funding agencies and even scientists—still has not grasped the size of the energy problem or why revolutionary solutions are needed. That is why he spends so much time on the lecture circuit, preaching solar salvation: “We are not yet treating this problem like one where we can’t afford to fail.” ■

MORE TO EXPLORE

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