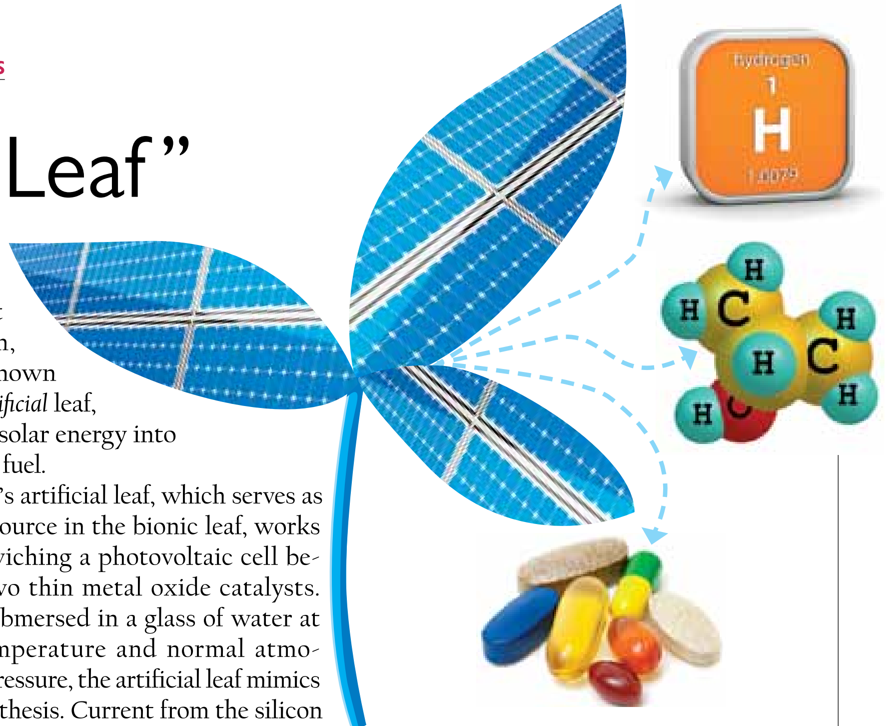
The "Bionic Leaf"



IMAGES BY ISTOCK; ILLUSTRATION BY HARVARD MAGAZINE/JC

HARVARD SCIENTISTS have created a "bionic leaf" that converts solar energy into a liquid fuel. The work—a proof of concept in an exciting new field that might be termed biomanufacturing—is the fruit of a collaboration between the laboratories of Adams professor of biochemistry and systems biology Pamela Silver at Harvard Medical School (HMS) and Patterson Rockwood professor of energy Daniel Nocera in the Faculty of Arts and Sciences (FAS). The pair, who began collaborating two years ago (Nocera came to Harvard from MIT in 2012), share an interest in developing energy sources that might someday have practical application in remote locales in the developing world. Silver dubbed the system "bionic" because it joins a biological system to a clever piece of inorganic chemistry previously developed by Nocera: that invention, widely known as the *artificial* leaf, converts solar energy into hydrogen fuel.

Nocera's artificial leaf, which serves as the fuel source in the bionic leaf, works by sandwiching a photovoltaic cell between two thin metal oxide catalysts. When submersed in a glass of water at room temperature and normal atmospheric pressure, the artificial leaf mimics photosynthesis. Current from the silicon solar wafer is fed to the catalysts, which split water molecules: oxygen bubbles off the catalyst on one side of the wafer, while hydrogen rises from the catalyst on the wafer's other side. Nocera has been perfecting the artificial leaf since he first demonstrated it in 2011; today, it is far more efficient than a field-grown plant, which captures only 1 percent of sunlight's energy. He says he can reach efficiencies of

70 percent to 80 percent of the underlying solar-wafer technology, which is improving constantly.

The hydrogen it produces is a versatile fuel from a chemical standpoint, Nocera reports, and could easily become the basis of a fuel cell, but it has not been widely adopted, in part because it is a gas. Liquid fuels are much easier to handle and store, hence the new *bionic* leaf's importance.

In the bionic leaf, the hydrogen gas is fed to a metabolically engineered version of a bacterium called *Ralstonia eutropha*. The bacteria combine the hydrogen with carbon dioxide as they divide to make more cells, and then—through a trick of bioengineering pioneered by Anthony Sinskey, professor of microbiology and of health sciences and technology at MIT—produce isopropanol (rubbing alcohol), which can be burned in an engine much like the gasoline additive ethanol.

"The advantage of interfacing the inorganic catalyst with biology is you have an unprecedented platform for chemical synthesis that you don't have with inorganic catalysts alone," says Brendan Colón, a graduate student in systems biology in the Silver lab and a coauthor of the *Proceedings of the National Academy of Sciences* paper (along with first authors Joseph Torella, a recent graduate of the department of systems biology, and Christopher Gagliardi, a postdoctoral fellow in FAS's department of chemistry and chemical biology). "Life has evolved for billions of years to produce catalysts capable of making chemical modifications on complicated molecules with surgical precision, many times at room temperature," Colón explains. "If you can use enzymes for building chemicals, you open the door to making many of the natural compounds we rely on every day," such as antibiotics, pesticides, herbicides, fertilizer, and pharmaceuticals.

Members of Silver's lab have been working to perfect the tricky interface between the catalyst and the bacteria, so that they will thrive and grow optimally. In its first iteration, the bionic leaf matched the efficiency of photosynthesis in plants, far below the capabilities of Nocera's underlying artificial leaf. Now the team is working to surpass blue-green algae, which—at 5 percent efficiency—do better at photosynthesis than plants. Colón has been developing a strain of the bacterium that grows well even at the lower voltages that might be emitted by the solar wafer at the system's core on a cloudy day, for example; this could dramatically improve overall efficiency.

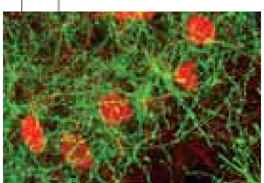
Ultimately, though, Silver's goal is not to create fuels from this work, but "high-value commodities" in remote places. Fuel, she notes wryly, is cheap "because we fight wars over it"—and developing a system that could make fuel at a price lower than gasoline would therefore be very difficult, she says. Drugs, on the other hand, are high-value commodities, so engineering a bacterium to produce not isopropanol but a vitamin or a drug may be her next goal for this system.

Modern society, says Nocera, has created an entire manufacturing economy based not only on burning fossil fuels, but on using petroleum to make things such as rubber and plastics. "A lot of chemistry was done which set that up," he notes. The present system makes sense now because petroleum costs so little; a sustainable system like the artificial or bionic leaf can't compete with that. But when oil becomes scarce, he says, "We might want to redo everything in terms of manufacturing. In the future, you might want to make everything renewably." ~JONATHAN SHAW

DANIEL NOCERA WEBSITE:
http://nocera.harvard.edu/Home
PAMELA SILVER WEBSITE:
https://sysbio.med.harvard.edu/facultys/pamela-a-silver-phd

HM Explore More

For more online-only articles on research in progress, see:



Consciousness, and a Cure?
A newly identified group of neurons that play a role in consciousness may have implications for the treatment of schizophrenia. **harvardmag.com/neurons-15**

2015 Dietary Recommendations
Changes to guidelines for fats, cholesterol, meat, and sugar are among the highlights. **harvardmag.com/diet-15**

Battling Ebola, Back to Basics
At Harvard Medical School, experts discussed lessons from the epidemic. **harvardmag.com/ebola-15**

THE SUNSHINE SUPPLEMENT

Is Vitamin D a Wonder Pill?

"IN THE CASE OF RELIGION, we put our faith in gods. And in nutrition, we have vitamins," writes journalist Catherine Price in *Vitamania*, in which she traces vitamin crazes from the 1920s to the present. Today's star is vitamin D, nicknamed "the sunshine nutrient" because ultraviolet-B radiation prompts the body to produce it. Long known to aid calcium absorption and play an essential role in bone health, it's often added to dairy products. More recent studies, linking low levels of the nutrient to conditions ranging from multiple sclerosis to high blood pressure, led *The New York Times* to declare in 2010 that "Vitamin D promises to be the most talked-about and written-about supplement of the decade."

Some of the excitement seems warranted: drawing on previous research into vitamin D's immune and anti-inflammatory benefits, two new epidemiological studies by scientists at Dana-Farber Cancer Institute (DFCI) have found that it may also inhibit cancer. One study investigated the nutrient's effect on colorectal cancer survival; the other examined its impact on colorectal cancer tumors and patient immune systems.

In the first study, the largest to date of