

The Norwegian government “uses Svalbard to showcase research. They want UNIS to excel. We get a lot of politicians [and dignitaries] here—Hillary Clinton, Ban Ki-moon, the Queen of Norway,” notes Lorentzen. He says rubbing shoulders with visiting Norwegian decision makers helped raise funds to build the Kjell Henriksen Observatory on Svalbard. It is the world’s largest optical observatory for auroral studies and hosts instruments from eight countries.

Some UNIS projects do have a policy connection. One is the Svalbard Integrated Arctic Earth Observing System, or SIOS, an international effort based at UNIS to coordinate Arctic data. Another is carbon dioxide sequestration. Ragnhild Rønneberg, who is on leave from the Research Council of Norway, oversees both. Svalbard relies on coal for energy, she explains. “It’s a bad image for Norway,” which uses mostly hydroelectric power. “We

have found a place to store CO₂. The area is an uplift from the Barents Sea. We try to get the CO₂ back to the rocks, so it doesn’t escape.” And some research has broad, potentially political implications. For example, Larsen notes that there has not yet been an oil spill on ice—and there is no solution if one occurs. But, he says, “oil companies are eager to get ahead of the curve.”

Toni Feder

Chips may replace corn for harvesting solar fuels

Researchers hunt for appropriate semiconductors and molecules to power self-contained systems that can improve on photosynthesis.

What if fuel could be made from sunlight, water, and atmospheric carbon dioxide? What if the intermediate step of growing, harvesting, and fermenting biomass could be eliminated and the arable land freed for food production? And what if the new fuel-making process could even reduce atmospheric CO₂? That’s the goal of artificial photosynthesis (AP), currently the focus of numerous government-sponsored research projects worldwide.

The basic principle of AP is to mimic the process that takes place in every plant leaf: splitting water with sunlight and recombining the hydrogen with carbon dioxide to make fuels. But accomplishing that at a meaningful scale without the green matter will require new materials that can efficiently perform the multiple tasks involved: light absorption, water oxidation, and hydrogen generation. And finding the right materials that can also operate under common environmental conditions has proved daunting.

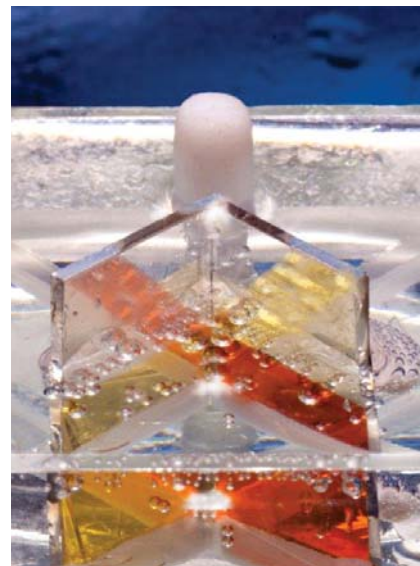
“Going from a fossil-fuel society to a renewable energy society is a huge step,” says Heinz Frei, a project leader at the Joint Center for Artificial Photosynthesis (JCAP) campus located at Lawrence Berkeley National Laboratory. “Biofuels we can start right away. Artificial photosynthesis needs more time because it’s not an existing technology. But it’s one that should get us all the way because it’s not limited to arable lands.” At least half the energy required by the transportation industry must come from liquid fuels, because batteries can’t store enough energy to power airplanes, heavy trucks, or ships. If AP technology can reach a sunlight-to-fuel conversion efficiency of 1%—about the same as nat-

ural photosynthesis—replacing US gasoline consumption with AP would require 24 million hectares. That’s roughly the area taken up by the entire US interstate highway system. At 3% efficiency, an area smaller than the Mojave Desert (about 12 million hectares) would suffice. Frei says an efficiency range of 6–8% is realistic.

Funded by the Department of Energy, JCAP is a five-year, \$122 million collaboration led by Caltech. It is by far the largest of the AP partnerships. Its 120 staff members work at two campuses (Caltech and Lawrence Berkeley), with additional collaborators at SLAC, a number of US universities, and several of the 46 DOE energy frontier research centers. JCAP’s goal is to make a self-contained device that can convert sunlight into fuels 10 times as efficiently as the 0.5–1% that occurs in the solar-energy-to-biomass conversion.

A two-stage process

In JCAP’s conceptual two-stage cell, a light-absorbing semiconductor coated with a catalyst oxidizes water into protons and oxygen. Reducing protons to hydrogen will occur in a second semiconductor layer containing a different catalyst. Although platinum and iridium oxide will do the job, they are much too rare and expensive to be scaled up into a meaningful energy source. As JCAP’s scientific director Nathan Lewis explains, the best Earth-abundant water-oxidation catalysts work by oxidizing hydroxide, plentiful only in alkaline solutions. But the best catalysts for proton reduction work most efficiently in an acidic environment. A semipermeable material capable of separating hydrogen from oxygen while allowing ions to pass to the reduction stage is a safety re-



MIKI KOREN

This light-trapping structure invented at Technion-Israel Institute of Technology boosts the efficiency of ultrathin-film iron oxide material for photoelectrolytic water splitting.

quirement with its own pH restrictions. “There are no membranes that can do this at pH 7,” says Lewis. “If the membranes only work in acid or base, then the catalysts also need to work either in acid or in base for the system as a whole to work.”

Candidate materials for light absorbers also are pH limited, notes Lewis. Silicon, the most widely used light absorber for photovoltaics (PVs), dissolves in basic solutions. Other potential materials, including titanium dioxide, other metal oxides, and existing PVs, either dissolve or corrode in acid. “This is like building an airplane. Just having an engine doesn’t mean the plane flies. You need wings, you’ve got to have avionics, got to have a fuselage, and the thing has to fly,” Lewis says.

There are other, less obvious problems. Although hydrogen bubbles indi-

cate success, they also refract light away from the catalytic structures. "We need to mitigate the effects and exploit the optical properties of these bubbles," Lewis says, "or we are going to get creamed on a real device the instant we bring it outside for more than 10 seconds."

Unique to JCAP is a high-throughput facility for synthesizing and screening potential catalyst compounds. Using large-format inkjet printers, researchers can make and reproduce 1-mm² samples of any mixture containing up to 8 of the 20 elements for which the center has created inks. Then, to rapidly measure the mixtures for their quantitative properties, the researchers use a variety of techniques, including x-ray diffraction, large-format x-ray photoelectron spectroscopy, and video recordings of bubble formation. "Basically, it's an analytical pipeline to give us the structures, compositions, and activities in a mineable, searchable database," Lewis says. He adds that the capability will accelerate progress for the community as a whole.

Discoveries so far have been "evolutionary, not revolutionary," Lewis says. Among them are new compositions of iron-nickel catalysts, with cerium and cobalt, that are 20–50% more efficient than existing state-of-the-art iron-nickel compounds.

Research is worldwide

Smaller AP centers are operating elsewhere around the globe. The Israel Solar Fuels Consortium is devoting about \$12 million over five years to developing photocatalysts. That effort focuses on metal oxides, iron oxide in particular. "We know it will never be as efficient as silicon, but we are trying to increase its efficiency so it can work together with silicon," says Avner Rothschild, a professor at Technion-Israel Institute of Technology, who heads the consortium's water-splitting work.

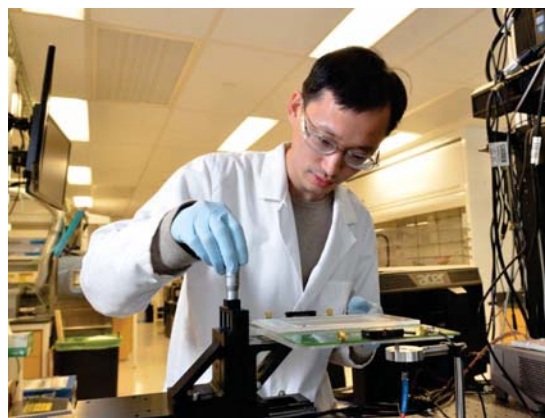
The biggest obstacle to the use of iron oxide has been its poor electrical transport properties. Researchers have struggled with the tradeoff between light absorption and the separation and collection of photogenerated charge carriers before they die out by recombination, he says. In December 2012 the group announced what it called a major advance: By combining resonant light trapping in quarter-wave films and photon re trapping in V-shaped structures (see the photograph on page 22), films as thin as 25 nm have been demonstrated to absorb light. At the same time, the ultrathin films efficiently collect charge carriers.

The Swedish Consortium for Arti-

cial Photosynthesis takes a different approach: finding molecular catalysts to mimic and improve on the Photosystem II protein complex, which captures light and splits water in plants. Based at Uppsala University in Sweden, the research involves 40–50 scientists, mostly from other countries. The Swedish Energy Agency is providing about \$10 million over four years to the consortium, with another \$7.6 million from the Knut and Alice Wallenberg Foundation.

Anders Hagfeldt, an Uppsala chemist who leads a group working with dye-sensitized solar cells, a low-cost thin-film PV, says the consortium has developed manganese and cobalt oxide complexes for water oxidation and iron oxide and ruthenium complexes for proton reduction. He predicts that molecular catalysts will make rapid gains in efficiency within the next two years.

In Japan, a consortium backed by major chemical companies and the Ministry of Economy, Trade, and Industry



Chengxiang Xiang, a staff scientist at the Joint Center for Artificial Photosynthesis, tests a rapid screening tool for assessing catalyst activity.

seeks to develop catalysts to reduce CO₂. The 10-year project focuses on producing olefins for chemical feedstocks, says Kazunari Domen, a University of Tokyo professor who heads the collaboration. Advances made by the Japanese consortium could also help improve the efficiency of turning the hydrogen produced from water splitting into more complex liquid fuels. "If we are successful, it's possible that eventually we could produce solar fuels," he explains.



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For Lewis, liquid fuels from hydrogen should be considered a long-term goal for JCAP. “It’s very clear that the first fuel we’re going to produce is [hydrogen] from water splitting,” he says. That hydrogen might be used to upgrade biofuels to higher energy content or to reduce CO₂ to make synthetic fuels. The choice of fuel could be left to the chemical and refining industries, which know how to convert one fuel to another with minimal energy loss, he notes.

What’s ahead

Looking ahead five years, Rothschild sees efficient, functioning AP arrays of perhaps 1 m². Those will need to be tested over thousands of hours for

durability and energy conversion efficiency, he says. Life-cycle analyses will indicate whether AP could produce hydrogen at a competitive cost, which Rothschild estimates is around \$3/kg in the US and €5/kg (\$6.70/kg) in Europe.

“This technology has only been demonstrated in the lab; it’s very difficult to make projections of how it will work in the field over many years,” Rothschild says. AP also could provide a solution to the grid-leveling challenge that increasing PV electricity generation will present; using combined water splitting and PV arrays would produce a clean-burning fuel for nighttime power generation. He cautions that AP will have its environmental impacts. “It’s clear that this is

not zero emission, because at a minimum you should count the CO₂ you use in making the devices. You also need to think about how much water we need and where we’ll get it.”

Frei and Lewis say they expect JCAP to have a working prototype by 2015, when the center’s five-year contract is up for renewal. To make a device with the targeted 5–10% efficiency could take another five years. Hagfeldt agrees that 10 years is a reasonable estimate for having AP technology in practical use. “It’s very important that you keep several options open. Whether you go for electricity or for fuels from solar energy is complementary. It’s not an either-or; you need both.”

David Kramer

Cost increases at fusion project going critical

US domestic program braces for budget cut as senators seek schedule for completion and cost of ITER.

How much will it cost to build what could well be the first machine to achieve a self-sustaining nuclear fusion reaction? Apparently no one really knows, and that information vacuum hasn’t been sitting well with some influential US lawmakers.

Construction of the international prototype fusion reactor is under way at Cadarache in southern France, but the project is proceeding without a formal cost baseline. In May, four senators who hold the purse strings for the US contribution to ITER ordered an investigation into ITER’s cost; they asked the Government Accountability Office to

figure out how much the project will cost and what the US will have to pay.

During a hearing of the Appropriations Committee’s energy and water development subcommittee, which she chairs, Senator Dianne Feinstein (D-CA) asserted that the US share of ITER will reach \$3 billion. The Department of Energy’s fiscal year 2014 budget request, released in April, put the value of the US contribution at \$2.4 billion but described that as a “subset of our obligations” that continue through to ITER’s achieving its first experimental plasma. Originally set by the project collaborators for 2016, the first plasma

date has been pushed back several times and now officially stands at 2020.

Feinstein said that “ITER has no cost, schedule, or scope baseline, and there is no way to evaluate how much it will cost or its impact on the domestic [fusion research] program and over what time frame. The lack of information is unacceptable. Congress can’t evaluate the cost without a project baseline.” Feinstein said she’d been told by DOE to expect the date for first plasma to slip to 2023.

The budget request from DOE for FY 2014 includes \$225 million for the US ITER contribution, more than double the \$105 million appropriated in FY 2012. The US domestic fusion energy research program is being asked to pay for part of the ITER contribution; the budget request would provide the US program with \$233 million, down from \$288 million in FY 2012. The cutback would include closure of MIT’s Alcator C-Mod, one of three US experimental tokamak reactors.

A currency-free cap

Although a cap on ITER’s budget has been in place since 2010, it’s expressed only in credits known as “ITER units of account.” The best guess, project officials say, is that ITER will cost €13 billion (about \$16.8 billion). That’s based on an extrapolation of what the European Union (EU) estimates it will cost its member states to build their share of the project’s components. But the actual costs will vary from country to country depending on individual industrial fabrication costs. As host, the EU is contributing 45% of ITER; the other six countries—Japan, Russia, South



An aerial photo of the ITER complex under construction in Cadarache, France, in February 2013.