Powering the Planet

The Caltech Center for Sustainable Energy Research

Solutions to the most important energy problems hinge upon fundamental advances in science and technology. Ultimately, we as a society will have to replace fossil fuels for much of our energy needs, yet at the present time, we are not positioned to do so and continued short-term reliance on fossil fuels appears inevitable. Unquestionably however, the most abundant source of energy is the Sun. A group of Caltech researchers under the umbrella of CCSER—the **Caltech Center for Sustainable Energy Research**—contends that the most fruitful research directions will be ones that embrace these realities. Their approach rests on advances in three areas: the development of low-cost, ultra-efficient solar-to-electric conversion mechanisms; conversion of solar energy into stored chemical fuels; and the creation of low-cost, lightweight, and high-energy output fuel cells.

Last November, we sat down for a conversation with the principals of this new initiative—Professors Harry Atwater, Harry Gray, Sossina Haile, Nate Lewis, and Jonas Peters—to find out more about their approach and motivations.

ENGenious: On the CCSER website, you state that your aim is to transform the industrial world from one that is powered by fossil fuel to one that is powered by sunlight.

Harry Atwater: The question is: how realistic is that?

ENGenious: Yes, how realistic is that, and how are you going to do that?

Atwater: Ultimately, all energy on Earth emanates, directly or indirectly, from the Sun. Until now, we have used only the long-term storage media for solar energy, namely, decayed plant matter that has compressed under geological timescales to form fossil fuels. What we are talking about is transitioning from using these non-renewable *stored* forms of energy to things that are renewable on the same timescale as their use. We are really a *fuels* economy. The sources of renewable energy that have been developed to date, and which are undergoing development—wind power, hydroelectric, solar-electric—are, by themselves, are not capable of generating the fuels that power our transportation economy. Only about 20% of energy use in the U.S. is in the form of electricity, so it is not enough to generate electricity. Of course, it would be a worthy goal to generate all the electricity in the United States renewably—it's certainly not done that way now. But our ambition is even bigger, which is, essentially, to *displace* the carbon-intensive fossil fuel use with a carbon-free, non-carbon intensive solar-driven fuel cycle.

ENGenious: Why can't the current approaches to renewable energy meet our needs?

Atwater: The renewable energy infrastructure we have now for solar and wind is really nothing more than the outcome of the investment that we made in the '70s.

Harry Gray: Yes, and much of it was developing silicon photovoltaics. This is what we've got now. But it's just too expensive. It's 20-25 cents per kilowatt-hour. One of our objectives is to get the cost of electrical generation per kilowatt-hour down by a factor of five. If we could get it down to 5 cents per kilowatt-hour, the cost of producing large amounts of renewable electrical power for the country would come way down. We have estimated we could outfit the whole country now for solar, in the next couple of years, using existing technology, for about 5 to 10 trillion dollars. That's a rough calculation.

Nate Lewis: The problem with energy, really, is that people who experience it everyday don't experience it on the *scale* that we need to produce it. They don't experience the fact that, over the next 40 years, if you want to avoid even a doubling of carbon dioxide, after accounting for population growth and economic growth, you have to build the equivalent of a new nuclear power plant *every day for 38 straight years*. So all of a sudden, most of the "solutions" are in fact not solutions when you consider the needed scale.

Atwater: And there are material limits. Let's take the example of silicon solar cells. Suppose we were to spend 5 to 10 trillion dollars outfitting the U.S. with silicon solar cells. Currently, the front contacts on silicon solar cells are silver screen-printed contacts. It turns out that if you were to deploy solar cells on that scale, you would run out of all the silver on the world market. There are limitations.

Sossina Haile: When you start thinking about energy on a global level, you start thinking about *all* the ways in which the Earth is resource limited. When you start really thinking about global solutions, all of a sudden these material resources become a real problem. And along those lines, platinum is one that people are starting to think about in terms of either fuel-cell catalysts or electrolysis catalysts. There will not be enough platinum.

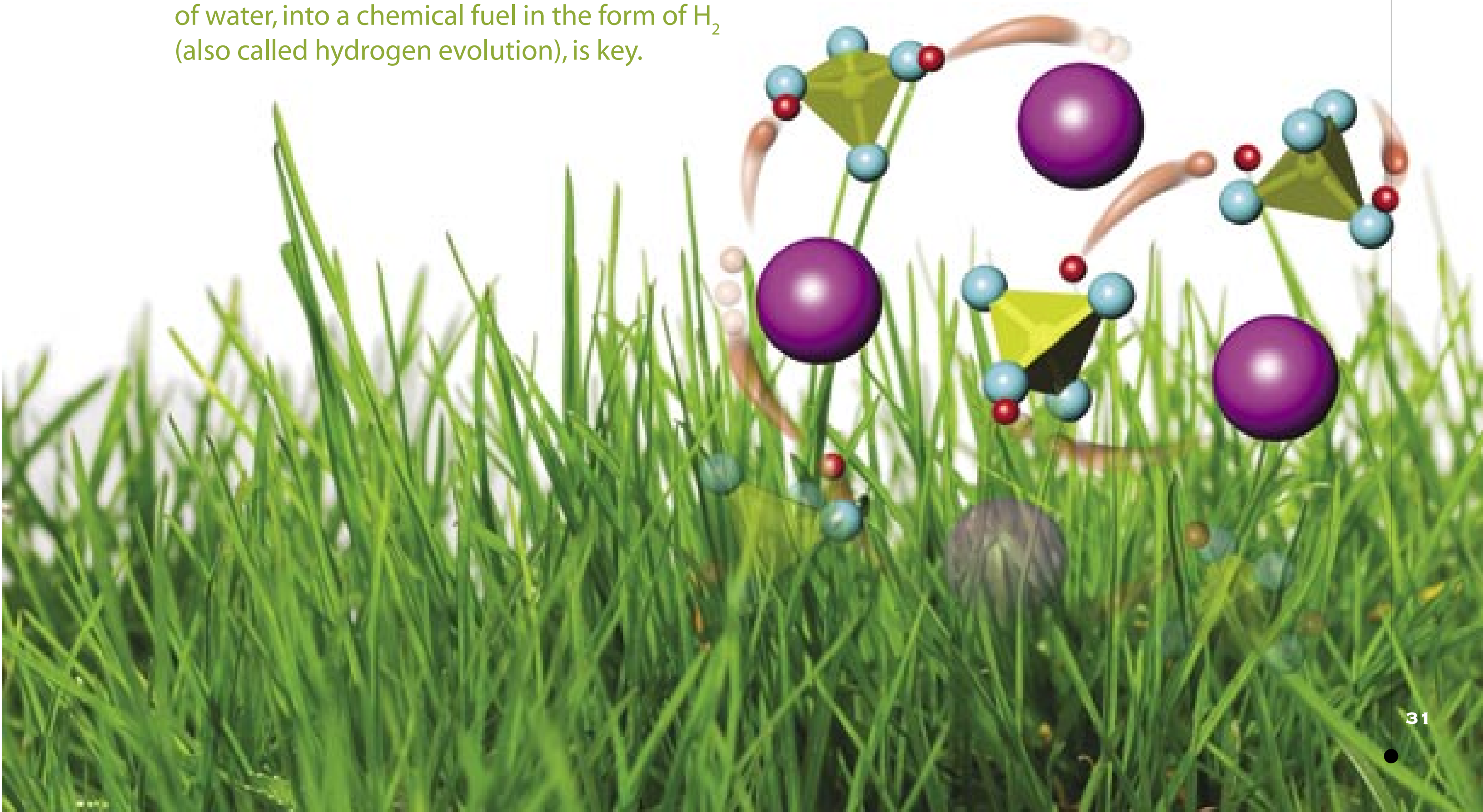
Atwater: Buy stock in platinum!

Haile: Platinum prices are skyrocketing, and it's all about hydrogen fuel cells.

Atwater: And then when we're successful in this CCSER initiative, you'll need to start shorting your platinum stock. [*laughter*]

Gray: One of Jonas's main areas of interest is replacing platinum with much cheaper, more available metal catalysts such as cobalt, nickel, and iron. That's one of the big areas of research in CCSER. Can we develop catalysts that are

Existing technologies cannot meet global needs because of efficiency and economic constraints, and well as the limited quantities of raw materials. This last constraint has led the CCSER group to place high on the priority list the development of catalysts made from non-precious metals. These catalysts will be designed to extract energy from water by pulling apart the two very strong hydrogen-oxygen bonds, rearranging them into weaker H-H bonds and a strong O-O bond. This results in making one really weak, high-energy fuel bond, effectively storing sunlight. This splitting of water, into a chemical fuel in the form of H_2 (also called hydrogen evolution), is key.



Left to right: Sossina Haile, Professor of Materials Science and of Chemical Engineering, Harry Gray, Arnold O. Beckman Professor of Chemistry, and graduate student Lisa Cowan.

closer to nature's catalysts, using much more abundant and biologically compatible materials? Because there is another angle on this—it's not only lowering the cost, it's also coming up with environmentally friendly materials. If the technology is going to be dispersed widely, then we can't have toxic metals all over the place. And so we need to use more of nature's kinds of metals, which are cobalt, nickel, iron, and copper.

Atwater: The things you have to do well—efficiently, and with abundant materials—are: absorb the light, convert that light to an electrochemical potential that's sufficient to split water, and then you have to catalyze hydrogen evolution from water by electrolysis.

Jonas Peters: So you are taking water and breaking it apart into hydrogen and oxygen. You shine light on it to break it apart. Then you've created a chemical potential. And when it comes back together, you get energy in the form of heat or light back again.

Haile: Or electricity.

ENGenious: Why is it so difficult to mimic nature's processes?

Gray: Because we don't know how to encapsulate these catalysts the way nature does. Nature encapsulates them in folded proteins in a membrane environment, and can keep them in place and manipulate their structures. We have not figured out how to do that yet.

Peters: There are basically dozens of details that count. *Every* detail counts. And nature has adapted an incredibly complex machinery to solve these really challenging chemical problems. We are still a long way off from actually being able to mimic nature.

Gray: If you look at an enzyme and ask how many weak interactions are critical in the function of the enzyme, it is something like 10^{15} weak interactions that are beautifully orchestrated in a folded protein structure. The weak interactions—things we call hydrogen bonds, van der Waals interactions, and so on—are orchestrated, tuned to work beautifully in these systems. What we do now is *cheat*. We use gold, and platinum, and rhodium, because on these surfaces you can get activation of bonds very simply. Whereas in a big enzyme framework, there's a whole orchestration of interactions that leads to the same thing with materials like iron in the center as the activating metal, or copper or manganese or cobalt or nickel. We haven't figured out how to do that yet in simple molecules.

Peters: Nature can't afford to waste energy when it does chemical transformations, so it has to tune all of its catalysts to operate right at the sweet spot where it's not wasting anything. Whereas humans, in the presence of abundant energy sources, can hit everything with a hammer. We use energy to "brute force" solutions in the chemical industry. That's how we get our fertilizers nowadays, and that's how we do can electrolysis. But the metabolic processes of nature cannot do that. So we, in the absence of energy, need to do the same transformations right at the thermodynamic sweet spot. That's hard. That's really hard.

ENGenious: On the bright side, since you are using sunlight…

Atwater: The resource potential of sunlight, relative to all of the other energy sources, is orders of magnitude larger—just considering the power striking the Earth or the power that can be derived. But it's a relatively low energy-density source, low energy-intensity source. That's why we need to cover large areas.

ENGenious: Are there other things you can accomplish once you have figured out how to split water?

Haile: Certainly. You can get a little more radical and think about taking CO_2 and water and making a hydrocarbon out of it in the same way that plants do. Plants make all sorts of things, but they generally don't make much hydrogen (although there are bacteria that make hydrogen). They make all sorts of hydrocarbon compounds—starches and sugars, you name it—to build themselves. That would be the next level: taking solar energy and using it to do something interesting chemically. Once you've got solar energy and converted it into a useful chemical form, it's like having sunlight in your back pocket. Now you've got a fuel that you can use on demand when the Sun is not shining. You can put that into a fuel cell to get electricity. Electricity is only 20% of our energy use; but if you think about converting vehicles to use fuel cells, then that becomes part of the electricity side rather than just the fuel side.

Peters: There are, however, huge basic science issues.

ENGenious: What are the hurdles that have to be overcome?

Haile: There are essentially two devices required. One device takes in the sunlight and makes a fuel, and the other device, which has very similar components, is the one that takes in the fuel, and makes electricity. They're connected in the sense that many of the components are the same, but they have some differences and they run in reverse.

Peters: For each component, there are huge basic science problems. So when people will ask: what would it look like? You can't really say exactly because we haven't actually figured out what the components must be. There's a lot of individual work to figure out answers to basic science questions that we all have our distinct expertise in, but then these components have to work in an integrated way. So those are two separate challenges.

Atwater: By the way, one thing you might ask is: If plants are so great, why don't we just do biomass? Why bother with an artificially engineered device? While plants are wondrous machines in generating sugars and carbohydrates as fuel, they are relatively inefficient in terms of their conversion efficiency from the photons into stored energy. We can make solar cells now that are between 15 and 40% efficient in the photon-electron conversion, whereas plants are at 1% or less. Our goal is to develop processes to leverage an ability to make very efficient solar photovoltaic converters to enable the efficient production of fuels. Essentially beat nature at its game, even though nature is very elegant in the way it works.

> But our ambition is even bigger, which is, essentially, to displace the carbon-intensive fossil fuel use with a carbon-free, non-carbon intensive solar-driven fuel cycle.

Gray: The critical catalyst in this case is the one for water oxidation—it's the manganese part of plants. There's a little cluster of four manganese atoms in a structure we're still not quite sure of. Even though there's a lot of x-ray work right now, we're still not quite sure what it looks like. But it's a marvelous catalyst for oxidizing water to oxygen. Far better than anything else known that has any biological kind of metal in it. You can use platinum of course, as usual—or even better for this reaction would be ruthenium. One of our objectives is to build an artificial oxygen evolving catalyst, more or less working on nature's design and figuring out how we can do better. Once you get that—and that's a big technical hurdle, a huge hurdle—then we will be able to take sunlight, this catalyst, evolve oxygen from water, and the byproducts then are protons and electrons, which we can combine to make hydrogen fuel. Or we can also use these products to make ammonia from nitrogen, or methanol fuel to give to Sossina for her extraction through the direct oxidation of methanol to get electricity.

ENGenious: How long do you think it's going to take to solve that problem?

Peters: Well, people have been working on it for more than three decades. I would say that I don't think the ingenuity to solve the problem is lacking; I think people have thought very clearly about the challenge for a long time. But what has changed is that we're now much faster at being able to build catalyst structures and rapidly characterize them. We can make a lot more mistakes more quickly and learn from those. The other thing that has happened is that there's been a huge revolution in the understanding of biological structures through protein crystallography and biochemical techniques. So with those two things now where they are, we are better equipped to discover the basic science. Once you have the basic science you can make a much more accurate prediction about the engineering required. But until the step discoveries are made, how can you predict?

Once you've got solar energy and converted it into a useful chemical form, it's like having sunlight in your back pocket.

Lewis: Another approach we are taking in photon-electron conversion is to create very cheap solar-cell nanostructures to absorb and capture sunlight. My group is collaborating with Harry Atwater's group on an important part of that: how do you make and grow nanowire-based solar cells that allow you to have very long absorption length but very short collection lengths? The nanowires would be very impure from a materials standpoint, so very cheap as well. As chemists, we are trying to grow these using wet chemical methods. As materials scientists, Harry Atwater's group is trying to grow them using chemical-vapor-deposition methods. We know that we need to find a way to fool all the surface atoms into thinking that they are like the bulk atoms, or else all we're going to do is make a lot of heat. We are working on the chemistry of fooling those surface atoms.

ENGenious: This sounds like the kind of research that's really done only at research universities. Shell, for instance, is not doing this kind of research. Is that correct?

Atwater: Right. Precisely. I think in some sense, this problem, and the scientific challenges with it, mesh with some of Caltech's most appealing qualities: the ability to quickly get together in a very organic sense and have scientists from different fields work together in a small group using ingenuity and collaboration.

Gray: Caltech, I think, is uniquely set up to do this because of our small size. Chemists and physicists talk to engineers here on almost a daily basis. Students are close by. We know everybody. I know the people who work with Sossina, some of them quite well. And we've been able to kick ideas around, quickly, all the time.

Haile: Note that CCSER is not addressing *all* aspects of energy technology. We pick our problems. We've identified what we think is a viable solution that includes all the components of the solution. So if all these parts work, this actually would lead to sustainable energy for the planet.

Atwater: One thing just to set the stage here, to generate some perspective—there are many issues in energy technology, a whole portfolio of issues, that we are not covering at all. Issues like how would you use fossil fuels and sequester the generated carbon.

Gray: All the fission energy, all the fusion—all of that stuff we are not dealing with.

Peters: We're focused really on a single approach of what we think is the most exciting area of energy research.

Haile: A truly viable solution.

Gray: We think sunlight is the only answer.

Peters: One obvious thing is: if you *could* do it this way, wouldn't you want to know? And so that justifies working like the dickens. It's so obvious that if you could do this, you'd want to do it. So you'd better figure out if you can.

Gray: I think the honest answer to your first question about whether we can predict what's going to happen is this: we are working on very fundamental problems right now that must be solved. Come back and look at CCSER after about five years—we are laying the groundwork for the technologies of the future in this field. And after five years of CCSER, we should be able to say, well, we can't do it, because we haven't solved anything. Or, we cracked a couple of these things, and now we can predict, that by 2035—which is my own year on this by the way—that by 2035 the price of a kilowatt hour generated by solar will be the same as that generated by oil. That's my prediction.

Peters: I'm not sure. Five years is only one PhD-student length of time away. [*Note new unit of measure. Ed.*] I wouldn't say that in five years we would be able to know whether some of the key discoveries that need to be made are going to be ready.

Gray: I'm more optimistic and I'm talking about the whole world, not just our group. I believe that we'll have an oxygen catalyst within five years that will be working great. There's no doubt we're going to have the manganese structure.

Peters: That is what's important about having integrated efforts. You can capitalize quickly as step-wise discoveries occur elsewhere. Moreover, you can decide if something that looks good actually has relevance to the ultimate goal at hand. There are lots of proof-of-principle catalysts that actually are going to be irrelevant to ever having a functional system.

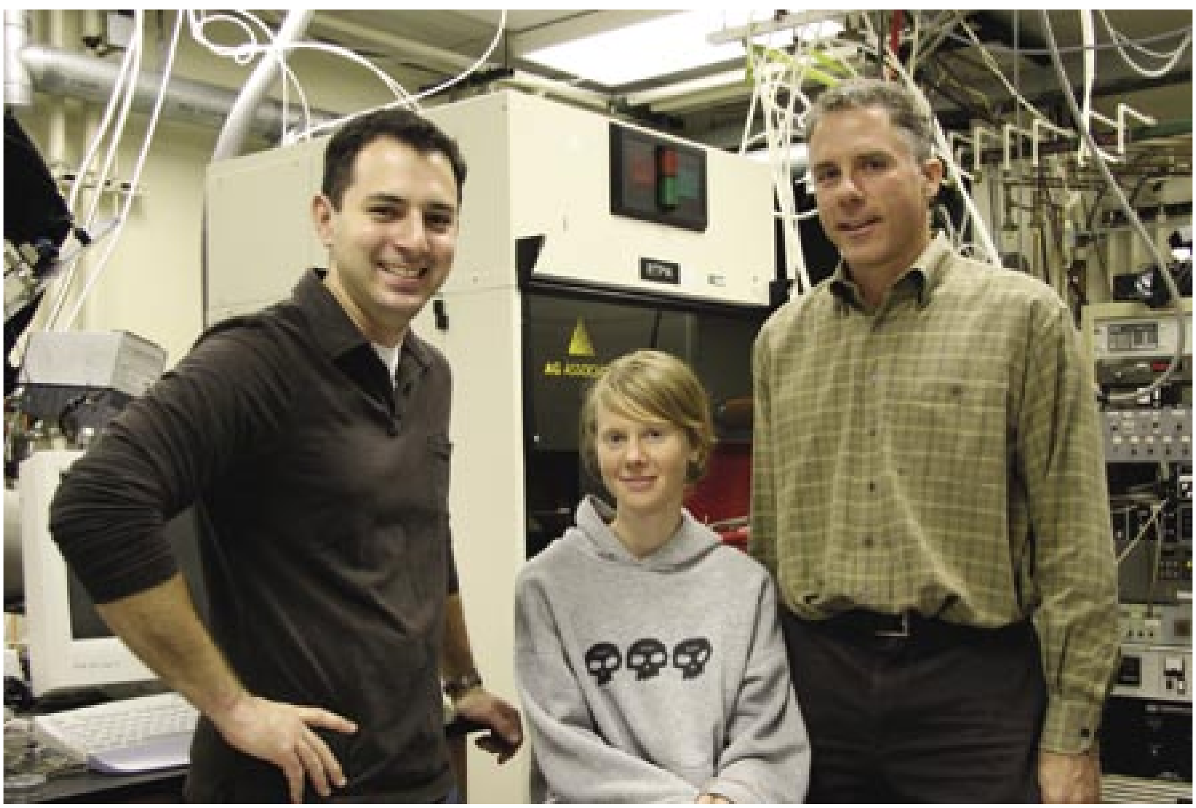
Gray: I believe we're going to see great investment in research in this area in the next five years, worldwide, because it's perceived to be a great problem.

Haile: There's an interesting challenge though. As you said, in the '70s, there was a lot of money that went into development and demonstration projects, but in areas where the technology was not yet ready. That's certainly the case in fuel cells now; there's a lot of development and demonstration technology. Money would, in my opinion, be better spent by solving the fundamental problems, rather than scaling up systems that you know already have problems.

ENGenious: What is different about the current environment than the one that existed in the '70s?

Atwater: Well, you know, if [the film] *The Graduate* had been made today, McGuire would have said to Benjamin: "nano." Nano-energy. Not plastics. [*laughter*]

Peters: It's clearly the case that the focus on global climate change is at an all-time high at the moment. So whether or not our interest in energy and climate change will wane with some new pattern that we'll go into in 15 or 20 years, the reality is that energy is a collector's item. Oil was only made once, and at the rates we need it, it will not be made again. We know that. Now, how long it's going to last,



Left to right: Dr. Michael Filler, postdoctoral scholar, graduate student Krista Langeland, and Harry Atwater, Howard Hughes Professor and Professor of Applied Physics and Materials Science.

nobody can exactly predict. But we've already done the rough calculation. We don't want to put a lot more CO_2 in the atmosphere if we can avoid it. So I think the difference is that people are acknowledging that we've got a situation here. In the '70s what drove it was the cost of fuel. I am not so worried about the cost of fuel—I'm more worried about how ugly this world will get when fuel gets scarce. Wars are created over this problem. And so most of us just look at it and say we don't want to live in a world where people are really scared about where their energy is coming from.

One obvious thing is: if you could do it this way, wouldn't you want to know?

Atwater: Scientifically speaking though, to come back to *The Graduate*—the understanding of nanoscale structures in matter and chemical reactions and of electron transport on the nanoscale are dramatically advanced beyond where they were in the 1970s. You could say we didn't know anything beyond very rudimentary things about nanostructures. All the reactions we are taking about—either the photovoltaic or photo-electrochemical reactions and the catalytic reactions—are really nanoscale phenomena. And we now have the theoretical, experimental, and synthetic tools to make nanostructures in an engineered fashion. That's a big difference.

Haile: It's true that all areas of science have advanced far from where they were in the '70s. And we're clearly able to leverage that—from the protein crystallography to the synthesis of exquisite structures that have exquisite function to the tools to be able to characterize them. On the other hand, we have this big impetus that we *know* we have to solve this, otherwise we really are not going to have a planet beyond this generation or two. Fundamentally we have to solve this. And the tools are in place for us to do that.

Lewis: The current situation is a perfect storm of three dollar a gallon gas prices, [Caltech Professor] David Goodstein's prediction that civilization as we know it will end in the 21st century if we don't solve the energy problem, and Al Gore bringing to the public's attention the climate and CO_2 connection.

Haile: We are now at CO_2 levels that the planet hasn't seen for 400,000 to 600,000 thousand years. If you plot CO_2 levels, they hover around 280 ppm for quite sometime, and then we hit the industrial revolution—boom. We are above 380 ppm now. If you look at plots of temperature, CO_2, and methane over the past 400,000 years, they all cycle. What's the cause of this 50,000-year cycle? Essentially, there's a slight change in the Earth's orbit every 50,000 years. So it's astounding, because now, this is the first time we are seeing CO_2 levels rise *before* the temperature rise. In all other cases it was that the Earth's orbit was changing a little bit, causing a change in temperature, and correlating with the increase of the concentrations in the atmosphere of CO_2 and methane. This is the first time we are seeing the CO_2 level rise *first*, and to such high levels, going up each year higher and higher. Who knows what's going to happen when you add the orbital cycle effect. It's scary, it really is scary.


Nate Lewis, George L. Argyros Professor of Chemistry.

Gray: I think there will be a catastrophe—in the next five years—a catastrophe having to do with energy availability. Just a little more of a glitch in the Middle East, and worldwide panic because there is no oil available. Long before global warming really knocks us off, there is going to be a crisis just having to do with the availability of fossil energy.

Haile: The other challenge is that whatever solution we want to implement will inevitably require energy as an input. So, if we're smart, we'll get on with it now while we have a reasonable amount of energy available.

Lewis: We know the CCSER approach encompasses physically allowed solutions. We know if we can find a way to make it happen, that there will be enough energy to keep everybody in the industrialized and the developing countries happy and independent. No other energy source allows that. We also know that we don't have that long, if you believe greenhouse gasses are the driver. Failure isn't really an option.

Atwater: Actually, I am profoundly optimistic. I see that the ability of humans to have such a big impact on climate can be turned around. Once we understand how to generate energy in a way that doesn't create that impact, or that offsets or mitigates that impact, we can do so on a scale that permits our planet to come back towards its natural state.

Gray: You asked what's new now compared to the '70s. If you look at the solar-fuel problem, there are three fundamental aspects. One is capturing all the light that reaches the Earth's surface—all the visible and near-infrared light. The second part is, once you capture it, to separate electrons and holes long enough to interface with catalysts to make fuel. We call that the electron-transfer part. And the third part is the catalyst. In the '70s, we didn't have any of the three solved. In 2006, we have the first two solved at least in concept. What remains to be solved is the catalyst part. But you see we've made *tremendous* progress in the other parts. And we can build nanostructures now to do all this, as Harry said.

Atwater: But currently they are not efficient enough.

ENGenious: What are the crucial problems in the fuel-cell domain that you need to solve?

Haile: We have to have a material, a membrane, that moves protons as opposed to moving electrons and holes. Like the photolysis systems, we also have catalysts on either side, but the catalysts are working in reverse relative to water splitting. Now in principle, if you have a good catalyst for oxygen evolution, it would also be a good catalyst for oxygen consumption. That's why we believe that if you make progress in fuel cells you make progress in water splitting and vice versa. Even though the functions are distinct, the catalyst components have lots of similarities. Getting back to the membranes, these materials in fuel cells are far less developed than the semiconductor materials for photovoltaics. A fuel cell only has to move one species, but it has to be very selective in moving that species. It should move no other species—no electrons, no water, no hydrogen, and no oxygen. For fuel-cell electrolytes, it's mainly a materials discovery problem.

Jonas Peters, Professor of Chemistry, third from left, top.

Atwater: We have silicon solar-cell solutions, but they're simply not low enough in cost per watt of power generated.

> But if you could go to Home Depot and buy a gallon of [solar] paint and paint it on your wall or your roof, you'd feel pretty good about running your meter backwards.

The ways in which you make them more efficient actually involve discovering new materials as well. The efficiency potential of silicon solar cells is near its theoretical limit. Remember, efficiency is enormously leveraging in solar photovoltaics: everything has a *per area cost*. If you have a more efficient solar cell, the cost per unit area of the whole system goes down: the land, the module, the person that's there waiting to clean it every week. In the same way that the catalyst developers are looking for earth-abundant materials, we're essentially trying to create a whole new class of photovoltaic materials. The materials we have to work with now (other than silicon) are ones that were developed in the opto-electronics, laser, and telecommunications fields. Gallium-arsenide, indium-phosphide, and so forth—they are quite rare, and they are quite expensive to produce on the scale needed for photovoltaics. But there's a whole untapped potential for solar-electric generation using earth-abundant materials—things like oxides and sulfides of iron, copper, cobalt. We're beginning to think along parallel lines about how we can create earth-abundant solar photovoltaic materials.

ENGenious: What about the idea of "solar paint?"

Lewis: That's a Harry Gray, Nate Lewis idea. No one wants to pay 5 or 10 or 50 thousand dollars—the way it is now—to have solar panels installed on their roof. But if you could go to Home Depot and buy a gallon of paint and paint it

on your wall or your roof, you'd feel pretty good about running your meter backwards. So we know solar technology needs to be really cheap, because you have to cover large areas, and really simple. It has to self-assemble. You have to change—really disrupt—the current approaches. We know what we need to do, we just don't quite know how to get there yet. The other thing you need to think about: it's not just the United States. If it costs 10% more than someone making $500 a year can afford, China's not going to do it. If it's not affordable at the China and India price, then it's not going to be effective in helping to get clean energy to everyone that needs it and to everyone who's emitting CO_2 now. You've got to make it really cheap, not just "United States cheap."

Atwater: You shouldn't underestimate the fact that the amount of energy that we need to displace is so enormous that the capital investments that are required to do that are going to be enormous. In other words, if we actually make a serious dent in U.S. energy use, it will become the largest industry in the United States. It will become the largest employer, it will become the largest consumer of capital. We are talking about a new infrastructure that will be replacing a huge hydrocarbon fuel infrastructure.

Peters: When you look at trying to replace huge chemical technologies, whether it be Haber-Bosch chemistry for fertilizer or anything else, you don't actually replace those technologies until the economics are so slanted that suddenly you don't have a choice.

Atwater: Or there is some policy push—a combination of economics plus policy push.

Peters: A part of the motivation for everyone here is that we like to discover new things and apply them to interesting problems. And this is an enormously interesting set of scientific problems.

Gray: And we are blatantly using this as a recruitment device for young people. There's enormous interest in this area. We're going to be able to recruit some of the best young people here just because we have this synergy. If it were just individuals working on isolated problems, we couldn't do nearly as well. But I think working together on the big picture will entice a lot of kids to sign up.

Atwater: Students are the glue. Students are the joinery between groups and are the key to developing interstitial, interdisciplinary knowledge.

ENGenious: How long have you been thinking about these problems?

Atwater: I've been working on one aspect or another of solar renewable energy since I was a graduate student, and suddenly the world has also joined in recognition that this is very important. I think it's an exciting scientific challenge—it's one of the most exciting science problems in the area of solid state materials and devices, and condensed matter physics—but it's also very important societally. I am now looking at the rest of my career thinking, what are the areas where I can have an impact not only scientifically, but potentially, on a problem where the applications would have enormous impact? That matters more to me than it did when I was an assistant professor.

Students are the glue. Students are the joinery between groups and are the key to developing interstitial, interdisciplinary knowledge.

Haile: I absolutely agree. I think that when we start off as foolish, bright-eyed, bushy-tailed kids, we have grand visions of how we are going to save the world. And then reality gets beat into us, and you have to do things that are not that grandiose, but are interesting scientific problems. And then at some stage, one starts to think back and say, wait a minute—what happened to my desire to save the world? And all of a sudden you say, how can I bring those two together? How can I use this incredible opportunity I had to learn all this great science, and use that for an important technical problem? It is a great way to draw in students because that is what they want also—they want to be able to use their technical skills to address important social problems—now more than ever.

Peters: [*with a wink*] I just want to make some money. I could care less. [*laughter*]

Gray: I've got 30 years of my life invested in this; to me it would be a great thrill to see someone really crack this. When I started in the '70s, I had to line up to get gas in Pasadena; literally, the gas lines at the corner of Lake and California went all the way around the block to Catalina and back down San Pasqual.

Peters: You'd use up all your gas in line.

Gray: I'd be reading journals thinking, I've got to do something. When I started I had this crazy idea that I could do better than nature. I really thought that I could build super molecules that would do everything—capture light, catalysis, everything at once. When we evaluated our solutions over the years, we found that they were tremendously limited in efficiency by crazy things that you couldn't control in these small packages. So nature wasn't that stupid after all. Nature had taken these three things that we've talked about—light capture, electron transfer, and catalysis—and separated them into pieces. But the younger people are going to solve this problem. The students we recruit are going to somehow figure out how to solve this thing, I am absolutely convinced of that. I'm excited about hopefully living long enough to see it. That's my goal. My goal is to live long enough to see this—and my other goal is to die funded. [*laughter*]

Lewis: We have to do this! It is not an option! I've been saying that for a long time. Everybody is repeating that mantra now, except maybe for the federal government. That's why it is so important and gratifying to have the Moore Foundation step in and get us off the starting block so we can move in that direction. E N G

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