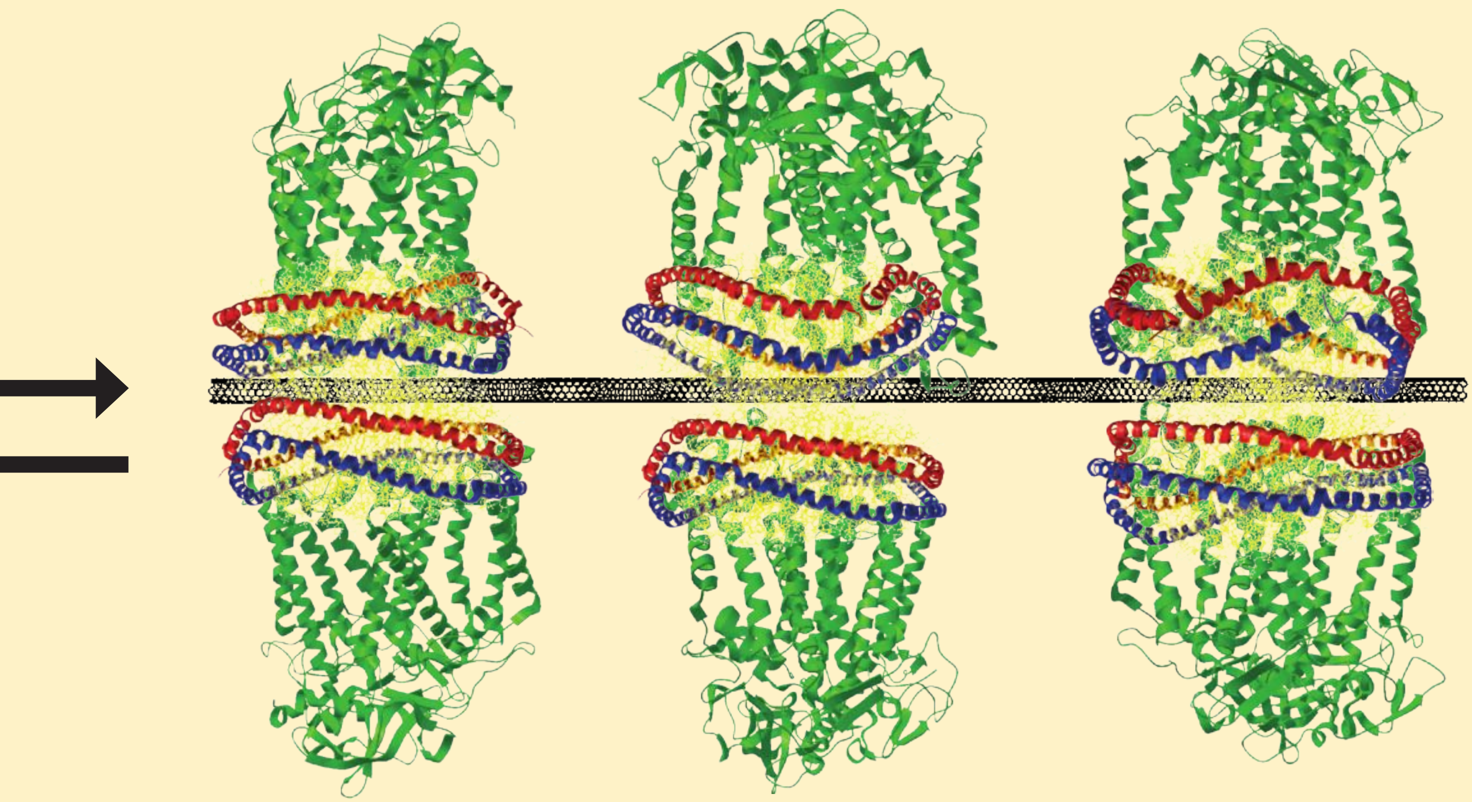
Energy Futures

MIT ENERGY INITIATIVE AUTUMN 2010



Nanoscale solar cells that self-assemble, self-repair

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Energy Futures

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Update on the MIT Energy Initiative

Dear Friends,

MITEI has just celebrated its fourth birthday. We spent our first year laying the groundwork and building the infrastructure for our programs in research, education, campus energy management, and policy outreach and the last three years advancing this agenda. Now is an opportune time to revisit and reflect on some of the choices made in structuring MITEI and to address the opportunities and challenges that lie ahead.

Fundamentally, the pathways laid out for each of the four mission areas have proved to be very productive, and new directions are also taking shape in each area. The success of MITEI to date has been accomplished through the efforts of an extraordinary group of faculty, students, staff, private- and public-sector partners, alumni, and friends.

A key initial commitment was advancing energy research both for innovations supporting today's energy systems and for transformational "game changers." This two-track approach was deemed essential for reaching a low-carbon and secure energy future in the 2006 MIT Energy Research Council planning report, the document that has guided our first four years of operation.

This judgment has been reinforced by the diminishing likelihood that a charge on carbon dioxide emissions will be implemented domestically any time soon. Internationally, expectations for the climate meeting in Cancun are considerably less than they were for the preceding meeting in Copenhagen.

The interplay of innovation and transformation is highlighted by results from the recent MIT Future of Natural Gas study, summarized on page 31. In the near term, an economically efficient path to a low-carbon future will likely be driven principally by the combination of reduced energy demand, notably through improved buildings and increased vehicle efficiency, and the substitution of natural gas for coal. This pathway will be supplemented by growth in nuclear power and renewable technologies. The combination of efficiency and natural gas forms the bridge to a low- or zero-carbon future.

To ensure that this is a "bridge to somewhere," game-changing "zero-carbon" technologies must scale up in dramatic fashion in just a couple of decades. Research articles in this edition of *Energy Futures* delve into some of MIT's work on these game-changing options, including solar energy (page 4), vehicle battery technology (page 8), and carbon dioxide sequestration (page 16). This work is supported by MITEI industry partners, either individually through sponsored research or collectively through the early-stage seed grant program. The lagging progress on the energy policy front heightens the importance of lowering the cost of these and other transformational technologies and rapidly moving them into the market.

MITEI's industry-led strategy has yielded a strong innovation and transformation research portfolio aligned with both faculty interests and company strategic directions. The programs of our earliest Founding members, BP and Eni, have emphasized solids conversion and solar frontiers, respectively. While that work continues, both collaborations are also leading to deepening strategic partnerships in new areas. Similar progress has been made with our earliest Sustaining members. At the same time, new partnerships continue to form. In October, we were pleased to announce that Shell had joined the Initiative as its newest Founding member (see photo at right).

A new direction is also taking hold, namely, substantial multiyear federal programs. Over the last two years, the US Department of Energy (DOE) has placed renewed emphasis on energy science and technology programs that are sustained and competitively awarded. These programs are complementary to our industry-supported programs and are opening up new opportunities for MITEI and for MIT. MIT's success in the Energy Frontier Research Center and the Advanced Research Projects Agency-Energy (ARPA-E) competitions has been chronicled in previous editions of *Energy Futures.*

We have also assumed a key role in the DOE-funded Nuclear Energy Innovation Hub, led by Oak Ridge National Laboratory. This hub is dedicated to providing and employing new petascale simulation tools to advance light water nuclear reactor technology. This effort is an excellent example of innovation focusing on today's energy systems: we will be using frontier modeling and simulation capabilities to improve the nuclear technology that will almost certainly dominate in the next several decades.

MITEI's initial focus on the education front was on creating new curriculum options for undergraduates. Under the continuing leadership of Professors Vladimir Bulović (Electrical Engineering and Computer Science) and Donald Lessard (Management) and the strong support of the MITEI Education Office

MITEI's research, education, campus energy, and outreach programs are spearheaded by Professor Ernest J. Moniz, director (right), and Professor Robert C. Armstrong, deputy director.

led by Dr. Amanda Graham, this goal is being realized in large part through the creation of an energy minor program and curricular offerings to support it.

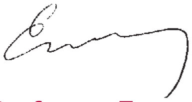
New developments will include project-based subjects and dissemination of new energy courses through Open-CourseWare. MITEI is also increasing its participation in and support for the Undergraduate Research Opportunities Program (UROP—page 26) and the Freshman Pre-Orientation Program (FPOP—page 27).

The campus energy management program is similarly coming into full stride, consistent with MITEI's original vision. The combined strengths of Professor Leon Glicksman (Architecture and Mechanical Engineering) and MIT Executive Vice President and Treasurer Theresa Stone have been essential in greening the MIT campus. Student engagement is high, and annual savings from campus energy projects will reach well over $3 million by the end of 2010, according to the MIT Department of Facilities. The collaboration with NSTAR will reduce campus electricity use by 15% over three years. In addition, MIT was the first university invited to join DOE's new Global Superior Energy Performance Partnership, a building energy management certification program (pages 29–30).

Finally, MITEI has been vigorously pursuing its commitment to policy outreach. The pace of our in-depth multidisciplinary studies on the future of low-carbon technology pathways—started in 2003 with nuclear power—has quickened. In the last several years, studies have examined the future of coal, geothermal, natural gas, nuclear fuel cycles, solar energy, and the electric grid. These studies—some completed and others still under way—have drawn on the expertise of 40 MIT faculty and senior researchers and a comparable number of graduate students and postdocs. The studies continue to have policy impacts and are now supplemented by an Associate member-supported symposium series that focuses on more specific and timely topics in need of technically grounded discussion.

In short, we have built a strong foundation that can accommodate new initiatives in each of MITEI's four mission areas. In our fifth year, we will revisit the MITEI roadmap in consultation with our many participants and friends. With the continuing contribution of so many talented faculty, students, and staff, we feel confident that "phase 2" will sustain MIT's leading role in developing critical energy solutions. We welcome your involvement and input in the days ahead.

Sincerely,



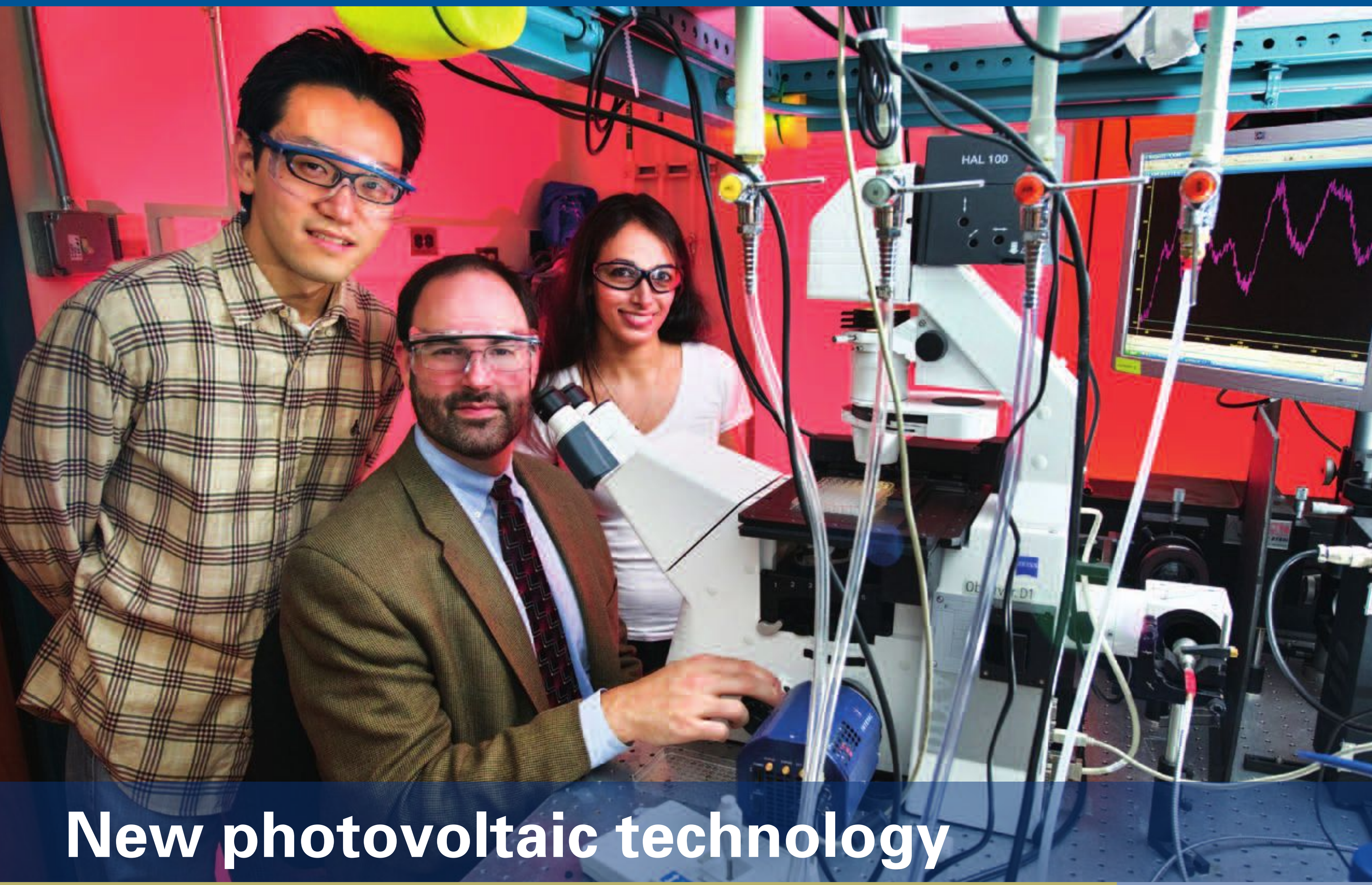
Professor Ernest J. Moniz
MITEI Director

Professor Robert C. Armstrong
MITEI Deputy Director

November 2010

Photos: Justin Knight

Gerald Schotman (right), chief technology officer, Royal Dutch Shell, signs an agreement with MIT President Susan Hockfield to collaborate on research and development of high-value, sustainable technologies designed to drive innovation in energy delivery. Under the agreement, signed October 13, 2010, Shell will provide $25 million to the MIT Energy Initiative (MITEI) for research and collaboration. Beginning this year, the research partnership will fund a suite of projects at $5 million per year for the coming five years. The projects will focus on advanced modeling, earth science, biofuels, nanotechnology, and carbon management. The agreement establishes Shell as a Founding member of MITEI, an extension of the collaborative projects Shell has been conducting with MIT in a variety of basic and applied research areas since 2002.



New photovoltaic technology

Nanoscale solar cells that self-assemble, self-repair

Photo: Justin Knight

Plants are good at doing what scientists and engineers have been struggling to do for decades: converting sunlight into stored energy, and doing so reliably day after day, year after year. Now some MIT scientists have succeeded in mimicking a key aspect of that process.

One of the problems with harvesting sunlight is that the sun's rays can be highly destructive to many materials. Sunlight leads to a gradual degradation of many systems developed to harness it. But plants have

Above: Professor Michael Strano (center) with postdoctoral researcher Moon-Ho Ham (left) and graduate student Ardemis Boghossian, all of the Department of Chemical Engineering.

adopted an interesting strategy to address this issue: They constantly break down their light-capturing molecules and reassemble them from scratch, so the basic structures that capture the sun's energy are, in effect, always brand new.

That process has now been imitated by Michael Strano, the Charles and Hilda Roddey Associate Professor of Chemical Engineering, and his team of graduate students and other researchers. They have created a novel set of self-assembling molecules that can turn sunlight into electricity; the molecules can be repeatedly broken down and then reassembled quickly, just by adding or removing an additional solution.

Strano says the idea first occurred to him when he was reading about plant biology. "I was really impressed by how plant cells have this extremely efficient repair mechanism," he says. In full summer sunlight, "a leaf on a tree is recycling its proteins about every 45 minutes, even though you might think of it as a static photocell."

One of Strano's long-term research goals has been to find ways to imitate principles found in nature using nanocomponents. In the case of the molecules used for photosynthesis in plants, the reactive form of oxygen produced by sunlight causes the proteins to fail in a very precise way. As Strano describes it, the oxygen "unsnaps a tether that keeps the protein together," but the same proteins are quickly reassembled to restart the process.

This action all takes place inside tiny capsules called chloroplasts that reside inside every plant cell—and which is where photosynthesis happens. The chloroplast is "an amazing machine," Strano says. "They are remarkable engines that consume carbon dioxide and use light to produce glucose," a chemical that provides energy for metabolism.

"We're basically imitating tricks that nature has discovered over millions of years"— in particular, "reversibility, the ability to break apart and reassemble."

— Professor Michael Strano

To imitate that process, Strano and his team produced synthetic molecules called phospholipids that form disks; these disks provide structural support for other molecules that actually respond to light, in structures called reaction centers, which release electrons when struck by particles of light. The disks, carrying the reaction centers, are in a solution where they attach

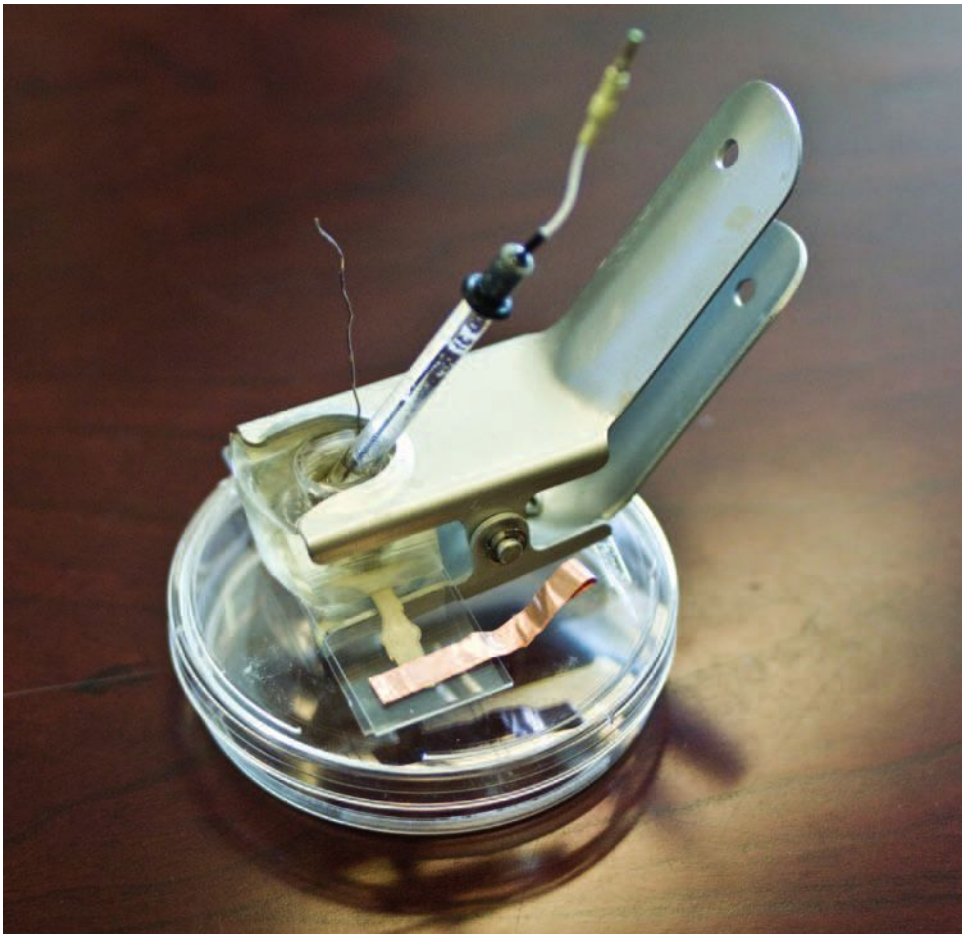
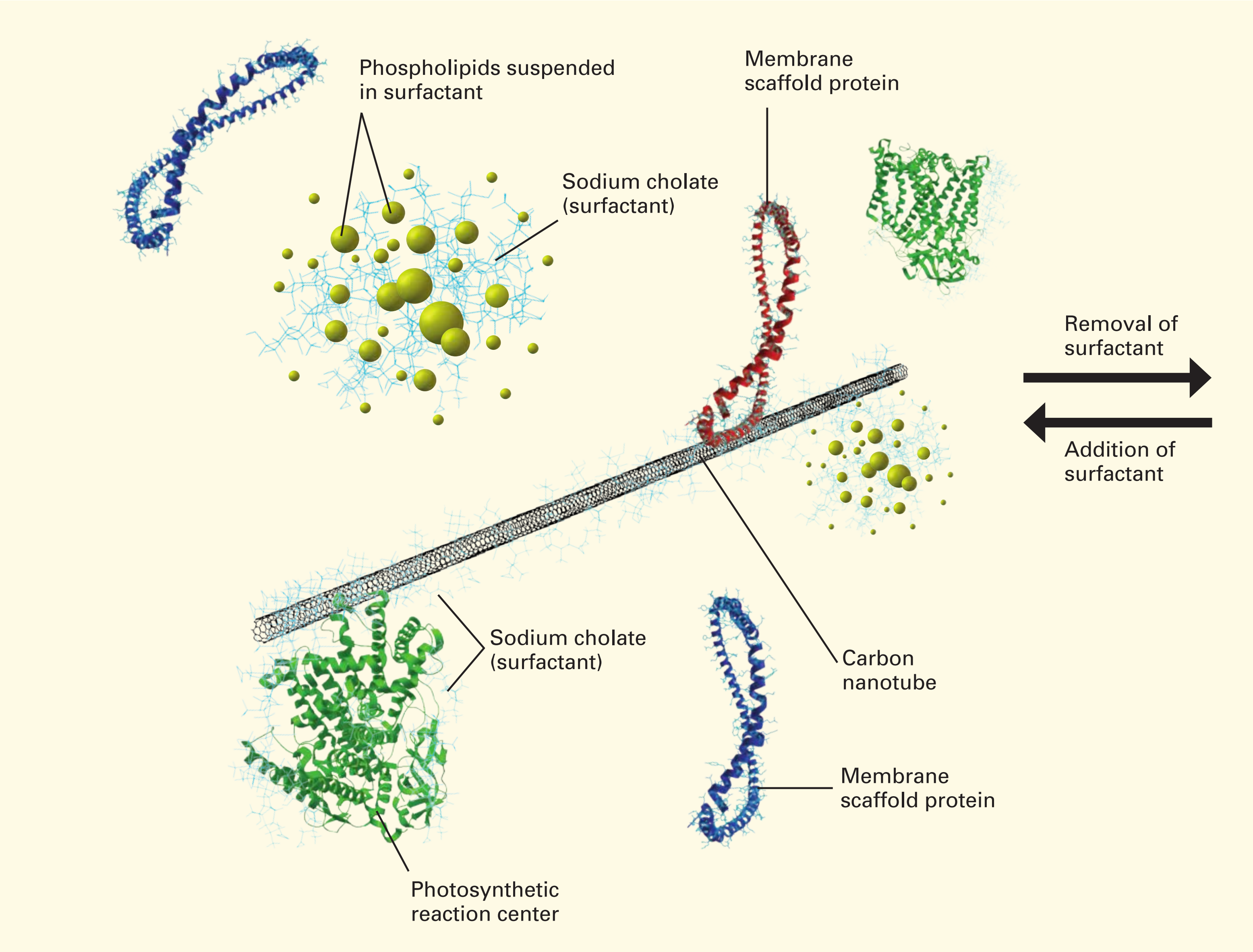


Photo: Patrick Gillooly, MIT

This proof-of-concept version of the photoelectrochemical cell, which was used for laboratory tests, contains a photoactive solution made up of a mix of self-assembling molecules (in the glass cylinder held in place by the metal clamp) with two electrodes protruding from the top, one made of platinum (the bare wire) and the other of silver (in the glass tube).

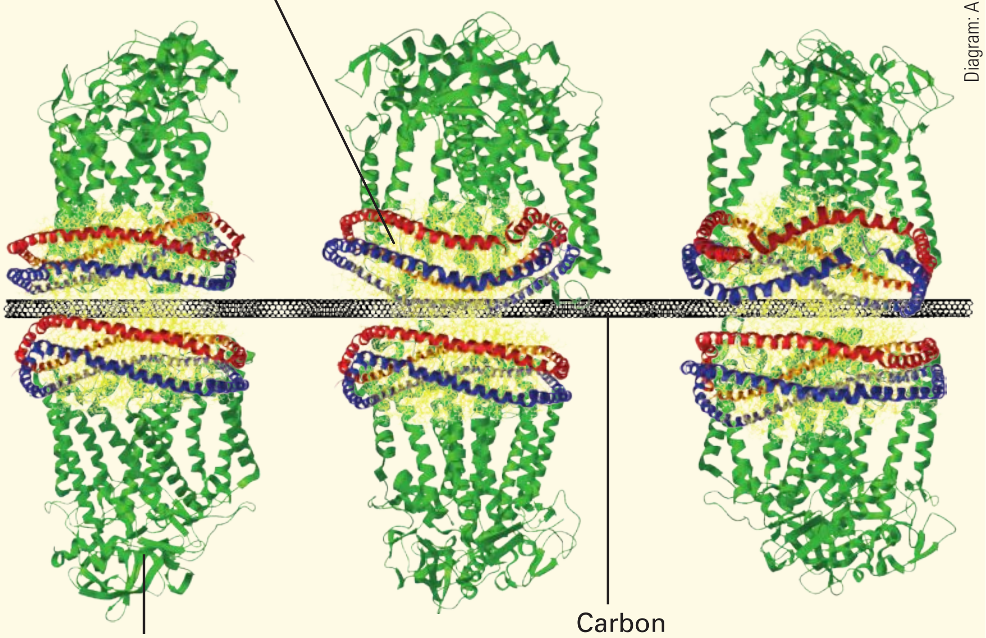
Schematic of decomposition and self-assembly of nanoscale solar cells



themselves spontaneously to carbon nanotubes—wire-like hollow tubes of carbon atoms that are a few billionths of a meter thick, yet stronger than steel and capable of conducting electricity a thousand times better than copper. The nanotubes hold the phospholipid disks in a uniform alignment so that the reaction centers can all be exposed to sunlight at once, and they also act as wires to collect and channel the flow of electrons knocked loose by the reactive molecules.

The system Strano's team produced is made up of seven different compounds, including the carbon nanotubes, the phospholipids, and the proteins that make up the reaction centers, which under the right conditions spontaneously assemble themselves into a light-harvesting structure that produces an electric current. Strano says he believes this sets a record for the complexity of a self-assembling system. When a surfactant—similar in principle to the chemicals that BP has sprayed into the Gulf of Mexico to break apart oil—is added to the mix, the seven components all come apart and form a soapy solution. Then, when the researchers removed the surfactant by pushing the solution through a membrane, the compounds spontaneously assembled once again into a perfectly formed, rejuvenated photocell.

"We're basically imitating tricks that nature has discovered over millions of years"—in particular, "reversibility, the ability to break apart and reassemble," Strano says. The team, which included postdoctoral researcher Moon-Ho Ham and graduate student Ardemis



The self-assembly process involves carbon nanotubes and photosynthetic reaction centers and occurs when a surfactant—here, sodium cholate—is removed. Filtering out the surfactant from the starting mixture induces spontaneous self-assembly of synthetic molecules called phospholipids plus membrane scaffold proteins to form phospholipid disks. These disks provide structural support for reaction centers, which release electrons when struck by light. The disks carrying the reaction centers attach themselves spontaneously to carbon nanotubes, which are suspended in an aqueous solution. The resulting highly ordered structure is shown in the right-hand panel. Addition of the surfactant sodium cholate completely decomposes the structure back into the individual components in the initial mixture (left-hand panel).

Boghossian, both of the Department of Chemical Engineering, came up with the system based on a theoretical analysis, but then decided to build a prototype cell to test it out. They ran the cell through repeated cycles of assembly and disassembly over a 14-hour period, with no loss of efficiency.

Strano says that in devising novel systems for generating electricity from light, researchers don't often study how the systems change over time. For conventional silicon-based photovoltaic cells, there is little degradation, but with many new systems being developed—either for lower cost, higher efficiency, flexibility, or other improved characteristics—the degradation can be very significant. "Often people see, over 60 hours, the efficiency falling to 10% of what you initially saw," he says.

The individual reactions of these new molecular structures in converting sunlight are about 40% efficient, or about double the efficiency of today's best solar cells. Theoretically, the efficiency of the structures could be close to 100%, he says. But in the initial work, the concentration of the structures in the solution was low, so the overall efficiency of the device—the amount of electricity produced for a given surface area—was also very low. They are working now to find ways to greatly increase the concentration.

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By David L. Chandler, MIT News Office

A grant from Eni S.p.A., under the Eni-MIT Solar Frontiers Center of the MIT Energy Initiative, supported work relating to photoelectrochemical cell regeneration, including design and fabrication. A grant from the US Department of Energy supported the spectroscopy and analytical chemistry of complexes in this work. Moon-Ho Ham received support from the Korea Research Foundation Grant funded by the Korean Government. Further information can be found in:

M.-H. Ham, J. Choi, A. Boghossian, E. Jeng, R. Graff, D. Heller, A. Chang, A. Mattis, T. Bayburt, Y. Grinkova, A. Zeiger, K. Van Vliet, E. Hobbie, S. Sligar, C. Wraight, and M. Strano. "Photoelectrochemical complexes for solar energy conversion that chemically and autonomously regenerate." *Nature Chemistry.* Published online: 05 September 2010, doi:10.1038/nchem.822.

A promising lightweight battery for electric cars

New catalysts push up lagging efficiency

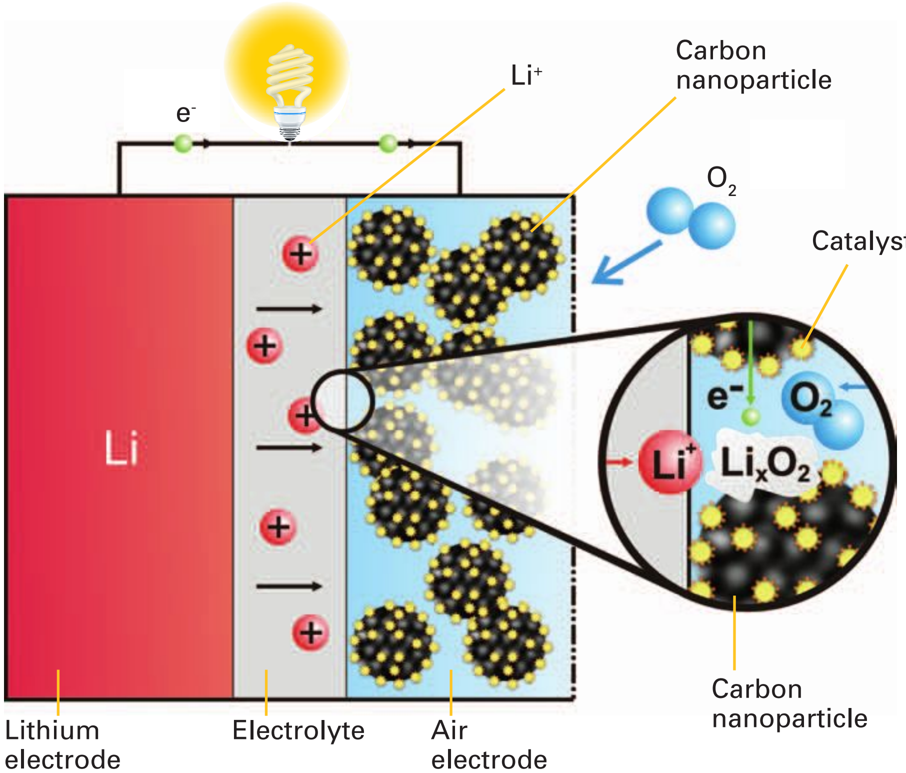
Photo: Justin Knight

If electric cars are to provide the range that drivers demand, they need batteries that can deliver lots more energy, pound for pound, than today's best lithium-ion batteries can. Lithium-air batteries could—in theory—meet that challenge, but while they are far lighter than their lithium-ion cousins, they are not nearly as efficient.

MIT researchers have now demonstrated significant gains on that front. Using specially designed catalysts, they have made lithium-air

Above: Professor Yang Shao-Horn (center) of mechanical engineering and materials science and engineering, with graduate students Yi-Chun Lu (right) of materials science and engineering and Koffi Pierre Claver Yao of mechanical engineering.

Processes on a lithium-air battery during discharge



When a lithium-air battery is discharged, positively charged lithium ions (Li^+) move from the lithium electrode through the electrolyte to the air electrode, while negatively charged electrons (e^-) travel through an external circuit, powering a device (the light bulb) along the way. The lithium ions and electrons plus oxygen (O_2) from air react to form lithium oxide (Li_xO_2), a solid that settles in open spaces among the carbon nanoparticles in the air electrode. During charging, the lithium oxide breaks apart, the three reactants go back where they came from, and the system is reset.

batteries with unprecedented efficiency, meaning that more of the energy put in during charging comes out as useful electricity during discharging. Less energy is lost at each recharge—an advance that addresses one of the major stumbling blocks with this promising technology.

Those results are just a first indication of what catalysts can do for the performance of the lithium-air battery, according to Yang Shao-Horn, director of the research and associate professor of mechanical engineering and materials science and engineering. She predicts that even higher efficiencies will come.

While other groups are working on lithium-air batteries, she and her team in MIT's Electrochemical Energy Laboratory are the first to perform fundamental studies of catalysts that will promote key electrochemical reactions in these batteries. "That makes this a fun area for us to work in," says Shao-Horn. "Every experiment is like a discovery for us because there's no previous experimental data to reference or to look at."

Shao-Horn stresses that development of a practical lithium-air battery is in its very early stages. "There are still many science and engineering challenges to be overcome," she says. But already her team's results are significant—and in some cases unexpected.

A lightweight technology

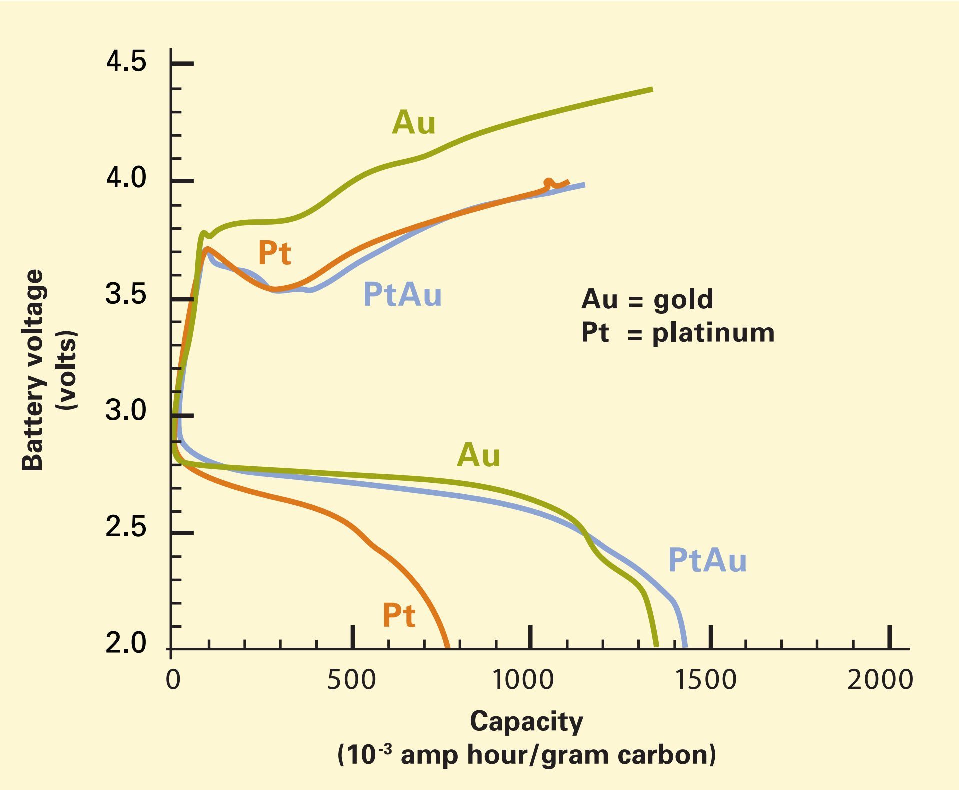
Understanding the promises and problems of lithium-air batteries requires understanding how they work. A lithium-air battery consists of two electrodes—a lithium electrode and an air electrode made of carbon—with an electrolyte between them. As the battery is charged and discharged, lithium ions (positively charged) and electrons (negatively charged) shuttle back and forth between the two electrodes.

The diagram above shows what happens as the battery is discharged. Electrons (e^-) travel from the lithium electrode to the air electrode through an outside circuit, powering a device (the light bulb) along the way. Lithium ions (Li^+) make the same journey through the electrolyte. At the air electrode (shown in the detailed view), the electrons combine with the lithium ions and oxygen (O_2) from the air to form lithium oxide (Li_xO_2).

To recharge the battery, an outside electrical supply forces the lithium oxide to decompose, releasing oxygen to the atmosphere and sending the lithium ions and electrons back to the lithium electrode, and the system is reset. The process of making and breaking the lithium oxide thus allows the battery to generate electricity and to be recharged.

In this design, the air electrode consists of a carbon "skeleton" that must both conduct electrons and provide empty space for storing the lithium oxide, which is a solid. (Oxygen does not need to be stored; it comes from the atmosphere.) As a result, fully 60% of the air electrode is empty space, making it far lighter than the heavy, solid electrode in a lithium-ion battery. The lithium-air battery can therefore deliver more energy per unit weight—a measure called energy density. Shao-Horn and her team project the energy density of

Impacts of platinum, gold, and platinum-gold catalysts on efficiency in a lithium-air battery



These measurements were taken in experimental lithium-air batteries with air electrodes containing three catalysts: pure platinum (orange), pure gold (green), and a platinum-gold alloy (blue). The bottom three curves show voltages as the batteries are discharged; the top three show voltages as they are charged. As predicted, the measurements with the platinum-gold catalyst track those with the gold catalyst during discharge and those with the platinum catalyst during charging. The platinum-gold alloy thus accelerates both of the key reactions in a lithium-air battery so that it delivers more voltage when it is discharged and requires less voltage when it is recharged. The net result: the highest "round-trip" efficiency ever reported in a lithium-air battery.

lithium-air batteries at 1,000 watt-hours per kilogram—significantly higher than the 200 watt-hours per kilogram of state-of-the-art lithium ion batteries now used in laptop computers and cell phones.

"With that kind of energy density, the lithium-air battery is a potential technology for electric vehicles," says Shao-Horn. But there are problems with the battery. One is low "round-trip efficiency" during discharging and charging. When the battery is discharging, energy comes out at about 2.7 volts. But charging it up requires putting in 4 volts. The round-trip efficiency is thus about 67%. "That means that each time you charge and discharge your electric car, you lose about a third of the energy you put in," Shao-Horn says. In state-of-the-art batteries, round-trip efficiency is typically 90–95%, putting energy loss at just 5–10%.

To improve efficiency, Shao-Horn and her team have been trying to speed up the lithium oxide reactions on the air electrode. Their goal: to find catalysts that will encourage lithium oxide to form as the battery discharges and to decompose as the battery charges. The result will be higher voltage coming out and lower voltage going in.

Their work to date has focused on three materials: platinum, gold, and carbon (as a control case). As a first test, they examined how the catalysts affect the rates of the lithium oxide reactions on pure catalyst surfaces. The results were not as they expected. In previous work with fuel cells, platinum had accelerated the combination of hydrogen and oxygen. In the new experiments, the platinum did not encourage the lithium and oxygen to combine. Instead, it promoted the opposite reaction: breaking the lithium oxide apart. Further examination showed that during lithium oxide formation, the organic (non-water) solvent that serves as the electrolyte can "poison" the platinum catalyst. During lithium oxide destruction, that process does not occur because the high voltage during recharging removes the solvent poisons.

Experiments on the gold surface also brought surprising results. Gold is usually assumed to be a poor catalyst because it is inert. Indeed, gold had little impact in the earlier fuel cell research. But in the new work, it proved effective at promoting the formation of lithium oxide.

Testing batteries

To test the relevance of the results on the pure catalyst surfaces, the researchers built a series of experimental lithium-air batteries. Their lithium electrode is pure lithium metal (though for safety reasons a commercial version would use lithium stored in a stable material such as graphite). The air electrode consists of the carbon skeleton made up of tiny particles, each one about 50 nanometers (nm) in diameter. In their novel design, the surface of each carbon particle is covered with even smaller particles of the material being tested—platinum, gold, or carbon. Those particles are just 5 nm in diameter—a tiny size that maximizes their surface area and therefore the

"Every experiment is like a discovery for us because there's no previous experimental data to reference or to look at."

— Professor Yang Shao-Horn

Photo: Patrick Gillooly, MIT

An experimental lithium-air battery developed and tested at MIT. The inlet and outlet on the sides permit air to flow through, providing oxygen for the battery's operation.

number of sites available for chemical reactions to occur.

The researchers then measured the voltage as they charged and discharged their batteries. The voltage trends agreed well with their measurements on the pure catalyst surfaces. Indeed, according to Shao-Horn, the platinum "exhibited extraordinarily high activity during charging."

"So we had learned two things about our catalysts," says Yi-Chun Lu, a graduate student in the Department of Materials Science and Engineering who is the lead author on this work. "We'd learned that on charging, platinum is best; and on discharging, gold is best. But both of those activities occur in the same place—on the air electrode—so why not try combining the two catalysts?"

In their next round of experimental batteries, they made the tiny test particles of a platinum-gold alloy, working in collaboration with Kimberly Hamad-Schifferli, associate professor of mechanical and biological engineering, and Hubert A. Gasteiger, formerly a visiting professor at MIT and now a professor at Technical University of Munich. Again they tracked the voltage while charging and discharging the batteries. They hypothesized that during discharge the voltage with the alloy would track that measured with gold alone, and during charge it would track that measured with platinum alone. As shown in the diagram on page 10, their experimental results supported their hypothesis.

"We demonstrated that our platinum-gold alloy exhibited bifunctional catalytic activity, which means that on discharge, gold is doing the work, and on charge, platinum is doing the work," says Shao-Horn. "Best of all, the battery with the platinum-gold nanoparticles demonstrates a round-trip efficiency of 75%—the highest efficiency ever reported in a lithium-air battery." With further work, she believes her team can push that efficiency up to 85–90%.

Added benefits, future plans

Speeding up the reactions on the air electrode may provide other benefits. Another shortcoming of lithium-air batteries is that they typically can be discharged and charged a limited number of times, in part because the lithium oxide tends to clog the air electrode. Moving it out more quickly may help. Also, speeding up reactions on the air electrode may help address the lithium-air battery's low "rate capability"—the significant drop in the amount of energy it can deliver during rapid or prolonged discharging.

Work with their platinum and gold catalysts now focuses on cutting costs. To that end, they are designing tiny particles that have those precious metals only on their surfaces, thereby reducing the amount needed. They are also working with other, less expensive materials that might provide the same or better battery performance.

Ultimately, they plan to map out activity trends on various metal surfaces so they can develop an understanding of the basic mechanisms—the step-by-step breaking and forming of chemical bonds—involved in the lithium-oxygen reactions. Guided by that understanding, they hope to design catalysts for lithium-air batteries that could one day be up to the task of powering electric vehicles, making possible a fundamental change in today's petroleum-based transportation sector.

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By Nancy W. Stauffer, MITEI

This research was funded by the US Department of Energy, the Materials Research Science and Engineering Centers (MRSEC) Program of the National Science Foundation, and an MIT fellowship from the Martin Family Society of Fellows for Sustainability. Further information can be found in:

Y.-C. Lu, H. Gasteiger, E. Crumlin, R. McGuire, Jr., and Y. Shao-Horn. "Electrocatalytic activity studies of select metal surfaces and implications in Li-air batteries." *Journal of the Electrochemical Society*, v. 157, no. 9, 2010.

Y.-C. Lu, H. Gasteiger, M. Parent, V. Chiloyan, and Y. Shao-Horn. "The influence of catalysts on discharge and charge voltages of rechargeable Li-oxygen batteries." *Electrochemical and Solid-State Letters*, v. 13, no. 6, 2010.

Y.-C. Lu, Z. Xu, H. Gasteiger, S. Chen, K. Hamad-Schifferli, and Y. Shao-Horn. "Platinum-gold nanoparticles: A highly active bifunctional electrocatalyst for rechargeable lithium-air batteries." *Journal of the American Chemical Society*, v. 132, no. 35, September 8, 2010.

Predicting natural gas use

Trends, trajectories, and the role of uncertainty

The work described here was a critical input to MIT's The Future of Natural Gas*, a two-year interdisciplinary examination of the role of natural gas in a carbon-constrained world out to mid-century. Key findings of that study are summarized on page 31.*

The emergence of techniques to exploit vast deposits of natural gas in shale in the US has raised hopes that gas can fulfill our expanding energy needs while also reducing emissions by replacing "dirtier" fuels such as coal and oil. A quantitative analysis by an MIT team confirms that outlook—though with some qualifications.

The MIT results show that gas use will indeed expand, especially if new policy measures put a price on carbon emissions. But if the limits on carbon are stringent, even the relatively low emissions of natural gas could disqualify it from the energy scene after mid-century. That projection underscores the need for intensive research to ensure that carbon-free alternatives are ready to take over by mid-century.

The evolution of markets for natural gas could also have a major impact on its use and price. Today, gas is traded on three separate markets—North America, Europe, and Asia. If a tightly integrated global gas market develops, the US would gain access to gas that is cheaper than our domestic resources. As a result, overall gas use would rise, benefiting the environment, and consumer costs would drop. Domestic production would continue, but by 2040 the US could be getting half or more of its energy resources from the Middle East and Russia—this time, imported gas rather than oil.

An uncertain future

The development of technology for producing "shale gas" is good news on many fronts. The resource is extensive, domestic, and relatively low cost; and its greenhouse gas (GHG) emissions are lower than those from coal or oil. Indeed, burning gas emits about half as much carbon dioxide as burning coal does.

So does this huge natural gas resource hand us a solution to our energy and environmental worries? Can we simply rely increasingly on natural gas—at least for a long time?

It's not so simple, warns a team of MIT researchers. The role of natural gas in the future US energy picture will depend on a number of factors, says Henry D. Jacoby, professor of management. He notes the following questions: "How much gas is there, and what will it cost? What will be the costs of competing technologies? Will we have a policy to control GHGs, and how strict will it be? And what will be the structure of the international gas markets?"

For each of those questions, there is a range of possible answers, some more likely than others, and their impacts on gas use will interact. For example, gas use will depend on the cost of natural gas as well as the costs of competing energy sources. Thus, any calculation of gas use must take into account not only the uncertainties associated with the various cost predictions but also how those uncertainties interact.

To get a quantitative look at how gas will fare, Jacoby, Sergey Paltsev, principal research scientist in the MIT Energy Initiative, and their colleagues in the MIT Joint Program on the Science and Policy of Global Change used their Emissions Prediction and Policy Analysis (EPPA) model. This sophisticated model tracks economic activity and associated energy use and GHG emissions, recognizing multiple regions of the world linked by trade. It can take into account technological change, resource estimates, population change, and the effects of specified emissions-abatement policies and regulations.

Up front, the MIT researchers stress that their analyses can't provide absolute answers. "We have to be careful about interpreting our numerical results," says Paltsev. "We don't know precise answers, but we can capture trends and trajectories and see the major implications of policy and regulatory choices and other uncertain factors."

Carefully selected assumptions

To perform their analyses, the researchers ran a series of simulations using various assumptions, each with its defined uncertainty. Based on the best available information and their best judgment, they selected the following parameters to model.

Scale and cost of gas resources. Based on data from various sources, an MIT team assessed existing and potential natural gas fields in the world to determine how much gas is recoverable at what prices. Combining that information, they created gas supply curves for all regions of their model and then defined three cases: low, mean, and high resources.

Timing, stringency, and design of GHG mitigation policy. The analysis looks at three options. The first assumes no climate-related policy. The second assumes a price-based policy that imposes an economy-wide price on carbon emissions designed to gradually reduce those emissions to 50% below 2005 levels by 2050. (The scenario allows no "offsets," that is, all actions are taken domestically, and emissions permits cannot be bought from abroad.) The third policy is a regulatory approach that mandates the gradual retirement of coal power plants such that 55% of current coal generation is retired by 2050; it also requires 25% of all electricity to come from renewable sources from 2030 onwards.

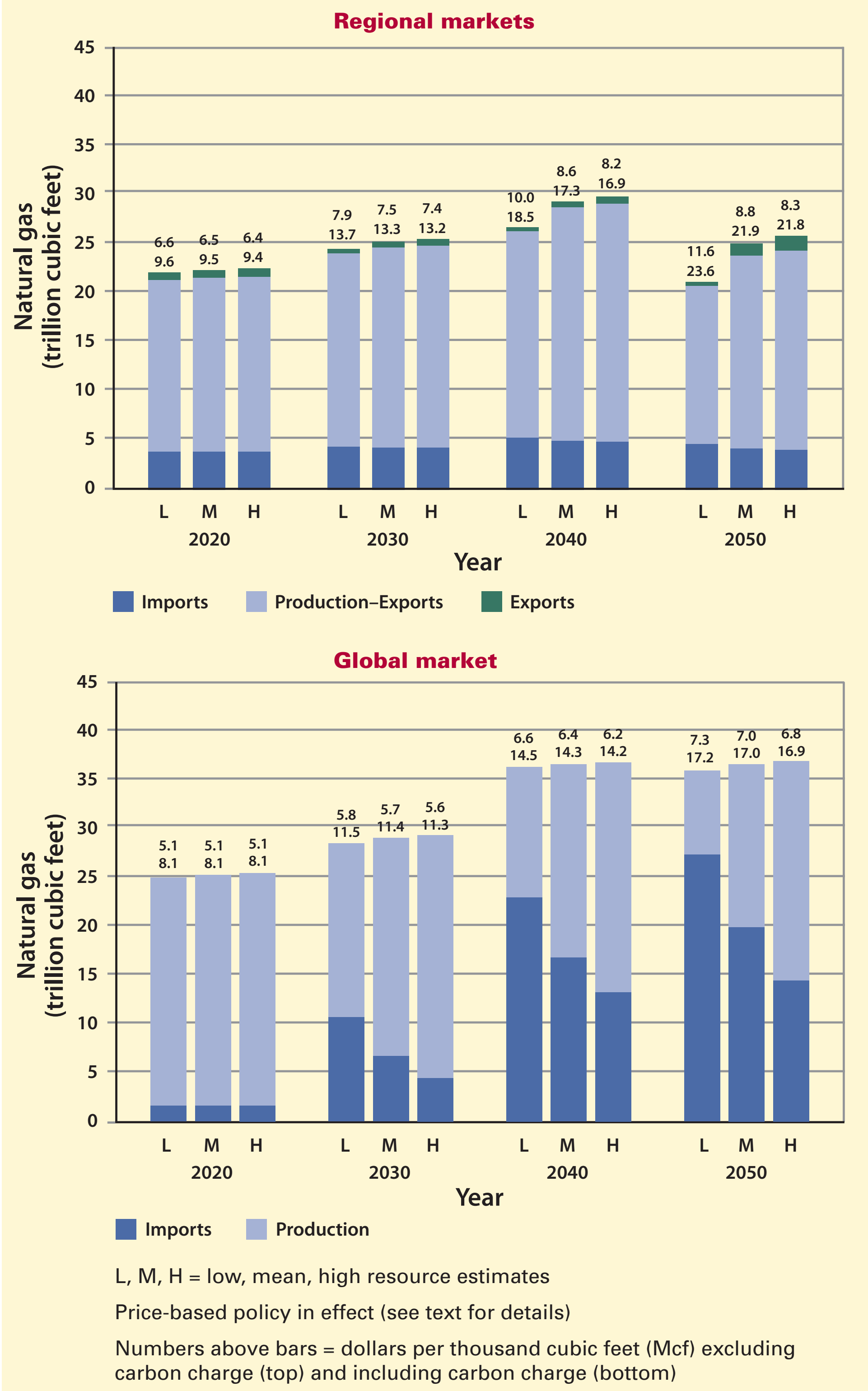
The technology mix. In general, the analyses estimate that competing technologies—specifically, nuclear power, renewables, and coal and natural gas with carbon capture and storage—continue to be relatively expensive compared with natural gas-based technologies. They also estimate that natural gas-powered vehicles do not significantly penetrate the transportation sector.

The evolution of global natural gas markets. Here they select two possible futures. One assumes that world trade in natural gas continues as it is today: concentrated in three regional markets—North America, Europe, and Asia—that have differing prices and types of contracts between buyers and sellers. The other assumes that there is a tightly integrated global gas market similar to today's international market for crude oil (but without supplier cartels). The researchers emphasize that those two views represent polar cases. In reality, future global markets will fall somewhere between those extremes.

The changing role of natural gas

In general, the simulations show that natural gas will play a major role in the US energy future. With no new climate policy (and assuming the mean resource estimates and regional

US natural gas outlook including effects of international market evolution



The top set of bars assumes that the regional markets of today persist, with trading largely occurring within three markets: North America, Europe, and Asia. The bottom set of bars assumes the existence of a tightly integrated global gas market (without supplier cartels). With a global market, natural gas use is higher and prices are lower than with regional markets, but by mid-century the US depends on imports for about half its natural gas (under the mean resource estimate).

markets), US gas use rises steadily from about 25 trillion cubic feet (Tcf) in 2020 to about 35 Tcf in 2050. With the low resource estimates, gas use still rises slightly and then in 2050 drops back down to roughly where it started in 2020. Prices gradually rise over time as lower-cost resources are depleted.

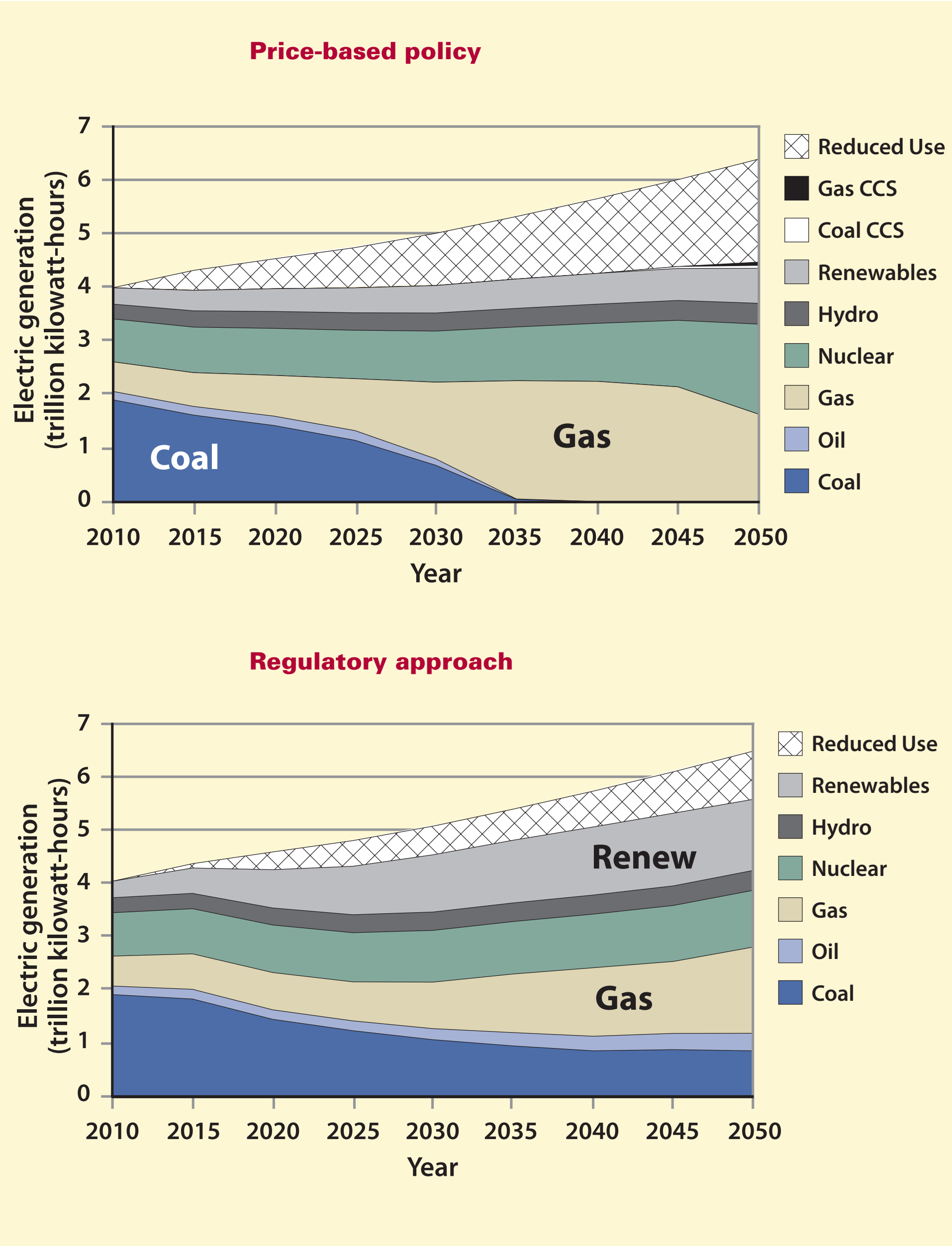
The top chart on page 13 shows what happens if the previously described carbon price-based policy is imposed (assuming regional international markets). The bars show total consumption, with exports and imports indicated. Above each bar are two prices. The top one excludes the carbon charge; the bottom one includes it.

With the climate policy, gas use is somewhat lower than in the no-policy case, because total energy use is reduced by the policy. But it still rises until about 2040, although at a slightly lower rate. However, by 2050 gas use has declined—a response to high gas prices due largely to the added cost of carbon emissions. By 2050 more than half the total price is due to the carbon charge. Imports and exports are steady over the time period, and domestic production expands until 2050, when it drops back.

Impact of global gas markets

The bottom chart on page 13 shows the effects of changing one assumption: regional markets are replaced by a tightly integrated global gas market. International gas resources (mostly in the Middle East and some in Russia) are likely to be less costly than most of those in the US. As the less expensive US resources are exhausted and the cost of US gas production ramps up, imports become more and more attractive. Nevertheless, domestic production continues from those

Energy mix in electric generation under two emissions-control policies



The top graph assumes a price-based climate policy that imposes a price on carbon emissions; the bottom graph assumes a regulatory approach that mandates increases in renewable generation and decreases in coal-based generation. (These policies are intended for illustration only. For details, see the technical report cited at the end of the article.) The most striking difference is in total electric generation. The assumed price-based policy brings a dramatic drop in electricity use—far greater than that elicited by the assumed regulatory approach.

US resources that are cheaper than imports. In this scenario, the US imports about half its gas by 2050.

Some people are surprised and some pleased by those results. "After all, US producers are still producing, consumers will see cheaper gas prices, and we have alternative sources of gas," says Paltsev. "But the irony is that even though we now have this wonderful domestic resource, if a global natural gas market is established—and if it's driven purely by economics, which is a big if—then we're still going to end up depending on the Middle East and Russia, not for oil but for natural gas. The reason: in 20 to 30 years, our relatively cheap domestic gas will have been produced, and lower-cost resources from other countries can enter the market."

Energy mix in electric generation with climate policies

How well does gas do against other energy sources? The figures to the left show forecasts of how the energy mix in the electric generation sector will evolve over time. The top figure assumes the price-based policy; the bottom figure, the regulatory approach. Both analyses assume mean estimates of gas resources and regional trading markets.

With the price-based policy, overall electricity use flattens out, and the high price of fossil fuels—due to the cost of carbon emissions—drives down their use. Coal and oil disappear by 2035, but natural gas keeps doing well until 2045, when the carbon price is so high that even gas is costly.

That drop-off in natural gas in 2045 should get our attention. In a longer-term analysis out to 2100, the researchers found that natural gas almost disappears by 2075. "So if we're really serious about climate policy and tough reductions in GHG emissions, we need to be working on economically competitive renewables, advanced nuclear power, and carbon capture and storage for both gas and coal. Gas is great, but it is not going to solve all the problems," says Paltsev.

The figure assuming the regulatory approach looks quite different. Here, the rapid expansion of renewables—required by the regulation—tends to squeeze out gas-based generation, though gas remains relatively strong; and coal and oil are still in the picture in 2050. Most important, overall electricity use does not drop as it does under the price-based policy—a reflection of lower prices due to the absence of the carbon charge.

Energy mix in all sectors

The researchers also looked at the energy mix in all sectors of the economy. With the economy-wide carbon price, gas use is relatively low in non-electricity sectors, where it competes against petroleum and electricity. In those cases, gas does not provide as big a carbon advantage as it does against coal in the electric sector. With the regulatory approach, gas continues to be a major player, but coal and especially oil are still used in 2050.

But the most remarkable difference is in total energy use. With the price-based policy, total energy use in 2050 is about 55 quadrillion Btu; with the regulatory approach, it is about 125 qBtu. While the carbon price affects emissions in all sectors, the regulatory approach focuses on the electric sector, leaving other GHG-emitting sectors such as transportation and industry relatively unaffected.

"The regulatory approach is sometimes portrayed as a climate policy, but it doesn't really buy you much in terms of emissions reduction," says Paltsev. "If your policies target just the electricity sector, you're not going to solve the climate problem."

The researchers emphasize the role of uncertainty in their study. Other assumptions—greater penetration of natural gas into the transportation sector, for example, or the discovery of vast amounts of shale gas in China—would profoundly alter their results. Nevertheless, they believe that their scenarios help to provide bounds on future prospects for natural gas and illustrate the relative importance of different factors in driving the results.

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By Nancy W. Stauffer, MITEI

This analysis was carried out as part of an interdisciplinary study, *The Future of Natural Gas* (see page 31). Development of the economic models applied in this work was supported by the US Department of Energy, Office of Biological and Environmental Research; the US Environmental Protection Agency; the Electric Power Research Institute; and a consortium of industry and foundation sponsors through the MIT Joint Program on the Science and Policy of Global Change. More information can be found in:

S. Paltsev, H. Jacoby, J. Reilly, Q. Ejaz, F. O'Sullivan, J. Morris, S. Rausch, N. Winchester, and O. Kragha. *The Future of US Natural Gas Production, Use, and Trade.* MIT Joint Program on the Science and Policy of Global Change, Report No. 186, June 2010. Available at globalchange.mit.edu/pubs/reports.php.

Underground storage of carbon dioxide

Microbes may help seal it in

Storing captured carbon dioxide (CO_2) emissions underground is one way to keep that greenhouse gas from entering the atmosphere. But how can we ensure that the CO_2 will not leak out over time? MIT researchers have identified an unlikely source of help: a microbe that thrives in the harsh environment of a CO_2-filled reservoir and naturally secretes a film that could—like plastic wrap—seal the reservoir shut. As an added bonus, the microbe may catalyze reactions that help the CO_2 become part of the surrounding rock—the ultimate in leak prevention.

"To my knowledge, our group is the first to report measurements of microbial growth under conditions of CO_2 sequestration," says Janelle R. Thompson, director of the project and the Doherty Assistant Professor in Ocean Utilization in the Department of Civil and Environmental Engineering. Thompson notes that those findings may have implications for the long-term stability and integrity of CO_2-filled reservoirs and therefore for the viability of carbon capture and sequestration (CCS) as a climate change mediator.

In the CCS process, CO_2 is captured from major emissions sources such as power plants and then compressed, transported, and injected into deep geologic formations, saline aquifers, or other reservoirs for long-term storage. "But at the densities and depths involved, CO_2 is quite buoyant, so making sure it doesn't leak back out into the atmosphere is a major concern," says Thompson.

In general, a sequestration reservoir consists of porous rock such as sandstone overlaid by a less permeable layer such as shale. But often there are wellbores drilled down through the "cap" rock—signs of earlier exploration for oil. Those openings have been sealed with cement, but CO_2 plus water forms an acid that can corrode the cement. As a result, sequestered CO_2 could escape not only through small natural fractures but also through intentionally drilled wellbores filled with crumbling cement.

One approach to securing such reservoirs involves biofilm barriers. Says Thompson, "If we can stimulate microorganisms to grow underneath the cap rock, they may create a sheet of slime and goo that will effectively seal shut the cement plugs and other possible escape routes." The diagram to the right illustrates the concept.

Other groups have demonstrated that biofilms created by microbes can retard the movement of "supercritical" CO_2—a highly concentrated, high-pressure gas—through porous rock. But can microbes live and grow in the presence of supercritical CO_2? Most experts assume that conditions would be too harsh for them to exist.

To test that assumption, Thompson and her civil and environmental engineering colleagues—Hector H. Hernandez, postdoctoral associate, and Kyle C. Peet, graduate student and 2008–2009 BP-MIT Energy Fellow—got help from investigators who were running pilot-scale tests of carbon sequestration in Frio Ridge, Texas. In those tests, teams from the University of Tennessee and Oak Ridge National Laboratory injected supercritical CO_2 into a 1.5 km-deep saline formation for 10 days, collecting groundwater samples as the underground plume evolved. They then filtered the samples to trap the biomass, some of which they sent to Thompson's team.

Using a specially designed high-pressure growth chamber, the MIT researchers cultivated the biomass samples in the presence of nutrients at conditions mimicking those in a CO_2 sequestration reservoir. And microbes in the samples grew. They doubled about once every day and a half. Examination of stained samples from the bioreactor under a fluorescent microscope revealed clusters of cells, each 0.5–1.0 micron in diameter, surrounded by a thick layer of extracellular material.

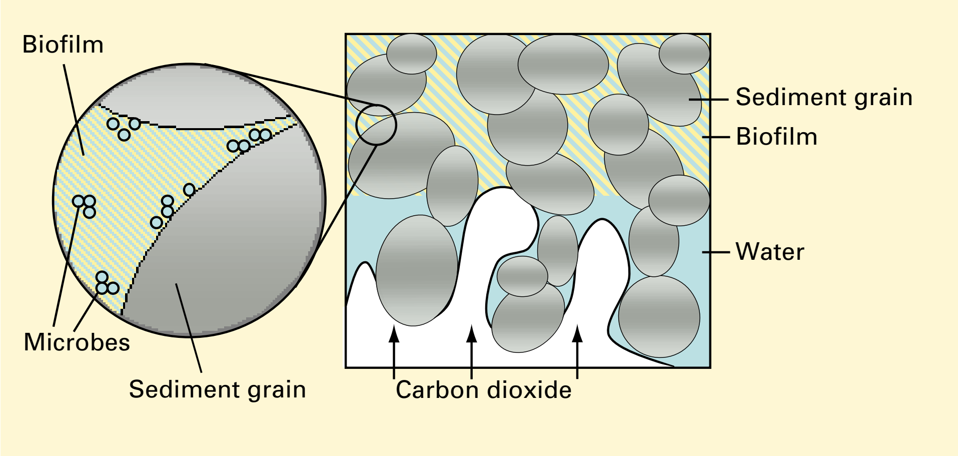
Closer examination

Ideally, Thompson and her team wanted to work with a single, pure strain so that they could study its physiology and genetic makeup in detail. "The better we understand microbial growth and activity in high-pressure CO_2 environments, the better we can engineer biofilm barriers in sequestration reservoirs," says Thompson. And by determining the genetic mechanisms that enable a strain to tolerate supercritical CO_2 they might be able to identify or genetically engineer strains with even higher tolerance.

To single out the best strain, they used a process called dilution subculturing. They allowed their mixture of organisms to grow for a period of time and then removed samples that they used as an "inoculant" for the next growth. By replicating that process, they weeded out the weaker strains and ended up with the fittest ones. (At each step, they cryo-preserved some samples so that they can regrow the entire mixture if necessary.)

Ultimately, they identified a single strain that does not just tolerate high-pressure CO_2 but actually requires a high-pressure environment for survival—a characteristic that classifies it as an "obligate

Conceptual model of microbial growth in a sequestration reservoir



This schematic illustrates how a biofilm barrier can prevent the escape of carbon dioxide (CO_2) through pores in a sequestration reservoir. The enlarged image at the left shows clusters of microbes (blue) suspended in their extracellular biofilm (green) between two grains of sediment (gray). The image at the right shows the stored CO_2 and water ahead of it being stopped by the biofilm, which shuts off spaces among the grains and keeps the CO_2 from migrating.

barophile." In subsequent testing, they found that this strain cannot survive at 1 atmosphere of pressure but grows nicely at 120 atmospheres—in nitrogen as well as CO_2.

To determine the identity of the strain with this unusual characteristic, the researchers sequenced a section of the microbe's DNA—specifically, a section from the 16S ribosomal RNA gene. That gene is a useful tool: some regions of it are critical to cellular metabolism so they are the same in all organisms while other regions can vary, exhibiting clock-like evolutionary behavior. "So we can take the 16S gene from several organisms, line up the constant regions, and then compare the variable regions to see how the organisms have diverged over time," explains Thompson.

Their analysis showed that at the 16S gene their strain is closely related to *Bacillus cereus*, a well-known organism that includes strains that cause food-borne illness in humans and other strains that are used as probiotics in animals. "To my surprise, our subsurface strain—an obligate barophile—has almost the same 16S ribosomal RNA gene sequence as a known non-barophilic strain that lives on the surface and can be either pathogenic or non-pathogenic," says Thompson.

The next step is to sequence the entire genome of their microbe and compare it to the already-sequenced genome of the *Bacillus cereus.* Seeing where the genomic signatures of the two strains differ will provide important clues into the molecular adaptations that enable their microbe to survive in the presence of supercritical CO_2 while closely related strains cannot.

Other ongoing work

Thompson and her team are continuing to examine the physiology of their strain and are working to determine conditions that will optimize its ability to grow and to make extracellular biofilms. They are also using fluorescent microscopy to examine the three-dimensional architecture of the biofilm and the spatial orientation of the microbial cells within it.

In other work, they are examining the effects of their microbe on "mineral trapping," another process that will prevent CO_2 leakage. Here, the CO_2 chemically reacts with rock minerals to form solid carbonate compounds. The rate at which that reaction occurs depends on temperature and various aspects of the reservoir's chemical environment—all of which has been captured in computer models of reservoir behavior.

In those models, one of the key factors limiting the reaction rate—and hence mineral trapping—is the availability in the subsurface of positively charged particles called cations. Research has shown that microorganisms can dissolve silicate minerals, a process that releases cations and could potentially accelerate those reaction rates by many orders of magnitude. However, current models generally assume a sterile environment, so the impact of microbial activity on mineral trapping is discounted.

"We now know that microbes will be present, so we plan to look at how much they may accelerate the production of cations," says Thompson. "If we can measure and quantify that rate, then that information can be fed into the models of reservoir behavior now being developed. The impact on the outcome may or may not be significant—but either way we need to know."

Thompson stresses the need to consider microbial activities in studies of CCS. While lots of people are working in the field of geologic carbon sequestration, relatively few are thinking about microbes. "But microbial activity is something that you just can't ignore. It's present in every environment, and it's essential to life as we know it on planet Earth," she says. "I think it's reasonable to assume that it will play a role in trapping and transforming the sequestered CO_2, and we need to take that role into account as we explore the viability of carbon sequestration."

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By Nancy W. Stauffer, MITEI

This research was funded by a seed grant from the MIT Energy Initiative and by the US Department of Energy's National Energy Technologies Laboratory. Publications are forthcoming.

New insights into capturing solar energy

An MIT team has developed a simulation technique that can provide critical insights into the behavior of electrons within sunlight-driven devices using days, not decades, of computer time. Using their technique, they have calculated how electrons move within an amorphous photovoltaic (PV) system. The ability to understand such processes at the atomic level will help to accelerate the improvement of technologies for turning solar energy into useful forms such as electricity.

Most people agree that sunlight is potentially our best long-term source of abundant energy. "But we can't run our cars on it," says Troy Van Voorhis, associate professor of chemistry. "We need to convert it into some other form—electricity or hydrogen or liquid fuels." He and his team focus on two approaches: PV technology to convert sunlight into electricity and photochemistry to produce chemical fuels. In both cases, cutting-edge technologies rely on carefully selected molecules to achieve the conversion.

While those technologies do the job, they are much less efficient than theory suggests they could be, and scientists don't always understand why. "We have a general idea of the fundamental processes involved, but the detailed physics of why one device works better than another or why this molecule works and that one doesn't—those things are much more opaque," says Van Voorhis.

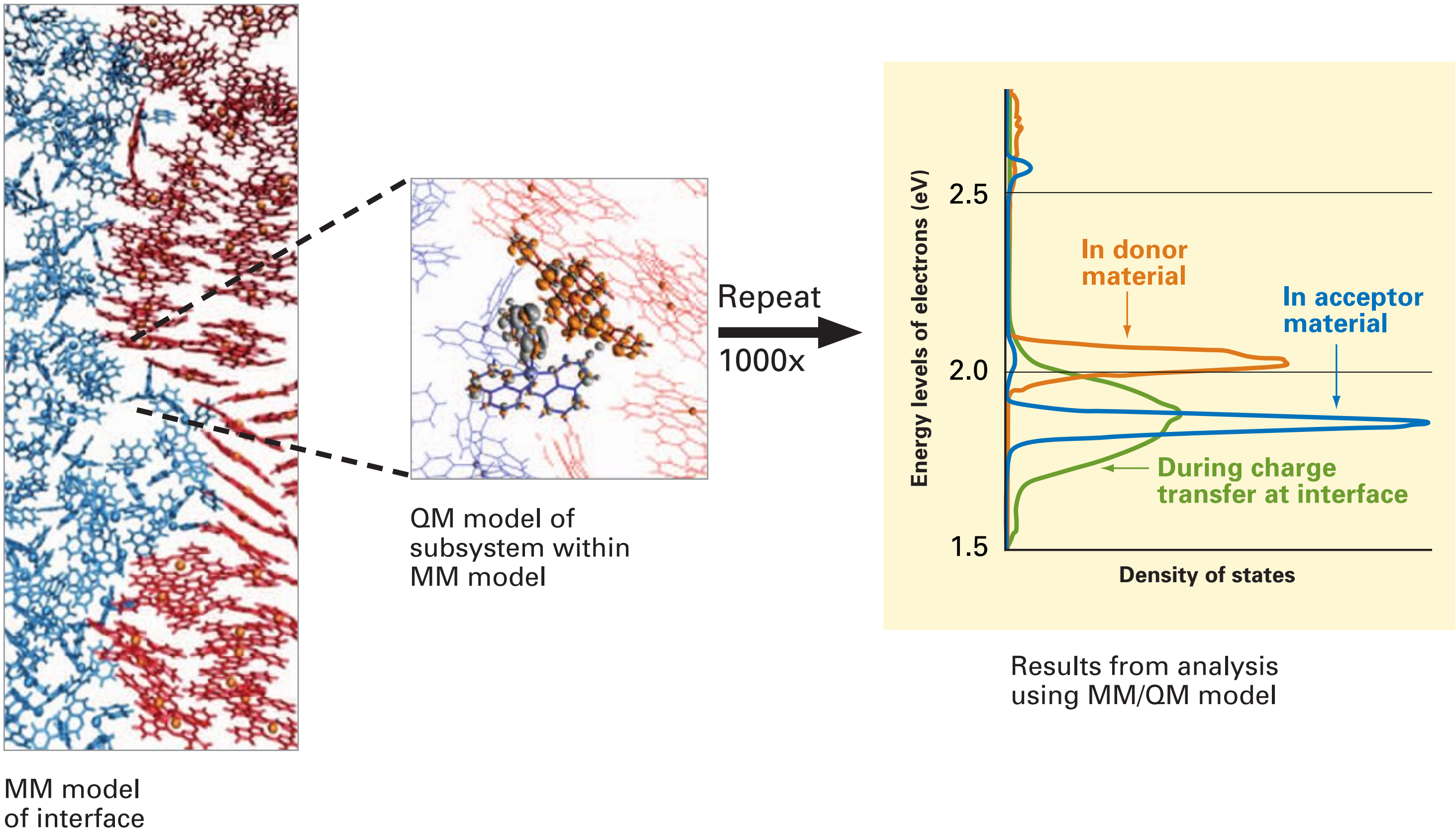
The PV challenge

As an example, he describes what happens in a PV device. Typically, the device is made of two materials with differing electron energy levels. When a photon (a packet of sunlight) strikes a molecule in one of the materials, the molecule gains extra energy. That extra energy can migrate through the device to the interface of the two materials. There, the energized material can dissipate the extra energy by losing an electron to a neighboring molecule in the other material—a process that leaves behind a vacancy called a hole. Over time, holes accumulate in the first material and electrons in the second. If the outside edges of the two materials are connected by a circuit, the electrons will flow back to the first material as a current.

The description of that process leads to several simple design principles. For example, the best results come when one material has a strong "affinity" for electrons and the other for holes. And a good design has lots of interface between the two materials so that the absorbed energy doesn't have far to go to reach the interface—a benefit because energy does not flow quickly through bulk material.

Microscopic studies confirm those principles: PV devices that perform well tend to have a sandwich structure with alternating layers of the two materials. But figuring out how to encourage an electron to jump across the interface, how to maximize its subsequent mobility, and how to keep electrons and holes from recombining requires a far more fundamental level of understanding of what is going on—a job for computer simulation.

Modeling organic photovoltaics



Example of MIT technique for simulating critical processes such as those that occur within a photovoltaic device made of amorphous organic semiconductors. The left-hand drawing shows a molecular mechanical (MM) model of a sample interface between two materials in such a device. The middle drawing shows a quantum mechanical (QM) model of an important subsystem within that MM model. The right-hand drawing presents results from an analysis in which an MM/QM model was run 1,000 times with varying parameters.

Simulating the system

One approach is molecular mechanical (MM) modeling, which draws on classical mechanics and Newton's laws and focuses on the forces connecting atoms together to make molecules. The electrons that actually hold the atoms together are not specified, but their effect is represented by bonds between atoms. The bonds can be thought of as rubber bands around two atoms or three atoms to keep them from pulling away from one another. MM models are valuable and efficient computational tools for many applications. But they do not provide the details needed by scientists trying to improve PV devices. For example, they do not tell how stiff the rubber bands are—that is, how strong the bonds are—or define the electron or hole affinity of molecules or how electrons move about.

Capturing those details requires quantum mechanical (QM) modeling, an approach drawing on theories that explain the behavior of matter and energy at the atomic and subatomic scale. But in a device just 100 nanometers wide, there are millions of electrons, and all of them interact. So tracking the migration of a single electron through the device (if it were possible) would require simulating the behavior of all those electrons. Running the necessary QM calculations would take decades—even with today's fastest computers.

An integrated approach

The solution to the dilemma comes in realizing that it is not necessary to understand the entire system at the quantum level. Indeed, the regions that need to be analyzed with QM methods may include just a few molecules—what Van Voorhis calls "the subsystems of interest."

To perform a simulation, therefore, the researchers begin by performing MM modeling of the overall system to define the important subsystems and how likely each one is to occur. They then use QM modeling on each type of subsystem to calculate the critical parameters that MM modeling cannot address. "Because the subsystems are relatively small," says Van Voorhis, "those simulations take a few hours rather than decades."

The next step is to "train" the MM model using the QM results. The researchers define parameters for the MM model—for instance, the strength of bonds—based on what their QM model revealed about the local interactions among electrons, atoms, and molecules. "We assume that the bigger system has the same local interactions, simply repeated on a larger scale," says Van Voorhis.

Finally, they run their refined MM model of the overall system to calculate the impact of incoming photons at the interface and to see how the subsystems of interest affect and are affected by the broader environment included in the MM model.

New ability to probe PVs

In recent work, the researchers used their technique to examine PVs made of amorphous organic semiconductors. These materials are more flexible and easier to process than their single-crystal counterparts, but they can be harder to understand. In single-crystal PVs, the locations of the molecules are known; in amorphous materials, the molecules are not ordered but mixed up, and their locations change over time. Van Voorhis likens it to traffic on city streets. "It may look ordered in a single snapshot, but sequential snapshots may show traffic moving and changing lanes and so on—that's disorder," he says. "Likewise, in a device, molecules may be vibrating and moving and fluctuating, and I need to know how that's going to affect the operation of my device. So I need to look at subsystems at different places and at different times." That ability could provide clues to preventing the biggest problem with these promising PVs: the tendency of electrons and holes to recombine.

The figure on page 19 demonstrates the technique. The left-hand drawing shows a sample interface (at the nanometer-length scale) simulated by the MM model. Within it is a subsystem of interest, expanded in the middle drawing. But that snapshot shows just one subsystem at one time. To capture the effects of disorder, the model must examine many subsystems at many times. "So in order to get a realistic picture, I actually have to analyze a thousand snapshots," says Van Voorhis. A hundred computers working in parallel can perform all those analyses within a few hours.

The right-hand drawing shows results from such a study. The three curves show the energy levels of electrons in the donor material (red), in the acceptor material (blue), and transferring between them (green). In each case, the width of the distribution reflects the presence of many different subsystems with slightly different properties. The results are consistent with what others have observed in experiments with these materials.

Van Voorhis and his team are continuing to use their new modeling technique to look at different PV devices as well as photochemical processes for producing hydrogen and liquid fuels. "The nature of these systems makes it necessary to tailor the detailed forces in the MM model to a particular device or process," says Van Voorhis. "But as our results have shown, the outcome can be a new understanding of how solar-driven devices and processes work and therefore new strategies for improving their efficiency and performance."

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By Nancy W. Stauffer, MITEI

This research was supported by an ignition grant from the MIT Energy Initiative, a fellowship from the David & Lucille Packard Foundation, and the US Department of Energy. Further information can be found in:

S. Difley, L.-P. Wang, S. Yeganeh, S. Yost, and T. Van Voorhis. "Electronic properties of disordered organic semiconductors via QM/MM simulations." *Accounts of Chemical Research,* v. 43, no. 7, July 2010, pp. 995-1004. DOI: 10.1021/ar900246s.

MITEI awards fifth round of seed grants for energy research

The MIT Energy Initiative's latest round of seed grants for energy research is supporting innovative work on solar energy conversion, fuel cell catalysts, algorithms for energy-efficient computing, systems for integrating renewable technologies into smart grids, and more.

In this round, a total of $1.9 million was awarded to 13 projects, each lasting between one and two years. The funded projects span 10 departments, laboratories, centers, and institutes.

As in previous rounds, many of the new awards involve junior faculty and faculty not previously engaged in energy-related research. For example, Cynthia Rudin, assistant professor of statistics at the MIT Sloan School of Management, is seeking to increase the reliability of the electric power grid—a growing challenge due to aging infrastructure combined with the evolution of new ways of using the grid. Rudin and others have developed statistical methods that predict the vulnerability of components—information that helps utility companies design maintenance plans that reduce service failures and increase public safety (see the figure). But such predictions must also be "actionable," that is, there must be no intermediate steps between the design of the vulnerability model and the prioritization of repair work. Rudin's team will develop a framework for "actionable ranking" that will immediately yield methods for improving the reliability and safety of electrical distribution networks.

In another project, Evelyn Wang, assistant professor of mechanical engineering, is focusing on thermal management for concentrated solar energy conversion systems. Such systems could deliver as much as 25% of the world's projected power needs by 2050. However, increasing their power production requires concentrating sunlight onto smaller and smaller areas of the solar absorber, which leads to significant heat generation and reductions in electricity output. Wang and her team are developing an innovative, completely passive nanofilm-based cooling system that can achieve high rates of heat removal with low thermal resistance. The cooling achieved will permit even higher concentrations to be used, enabling major advances in solar conversion technologies and other important energy systems.

Carbon capture and sequestration (CCS) is the focus of a project led by Alison Malcolm, assistant professor, and Michael Fehler, senior research scientist, both of earth, atmospheric, and planetary sciences and MIT's Earth Resources Laboratory. The industrial viability of CCS requires reliable techniques for determining the amount and location of the sequestered carbon dioxide (CO_2) and for detecting potential leakage. The oil industry has seismic-based methods that can almost certainly be adapted to perform those tasks, but their high cost will likely preclude their use at every sequestration site. The researchers are therefore developing new imaging methods that should be able—with a significantly smaller data set—to delineate the spatial distribution of injected CO_2 in a reservoir and other methods that can act as alarms, detecting CO_2 leakage through the cap rock. The methods are designed to work together, guaranteeing the stable sequestration of the CO_2 in the subsurface.

Information on the vulnerability of electrical grid components can help utility companies plan repair work so as to reduce service failures and increase public safety. This image shows a manhole in the Chelsea neighborhood of Manhattan that was highly ranked by the vulnerability model of Professor Cynthia Rudin and her colleagues, published in the journal *Machine Learning* in July 2010. Dots superimposed on the satellite image are manholes, colored according to the predicted vulnerability of the manhole to serious events (fires and explosions). Red indicates higher vulnerability; white indicates lower vulnerability. Lines connecting the manholes represent underground electrical cables.

John Joannopoulos, Francis Wright Davis Professor of Physics and director of the Institute for Soldier Nanotechnologies (ISN), and Srinivas Devadas, professor of electrical engineering and computer science—both newcomers to MITEI—plus Ivan Celanovic, research engineer in the ISN, are addressing power electronics and their role in incorporating renewable energy generation sources into the future smart grid. The MIT team will develop and deploy novel digital tools for the design and testing of power electronics-enabled renewables integrated into the smart grid. Enabling real-time simulations with ultra-high fidelity will revolutionize the design of power electronics since it will allow real-time measurement and control of prototype systems that can be redesigned, refined, or tuned for increased reliability and efficiency. The concept will be demonstrated on two representative systems—the variable speed wind turbine and the hybrid-electric vehicle.

Martin Bazant, associate professor of chemical engineering, is focusing on a different energy-related concern: the growing global shortage of fresh water. Massive amounts of energy are required to transport or produce fresh water from seawater, especially for remote locations. A critical goal for energy-related research and policy is therefore developing new means of water desalination and purification. In this seed project, Bazant and his colleagues will focus on "shock electrodialysis," a novel electrochemical approach to achieving those processes. The approach exploits the spontaneous separation of salt and charged impurities from pure water in charged porous media, passing current to electrodialysis membranes. The researchers will explore the basic physics of desalination shocks in microstructures and will begin to engineer a new class of desalination systems that are both energy efficient and well suited for small-scale, portable applications such as in remote regions or for the military.

As in the past, the response to MITEI's call for proposals was strong, with 44 submissions involving a total of almost 70 researchers, according to Ernest J. Moniz, director of MITEI and the Cecil and Ida Green Professor of Physics and Engineering Systems. "Once again, the proposals included surprising, thoughtful, and potentially impactful concepts and ideas," he said. "The task of choosing among them was challenging for the review committee, which consists of faculty on the MIT Energy Council and representatives from MITEI's Founding and Sustaining members."

Funding for the new grants comes chiefly from MITEI's Founding and Sustaining members supplemented by funds from the Chesonis Family Foundation, an anonymous donor, and MITEI.

To date, MITEI's seed grant program has supported 67 early-stage research proposals, with total funding of more than $8.4 million. In addition, eight groups have been awarded smaller, shorter-term ignition and planning grants.

"As projects from the first few rounds of awards are completed, we're receiving reports, papers, and presentations that have resulted from them," said Robert Armstrong, deputy director of MITEI and the Chevron Professor of Chemical Engineering. "Some of those novel projects have already had significant practical impacts, while others have led to long-term funding, opening up new and exciting areas of research for the Institute."

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By Nancy W. Stauffer, MITEI

For a complete list of awards, please see page 40.

A breath of fresh air

Students explore alternatives for lab safety test

A gas known as SF_6—odorless, colorless, and nonflammable—insulates double-paned windows and helps blood vessels show up on ultrasounds. At MIT and elsewhere, it is also widely used as a tracer gas to determine whether laboratory ventilation hoods are working to protect users from noxious fumes.

But there's a problem. SF_6—properly called sulfur hexafluoride—is considered to be the most potent greenhouse gas evaluated by the Intergovernmental Panel on Climate Change. Over 100 years, SF_6 has a global warming potential that is 22,200 times that of carbon dioxide. Alarmingly, the concentration of SF_6 in the atmosphere is increasing.

Photo: Jennifer DiMase, MITEI

UROP advisor Pamela Greenley (left), associate director of the Environment, Health, and Safety Office, observes WunMin Wong '11 (center) and Evelyn Zuniga '13 (right) as they set up equipment for experiments with a tracer gas that would be more environmentally friendly than the one now used in tests of fume hood performance. The mannequin at the far left (affectionately named "Betty" by the student researchers) simulates a laboratory researcher and plays a key role in determining how well the fume hood contains the tracer gas—an indicator of its efficacy at protecting human users from noxious fumes.

In response to those concerns, MIT students have been investigating the possibility of switching to a different tracer gas that would have a less-negative environmental impact. In spring 2010, then-freshman Evelyn L. Zuniga came upon the Tracer Gas Substitute Test UROP project after a detailed search of the MIT Energy Initiative (MITEI) website. The project was developed and funded by the Environment, Health, and Safety (EHS) Office in collaboration with MITEI as part of an innovative program to bring student expertise to bear on MIT's real-world campus energy and environmental challenges.

Zuniga, a materials science and engineering major, jumped at the hands-on project, as did WunMin Wong, then a junior in the MIT Sloan School of Management. "I'm deeply interested in sustainability and energy, particularly MIT's initiatives to be a more 'green' campus," says Zuniga. "Pam Greenley (associate director of EHS) and Les Norford (professor of building technology) who served as advisors on the project were absolutely amazing, and their excitement for the project was also a motivation for me."

More than 1 million fume hoods in the United States must be tested to meet national industry standards, so the impact of the gas used in the process can be significant. Greenley said she developed the UROP project because a study at San Francisco State University indicated that nitrous oxide might be a promising substitute for SF_6 in testing the operation of the 1,000-plus fume hoods on the MIT campus. "We don't want to see health and safety issues negatively impacted because of environmental issues," she says. "If (SF_6) has gotten that serious, it's worth finding a different gas."

Reducing energy use from MIT's ubiquitous fume hoods has been a priority for the Institute, which has achieved significant energy savings by lowering the volume of air moving through nearly 200 hoods on campus from 100 to 80 feet per minute. Testing the effects of this change highlighted the opportunity to consider alternative approaches. Professionally conducted tests using SF_6 proved the lower flow rates were safe. Zuniga and Wong repeated some of those tests with nitrous oxide as well as SF_6 and compared the results.

With access to a lab full of unused fume hoods, Zuniga and Wong went to work in Building 18 three mornings a week. Using a mannequin with sampling tubes attached to its face, the students mimicked the real-time use of fume

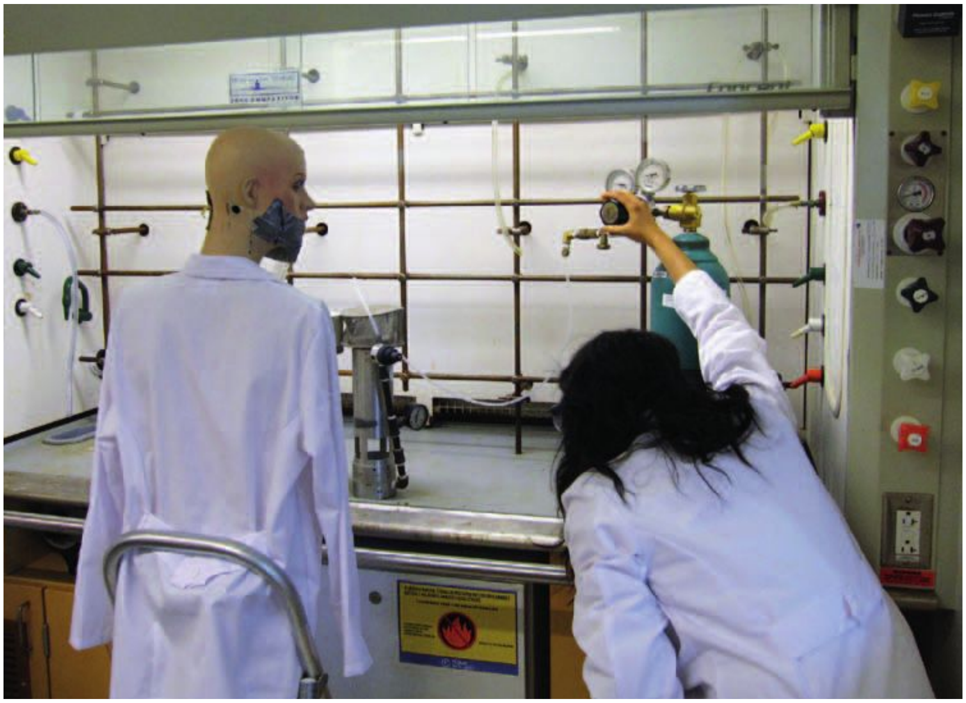

Photo: Jennifer DiMase, MITEI

UROP student Evelyn Zuniga adjusts the release of the tracer gas substitute into the fume hood as "Betty" the test mannequin looks on. An air intake at Betty's mouth and nose will simulate the breathing of a researcher to test for the possible presence of the tracer gas in front of the fume hood.

hoods and measured changes in airflow patterns within the laboratory equipment. "The goal is to make tests closer and closer to real-world conditions without being too costly or too cumbersome," Greenley says.

"This project was my first lab-based UROP," says Wong. "I was glad that I gained useful lab skills despite coming from a management science background."

During fall 2010, mechanical engineering senior Eric Guffey focused his senior thesis on this work, continuing where Zuniga and Wong left off with the nitrous oxide-SF_6 comparison. He has been conducting a more thorough analysis of the data collected in the spring, and he also has performed some of his own testing of fume hoods around campus, including in the chemistry, mechanical engineering, and materials science and engineering departments, at the Koch Institute, and at MIT Facilities.

"This project is a great example of how we can partner with MITEI to use the campus as a learning lab, with students, faculty, and staff working together on global problems," says Norford. MITEI works with members of the community from across MIT to develop projects that benefit both the Institute and the students.

As her first UROP, the project helped Zuniga gain "essential lab skills and a great introduction to research," she says. "Collaborating with WunMin, I also learned a lot about lab procedures and MIT in general. But the most interesting part for me was to see all the opportunities MIT offers for ways to positively impact the environment, and I was excited that even as a freshman I was able to take part in the initiative and make an impact."

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By Deborah Halber, MITEI correspondent

Named Energy Fellows, 2010–2011

The Society of Energy Fellows at MIT welcomed 52 new members in September 2010. The Energy Fellows network now totals 139 graduate students and spans 20 MIT departments and divisions and all five MIT schools. This year's graduate fellowships are made possible through the generous support of 19 MITEI member companies.

Photo: Justin Knight

ABB
Erica Lin Materials Science and Engineering
Peter Montag Physics

b_TEC
Matthew Aldrich Media Arts and Sciences

Bosch
Kaitlin Goldstein Architecture
Fahri Hizir Mechanical Engineering

BP
Kenny Ching MIT Sloan School of Management
Bomy Lee Chung Chemical Engineering
Adam Freedman Civil and Environmental Engineering
Wen Ma Nuclear Science and Engineering
Andrew Nanopoulos Mechanical Engineering
Peter Swartz Political Science
Ping Wong Mechanical Engineering
Guoqiang Xu Materials Science and Engineering

Chevron
Aditya Kunjapur Chemical Engineering
James Meredith Mechanical Engineering

Cummins
Tommy Leung Engineering Systems Division

Denbury
Ibrahim Toukan Engineering Systems Division

EDF
Lindsey Gilman Nuclear Science and Engineering

Enel
Giancarlo Lenci Nuclear Science and Engineering
Matthew Thoms Mechanical Engineering

Eni
Jennifer Brophy Biological Engineering
Martina Coccia Earth, Atmospheric, and Planetary Sciences
Daniel Graham Chemistry
Sayalee Mahajan Chemical Engineering
David Ramberg Engineering Systems Division
Daniel Rowlands Chemistry
Sven Schlumpberger Chemical Engineering
Ruoshi Sun Materials Science and Engineering
Gregory Thiel Mechanical Engineering
Qing Xu Chemical Engineering

Exelon
John Michael Hagerty Engineering Systems Division

GTI
Karen Tapia-Ahumada Engineering Systems Division

Lockheed Martin
Sudhish Bakku Earth, Atmospheric, and Planetary Sciences
Kento Masuyama Aeronautics and Astronautics

Saudi Aramco
Po-Yen Chen Chemical Engineering
Eric Hontz Chemistry

Schlumberger
David Cohen-Tanugi Materials Science and Engineering
Matthew D'Asaro Electrical Engineering and Computer Science

Shell
Qin Cao Earth, Atmospheric, and Planetary Sciences
Diana Chien Biology
John Ranson Electrical Engineering and Computer Science
David Rosen Electrical Engineering and Computer Science
Jacob Rubens Biology
Yunjian Xu Aeronautics and Astronautics
Tauhid Zaman Electrical Engineering and Computer Science

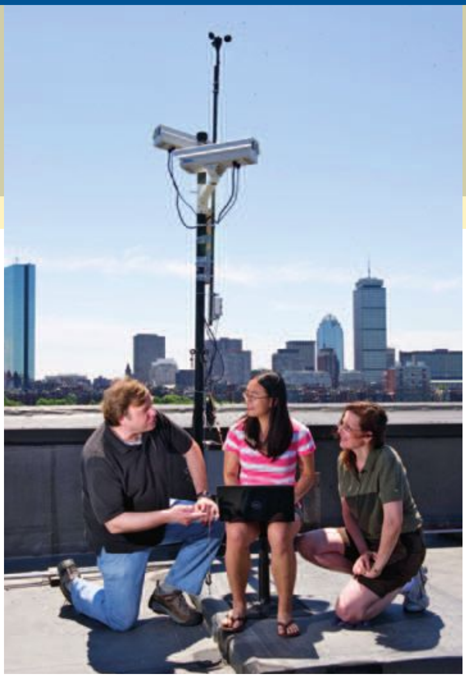
Siemens
William Hasenplaugh Electrical Engineering and Computer Science
Leah Stokes Urban Studies and Planning

Total
Ruel Jerry Earth, Atmospheric, and Planetary Sciences
Rebecca Saari Engineering Systems Division
Benzhong Zhao Civil and Environmental Engineering

Weatherford
Alan Lai Materials Science and Engineering
Michael Reppert Chemistry

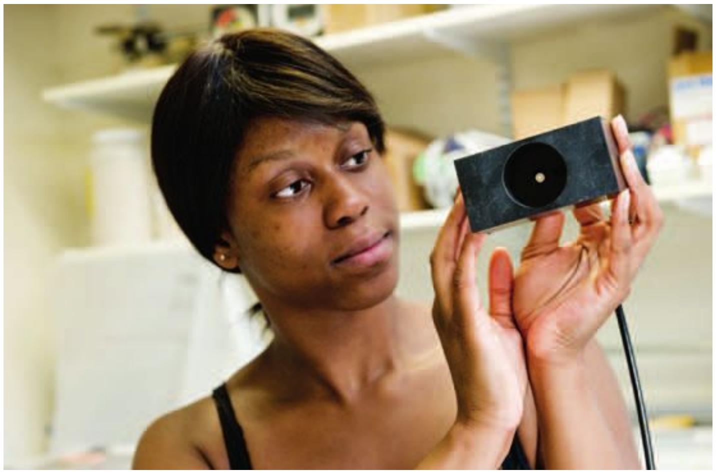
MITEI's undergraduate energy research flourishes

This past summer, 23 undergraduate students worked on energy-related Undergraduate Research Opportunities Program (UROP) projects on topics such as ocean wave energy, lithium-air fuel cell catalysis, chemically driven thermo-power waves, and portable light and power textiles for the developing world. Funding for MITEI UROP projects is provided by private donors and by MITEI members, including Founding Member BP and individual Affiliate members with a particular interest in supporting undergraduate research. For more information on the summer 2010 participants and projects, go to web.mit.edu/mitei/docs/education/urop/project-descriptions-2010.pdf.



Photos: Justin Knight

Above: Sharon Xu '13 of architecture (center) downloads wind speed data from an anemometer atop Building E52 and discusses next steps in the campus wind resource monitoring project with research advisor Stephen Connors of the MIT Energy Initiative and graduate advisor Kathleen Araujo of urban studies and planning.



Jennifer Hammond '12 of mechanical engineering demonstrates a device that measures the reflectivity of a surface. Using the device, she has been examining how dust or sand deposited on reflective surfaces can reduce the efficiency of a parabolic solar trough in the desert.

Pretreatment of sugarcane bagasse (shown here) has yielded high levels of fermentable sugars—a key step in producing ethanol from such ligno-cellulosic materials. That research helped guide students working with other feedstocks (see below).

Rebecca Krentz-Wee '12 of nuclear science and engineering reviews a geologic map of California to determine the viability of heavy oil reservoirs to serve as heat storage systems for combined nuclear-geothermal peak electricity production.

Perry Nga '12 (left) and Sebastian Velez '12 of chemical engineering discuss their UROP projects aimed at developing less expensive, more efficient methods of producing high ethanol yields using sorghum forage bagasse and ligno-cellulosic materials as feedstocks.

First week on campus energizes freshmen

Design a wind turbine. Negotiate climate change with leaders of the developing world (in simulated fashion). Make fast friends by working closely with people you barely know. Discover how much energy MIT saves when people use revolving rather than conventional doors.

Numerous doors were opened—physically, socially, and conceptually—for the 24 incoming freshmen enrolled in a Freshman Pre-Orientation Program called Discover Energy: Learn, Think, Apply. Held by the MIT Energy Initiative during the last week in August 2010, "DELTA FPOP" treated students to provocative lectures from world-class experts, intriguing campus tours, and an array of hands-on activities. The result of this total immersion? A deeper understanding of the challenges and opportunities of energy and climate change—and a chance to get a jump-start on establishing new friendships before classes even started.

To introduce the students to the region they now call home, the schedule took them to diverse Boston locales, ranging from the State House and Museum of Science to Boston Harbor and the Charles River. According to participants, however, one of the week's most impressive features was its campus focus, where the students literally followed the Institute's energy flow, from generation and distribution to conversion and end-use consumption in the electrical outlets, switches, and hot water faucets used daily by the MIT community. After stopping to study Building 32's electrical and mechanical rooms, the group traced steam, water, and electricity paths through underground and overhead conduits to MIT's cogeneration plant. Their tour ended on the 8th floor of Building 36, where they got a bird's-eye

Photo: Justin Knight

Participants in MITEI's 2010 Freshman Pre-Orientation Program called Discover Energy: Learn, Think, Apply.

glimpse of the central utility facility. Along the way, they learned about the energy losses associated with various distribution networks—through uninsulated pipes, leaks, and most conspicuously, the aging, maintenance-intensive steam system. By getting an in-the-trenches look at the campus-wide energy system, the students came to understand a small-scale analogue to the country's full-scale energy infrastructure.

"We learned about the technologies—what works, what doesn't, what needs to be improved, and what MIT is doing about them," says FPOP participant Kelly Snyder, from Alaska. "MIT has a 'walk-the-talk' approach, trying to decrease its own energy consumption, which I think is very cool."

The students also gained a more robust view of alternative energy, supplementing their general understanding of its potential benefits with new insights on its lesser-known limitations, such as energy-storage issues. "It was scary but interesting to learn there's a really long way to go with all these alternative energies," says Snyder. "The possibility that I can be part of the solution to energy storage and alternative energy is invigorating."

The difficulties of finding solutions, especially on a global scale, were brought home in an interactive climate negotiation simulation. Students role-played the stances of selected developed and developing countries as well as small island nations. Negotiations were informed by numerous factors—emission reduction targets, deadlines for those cuts, financial sums countries would invest in a development fund—all of which were plugged into the C-LEARN model, a web-accessible international simulation developed by a team led by John Sterman, the Jay W. Forrester Professor of Management. The simulation helps users understand the long-term climate impacts of various parameters using easily comprehended graphical displays.

"We saw how our negotiating terms would actually affect the environment," explains FPOP participant Anvisha Pai, a 17-year-old from Mumbai, India. "It helped us see how difficult it is to come up with a comprehensive solution, and how and why global politics has been so inefficient in slashing emissions."

The local side of energy politics was also dramatically spotlighted. Students were introduced to the collective impact of leaving lights on, keeping electronics plugged in, and not using revolving doors. "Letting people know how to decrease our own personal consumption—it made me more excited to come to a place where all this is going on," says Snyder, adding that the FPOP experience "was my first exposure to people who care about these kinds of critical things, which other people find nerdy or dorky. It's important to see that as a teenager it's OK to be interested in energy, rather than going to the mall. It was refreshing."

For Pai, the DELTA FPOP was similarly eye-opening. In addition to learning how to work better in a culturally diverse group and understanding that she needs "to focus equally hard on social sciences as on engineering," Pai says she came to a few realizations. One concerns her future—"I'm definitely going forward with energy work and research." Another is about her fellow students. "I thought American kids would be very different from me, but we're all on the same page. Before coming here, the only thing I knew about MIT was that it's a number-one university. I was awed thinking there's always someone smarter than you." DELTA FPOP took away her intimidation factor. Fifteen days after arriving in the United States, Pai says, "DELTA FPOP helped me feel that MIT is more like home."

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By Orna Feldman, MITEI correspondent

Aiming at campus energy savings, hitting the targets

Photo: courtesy of Bond Brothers

MIT's chiller plant expansion has added two 2,500-ton high-efficiency chillers in otherwise unusable space over a railroad right-of-way. Here, one of the chillers is lowered into place by a 600-ton crane.

Three new initiatives at MIT are taking aim at energy savings from multiple directions. The goal: saving tens of millions in energy costs, reducing the Institute's carbon footprint, and forging new partnerships that encourage and reward strategic energy use. So far, the new programs are all hitting their targets.

Fast forward to savings

Massachusetts gas and electric utility NSTAR and MIT have embarked on what the utility has dubbed its most aggressive efficiency project to date.

The MIT Efficiency Forward program aims to save up to $50 million in energy costs over a period of 10 years. Upgrades to heating, ventilation, and air conditioning (HVAC), electrical systems, and lighting are expected to set the stage for the long-term savings by cutting electrical use by 15% over the next three years.

"What we are launching with MIT is a bold new plan for confronting climate change and a proposal to officially establish energy efficiency as the 'first fuel' in Massachusetts," said NSTAR president and CEO Tom May when the initiative was announced in spring 2010.

MIT's goal over the next three years is to conserve 34 million kilowatt-hours (kWh)—the equivalent electrical use of 4,500 Massachusetts homes in a year. MIT's current average electricity consumption is around 18 million kWh per month. The Institute is making rapid progress toward this year's goal of saving 10 million kWh. To date, the Institute has saved 7.7 million kWh through its Efficiency Forward program, including completion of several new lighting retrofit projects in buildings in the northwest section of campus; the completion of several new building projects, including the Sloan School of Management building; a chiller plant expansion; and other projects that include efficiency enhancements.

"We have over 2 million kilowatt-hours of projects in the planning stage, and we expect to meet or exceed our 2010 goal," said Walter E. Henry, director of the systems engineering group for the Department of Facilities. The $50 million in savings will be achieved over the lifetime of the projects, NSTAR and MIT said.

According to Steven M. Lanou, MIT's deputy director for environmental sustainability, lighting retrofits are expected to contribute about half the savings and new construction features about 20%. Improvements to HVAC and cooling and compressed air systems—as well as behavior change measures—are expected to round out the balance. The company will work with MIT to conduct HVAC, electrical, and lab systems improvements, and lighting fixture and control upgrades, in addition to other steps.

Several factors made MIT an especially promising partner for NSTAR, according to Lanou. Among those factors are a newly established revolving fund for campus energy and efficiency projects; a set of pilot projects established last year; and a disciplined, long-term energy management program with a robust measurement and verification component for energy savings.

With a $1 million gift from Jeffrey Silverman '68 in April 2009, the Institute established the Silverman Evergreen Energy Fund to support campus energy and efficiency projects that have rapid paybacks. David Desjardins '83, a consultant and investor who is also passionate about campus energy issues, has since donated an additional $500,000 to the effort.

To date, the fund has paid to upgrade the lighting systems in the Ray and Maria Stata Center for Computer, Information, and Intelligence Sciences, as well as in the Stratton Student Center. The two projects required a combined investment of nearly $600,000 and have resulted in estimated annual savings of about $185,000, meaning they will have paid for themselves after about three years.

In addition, the Silverman fund allocated $430,000 to recalibrate and improve the efficiency of the nearly 200 fume hoods in the Dreyfus Chemistry Building (Building 18). Fume hoods are energy-intensive ventilation devices that protect researchers from chemical fumes. They work well at lower flow volumes, saving about $160,000 annually.

The ups and downs of megawatts

In 1995, MIT installed a natural gas-fired cogeneration plant that provides electricity, steam heat, and chilled water to more than 100 campus buildings. By generating much of its own power, MIT cuts costs and reduces pollution, but operating the plant requires a decision-making process similar to that used in running full-scale utilities.

The cogeneration facility provides 21 megawatts of electricity plus heating and cooling to meet about 75% of campus energy needs. For the remaining 25%, MIT buys electricity from NSTAR. But with energy prices constantly fluctuating, it can be difficult to figure out when it's more cost-effective for MIT to buy electricity from the grid or to produce its own.

Enter ICETEC, Industrial/Commercial Energy Technologies. Earlier this year, MIT contracted with the Pennsylvania-based company to test a service and software package designed to increase the plant's effectiveness and manage the economic risks associated with being your own utility.

ICETEC has provided MIT with a computer server through which people like plant engineer Seth Kinderman connect through a web interface that presents graphed data from multiple sources. Using data from the plant's own control center, it shows how many megawatts the plant is producing, which chillers are running, and the current load. It predicts how the weather may boost electricity costs, stress the grid, and create congestion in energy delivery.

"If it's going to get hotter, consumers are going to use more electricity, and costs are going to go up," Kinderman said. "ICETEC makes recommendations to us on how we should run the plant.

"Before, we had to run the turbine on the highest output—set it and forget it, so to speak. If the campus load dropped, we produced less. If it went up, we produced more.

"But there is a huge variation in electricity prices. A megawatt-hour could cost $300, $30, or $5, depending on demand and time of day or night. The ICETEC software tells us when to produce more or less, whether it's cheaper to make chilled water for air conditioning using steam or electricity. If electricity prices are high, we run all steam. It sets up a kind of batting order for the chillers, so we use the most cost-effective unit first, and so on."

"Because it tells us which unit is most efficient to run, the system saves MIT energy as well as money," he said.

ICETEC's real-time monitoring of energy prices and load levels on campus and in the region helps dictate when MIT should run the cogeneration plant and when to buy power from the grid for maximum efficiency. The numbers are not yet in, but the collaboration looks promising. "We knew historically what we would have done in a particular month. Rough numbers are showing significant savings since we partnered with ICETEC," Kinderman said.

Partnering globally

Moving beyond campus, MIT has signed on to pilot a new public-private partnership aimed at cutting energy use and greenhouse gas emissions at industrial and commercial facilities—including academic institutions—around the world.

Initially, MIT will join eight companies to pilot the program, which emerged from the Clean Energy Ministerial public forum held in Washington, DC, in July hosted by US Department of Energy Secretary Steven Chu. Corporate leaders and more than 26 energy ministers and secretaries of energy from around the world attended, and many spoke at the event, which launched the partnership called the Global Superior Energy Performance (GSEP) Partnership.

Through GSEP, institutions such as MIT can win global certification and recognition by adopting approved energy management systems. The goal is to achieve significant and independently validated efficiency improvements over time.

GSEP certification will be piloted in commercial buildings by Cleveland Clinic, Grubb & Ellis Co., Marriott International Inc., Target, and Walmart; in industrial facilities by 3M Co., Nissan, and Dow Chemical; in public buildings by the United States and Canada; and in an educational setting by MIT.

"To achieve certification, institutions and industry must implement an energy management standard to identify pathways to reduce energy use," said Henry. GSEP-certified facilities also need to demonstrate a level of energy performance improvement that exceeds business-as-usual levels. What's more, reaching their targets will need to be validated by an accredited third party.

"MIT's being selected by Secretary Chu and the Department of Energy as the only university invited to help develop this new international energy performance standard, as well as our partnership with NSTAR, speaks volumes about the leadership position MIT is establishing in campus energy management," said Lanou. "It is our goal to share our experience through this program and our other activities to show other universities what is possible."

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By Deborah Halber, MITEI correspondent

MIT study confirms natural gas as bridge to low-carbon future

Natural gas will play a leading role in reducing greenhouse gas emissions over the next several decades, largely by replacing older, inefficient coal plants with highly efficient combined-cycle gas generation. That's the conclusion reached by a comprehensive study of the future of natural gas conducted by an MIT study group composed of 30 MIT faculty members, researchers, and graduate students. The findings, summarized in an 83-page report, were presented to lawmakers and senior administration officials in Washington in late June.

The two-year study, managed by the MIT Energy Initiative (MITEI), examined the scale of US natural gas resources and the potential of this fuel to reduce greenhouse gas (GHG) emissions. Based on the work of the multidisciplinary team, with advice from a board of 16 leaders from industry, government, and environmental groups, the report examines the future of natural gas through 2050 from the perspectives of technology, economics, politics, national security, and the environment.

The report includes a set of specific proposals for legislative and regulatory policies, as well as recommendations for actions that the energy industry can pursue on its own, to maximize the fuel's impact on mitigating GHGs. The study also examined ways to control the environmental impacts that could result from a significant expansion in the production and use of natural gas—especially in electric power production.

"Much has been said about natural gas as a bridge to a low-carbon future, with little underlying analysis to back up this contention. The analysis in this study provides the confirmation—natural gas truly is a bridge to a low-carbon future," said MITEI Director Ernest J. Moniz in introducing the report.

Moniz further noted, "In the very long run, very tight carbon constraints will likely phase out natural gas power generation in favor of zero-carbon or extremely low-carbon energy sources such as renewables, nuclear power, or natural gas and coal with carbon capture and storage. For the next several decades, however, natural gas will play a crucial role in enabling very substantial reductions in carbon emissions."

Two major factors that can make a significant difference in the near term in reducing carbon emissions are using less energy and using gas instead of coal—especially by replacing the oldest, least-efficient coal plants with the most-efficient modern combined-cycle gas plants, said Moniz, who chaired the study along with co-chairs Henry Jacoby, professor of management, and Tony Meggs, MITEI visiting engineer.

The study found that there are significant global supplies of conventional gas. How much of this gas gets produced and used and the extent of its impact on GHG reductions depend critically on some key political and regulatory decisions.

In the United States, for example, there is a substantial amount of low-hanging fruit available by displacing inefficient power generation with more efficient, lower carbon dioxide (CO_2) emitting gas plants. "That kind of substitution alone," Moniz said, "reduces those carbon emissions by a factor of three. It does, however, raise complicated regulatory and political issues that will have to be resolved to take advantage of this potential."

Some key findings

1. The United States has a significant natural gas resource base, enough to equal about 91 years' worth of supply at present domestic consumption rates. Much of it is from unconventional sources, including gas shales. While there is substantial uncertainty surrounding the producibility of this gas, there is a significant amount of shale gas that can be affordably produced.

Globally, baseline estimates show that recoverable gas resources probably amount to 16,200 trillion cubic feet (Tcf)—enough to last over 160 years at current global consumption rates. Further, with the exception of the US and Canada, this global resource figure does not include any unconventional gas resources, which are largely uncharacterized in the rest of the world. The Middle East, Russia, and the US have the highest concentration of global gas reserves (see the figure on page 32).

In the US, unconventional gas resources are rapidly overtaking conventional resources as the primary source of gas production. The US currently consumes around 22 Tcf per year and has a gas resource base now thought to exceed 2,000 Tcf.

To bring about the kind of significant expansion in the use of natural gas identified in this study, substantial additions to the existing processing, delivery, and storage facilities will be required in order to handle greater amounts and the changing patterns of distribution (such as the delivery of gas from newly developed sources in the Midwest and Northeast).

2. Environmental issues associated with producing unconventional gas resources are manageable but challenging. Risks include shallow freshwater aquifer contamination with fracture fluids, surface water contamination by returned fracture fluids, excessive demand on local water supply from fracturing operations, and surface and local community disturbance due to drilling and fracturing activities.

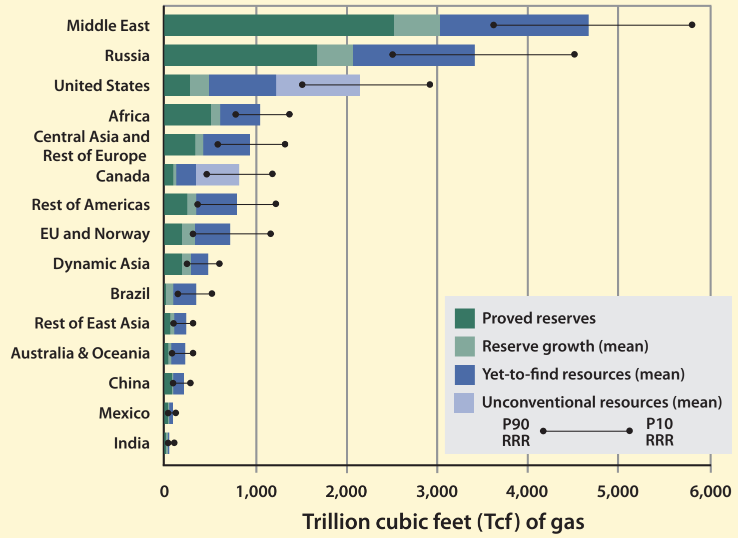
3. Natural gas consumption will increase dramatically and will largely displace coal in the power generation sector by 2050 (the time horizon of the study) under a modeling scenario where, through carbon-emissions pricing, industrialized nations reduce CO_2 emissions by 50% by 2050 and large emerging economies, e.g., China, India, and Brazil, reduce CO_2 emissions by 50% by 2070. This assumes incremental reductions in the current price structures of the alternatives, including renewables, nuclear, and carbon capture and sequestration.

4. The introduction of large intermittent power generation from, for example, wind and solar will have specific short- and long-term effects on the mix of generation technologies. The short-term effects (meaning daily dispatch patterns of various fuels) of large amounts of wind generation, for example, will reduce gas generation significantly and could force baseload coal plants to cycle, an outcome that is highly undesirable from an operational perspective.

In the longer term, the reliability of a system in which renewables assume a baseload role in power generation will require additional flexible natural gas peaking capacity, although this capacity may be utilized for only short periods of time. Renewables as baseload power, firmed by natural gas generation, will require new regulatory structures to ensure reliability of the system and incentivize the building of flexible gas capacity.

Remaining recoverable natural gas resources

(excludes unconventional gas outside North America)



Definitions: "Resource" refers to the sum of all gas volumes expected to be recoverable in the future, given specific technological and economic conditions. Resource is disaggregated into the following subcategories: proved reserves, reserve growth (via further development of known fields), and yet-to-find resources (gas volumes that will be discovered in the future via the exploration process).

Uncertainty bars: There is a 90% chance that the true value of remaining recoverable resources (RRR) is greater than the lower end of the uncertainty bar (P90) and a 10% chance that it is greater than the upper end (P10).

5. The overbuilding of natural gas combined-cycle (NGCC) plants starting in the mid-1990s presents a significant opportunity for near-term reductions in CO_2 emissions from the power sector. The current fleet of NGCC units has an average capacity factor of 41%, relative to a design capacity factor of up to 85%. However, with no carbon constraints, coal generation is generally dispatched to meet demand before NGCC generation because of its lower fuel price.

Modeling of the ERCOT region (largely Texas) suggests that CO_2 emissions could be reduced by as much as 22% with no additional capital investment and without impacting system reliability by requiring a dispatch order that favors NGCC generation over inefficient coal generation; preliminary modeling suggests that nationwide CO_2 emissions would be reduced by more than 10%. At the same time, this would also reduce air pollutants such as oxides of sulfur and nitrogen.

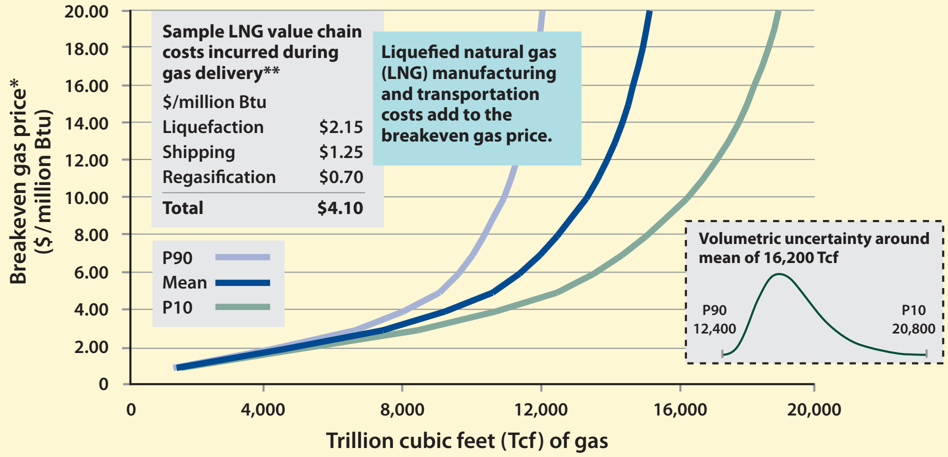
6. In the transportation sector, the study found a somewhat smaller role for natural gas. The use of compressed or liquefied natural gas as a fuel for vehicles could help to displace oil and reduce GHG emissions but to a limited extent because of the high cost of converting vehicles to use these fuels. By contrast, making methanol, a liquid fuel, out of natural gas requires much less up-front conversion cost and could have an impact on oil usage and thus improve energy security, but would not reduce GHGs.

7. A global "liquid" market in natural gas in which supply sources are diverse and gas prices are transparent, set by supply and demand with price differences based on transportation costs, is desirable for US consumers.

There are currently three regional gas markets—North America, Europe, and Asia—which have very little integration and rely on completely different pricing structures. Modeling suggests that the integration of these markets would result in substantially lower prices for US consumers.

Global gas supply curve

(excludes unconventional gas outside North America)



* 2007 cost base. North American breakeven prices are calculated at the wellhead; for regions outside North America, breakeven prices are calculated at the point of export. Breakeven prices calculated using 10% real discount rate and ICF Hydrocarbon Supply Model.

** Assumes two 4 million metric ton LNG trains with about 6,000-mile one-way delivery runs, per Jensen and Associates. Excludes cost of the gas.

Recommendations

The study makes many recommendations regarding the role of natural gas in a carbon-constrained world, suggesting that policymakers should consider supportive policies in the following areas.

Supply

- Require disclosure of all components of hydraulic fracture fluids.
- Require integrated regional water usage/disposal plans for unconventional gas production.
- Support a renewed Department of Energy (DOE) R&D program weighted toward basic research and an "off-budget" industry-led program weighted toward technology development, demonstration, and transfer. Programs should be designed to optimize gas resources and ensure that they are produced in environmentally sound ways.

Power generation

- Pursue displacement of inefficient coal generation with NGCC generation.
- Develop policy and regulatory measures to facilitate natural gas generation capacity investments concurrent with the introduction of large intermittent renewable generation.

Transportation

- Remove policy and regulatory barriers to natural gas as a transportation fuel.

Global markets

- Support policies to foster an integrated global gas market, including the integration of natural gas issues into the foreign policy apparatus, with strong involvement of the Executive Office of the President supported by a strengthened natural gas policy apparatus at DOE.
- Export US knowledge in unconventional gas characterization and production to nations that can advance US strategic interests.

While the new report emphasizes the great potential for natural gas as a transitional fuel to help curb GHG emissions and dependence on oil, it also stresses that it is important as a matter of national policy not to favor any one fuel or energy source in a way that puts others at a disadvantage. The most useful policies, the authors suggest, are ones that produce a truly "level playing field" for all forms of energy supply and for demand reduction, and thus let the marketplace and the ingenuity of the nation's researchers determine the best options.

Illustrating the role of natural gas as a bridge to a low-carbon future, the study's authors stress that it would be a mistake to let natural gas crowd out research on other low- or no-carbon energy sources, but it would also be a mistake to let investments in such alternatives crowd out the expansion of natural gas resources in the near term, particularly for the purposes of CO_2 emissions mitigation.

"In a carbon-constrained world, natural gas will become a larger part of the energy mix," Moniz said. But in the longer term, it will be necessary to shift to "essentially zero-carbon" sources, so "we better not get mesmerized by gas either. We need to do the hard work of getting those alternative technologies ready to take over."

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By Melanie A. Kenderdine, MITEI, and David L. Chandler, MIT News Office

This study received support from the American Clean Skies Foundation, Hess Corporation, Agencia Nacional de Hidrocarburos of Colombia, and the Energy Futures Coalition and the MIT Energy Initiative. The report issued is a preliminary overview of a more detailed report that will be released later this year. To download a pdf of the interim report, go to web.mit.edu/mitei/research/studies/naturalgas.html.

MITEI releases report on critical elements for new energy technologies

The strategic importance of rare earth elements was one of several issues highlighted in a recent report, *Critical Elements for New Energy Technologies*, released by the MIT Energy Initiative (MITEI) and its co-sponsors, the American Physical Society's Panel on Public Affairs and the Materials Research Society. The report summarizes the six commissioned white papers, presentations, and discussions at the April 29 workshop held at MITEI headquarters on the MIT campus.

Rare elements are critical for advanced manufacturing of, for example, photovoltaics, superconductors, high-performance permanent magnets, batteries, key catalysts, hybrid car components, and compact fluorescent lights. Elements such as gallium, indium, lanthanum, lithium, neodymium, tellurium, and terbium are now routinely part of the discussion about novel energy technologies, but many of these elements are not at present mined, refined, or traded in large quantities and could present scale-up challenges.

The workshop, co-chaired by Robert Jaffe, the Morningstar Professor of Physics at MIT, and Jonathan Price, the state geologist of Nevada and professor at the University of Nevada, Reno, examined how geologic, technical, socioeconomic, political, and economic factors might limit consumer access to these minerals and the implications for the manufacturing and deployment of new energy technologies.

Some of the conclusions in the report are:

- Many novel technologies are materials intensive and if widely deployed will compete with other uses of rare elements.
- China has emerged as a primary producer of energy-critical elements and has less stringent environmental requirements for mining/production. There are concerns about monopoly and access restrictions, especially because substitution opportunities for rare earths in energy-critical applications are limited. China now meets more than 95% of the world's demand for rare earths.
- There are new potential sources of rare elements, but they are usually expensive and technically challenging to develop and produce. Research and development is needed.
- The long lead times of 5 to 15 years for new mining ventures could lead to shortages and price spikes.
- The cadmium telluride photovoltaic industry currently has an annual growth rate greater than 100%. If supplies of tellurium obtained as by-products of copper production prove insufficient, other sources can be brought into play, but the associated time constants are hard to predict.
- The United States needs transparent, accurate data on production, reserves, and reserve bases for energy-critical elements. The US Geological Survey should be resourced to conduct a comprehensive estimate of the reserve bases for those elements.
- The public and policymakers now have limited awareness of the mineral footprint, similar to the earliest stages of the environmental movement. Raising awareness is important for the conservation of these rare materials as well as for the associated recycling and R&D that are needed to meet growing demand.

To download a copy of the report, please go to web.mit.edu/mitei/research/energy-studies.html.

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By Melanie A. Kenderdine, MITEI

MITEI seminars and colloquia

MITEI Seminar Series, 2010–2011

October 12, 2010
Mitigating manhole events in Manhattan
Cynthia Rudin, Assistant Professor of Statistics,
MIT Sloan School of Management

November 9, 2010
Solar photovoltaic materials, processes, and devices
Tonio Buonassisi, Assistant Professor,
Mechanical Engineering, MIT

December 14, 2010
Response to the Gulf oil spill and the larger issue of energy and national security
Juliette Kayyem, Assistant Secretary for Intergovernmental Affairs,
US Department of Homeland Security

February 8, 2011
Decision making in electricity markets and control problems of large energy systems
Marija Ilic, Professor,
Electrical and Computer Engineering,
Carnegie Mellon University

March 8, 2011
Organic semiconductors, nanostructures, and solar cells
Michael McGehee, Associate Professor,
Materials Science and Engineering,
Stanford University

April 12, 2011
Catalysis for hydrogen production
Claus Hviid Christensen,
Lindoe Offshore Renewables Center,
Denmark

May 10, 2011
Catalysis and surface chemistry
Marc Koper, Professor, Chemistry,
Leiden University,
The Netherlands

Photos: Justin Knight

On October 15, George P. Shultz PhD '49, chair of MITEI's External Advisory Board, discussed nuclear disarmament after a screening of the documentary film *Nuclear Tipping Point.* In the film, former secretaries of state Shultz and Henry Kissinger, former secretary of defense William Perry, and former senator Sam Nunn call for the complete disarmament of the world's nuclear arsenals—a stance motivated by the rise of terrorism combined with the anticipated spread of weapons materials, which could be widely produced through the international reprocessing of nuclear reactor spent fuel. The event was co-sponsored by MITEI and the MIT Center for International Studies.

During a MITEI colloquium on October 13, Arun Majumdar, director of the US Department of Energy's Advanced Research Projects Agency-Energy (ARPA-E), discussed the global energy challenge and the role his agency plays in trying to foster transformational energy research and development. Majumdar's presentation to a standing-room-only crowd served as both a wake-up call and a source of inspiration. He noted that the US spends more on dog food R&D than on electrical power R&D. He also discussed some of the very real and exciting energy projects his agency is funding, including several at MIT.

Martin Fellows explore the changing coastal environment

In September 2010, Martin Fellows for Sustainability spent a weekend retreat at Plum Island, an 11-mile-long barrier island off the shore of Newburyport, Massachusetts. The island is home to the Parker River National Wildlife Refuge, a 4,662-acre sanctuary that provides feeding, resting, and nesting habitat for migratory birds. The fellows learned about bird migration strategies and how they are impacted by changing environmental conditions. Massachusetts Audubon Society's Joppa Flats Education Center staff and volunteers led the weekend's activities.

Photo: Mitul Luhar, MIT

Left: Retreat attendees spotted great blue herons and other wildlife during a river cruise that meandered through miles of the refuge's Great Marsh.

Photo: Mitul Luhar, MIT

Ben Flemer, manager of the Education Center's bird banding station, holds a plains warbler. Behind him is a list of warbler species that were banded at the station in early fall 2010.

Below: Birds caught at the Joppa Flats banding station are tagged with these lightweight ankle bracelets. After gathering data (species, weight, age, gender) and banding the birds, the volunteers release them to continue their journeys.

Photo: Justin Knight

Here, Flemer blows gently to separate a towhee's feathers as Martin Fellows look on. The pinkness of the underlying skin indicates the bird's level of fat, which must sustain the migrant as it travels hundreds or thousands of miles.

Photo: Jennifer DiMase, MITEI

Anita Ganesan, a 2010 Martin Fellow in earth, atmospheric, and planetary sciences, looks through a telescope as Joppa Flats Sanctuary director Bill Gette describes the habitat.

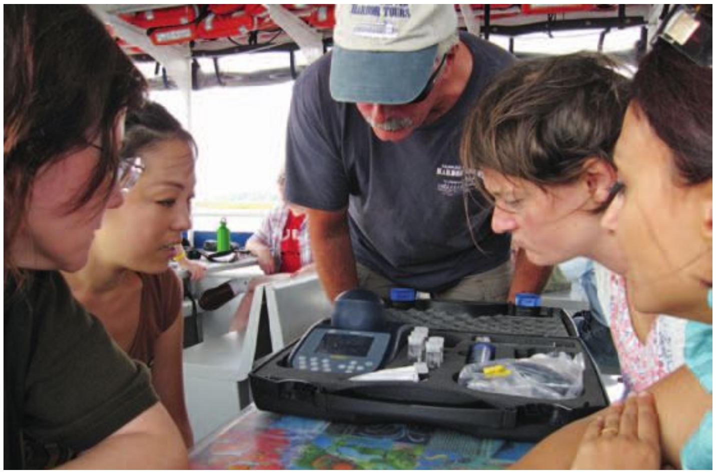

Photo: Jennifer DiMase, MITEI

Mass Audubon volunteer John Halleran (center) demonstrates how to measure the turbidity of river water to Martin Fellows (from left) Kathy Araujo (2009), Lily Song (2010), Isabelle Anguelovski (2008), and Madhu Dutta-Koehler (2010), all of urban studies and planning.

Photo: courtesy of John M. Deutch, MIT

Deutch named to Secretary of Energy Advisory Board

Institute Professor John M. Deutch has been named to the Secretary of Energy Advisory Board (SEAB), which will serve as an independent advisory committee to US Secretary of Energy Steven Chu, the US Department of Energy (DOE) announced on August 10, 2010.

Deutch has served in a number of positions for DOE, including director of energy research and undersecretary of the department. He served as director of central intelligence from 1995 to 1996 and deputy secretary of defense from 1994 to 1995.

A member of the MIT faculty since 1970, Deutch has served on the six-member MIT Energy Council since it was formed in November 2006 to help guide development of the newly created Institute-wide MIT Energy Initiative. At MIT, Deutch has also served as head of the Department of Chemistry, dean of science, and provost.

The 12-member SEAB—consisting of scientists, business executives, academics, and former government officials—will provide advice and recommendations to Secretary Chu on DOE's basic and applied research and development activities, economic and national security policy, educational issues, operational issues, and other activities as directed by the secretary.

Photo: Mary Gallagher, MITEI

Herzog receives international award

Howard Herzog, senior research engineer at the MIT Energy Initiative, has been presented the 2010 Greenman Award by the International Energy Agency Greenhouse Gas R&D Programme (IEAGHG) in recognition of his longstanding national and international commitment to carbon capture and storage (CCS) research and development.

An MIT staff member since 1989, Herzog has focused his research on energy and the environment, with an emphasis on greenhouse gas mitigation technologies. In 2000, he founded the MIT Carbon Sequestration Initiative, an industrial consortium dedicated to investigating CCS technologies. The initiative now has 18 members.

Herzog was a coordinating lead author on the *IPCC Special Report on Carbon Dioxide Capture and Storage* (released September 2005), a co-author on *The Future of Coal: An Interdisciplinary MIT Study* (released March 2007), and a US delegate to the Carbon Sequestration Leadership Forum's Technical Group (June 2003–September 2007).

Kelly Thambimuthu, chairman of the IEAGHG, presented the award to Herzog on September 23, 2010, during the International Conference on Greenhouse Gas Control Technologies (GHGT-10) in Amsterdam. The weeklong conference, one of the most significant in the field of greenhouse gas emissions reduction, attracted more than 1,500 delegates this year.

MITEI External Advisory Board meets

The MIT Energy Initiative's External Advisory Board met on October 14–15, 2010. The board, chaired by George P. Shultz PhD '49, former MIT faculty member and secretary of state in the Reagan administration, meets annually to provide high-level strategic direction for the initiative and to review MIT's progress in energy fields. In 2010, MITEI welcomed seven new EAB members: Susan Eisenhower, Walter B. Hewlett, Frank E. Mars, Thomas F. McLarty III, Güler Sabanci, Gerald Schotman, and Ratan N. Tata. In addition, MITEI welcomed Lamar McKay representing BP America, Inc., and Paolo Scaroni representing Eni S.p.A. Special campus-wide events associated with the board meeting featured Shultz and Arun Majumdar, director of the Department of Energy's Advanced Research Projects Agency-Energy (see page 35).

Members as of November 2010

Sultan Ahmed Al Jaber
Chief Executive Officer,
Abu Dhabi Future Energy Company

Stephen D. Bechtel, Jr.
Chairman, SD Bechtel, Jr. Foundation and Stephen Bechtel Fund

Frances Beinecke
President, Natural Resources Defense Council

Denis A. Bovin
Co-Chairman and Co-Chief Executive Officer, Stone Key Partners LLC

Rafael del Pino
Chairman, Grupo Ferrovial SA

Susan Eisenhower
Chairman Emeritus,
Eisenhower Institute

Arthur L. Goldstein
Retired Chairman and Chief Executive Officer, Ionics Incorporated

Walter B. Hewlett
Chairman, The William and Flora Hewlett Foundation

Baba N. Kalyani
Chairman and Managing Director, Bharat Forge Company Limited

Anne Lauvergeon
Chief Executive Officer, AREVA

Lawrence H. Linden
Founder and Trustee, Linden Trust for Conservation

Frank E. Mars
President, Mars Symbioscience

Lamar McKay
Chairman and President,
BP America, Inc.

Thomas F. McLarty III
President, McLarty Associates

Robert M. Metcalfe
General Partner,
Polaris Venture Partners

Robert B. Millard
Managing Partner,
Realm Partners LLC

Mario J. Molina
Professor, University of California, San Diego

Sam Nunn
Co-Chairman and Chief Executive Officer, Nuclear Threat Initiative

Ngozi N. Okonjo-Iweala
Managing Director, World Bank

John S. Reed
Chairman, MIT

Güler Sabanci
Chairman and Managing Director, Haci Omer Sabanci Holding AS

Kenan E. Sahin
President and Founder, TIAX LLC

Arthur J. Samberg
Chairman and Chief Executive Officer, Pequot Capital Management Incorporated

Paolo Scaroni
Chief Executive Officer, Eni S.p.A.

Gerald Schotman
Executive Vice President Innovation/R&D and Chief Technology Officer, Royal Dutch Shell plc

Philip R. Sharp
President, Resources for the Future

George P. Shultz (Chair)
Thomas W. and Susan B. Ford Distinguished Fellow, Hoover Institution

Robert M. Solow
Institute Professor Emeritus, MIT

Ratan N. Tata
Chairman, Tata Sons Limited

James D. Wolfensohn
Chairman and Chief Executive Officer, Wolfensohn & Company, L.L.C.

Daniel Yergin
Chairman, IHS Cambridge Energy Research Associates

New technologies unveiled at Eni-MIT press briefing

New MIT innovations such as imprinting solar cells on paper and a material that could help clean up oil spills were unveiled October 18 at a press briefing led by MIT President Susan Hockfield and Paolo Scaroni, CEO of the Italian energy company Eni S.p.A., a founding member of the MIT Energy Initiative.

The event highlighted new joint technologies coming out of the Eni-MIT Alliance, a five-year research program focusing on advanced solar research and other strategic research central to Eni's core business, including oil and gas production.

Hockfield credited Eni with "making far-sighted investments that could transform the long-term energy equation," and noted that the alliance—formed in 2008—has resulted in 18 published studies and five patent filings to date.

At the briefing, Professor Karen Gleason of chemical engineering and associate dean of engineering for research, reported on a revolutionary way to produce ultra-lightweight, inexpensive, flexible solar cells. She demonstrated how an index-card-sized square of ordinary tracing paper imprinted with these cells could power an LED clock. "You really can make solar cells on paper that are usable and that power a device," said Gleason.

The new approach, developed by Gleason in collaboration with Professor Vladimir Bulović of electrical engineering and computer science and his team, involves rapidly depositing materials at room temperature using only environmentally friendly methods. With this technique, solar cells could be layered on roof tiles, window blinds, or laptops.

Professor Phil Gschwend of civil and environmental engineering presented

Photo: © Rick Friedman

MIT Professor Karen Gleason (center), with MIT President Susan Hockfield (left), demonstrates Eni-supported research on "paper-thin photovoltaics" for Eni CEO Paolo Scaroni.

a nanotech-based material—developed by his collaborator Professor Francesco Stellacci of materials science and engineering—that repels water but allows oil to pass. "It's possible we can create devices that, when oil is escaping, can recapture and accumulate it so it can then be pumped into a tanker," he said.

He showed a video of a cone of the material submerged in a beaker of oil and water simulating an oil spill. Oil pooled in the device and was removed with no water in the mixture. Gschwend said such oil-collecting devices could one day be permanently "on call" for emergency use in areas such as the Gulf of Mexico.

Scaroni said he was impressed with MIT's research results and emphasized the urgency of making products such as the oil-collecting device available to address catastrophes such as the BP spill in the Gulf of Mexico. That incident "has pushed us to work in two fields—prevention and solutions—to provide answers to what happens if we have an accident," Scaroni said.

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By Deborah Halber, MITEI correspondent

MIT Energy Fellows Symposium

The MIT Energy Initiative hosted the annual MIT Energy Fellows Symposium at the new Media Laboratory building on October 27, 2010. Faculty presented research in solar energy to fellows from the past three years and representatives from their sponsoring companies. A poster session followed.

Photos: Justin Knight

Evelyn Wang, the Esther and Harold E. Edgerton Assistant Professor of Mechanical Engineering, describes nanoengineering of hydrophobic surfaces for solar thermal energy applications.

Gaudenzio Mariotti, head of nuclear energy, Energy and Innovation Division, Enel Produzione SpA, confers with Giancarlo Lenci, 2010–2011 Enel-MIT Energy Fellow in nuclear science and engineering.

Students and representatives of MITEI member companies discuss energy research at a poster session featuring projects from the MITEI Energy Research Seed Fund Program.

Latest seed grant projects supported by MITEI members

Recipients of MITEI seed grants, Spring 2010

Energy-efficient desalination by shock electro-dialysis in porous media
Martin Bazant
Chemical Engineering

Energy-efficient algorithms
Erik Demaine, Martin Demaine
Computer Science and Artificial Intelligence Laboratory (CSAIL)

Solar energy conversion using the phenomenon of thermal transpiration
Nicolas Hadjiconstantinou
Mechanical Engineering

Synthesis of bimetallic nanoparticle structures as catalysts for fuel cells
Klavs Jensen
Chemical Engineering

Advanced multi-core processor architectures for power electronics controls and simulation: enabling efficient integration of renewables into the smart grid
John Joannopoulos
Physics
Ivan Celanovic
Institute for Soldier Nanotechnologies
Srini Devadas
Electrical Engineering and Computer Science

Multi-functional self-assembled photonic crystal nanotexture for energy-efficient solid state lighting
Lionel Kimerling
Materials Science and Engineering

Subsurface change detection for CO_2 sequestration
Alison Malcolm, Michael Fehler
Earth, Atmospheric, and Planetary Sciences

Self-assembled polymer-enzyme nanostructures for low-temperature CO_2 reduction
Bradley Olsen
Chemical Engineering

A novel framework for electrical grid maintenance
Cynthia Rudin
Management

Novel bioprocess for complete conversion of carbon feedstocks to biofuels
Gregory Stephanopoulos
Chemical Engineering

Ultra-low drag hydrodynamics using engineered nanostructures for efficiency enhancements in energy, water, and transportation systems
Kripa Varanasi
Mechanical Engineering

Nanofilm-based thermal management device for concentrated solar energy conversion systems
Evelyn Wang
Mechanical Engineering

Experimental study of millimeter-wave rock ablation
Paul Woskov
Plasma Science and Fusion Center

For more information, see the article on page 21.

MITEI Founding and Sustaining members

MITEI's Founding and Sustaining members support "flagship" energy research programs or individual research projects that help them meet their strategic energy objectives. They also provide seed funding for early-stage innovative research projects and support named Energy Fellows at MIT. To date, members have made possible 67 seed grant projects across the campus as well as fellowships for more than 100 graduate students in 20 MIT departments and divisions.

FOUNDING MEMBERS

BP (inaugural member)
Eni S.p.A.
Shell

FOUNDING PUBLIC MEMBER

Masdar Institute

SUSTAINING MEMBERS

ABB Research Ltd.
Robert Bosch GmbH
Chevron U.S.A. Inc.
Enel Produzione SpA
Ferrovial
Lockheed Martin
Saudi Aramco
Schlumberger
Siemens
Total
Weatherford International Ltd.

SUSTAINING PUBLIC MEMBER

Portuguese Science and Technology Foundation

Members as of December 1, 2010

MITEI Associate and Affiliate members

MITEI's Associate and Affiliate members support a range of MIT energy research, education, and campus activities that are of interest to them. Current members are now supporting various energy-related MIT centers, laboratories, and initiatives; fellowships for graduate students; research opportunities for undergraduates; campus energy management projects; outreach activities including seminars and colloquia; and more.

Associate members

Agencia Nacional de Hidrocarburos (ANH)—Colombia
Cummins
Denbury Resources, Inc.
EDF
Entergy
Exelon
Fundació Barcelona Tecnológica (b_TEC)
Hess

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Beacon Power
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Gabelli Capital Partners
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Harris Interactive
ICF International
IHS Cambridge Energy Research Associates (IHS CERA)
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Mohave Sun Power, LLC (Mitchell Dong)
Moore and Van Allen
New Energy Finance
Nexant, Inc.
NGP Energy Technology Partners, LP
Nth power, LLC
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Palmer Labs, LLC
Patriot Renewables
Redpoint Ventures
Philip Rettger (inaugural member)
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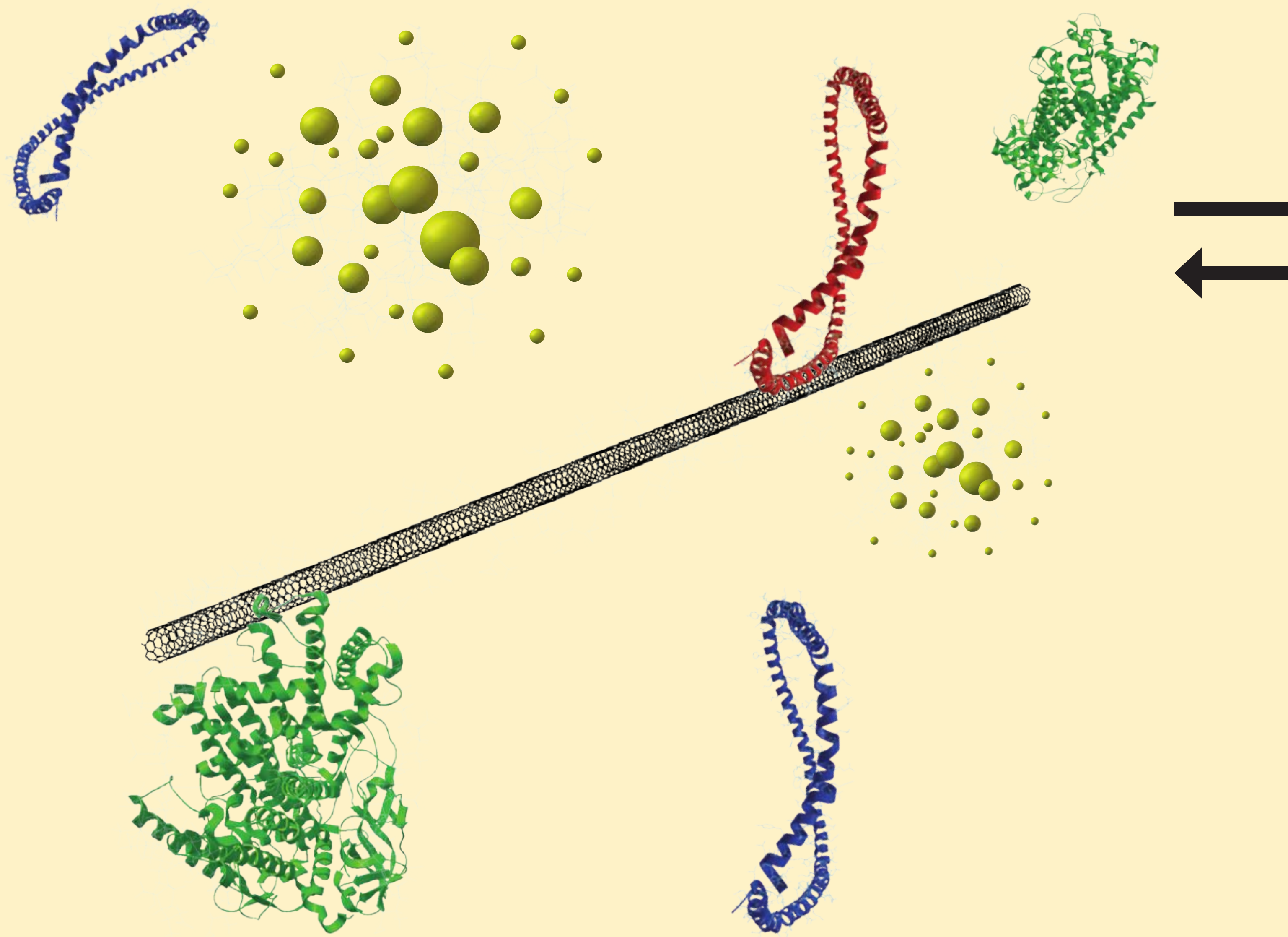

New photovoltaic technology

The sun's rays can be highly destructive to materials, so some of the novel solar energy systems now being developed may get less efficient as they are used. Plants deal with that problem by continually disassembling and reassembling their light-gathering molecules so they're in effect always brand new. MIT researchers have now been able to mimic that strategy. They start with a mixture of components suspended in a soapy solution (above). They then filter out one of the components, and those that remain assemble themselves into a highly ordered series of light-harvesting, electricity-producing structures (front cover). For more details on the diagram and the research, see page 4.