Energy Futures

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Novel bromine battery: Small-scale demo, large-scale promise

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Energy Futures

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MIT Energy Initiative

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MITEI MEMBERS

A letter from the director

Photo: Webb Chappell

MITEI's research, education, campus energy, and outreach programs are spearheaded by Professor Robert C. Armstrong, director.

Dear Friends,

Innovation is central to solving today's complex energy challenges, and there is no better place to find cutting-edge innovations than in the labs and classrooms of MIT.

In March, a group of outstanding MIT faculty and I carried this message with us to Houston, Texas, for the annual CERAWeek, one of the world's preeminent energy conferences. In a room filled largely by energy industry executives, it was innovation that excited the crowd. The faculty demonstrated game-changing technologies coming out of MIT—from transparent solar cells to offshore wind turbines that double as large-scale energy-storage devices. I've never been prouder to represent MIT than I was after hearing the applause from this group of leaders. (Read more about CERAWeek on page 46.)

MIT's presence at CERAWeek emphasized the vital role that universities play in the innovation pipeline, serving as incubators of talent and technology. Each year, we admit a brand new set of students who come into the Institute asking tough questions that cause us—experienced researchers—to examine conventional reasoning and to think outside the box to find creative solutions to various energy problems.

To help support such creativity, we at the MIT Energy Initiative (MITEI) award seed funds to promising early-stage research projects that can inject new ideas into the pipeline. Since its beginning, the MITEI Seed Fund Program has supported 129 such projects, with total funding of about $15.8 million. Once again, this year's call for proposals elicited submissions from faculty across the Institute. Of the 11 funded projects, more than half are led by faculty new to MITEI who proposed exciting ideas ranging from novel materials for carbon capture, wastewater filtration, and natural gas storage, to a fresh approach for harvesting ambient vibrations to power portable electronics and other devices.

We also support new ideas by using our own backyard—the MIT campus—as a model to put research into action and to demonstrate best practices. One example is "MIT.nano," a building now being planned that will house state-of-the-art cleanroom, imaging, and prototyping facilities supporting research with nanoscale materials and processes across the campus. Cleanroom facilities are by nature energy-intensive, so MIT.nano is being designed with dozens of special energy-saving features to make the building as efficient and sustainable as possible. Starting in 2018, MIT's energy researchers will be able to take advantage of the new facilities as they use nanotechnology to achieve printable photovoltaic solar cells, high-performing lithium-air batteries, faster and more energy-efficient chips, and more.

Saving energy in all types of commercial buildings is of paramount importance. Such buildings account for nearly 20% of all US energy consumption, and energy is often the leading operating expense in these buildings. Many promising approaches are being explored to reduce energy use and operating costs in commercial buildings. But there is an added complication: We must make those changes in an age of intermittent renewable energy technologies, evolving smart grids, and distributed generation and storage. To discuss the challenges—and opportunities—involved, MITEI hosted a symposium for its member organizations and stakeholders in early May 2014. We had a stimulating discussion about emerging building efficiency and smart grid technologies, and the financial and regulatory factors surrounding their adoption. We will be synthesizing the findings and analysis from those conversations in the coming months.

We would not be successful in all these efforts without our dedicated faculty, staff, and students, and without the support and engagement of our members, collaborators, and friends. We are grateful for your continued interest in MITEI and hope that you enjoy this issue of *Energy Futures*.

Robert C Armstrong

Professor Robert C. Armstrong
MITEI Director

May 2014

Game Changers: Energy on the Move
Edited by George P. Shultz and Robert C. Armstrong

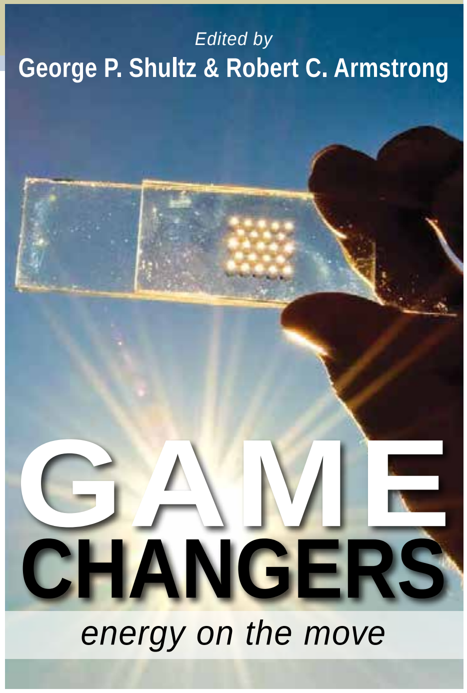
New book highlights five R&D efforts from American universities that offer a cheaper, cleaner, and more secure national energy system.

The United States needs reliable and inexpensive energy to propel our economy and protect our national security interests. *Game Changers* presents five research and development efforts from US universities that offer a cheaper, cleaner, and more secure national energy system. Drawing from the efforts of Stanford, MIT, and other leading university research centers, the book describes some of the energy innovations that are transforming our energy landscape:

- natural gas from shales
- solar photovoltaics
- grid-scale electricity storage
- electric cars
- LED lighting

For each innovation, the authors detail the fruits of individual research and development projects organized into three categories: technologies that have been commercialized, technologies on the cusp of becoming operational, and potential blockbuster technologies down the road that hold real promise of major importance. All are portrayed against the backdrop of three key objectives: national security, economic well-being, and an improved environment.

The authors reveal, for instance, how a new generation of research into compressed air energy storage technology reduces costs and improves efficiency by changing how these systems handle heat during compression and expansion. They show how MIT's carbon nanotube–enhanced ultracapacitor, now commercially available, stores twice as much



energy as conventional alternatives and delivers seven to fifteen times more power for electric cars. And they describe how a Stanford program in cross-disciplinary "design thinking" has helped launch an affordable, solar-powered LED lantern for the developing world.

The authors also show how the ongoing efforts of the military to dramatically reduce its energy consumption are both driving sponsorship of energy R&D and simultaneously allowing the Department of Defense to act as an "early adopter"—piloting the use of civilian energy innovations prior to more widespread commercial use.

Game Changers (ISBN: 978-0-8179-1825-5) was edited by George Pratt Shultz, the Thomas W. and Susan B. Ford Distinguished Fellow at the Hoover Institution, and Robert C. Armstrong, director of the MIT Energy Initiative (MITEI). Shultz is chair of the MITEI External Advisory Board.

To order copies, go to Amazon (www.amazon.com) on or after July 1, 2014.

MITEI Sustaining Members join, renew

Photo: Justin Knight

Statoil

Statoil joined the MIT Energy Initiative (MITEI) as a Sustaining Member on February 1, 2014, and followed up with a four-day visit in April to develop the company's research portfolio. Front row, left to right: Bruce Tocher, Hanne Wigum, and Per Ivar Karstad of Statoil; back row, left to right: MITEI Director Robert C. Armstrong; Jonathan Matthews, Dag Schanke, and Svenn Ferry Utengen of Statoil; and Professor Donald Lessard of the MIT Sloan School of Management.

Photo: Dominick Reuter

Schlumberger

Tarek Habashy, managing director (left), and François Auzerais, senior technology advisor (right), of Schlumberger-Doll Research Center pose with MITEI Director Robert C. Armstrong. Schlumberger renewed its Sustaining Membership with MITEI through 2016, continuing its support for a variety of energy projects, student fellowships, and consortia memberships.

Novel bromine battery

Small-scale demo, large-scale promise

Left to right: William Braff PhD '14, now of Exponent, Inc., Martin Z. Bazant of chemical engineering and mathematics, and Cullen Buie of mechanical engineering are developing a low-cost, high-capacity, rechargeable battery that could one day enable widespread adoption of intermittent renewable energy sources such as solar and wind.

This research was funded in part by the MIT Energy Initiative Seed Fund Program. See page 8 for more information about funding.

Photo: Stuart Darsch

An MIT team has performed the first small-scale demonstrations of a new battery that could one day provide critical low-cost energy storage for solar and wind installations, microgrids, portable power systems, and more. The battery uses bromine—an inexpensive, abundant element—combined with hydrogen. Inside the battery, the reactants are kept apart not by the usual expensive, vulnerable membrane but rather by natural processes whereby rapidly moving streams of liquid flow side by side without mixing. And the products that exit can be fed back in along with electricity to recover the original reactants, recharging the battery. Already the system generates up to three times more power per square centimeter than other "membrane-less" systems can. Redesigns now under way promise even higher performance from this novel battery.

Photos: Stuart Darsch

Shown above are key components of the hydrogen bromine battery, including the liquid bromine and the carbon cathode. The assembled small-scale prototype is shown at the left.

The availability of low-cost, high-capacity energy storage technology could profoundly change today's energy landscape. The ability to store electricity when supplies are abundant and deliver it later when they're not would permit widespread use of intermittent sources such as solar and wind; would ensure efficient, reliable power delivery by both central and distributed grids; and would make possible portable energy storage for developing nations and for mobile industrial operations. Electrochemical systems such as batteries and fuel cells seem promising candidates for the energy-storage job. They can be sited wherever they're needed, and they can be discharged and recharged quickly and efficiently. Coupled with a solar or wind farm, for example, they could store electricity when the sun shines or the wind blows and then deliver it in minutes when the day gets cloudy or still.

But the best-performing electrochemical devices typically can't provide large storage capacity at a reasonable cost. A truckload of lithium ion batteries, for example, can provide plenty of power, but the cost is too high. "What's holding back the renewable technologies now is not so much needing, say, a better solar cell, but rather needing a way to store the energy cost-effectively," says Cullen Buie, assistant professor of mechanical engineering.

Promising chemistry, promising design

In the search for large-scale electrochemical devices, much attention has focused recently on systems using hydrogen and bromine. This combination of reactants offers several attractive features. Bromine is inexpensive, readily available, and abundant compared to storage options such as lithium. Bromine is also very "electronegative," meaning that it really wants to pick up another electron; and hydrogen is happy to provide it. Chemical reaction between them therefore occurs extremely rapidly—much faster than the hydrogen-oxygen reaction in most high-capacity electrochemical devices such as fuel cells—and large amounts of current flow when the electrons are forced to move from the hydrogen to the bromine through an external circuit. But there's a catch. If the hydrogen and bromine react spontaneously, the energy of the reaction will be wasted as heat. Electrochemical system designers generally keep them apart using an expensive membrane, but that membrane becomes damaged over time by hydrobromic acid produced inside the device. As a result, three decades of research has yielded little improvement in hydrogen bromine flow batteries.

To Buie, Martin Z. Bazant, professor of chemical engineering and of mathematics, and William Braff PhD '14, the obvious answer was to get rid of the membrane. They're not the first to have that idea. Membranes tend to be finicky and expensive, regardless of the chemistry involved. As a result, for the past 10 years, research groups have been designing membrane-less electrochemical systems in which the reactants are separated using fluid mechanics—specifically, the physics of laminar flow. Under the right conditions, two streams of liquid will flow in parallel, right next to one another with little or no mixing between them. However, none of the membrane-less fuel cells using various chemistries have achieved power densities as high as their membrane-based counterparts. "So this architecture was largely viewed as interesting from an academic perspective but probably not commercially viable," says Bazant.

A novel combination

Four years ago, Buie and Braff—then a graduate student in mechanical engineering and now an associate at Exponent—began to explore a novel idea: combining the hydrogen bromine chemistry with the membrane-less cell architecture. "Our idea was to take these two limited technologies and put them together to get something better than what was possible with either one on its own," says Buie. Their approach could get rid of the membrane that has limited hydrogen bromine fuel cell development, and it could replace the typical oxygen-based chemistry that has slowed performance of previous membrane-less cells.

An added bonus is the reversibility of the hydrogen bromine reaction. In most membrane-less cells, the reactants that go in and the products that come out differ. As a result, those systems are typically "once-through" fuel cells that require a continuous stream of fresh reactants. With the hydrogen bromine chemistry, the product of the reaction is the electrolyte itself. Recycling that electrolyte back into the cell—along with electricity from an external source—produces hydrogen and bromine, thereby recharging the system. It can thus operate in a "closed-loop" mode, making possible the first membrane-less rechargeable battery.

To test the feasibility of their new idea, Buie and Braff spent a year performing theoretical studies of the membrane-less hydrogen bromine system. Based on their promising results, they teamed up with Bazant to bring his modeling expertise to the project and to undertake experimental implementation of the concept.

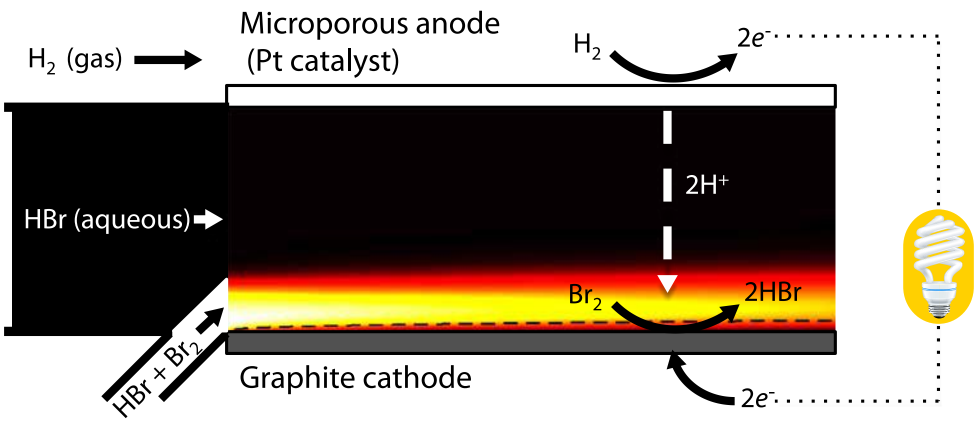
Battery design and operation

The diagram below shows their system. At the top is a porous anode containing a small amount of platinum (Pt) catalyst. At the bottom is a solid graphite cathode. Between them flows the electrolyte—hydrobromic acid (HBr), an electrically neutral combination of negatively charged bromine and positively charged hydrogen suspended in water.

The diagram shows the cell operating in discharge mode (that is, delivering electricity). The hydrobromic acid electrolyte enters the main channel at the left and flows between the top and bottom electrodes. A water-repelling metal mesh on the bottom surface of the porous anode keeps the electrolyte from seeping in. Neutral hydrogen gas (H_2)—the fuel—flows across the top, and some of it enters the porous anode. At the same time, more hydrobromic acid is fed in through a separate channel along with a small amount of neutral molecular bromine (Br_2)—the oxidant longing to add an electron. The two streams flow next to each other with minimal mixing.

At the anode, the platinum catalyzes a reaction that breaks down hydrogen gas, forming positively charged hydrogen ions (H^+) and negatively charged electrons (e^-). Both move to the cathode but via different paths. The hydrogen ions pass through the electrolyte, but the electrons can't follow and instead flow through an external circuit, powering a device along the way. At the cathode, the bromine quickly picks up the electrons and becomes negatively

The membrane-less hydrogen bromine battery (in discharge mode)



This diagram shows the battery operating in discharge mode. Hydrobromic acid (HBr in water)—the electrolyte—enters the main channel from the left. Gaseous hydrogen (H_2)—the fuel—flows along the top, some of it seeping into the porous anode. More HBr plus a small amount of molecular bromine (Br_2) enters through the channel at the lower left and then flows along the cathode. A platinum (Pt) catalyst in the anode splits the H_2 into positively charged hydrogen ions (H^+) and negatively charged electrons (e^-). Both travel to the cathode—the former through the electrolyte and the latter through an external circuit. At the cathode, Br_2 picks up electrons, becomes negatively charged Br^-, and joins the H^+ in solution to balance the electrical charge, producing more HBr—the electrolyte. Colors in the diagram indicate Br_2 concentrations, as calculated by a novel theoretical model.

charged. The negatively charged bromine joins the positively charged hydrogen ions in solution to form more hydrobromic acid—the electrolyte.

During recharging, the hydrobromic acid is fed back into the cell, along with electrons from an external power supply. The hydrogen ions go back to the anode, where they become molecular hydrogen, and the molecular bromine reforms at the anode. The system is now reset.

One key challenge with relying on laminar flow is keeping the reactants from reaching the "wrong" electrode. That phenomenon—known as crossover—can cause damage, especially of the costly catalyst on the anode. In the new design, the metal mesh keeps the hydrogen gas from entering the liquid electrolyte. But the bromine is an issue. Using a novel numerical model, the researchers estimated concentrations of molecular bromine at various locations inside their flow battery. The colors in the schematic diagram show their results. White indicates the highest bromine concentration. Concentrations decrease from yellow to orange, reaching zero in regions colored black.

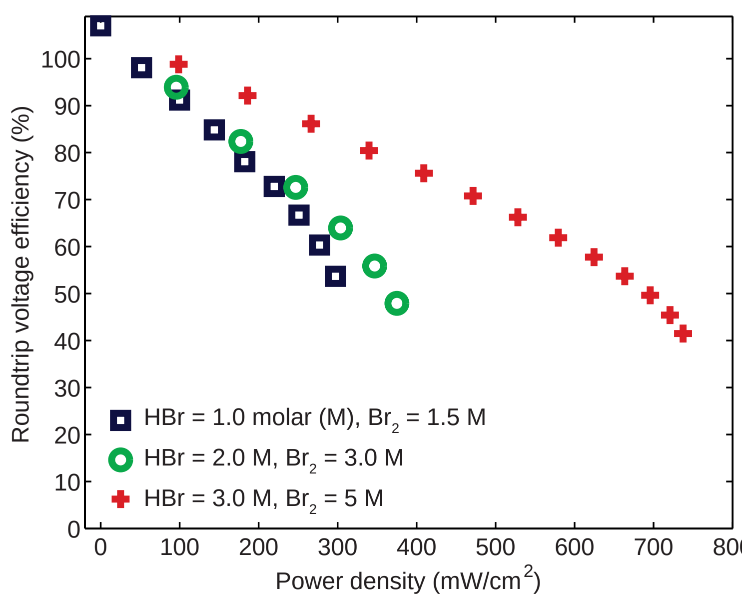
The diagram shows that bromine is being depleted along the cathode, where it turns into hydrobromic acid. Concentrations of bromine are also decreasing next to the electrolyte—a result of its diffusion into the electrolyte stream. Given enough time, the bromine would eventually reach the anode, bringing unwanted crossover effects. However, in their design, the reactants exit the system long before that happens. "We can see that the bromine is getting nowhere near the anode," says Buie. "That's what we want."

Initial demonstrations, cost estimates

As a first test of the membrane-less hydrogen bromine concept, Braff designed and built a small demonstration cell shown in the photo on page 5. It consists of two electrodes 0.8 mm apart, with a 1.4 cm-long flow channel between them, plus inlets that guide the reactants into the device. He then performed a series of experiments over a range of flow rates and reactant concentrations. The demonstration cell—even before being optimized—achieved a maximum power density of 795 milliwatts per square centimeter (mW/cm^2) at room temperature and pressure. That performance is comparable to the best hydrogen bromine cells with a membrane, and it's two to three times better than any previous membrane-less design using any chemistry.

The demonstration battery's potential to recharge efficiently is likewise promising. The researchers are now testing operation in closed-loop mode, recycling the reaction products into the device for the charging cycle. But in previous work, they tested reverse operation by flowing in pure hydrobromic acid plus electricity and successfully made hydrogen and bromine, thereby recovering their starting materials. By combining results from experiments in the forward and reverse modes, they produced the diagram below, which shows round-trip voltage efficiency as a function of power density for three

Power versus round-trip efficiency in the demonstration cell



As a first test of the discharging-recharging efficiency of their battery, the researchers ran it in discharging mode and then—using fresh hydrobromic acid—in charging mode to recover the reactants. These curves show the efficiency of those processes combined as a function of power density at various concentrations of hydrobromic acid and bromine. Power density is highest at the highest concentration, and roundtrip efficiency exceeds 90% at a power density of 200 milliwatts per square centimeter.

reactant concentrations. The highest concentration brings the greatest power density, with roundtrip voltage efficiency exceeding 90% at 200 mW/cm^2—about 25% of peak power. Those early results demonstrate the potential for an efficient discharge-charge cycle at high power.

The researchers' preliminary cost projections are also promising. In a traditional hydrogen-oxygen fuel cell with a proton exchange membrane, the catalyst and membrane together can make up as much as half of the total cost per kilowatt-hour. The new hydrogen bromine battery needs no membrane, no catalyst at the cathode, and far less catalyst at the anode. In addition, because the power density is higher in the hydrogen bromine battery, the size of the system needed to extract the power decreases, further reducing cost. "So you get dramatically lower costs—and that's our basic motivation," says Bazant. "We believe that our system has the potential to supply energy storage at a cost attractive to utility companies—and it may be the first system that can do that."

More improvements to come

The researchers are continuing to improve their system. For example, they're trying to get to even higher power densities by bringing the electrodes closer together. Because all the reactions are so fast, the time it takes for the hydrogen ions to cross the stream of electrolyte—even with its high conductivity and without a membrane—is the major limitation in their system.

In addition, they're developing a completely new cell architecture that will ensure that the electrolyte contains no molecular bromine when it's captured and recycled during closed-loop operation. "The new design is based on the same concept, but it's a quite different architecture," says Bazant. "That's where we're really breaking new ground now....We're moving in a direction that nobody's gone before." At this point, the issues with their system all involve what he calls known physics. "If it's not performing as well as we'd like, we have predictive models that can help us redesign the shape of the channels and the speed of the flows to make it better," he says. "It's a solvable problem."

• • •

By Nancy W. Stauffer, MITEI

This research was funded by the MIT Energy Initiative Seed Fund Program, the US Department of Defense through the National Defense Science and Engineering Graduate Fellowship Program, and the Massachusetts Clean Energy Center Catalyst Program. More information can be found in:

W.A. Braff. *Hydrogen Bromine Laminar Flow Battery for Large Scale Energy Storage*. PhD thesis, MIT Department of Mechanical Engineering, February 2014.

W.A. Braff, M.Z. Bazant, and C.R. Buie. "Membrane-less hydrogen bromine flow battery." *Nature Communications,* 4:2346 doi:10:1038/ncomms3346, 2013.

W.A. Braff, C.R. Buie, and M.Z. Bazant. "Boundary layer analysis of membraneless electrochemical cells." *Journal of The Electrochemical Society*, vol. 160, no. 11, pages A2056–A2063, 2013.

Ocean microbes display a hidden talent: releasing countless tiny lipid-filled sacs

Steven Biller (left) and Sallie (Penny) Chisholm of civil and environmental engineering have discovered that abundant ocean-dwelling bacteria continually release tiny, never-before-observed spherical structures that contain lipids—a finding that could one day lead to new approaches for manufacturing biofuels.

This research was supported in part by the MIT Energy Initiative Seed Fund Program. For more information about funding, see page 13.

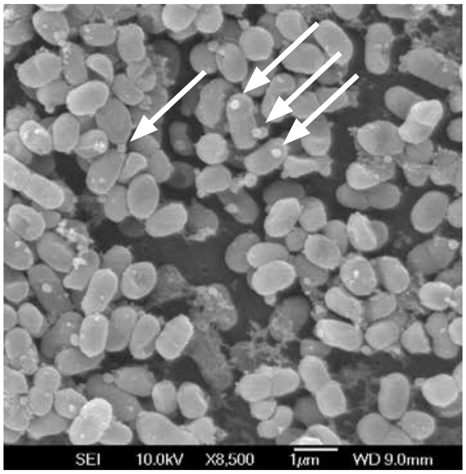
Photo: Stuart Darsch

Earth's oceans are filled with microorganisms that use solar energy and carbon dioxide to make their own nourishment, including lipids that are of interest for making biofuels. Using novel analytical techniques, MIT biologists have come up with unexpected news about the most abundant of those organisms, *Prochlorococcus*. This bacterium not only retains lipids inside the cell but also releases them into seawater as self-contained, lipid-bound "vesicles"—structures so small they've never before been detected in cultures of marine bacteria or microbes that perform photosynthesis. This property is intriguing in the context of biofuel production: In a future system, lipids could be retrieved by simply scooping off the vesicles while the cells—left intact—continue to grow and produce more. The researchers are now exploring the mechanisms that control vesicle formation and release as well the impact of this process on marine ecosystems and carbon cycles.

In the search for a renewable energy source, systems using algae look like a good bet. Algae can grow quickly and in high concentrations in areas unsuitable for agriculture; and as they grow, they accumulate large quantities of lipids, carbon-containing molecules that can be extracted and converted into biodiesel and other energy-rich fuels. However, after three decades of work, commercially viable production of biofuels from algae hasn't been achieved, in part because the processes needed to break apart the algae and recover the lipids are costly and energy-intensive.

Another option is to use bacteria. For the past 25 years, Sallie (Penny) Chisholm, the Lee and Geraldine Martin Professor of Environmental Studies, has been studying *Prochlorococcus*, an ocean-dwelling bacterium that she calls "a pretty spectacular organism." Of all organisms that perform photosynthesis, this single-celled bacterium is both the most abundant and the smallest—less than 1 micron in diameter. It accounts for fully 10% of all photosynthesis on Earth and forms the base of the ocean food chain. It also has the smallest genome of any known photosynthetic cell. "Three billion years of evolution has streamlined its genome, and it now contains the least amount of information that can make biomass from solar energy and carbon dioxide," says Chisholm, who has a joint appointment in civil and environmental engineering (CEE) and biology. "It makes sense that we try to understand it—inspired by its simplicity—and see if we can use this understanding to help us design microorganisms that efficiently produce biofuels directly from sunlight."

In 2010, Chisholm's much-studied bacterium delivered a surprise: As it grows, it naturally releases small, spherical, membrane-bound vesicles containing fatty oils related to those that make algae so appealing. This was a serendipitous discovery. In 2008, Chisholm's group needed some images of *Prochlorococcus* for a publication. Using a scanning electron microscope, then-graduate-student Anne Thompson PhD '10 took the images—and they showed small spheres near the surfaces of the *Prochlorococcus* cells (see the image above). The spheres remained a mystery to the ocean biologists until 2010, when Steven Biller joined Chisholm's group as a postdoctoral associate in CEE. Based on his work with soil bacteria, he proposed—and subsequently confirmed—that the spheres are lipid-bound vesicles.



This scanning electron micrograph shows cells of a lab-cultured strain of *Prochlorococcus* plus small, spherical vesicles (indicated by arrows), which are released by the cells as they grow. This is the first time vesicle formation and release have been detected in a marine organism or in an organism that performs photosynthesis. The vesicles contain DNA, RNA, a variety of proteins, and lipids—molecules that potentially could be used to produce biofuels.

That finding is remarkable for two reasons. While many species are known to release vesicles, the behavior has never before been observed in a marine organism—and it could significantly change today's understanding of marine ecosystems, including their influence on the global carbon cycle. "*Prochlorococcus* is making organic carbon from sunlight and then packaging it up and releasing it into the seawater around it," says Chisholm. "What we need to figure out now is, Why and how? And what role do these vesicles play in ocean food webs and the ocean carbon cycle?"

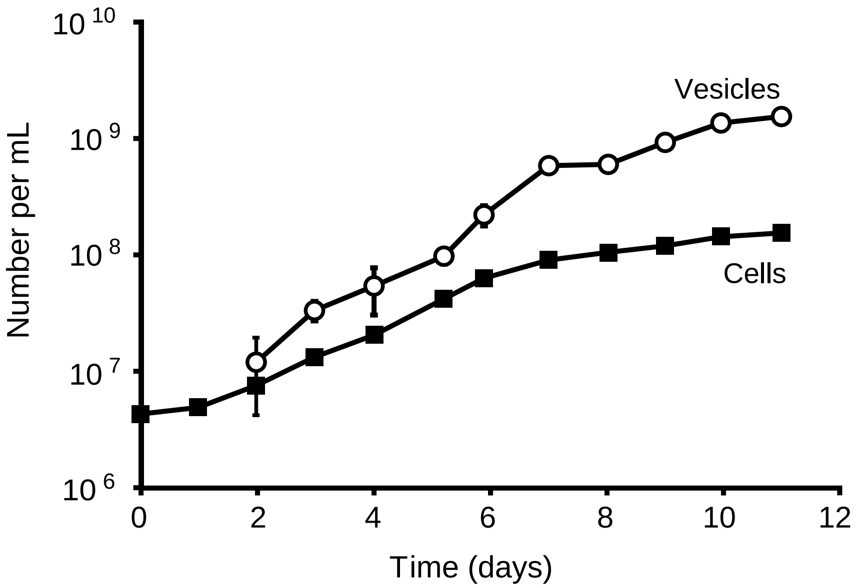
Equally surprising, this is the first observation of vesicle release in an organism that performs photosynthesis. The implications for industrial use—including biofuels production—are significant. Given just sunlight, carbon dioxide, and water, *Prochlorococcus* would continually release lipid-containing vesicles, which could be collected without disturbing the growing bacteria. "With algae, retrieving the lipids requires destroying one batch of cells and starting with a new batch," says Biller. "With *Prochlorococcus*, it could be a 'continuous culture.'"

Technical challenges, new insights

Chisholm stresses that such commercial applications are "way down the road." For now, research in her lab focuses on developing a fundamental understanding of the newly observed behavior. For example, how often does a *Prochlorococcus* cell release vesicles? How many does it release? And what's inside them?

To answer those questions, Biller overcame a series of technical challenges. First he developed improved methods of culturing large quantities of *Prochlorococcus* cells. Then he designed techniques for filtering off the vesicles and concentrating and purifying them—while keeping them

Vesicle production by *Prochlorococcus*



These curves indicate *Prochlorococcus* cells and vesicles present in samples taken daily from one lab-cultured strain of the bacterium. Cell concentrations are noted by solid squares; vesicle concentrations are noted by open circles. Based on similar tests with three different *Prochlorococcus* strains, the researchers estimate that the rate of release varies from two to five vesicles per cell per generation.

intact. But his biggest problem was how to count the individual vesicles. Standard methods of counting particles don't provide sufficient resolution to look at the vesicles, which are less than 100 nm in diameter. After some trial and error, Biller was successful in adapting recent advances in nanoparticle analysis techniques to studying these tiny bacterially derived structures.

Using his new approaches, he determined that vesicles are present in large concentrations in growing cultures. Indeed, they outnumber the *Prochlorococcus* cells themselves—in some cases by a factor of 10 (see the figure above). They are generated by strains of *Prochlorococcus* that grow in bright light (such as near the ocean surface) as well as in dimmer light (typical of the deep ocean). Vesicles appear to be produced continually during some phases of cell growth, and they are stable under laboratory conditions: Over the course of two weeks, the size and concentration of vesicles in a laboratory culture remained essentially unchanged. Finally, the vesicles contain not only lipids but also DNA, RNA, and a diverse set of proteins.

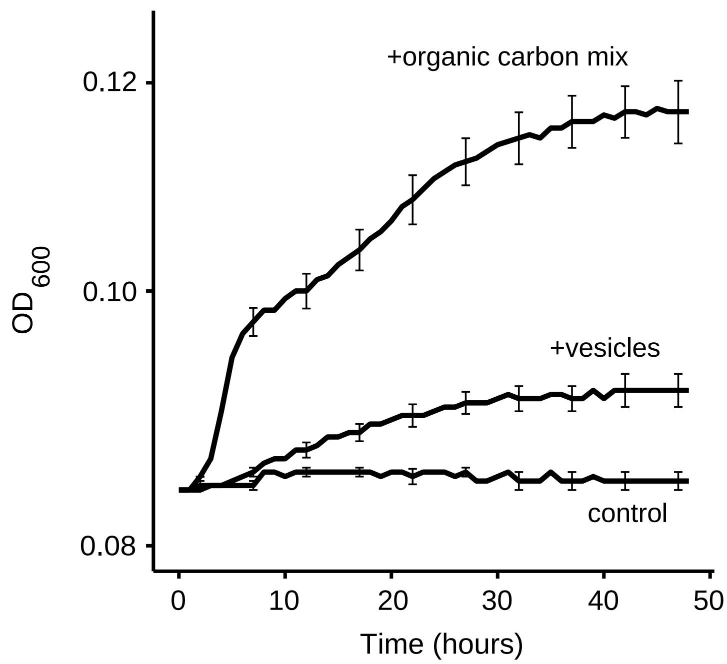
Unfortunately, the lipids in the vesicles from *Prochlorococcus* are not the optimal kind for making biofuels, notes Biller. "But because of its simple genome, it's a good model for us to use in exploring the mechanisms that control the formation and extrusion of vesicles and determine their content," he says. "Once we understand how it works, that mechanism could eventually be utilized in more robust and fast-growing organisms, and the contents of the vesicles could be manipulated."

Fieldwork expands the options

Based on their laboratory data, the researchers estimated that *Prochlorococcus* worldwide could release on the order of 10^{27} vesicles per day—a significant contribution to the marine ecosystem. But many factors could influence vesicle production in the wild, so the team decided to take direct measurements. They collected hundreds of liters of seawater in two locations: the nutrient-rich coastal waters of Vineyard Sound in Massachusetts and the nutrient-sparse waters of the Sargasso Sea near Bermuda. They used their laboratory techniques—scaled up to handle larger volumes of water—to test the samples on board research vessels. As with their lab cultures, they found numerous vesicles in the samples from both types of ocean environments. And their analyses showed that the vesicles contained DNA from many kinds of bacteria—not just *Prochlorococcus*.

That finding potentially extends vesicle production to organisms that are ubiquitous in ocean systems extending from pole to pole. "This adds a whole new dimension to marine microbial ecosystems that we hadn't realized was there," says Biller. "And while *Prochlorococcus* was our entry point into this concept for biofuels production, it looks like there may be applications to many other organisms."

Vesicles as nutrients for other bacteria



These curves show the growth of a marine heterotroph—a nonphotosynthetic organism—in three laboratory cultures. One culture includes a mixture of organic carbon compounds ("+organic carbon mix"); another includes only added *Prochlorococcus* vesicles ("+vesicles"); and the last has no source of fixed carbon ("control"). OD, or optical density, is a common measure used for estimating cell concentrations in liquid cultures. The data show that the vesicles alone provide enough nourishment for the cells to increase in number over 50 hours. *Prochlorococcus* thus appears to facilitate the growth of heterotrophs—and in return, the heterotrophs may protect *Prochlorococcus* by neutralizing toxic compounds that would harm it.

Wasteful behavior?

An intriguing question is why *Prochlorococcus* would make and release vesicles. Jettisoning their hard-earned organic carbon seems inconsistent with the need for this streamlined organism to make efficient use of scarce resources. What function could the vesicles serve? Biller and Chisholm don't have an answer to that question, but they've come up with several hypotheses—ideas with potential impacts on both understanding marine ecosystems and developing commercial-scale biofuels systems.

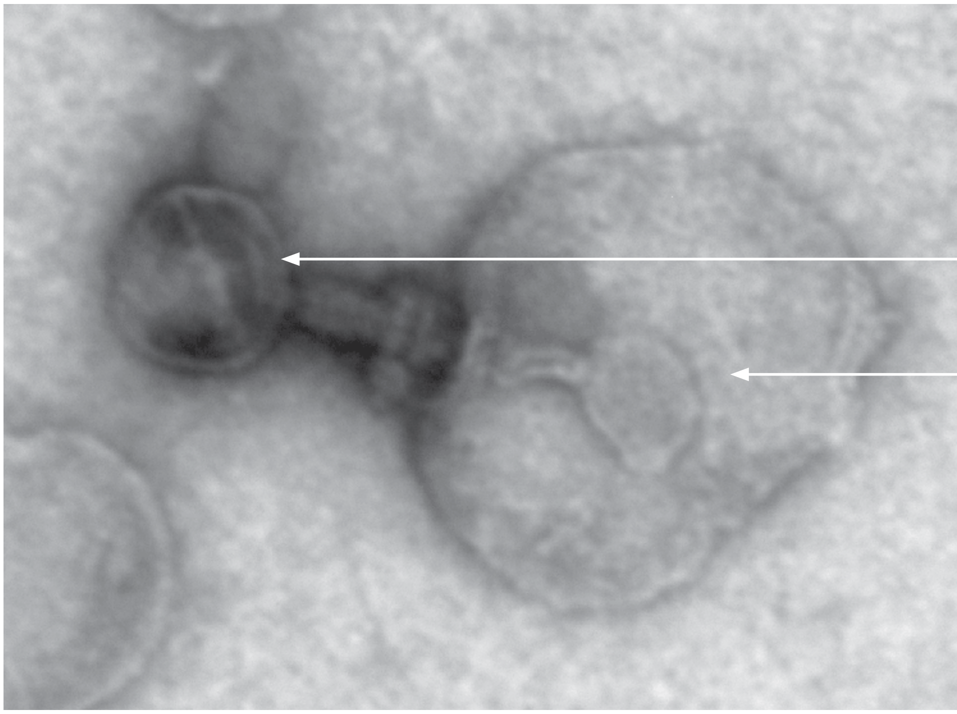
In working with *Prochlorococcus*, Chisholm and her colleagues have found that the bacterium is "happier" in the company of heterotrophs—organisms that can't synthesize their own food and need a source of organic carbon to grow. "We went through heroic efforts to separate the *Prochlorococcus* and their heterotrophic friends in seawater samples," says Chisholm. "Then we realized that when we grow them together, the cultures grow faster and are more stable." In a series of experiments, Biller showed that the newly identified lipid vesicles can serve as nutrients for the heterotrophs (see the figure above).

What does *Prochlorococcus* get in return? It is not fully understood, but others have shown that in the process of becoming streamlined, *Prochlorococcus* lost certain enzymes that other species use to neutralize toxic oxygen compounds produced during metabolism. The heterotrophs can perform that detoxification task, taking care of the problem for *Prochlorococcus*.

Another hypothesis is that the vesicles help protect *Prochlorococcus* from phage, viruses that infect bacteria. The surface of a vesicle contains material from the outer membrane of its parent cell, including protein receptors that phage use to identify their "prey." The vesicles therefore may serve as a decoy—"much as a fighter jet trying to evade an incoming missile may throw out chaff so that the missile goes after the chaff instead of the jet," says Biller. To test that idea, Biller mixed purified *Prochlorococcus* vesicles with a phage known to infect the *Prochlorococcus* source of the vesicles. Electron micrographs revealed many phage attached to vesicles. Moreover, their shortened tails suggest that they have injected their DNA into the vesicles, thereby becoming inactive (see the image on page 13).

A final hypothesis is that the vesicles assist in the exchange of genetic material between individual bacteria—a phenomenon known to occur in some bacteria as a means of developing genetic diversity and sharing useful genes. "We know that bacteria are swapping genes among themselves at surprisingly high frequencies—maybe by using phage or direct cell-to-cell contact," says Biller. "But it wasn't clear that those mechanisms alone

Defense against viral predators



Another interesting hypothesis is that the vesicles help defend *Prochlorococcus* against attack by phage—viruses that would infect and kill it. That idea is supported by this transmission electron micrograph of a phage attached to a vesicle. The shortened tail of the phage suggests that it has injected its DNA, rendering it unable to infect again. The surface of each vesicle includes protein receptors from its parent cell that serve as a target for phage. The vesicles thus act as a decoy, diverting phage away from the *Prochlorococcus* cells.

could explain the apparent rates at which genes are moving around. This is one possibility of another way that DNA might be exchanged in these communities."

Benefits of multiple-scale study

The researchers' latest results confirm the validity of Chisholm's decades-long approach to studying *Prochlorococcus*. "Our studies of this bacterium have ranged in scale from genes to cells to populations and then to the community they're embedded in and up to the global scale," she says. That approach, called integrative systems biology, has obvious benefits for understanding global ecosystems and—in the longer term—for developing practical systems involving mass cultures that are fast-growing, stable, and productive. Says Chisholm, "Studying model systems such as *Prochlorococcus* in an expansive sense—from the phage that infect them to the other microbes that they grow with in nature—will ultimately have relevance for any kind of large-scale production of biomass for biofuels and other types of high-energy compounds."

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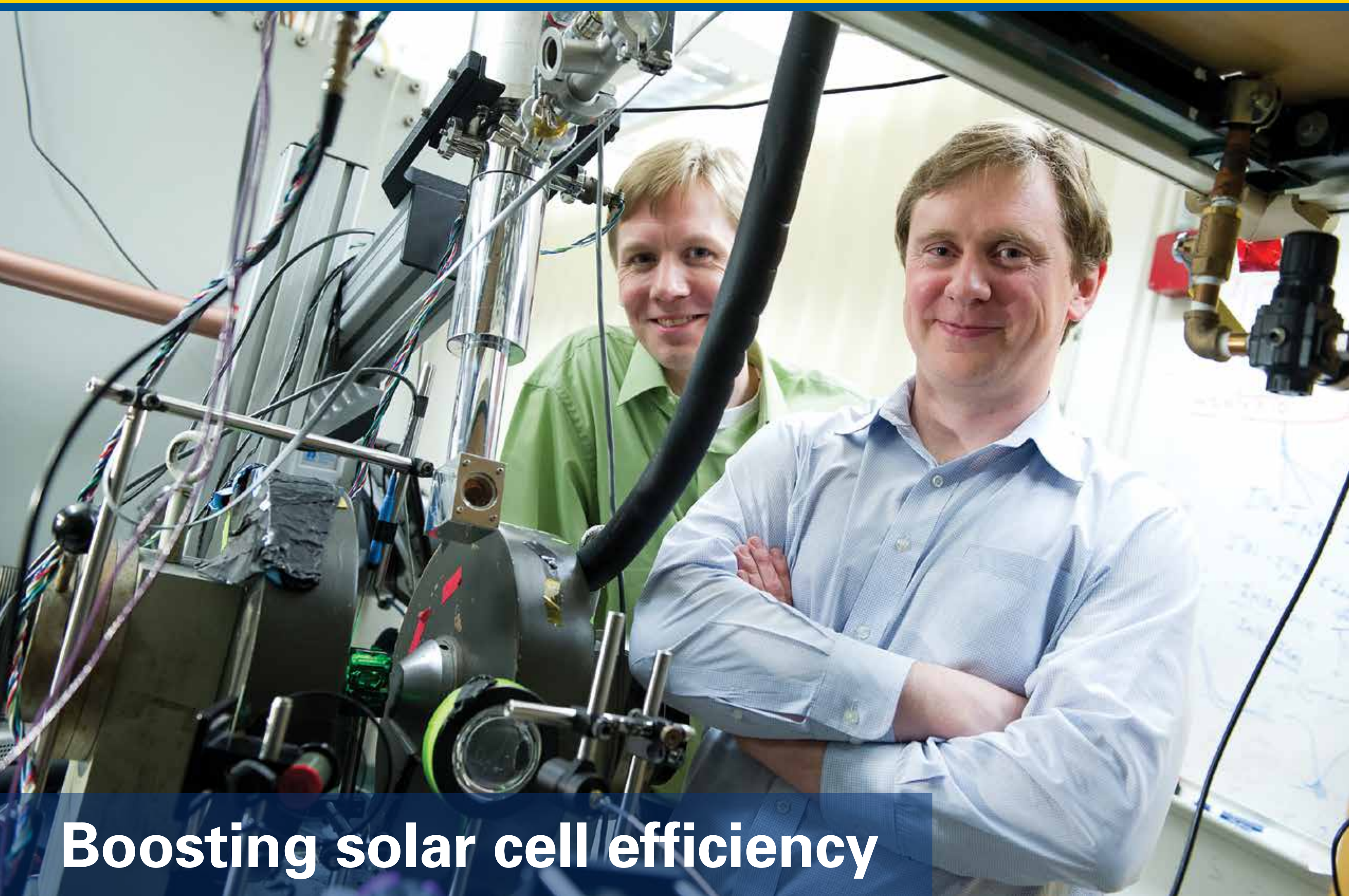
By Nancy W. Stauffer, MITEI

This research was supported by grants from the MIT Energy Initiative Seed Fund Program; the Gordon and Betty Moore Foundation; and the National Science Foundation's Center for Microbial Oceanography: Research and Education and its Biological Oceanography Program. Further information can be found in:

S.J. Biller, F. Schubotz, S.E. Roggensack, A.W. Thompson, R.E. Summons, and S.W. Chisholm. "Bacterial vesicles in marine ecosystems." *Science*, vol. 343, pages 183–186, 2014.



Boosting solar cell efficiency

Less wasted heat, more useful current

Troy Van Voorhis of chemistry (left) and Marc Baldo of electrical engineering and computer science are designing and building solar cells that take advantage of a phenomenon first observed decades ago to generate more electricity and less waste heat from sunlight than had previously been thought possible.

This research was supported as part of the Center for Excitonics, an Energy Frontier Research Center funded by the US Department of Energy. For more details about funding, see page 18.

Photo: Stuart Darsch

MIT chemists and electrical engineers have joined forces to make the first solar cell that produces two electrons for every incoming photon of sunlight in the visible spectrum, thereby wasting less heat and generating twice as much electrical energy from those wavelengths as conventional solar cells do. With that achievement, the researchers have broken a long-standing barrier on energy conversion efficiency in photovoltaic cells. Moreover, they have provided the first quantitative understanding of the process by which the "exotic" materials exhibiting that behavior produce extra current. The researchers envision using their novel technology in conjunction with today's silicon cells. Applied as an inexpensive coating, it could increase the fraction of solar energy converted to electricity in silicon cells by as much as 25%.

Today's solar photovoltaic cells waste a large fraction of the energy that is abundant in sunlight. They absorb a range of wavelengths, typically from the blue to the near infrared. When one of these photons (a packet of sunlight) strikes the semiconductor inside a solar cell, a single electron is excited to a higher energy level. Gathered together, those excited electrons can travel through a wire as current. But higher-energy blue and green photons deliver much more energy than needed to excite an electron, and the excess is released as heat. Indeed, there's an accepted limit on the efficiency that can be achieved in a solar cell designed with a single semiconductor. Given the distribution of photons in sunlight—each with its distinctive wavelength and energy—even an ideal solar cell could turn only 34% of the total energy into electricity.

One way to deal with that efficiency limit is to stack up layers of different semiconductors, each absorbing different colors of sunlight. But that approach is proving to be costly. At MIT, Marc Baldo, professor of electrical engineering and director of the Center for Excitonics, and Troy Van Voorhis, professor of chemistry, have been revisiting another approach to breaking that barrier: They're aiming to get two electrons out for each incoming photon.

That phenomenon—called singlet exciton fission—was first identified in the 1960s, when researchers observed an unusual phenomenon inside several organic molecules, one of them called pentacene. Generally, an excited molecule gets rid of its extra energy by giving off an electron and heat. But special rules of quantum mechanics forbid a pentacene molecule from dropping back to its low-energy state. Instead, the high-energy excited state spontaneously splits into two, each with half of the original energy—and each of them can generate one electron.

Over the past 10 years, singlet exciton fission has gone from an obscure phenomenon to a hot topic among solar researchers. The phenomenon has been observed in a variety of materials, all similar to pentacene and all discovered—like pentacene—by chance. And while exciton fission has been confirmed within materials, it has never been achieved in a functioning solar cell.

"The problem is that we can't rationally design materials and devices that take advantage of exciton fission until we understand the fundamental mechanism at work—until we know what the electrons are actually doing," says Van Voorhis. Research groups have proposed a variety of what Van Voorhis calls "exotic" mechanisms, which have become the subject of intense controversy in the field. But solid proof of what is actually happening has remained elusive.

Four years ago, Baldo and Van Voorhis decided to pool their expertise to tackle this problem. Baldo would assemble solar cells demonstrating exciton fission, and he would gather experimental data in sample fission materials. Drawing on those data, Van Voorhis would attempt to define the mechanism using simulation techniques he has developed that can calculate how electrons move within photovoltaic systems. "We wanted to do a big, comprehensive study—not just pick one material but do a whole sweep and vary all the parameters we thought might be important," says Baldo. "Then we could ask: What is the mechanism that explains all the data?"

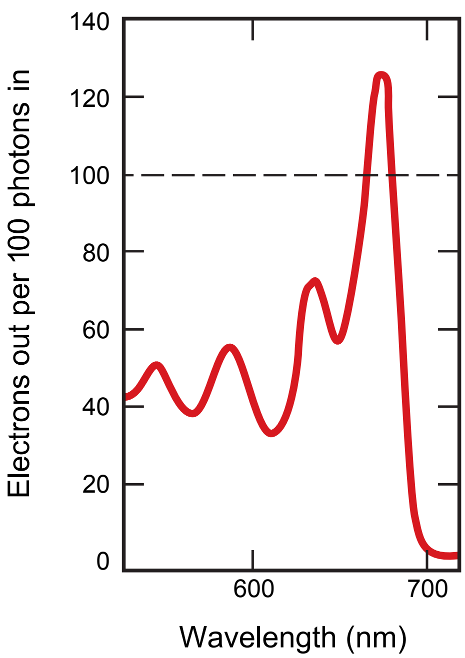
Achieving fission in a device

Baldo's first challenge was to build a solar cell that generates extra electrons. In 2009, he and his team designed and built devices using pentacene combined with a fullerene, a hollow, all-carbon molecule that captures the exciton (the excited state) and releases electrons as current. Their results were mixed. Using special diagnostic techniques, they confirmed that exciton fission was occurring inside the device at a rate that varied with the thickness of the pentacene layer. "But we couldn't detect any electrons unless we pulled them out using voltage from an external power source—and that's not useful in a solar cell," says Baldo.

Re-examining that earlier work, he, Jiye Lee and Daniel Congreve, graduate students in electrical engineering and computer science, and Nicholas Thompson, a graduate student in materials science and engineering, realized that most of the excitons in the pentacene were getting destroyed, either by the fullerene or by the conductive electrode under the pentacene layer. They therefore added a polymer layer that protects the bottom interface of the pentacene layer, blocking the excitons but letting current flow through. They also changed the spacing of the pentacene and fullerene layers. In addition, working with Vinod Menon, associate professor of photonics and optoelectronic materials at the City University of New York, they included within the structure a tuned mirror that enhances light absorption by the pentacene layer.

The new design was successful. As the figure on page 16 shows, at some wavelengths, the device generates more electrons than can be extracted from a conventional solar cell. Maximum

Electron output in novel solar cell



MIT researchers have made the first solar cell that can produce more than one electron for each photon coming in—the usual limit in a conventional photovoltaic cell. This figure shows the number of electrons produced for every 100 photons that strike the pentacene-based device. Peak production is 126 electrons for every 100 photons at a wavelength of 670 nm.

production occurs at pentacene's peak absorption wavelength of 670 nm, when 126 electrons come out for every 100 photons going in.

That outcome is significant. Baldo and Van Voorhis believe that this is the first time that anyone has generated more than one electron per photon using visible light, which makes up almost half the sun's electromagnetic radiation at the Earth's surface.

Explaining the phenomenon

Van Voorhis' theoretical work has likewise produced remarkable results. To gather experimental data for the theoretical studies, Baldo and his team prepared thin films of pentacene and three other materials in which exciton fission has been detected. According to the "classic" theory, during exciton fission, an electron in an excited molecule swaps places with one in a neighboring not-excited molecule. The electron from the excited molecule takes some of its energy with it and leaves some behind, in the process creating two lower-energy excitons, each of which can release an electron.

If the electron-swapping mechanism is correct, then exciton fission would work best when molecules are close together physically and well-connected electronically. To examine that possibility, the team used molecules specially synthesized by Timothy Swager, MIT's John D. MacArthur Professor of Chemistry, to include bulky side groups of atoms—known among organic chemists as "spinach"—that change the molecular spacing or alignment but don't affect the physics or chemistry of the material (see the top diagram at the right).

Ultimately, the team tested 10 variants of the four basic exciton fission materials. While the MIT researchers have the capability to count the numbers of photons and electrons, doing so fast enough proved to be a challenge. The fission process can occur as quickly as a few femtoseconds (10^{-15} seconds). For these ultrafast measurements, they turned to experts and specialized equipment at Brookhaven National Laboratory and the University of Cambridge.

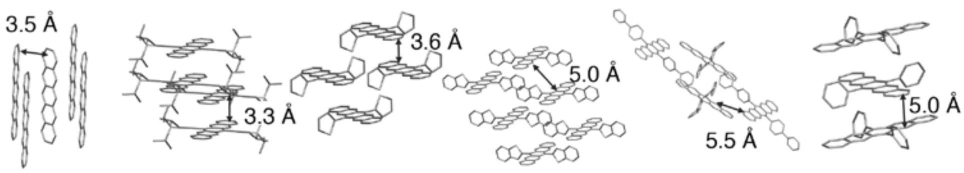
Using the new experimental data, Van Voorhis developed a formula based on fundamental rules of physics that successfully predicts the fission rate in materials with vastly different structures. Notably, the work confirms the classic electron-swapping mechanism. "The simplest explanation is the right one," says Van Voorhis. "The controversial or exotic mechanisms aren't required to explain what's actually being observed here."

Design principles

Results to date have already provided some useful design principles. For example, the most important step is choosing a material with the right energy levels. If the energy level of the original exciton is more than twice the energy level of the two new excitons, then fission occurs spontaneously and rapidly.

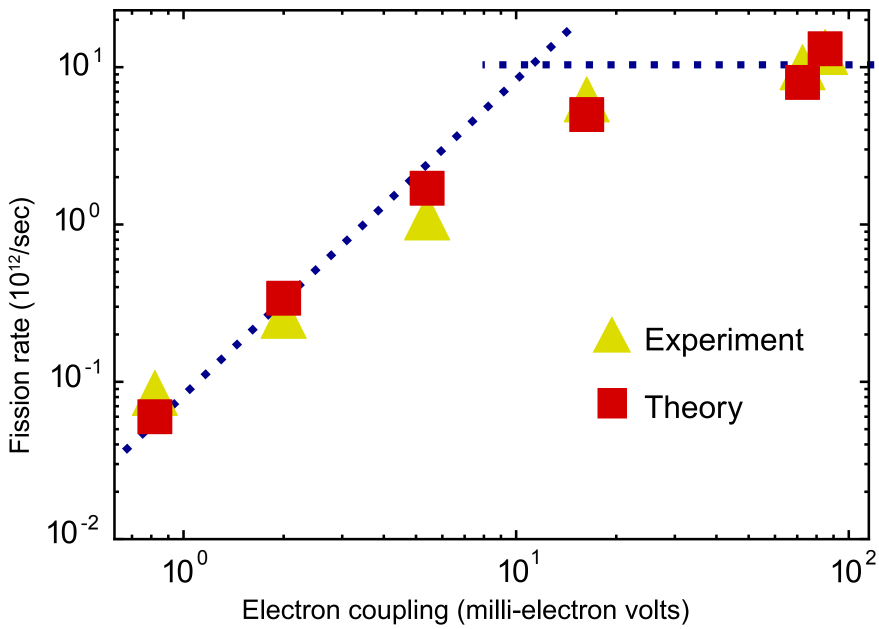
Given a material with favorable energy levels, changing the molecular packing does affect the rate at which fission occurs. The rate is a thousand times

Testing the effect of molecular packing on exciton fission



To see if electron exchange between molecules plays a role in exciton fission, the researchers prepared a variety of samples in which they altered the physical packing and electronic coupling of the molecules by adding bulky side groups. The examples shown here all have pentacene molecules at their core with various add-ons to alter the molecule-to-molecule spacing and alignment.

The effect of electronic coupling on exciton fission rate



This figure shows measured and calculated rates of exciton fission in thin films made of the six pentacene-based materials. As the electronic coupling of the material becomes stronger, the rate of exciton fission increases dramatically—until it finally plateaus. At that point, the electrons are moving so fast that the molecules don't have time to make the adjustments needed to accommodate the swap. The rate of exciton fission is now limited by the rate at which the molecules can adapt.

faster in a well-packed system than it is in a poorly packed system. But as long as the energy levels are right, even the slowest rate is "still incredibly fast—plenty fast to get efficiency gains," says Van Voorhis.

However, there is a "speed limit." The bottom figure at the left shows the rate of fission—calculated as well as measured—in the pentacene-based materials. As the electronic coupling between molecules in the material becomes stronger, the fission rate increases. But eventually the fission rate plateaus, despite increases in coupling strength. The explanation: Before electrons can move, the molecules they're moving into and out of need time to shift other atoms around. If the electrons move too quickly, the molecules may not be ready to release or receive them. The fission rate is thus limited by the speed of molecular rearrangement.

The researchers are pleased with the agreement between their experimental and theoretical data—especially given the systems being modeled. Each molecule has about 50 atoms, and each atom has 6 to 10 electrons. "These are complicated systems to calculate," says Van Voorhis. He adds, "That's the reason that 50 years ago they couldn't compute these things—but now we can."

The robustness of exciton fission against changes in packing was also good news. "Many people thought pentacene had magic packing that led to fast fission…and that if you messed it up at all, you'd be out of luck," says Van Voorhis. But that appears to be untrue, which is a relief to Baldo and other makers of solar cells because controlling molecular packing synthetically is difficult.

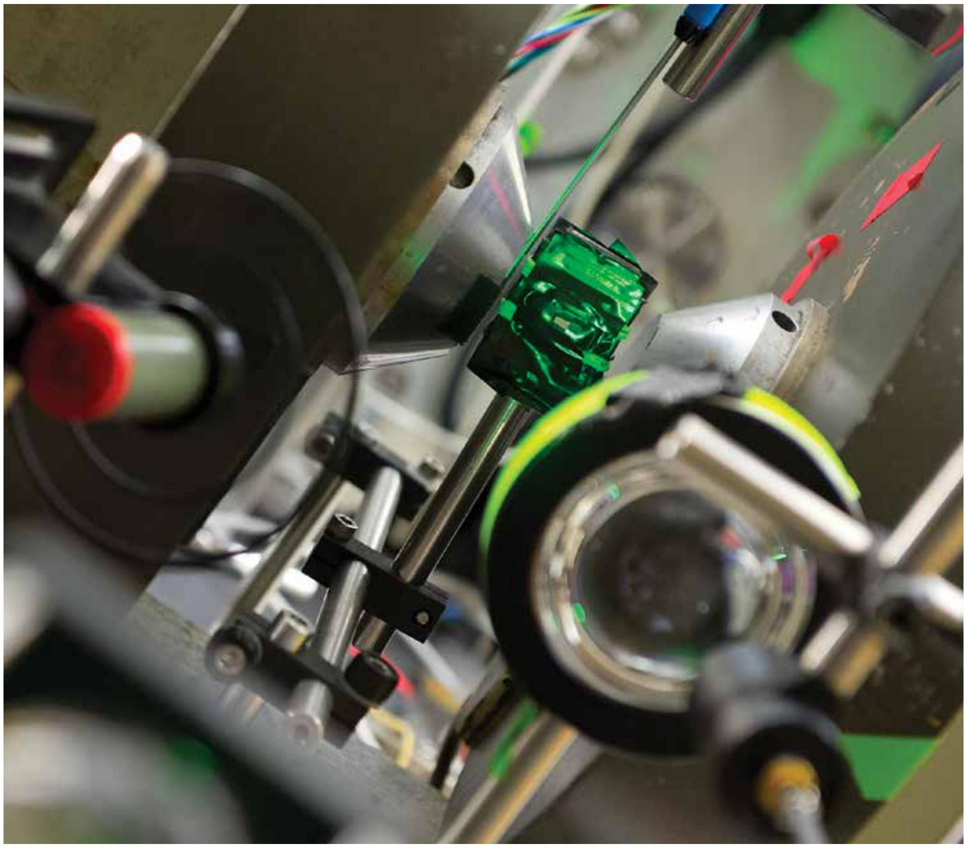


Photo: Stuart Darsch

To measure exciton fission in their solar cells, the researchers use this experimental setup, which takes advantage of the known sensitivity of exciton fission to an applied magnetic field. They shine an LED light onto their device (glowing green here) and measure the current that flows. Using an electromagnet, they then modulate the magnetic field. Based on the measured change in current, they can calculate the yield of exciton fission events.

Improving and applying the new device

To date, the energy conversion efficiency of Baldo's assembled devices is less than 2%. However, the researchers note that this is a "proof of principle" system. They are confident that further optimization will bring dramatic increases in efficiency.

Even so, they are quick to emphasize that their research findings won't double the efficiency of solar cells because fission affects only the high-energy photons. Moreover, to get out twice as many electrons, they have to halve the energy per electron, and that effectively halves the voltage that the solar cell puts out. ("We're not breaking energy conservation!" Baldo points out.)

As a result, they envision their system not as a stand-alone but rather as a coating on a conventional silicon solar cell. The low-energy photons (the infrared wavelengths) will be absorbed in the silicon, each generating one electron at the standard 0.6 volts. The coating will capture the high-energy photons (the blues and greens), create two low-energy excitons, and transfer the energy to the silicon, generating two electrons, also at 0.6 volts. The net result: Two photons can produce three electrons, all at the same energy.

"We would like to put our inexpensive coating on every silicon solar cell, and we believe it'd boost efficiency from today's maximum of about 24% to more than 30%," says Baldo. That's a significant change in a field where improvements are typically measured in fractions of a percent.

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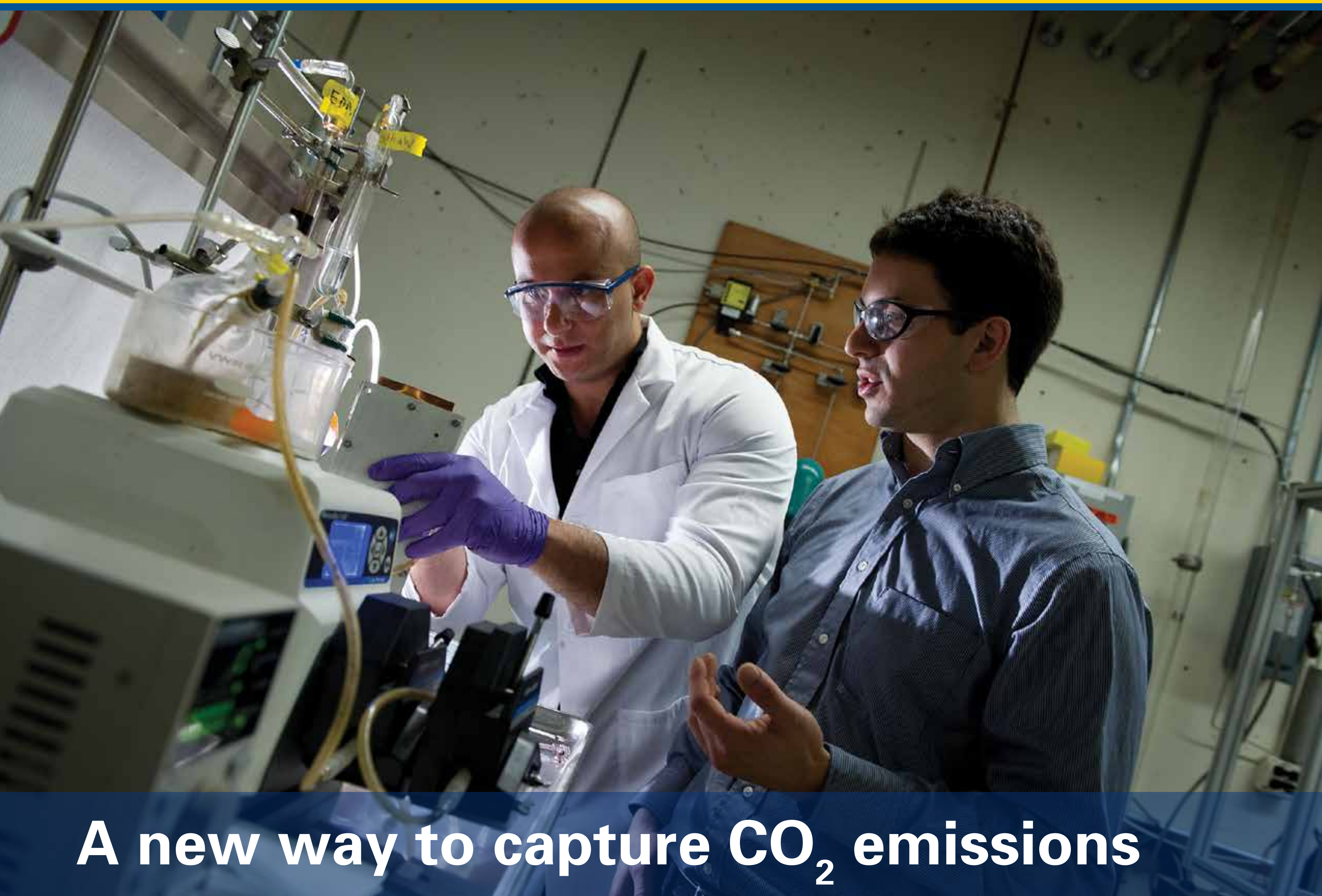
By Nancy W. Stauffer, MITEI

This research was supported as part of the Center for Excitonics, an Energy Frontier Research Center funded by the US Department of Energy, Office of Science, Office of Basic Energy Science. Additional support came from the United Kingdom's Engineering and Physical Sciences Research Council and in the form of graduate fellowships from the National Science Foundation and Corpus Christi College, University of Cambridge. Research was carried out in part at the Center for Functional Nanomaterials, Brookhaven National Laboratory. Further information can be found in:

D.N. Congreve, J. Lee, N.J. Thompson, E. Hontz, S.R. Yost, P.D. Reusswig, M.E. Bahlke, S. Reineke, T. Van Voorhis, and M.A. Baldo. "External quantum efficiency above 100% in a singlet-exciton-fission–based organic photovoltaic cell." *Science*, vol. 340, pages 334–337, 19 April 2013.

N.J. Thompson, D.N. Congreve, D. Goldberg, V.M. Menon, and M.A. Baldo. "Slow light enhanced singlet exciton fission solar cells with a 126% yield of electrons per photon." *Applied Physics Letters,* vol. 103, pages 263302-1-3, 2013.

S.R. Yost, J. Lee, M.W.B. Wilson, T. Wu, D.P. McMahon, R.R. Parkhurst, N.J. Thompson, D.N. Congreve, A. Rao, K. Johnson, M.Y. Sfeir, M. Bawendi, T.M. Swager, R.H. Friend, M.A. Baldo, and T. Van Voorhis. "A transferable model for singlet fission kinetics." *Nature Chemistry*, doi:10.1038/nchem.1945, 2014.



A new way to capture CO_2 emissions

Lower costs, easier installation

Aly Eltayeb of chemical engineering (left), Michael C. Stern PhD '13, now at Exponent, Inc., and T. Alan Hatton of chemical engineering (pictured on page 20) are demonstrating an efficient, low-cost approach to capturing carbon dioxide from exhaust gases that is especially suited for installation at existing power plants as well as in manufacturing plants and confined spaces such as submarines and space shuttles.

This research was supported in part by the US Department of Energy through the Advanced Research Projects Agency–Energy. For more information about funding, see page 23.

Photo: Stuart Darsch

MIT researchers have developed a process for capturing carbon dioxide (CO_2) from power plant exhaust that solves several problems now inhibiting the widespread adoption of conventional "scrubber" technologies. Operating a scrubber uses about a third of the low-pressure steam in a power plant, reducing the output of electricity and significantly increasing its price. Instead of steam, the new system uses electricity to trigger chemical reactions that control the CO_2 capture process. Bench-scale experiments and simulation studies show that the new system should capture CO_2 as well as scrubbers do but consume less of the plant's electricity and require far lower capital investment. And because the system doesn't require major restructuring of steam delivery systems, it could easily be added to existing power plants. Next up: testing at larger scale and under optimized operating conditions.

Power plants using fossil fuels spew out huge quantities of CO_2, the greenhouse gas considered most responsible for climate change. Researchers have known how to capture CO_2 in power plant exhaust since the 1930s. Flow a plant's flue gas through a solution containing molecules called amines, and the amines will pluck out the CO_2 and hold onto it. The exhaust gases that reach the atmosphere are then cleansed of CO_2.

The challenge is to get the amines to release the CO_2 so that the pure CO_2 can be either sequestered or utilized and the amines can be recycled and reused. Heating the CO_2-amine "complex" up in a separate chamber works, but getting enough steam to both separate the CO_2 and sweep it away requires diverting much of the power plant's steam from its usual job of turning turbines. Additional energy is needed to compress the captured CO_2 prior to its utilization or injection into an underground reservoir for long-term storage. Given the reduction in electricity output and the increase in price, it's not surprising that such thermal scrubbers have not been widely deployed.

At MIT, a team led by T. Alan Hatton, the Ralph Landau Professor of Chemical Engineering Practice, is developing a process that should prove more attractive. Called Electrochemically Mediated Amine Regeneration, or EMAR, the process uses electricity to produce chemical changes that separate the CO_2 from the amines. Rather than heating up the entire solvent solution, the approach targets just the CO_2-amine molecules that need to be separated; and it doesn't involve diverting any of the power plant's steam.


Photo: Stu Rosner

T. Alan Hatton, the Ralph Landau Professor of Chemical Engineering Practice.

Using electrochemistry to do the CO_2–amine separation isn't a new idea. Research groups have been working on it since the 1970s. But they haven't been able to come up with an efficient process that uses a widely available, low-cost sorbent and generates a pure CO_2 outlet stream. The problem, says Michael C. Stern PhD '13, now an associate at Exponent, is that they've been searching for a single compound that both picks up and releases the CO_2 efficiently. The trick was to introduce a second compound. "We decided that the best way to convince the amine to let go of the CO_2 would be to give it a better alternative—something that it'd preferentially choose to bind with over the CO_2," says Stern, who initially proposed the idea in 2010 when he was a graduate student in Hatton's lab. "Then it'll let go of the CO_2 in order to grab this other molecule."

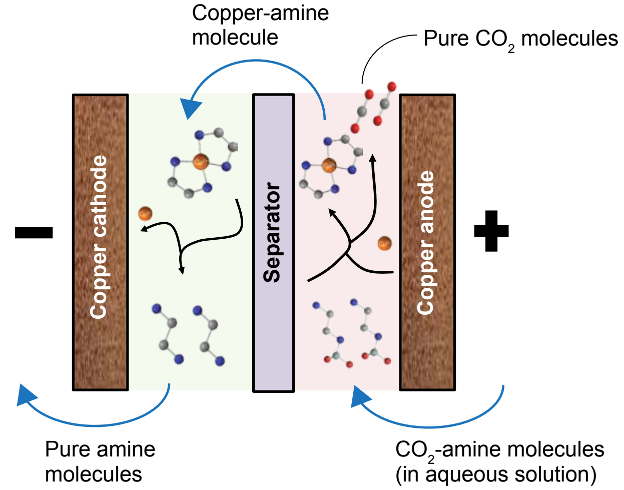
The top figure on page 21 shows the chemistry that occurs inside the electrochemical cell at the heart of the EMAR process. The cell consists of two chambers with copper walls—a positively charged anode in one and a negatively charged cathode in the other. Carried by an aqueous solution, the CO_2-amine molecules enter the first chamber, where they come into contact with copper ions released by the copper anode when it's electrically charged. The amines react with the copper ions, dropping the CO_2 molecules in the process. The amines—now carrying tightly bound copper ions—flow into the other chamber, where the copper cathode pulls away the copper ions. The amine molecules are once again unburdened and ready for more CO_2. Meanwhile, the other molecules in the solution are unaffected by the electrochemical activity.

Putting the process into practice

The schematic diagram on the bottom on page 21 shows the overall setup of the EMAR system. The electrochemical cell is at the right, an absorber at the left. The CO_2-containing flue gas flows upward in the absorber, passing through the amine solution injected near the top. The amines grab out the CO_2 molecules, and the remaining flue gas flows out the top. The CO_2-amine solution drops to the bottom of the absorber and is pumped to the anode side of the cell. There, the amines pick up copper ions and release CO_2 gas into the solution. The gas-liquid mixture goes to the flash tank, where the CO_2 exits—no steam required. The solution flows to the cathode side, where the copper-amine molecules lose their copper ions. The empty amine molecules flow back to the absorber to capture more CO_2.

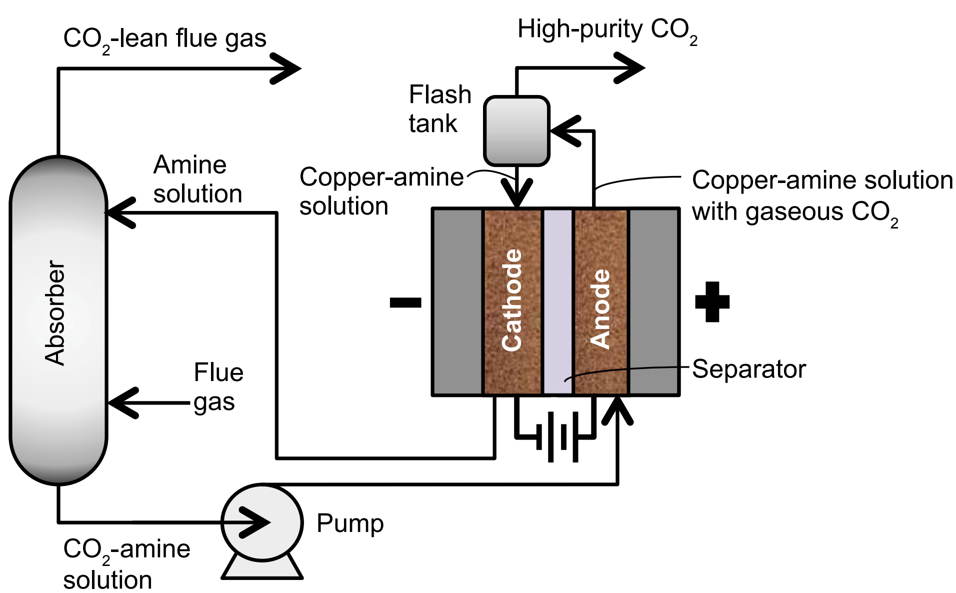
Throughout this process, the copper anode loses material, and the copper cathode gains it. "We can't let that go

Chemical reactions in the EMAR process



The chemical reactions in the EMAR process occur inside an electrochemical cell with two chambers. Two CO_2-carrying amine molecules enter the right-hand chamber, where they encounter a copper ion released by the anode. They drop their CO_2 molecules and bond together to pick up one copper ion. The CO_2 exits the cell, and the copper-amine molecule flows to the left-hand side, where the copper cathode pulls the copper ion away from the amines. The two original amine molecules separate and are ready to pick up more CO_2.

Schematic diagram of the EMAR process



Inside the absorber at the left, flue gas from a power plant flows upward through an injected solution of amines, which capture the CO_2 molecules. The cleaned flue gas exits at the top, while the CO_2-amine solution drops to the bottom and is pumped to the anode side of the electrochemical cell. There the amines pick up copper ions given off by the copper electrode, releasing the CO_2 in the process. The CO_2 bubbles off in the flash tank, while the copper-amine solution is sent to the copper cathode, which attracts the copper away from the amines. The empty amines are sent back to the absorber to clean up more flue gas.

on indefinitely or the anode would dissolve away," says Hatton. "So we solve the problem by swapping sides." They switch the direction of the current—so the anode becomes the cathode and vice versa—and reverse the direction of the flow through the cell. "That then builds up the side that's been depleted and depletes the side that's been built up," says Hatton. The switching is easily accomplished and could be done automatically.

Like a conventional thermal scrubber, the EMAR technology should remove 90% of the CO_2 in flue gas. But it offers significant practical advantages over a scrubber. For one thing, it's easy to retrofit. Installing a steam system in an existing facility requires major structural changes to redirect tremendous amounts of steam. In contrast, EMAR is a "drop-in technology" that requires only electricity. Also, because the EMAR process doesn't rely on steam from the operating plant, it's highly flexible. When electricity supply is strained or prices are high, the flow of exhaust through the capture system can be cut off, and all the plant's output can be sent to the grid.

In addition, the EMAR system can be used in steam-free environments. For instance, it can be installed in cement, steel, and aluminum manufacturing plants, which together account for nearly 10% of global carbon emissions. And because of its targeted nature, it can be used in settings where CO_2 is present in low concentrations but must be removed to protect human health, for example, in submarines, space shuttles, and other confined spaces.

Demonstrations in the lab

To demonstrate and test the EMAR process, Stern and Hatton built a bench-scale prototype including all the components in the schematic diagram. Tests in the prototype confirm the effectiveness of the system.

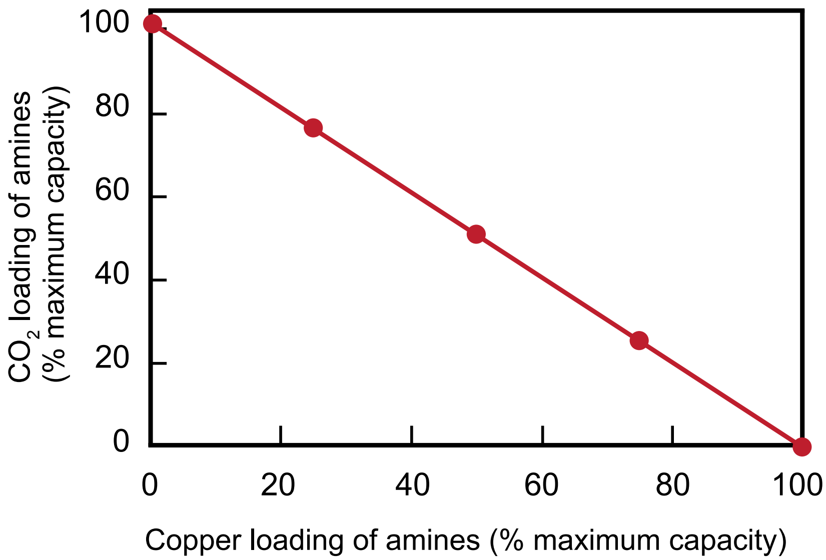
For example, one experiment tested the impact of adding copper ions to the CO_2-amine solution. At the start of the experiment, the amines were completely "loaded" with CO_2, that is, holding as much as they could, just as they would in the absorber. The researchers then slowly added copper ions, at each step measuring the fraction of the amines combined with CO_2 and the fraction combined with copper ions. As shown in the top figure on this page, as the copper-amine fraction increases, the CO_2-amine fraction decreases. When the copper loading reaches 100%, the CO_2 loading reaches zero. The process has successfully separated all of the CO_2 from the amines.

In another series of tests, the researchers measured CO_2 output as they varied the input current—a change that affects the rate at which the copper ions are released in the anode and picked up in the cathode. The bottom figure on this page shows the experimental results. Over a period of five hours, the team altered the current every 45 minutes and simultaneously measured the mass of CO_2 leaving the cell. The correlation between the input current and CO_2 output confirms the effectiveness as well as the flexibility of the EMAR process.

Theoretical simulations, promising outcomes

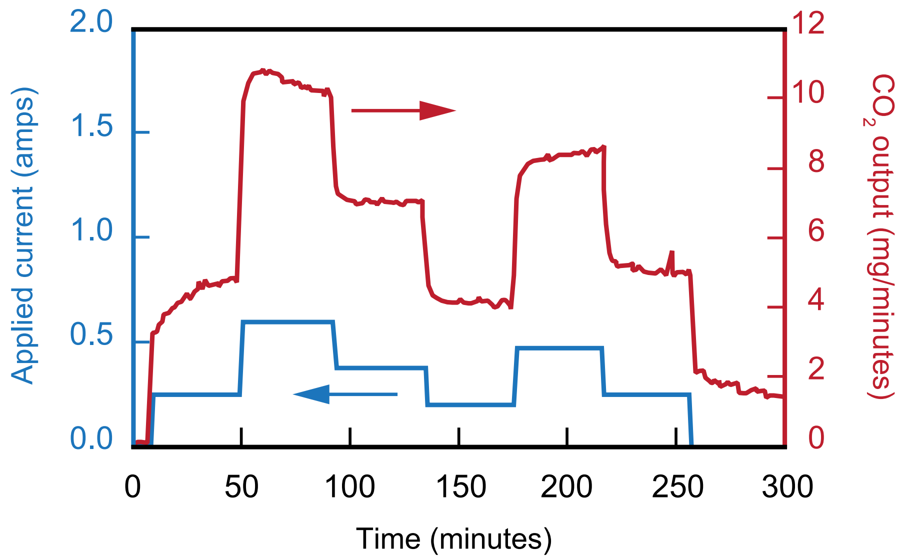
The bench-scale prototype is, of course, a proof-of-concept system, not yet optimized in terms of design and operating conditions. "Our mathematical models show that the energy

Binding of amines with CO_2 and copper



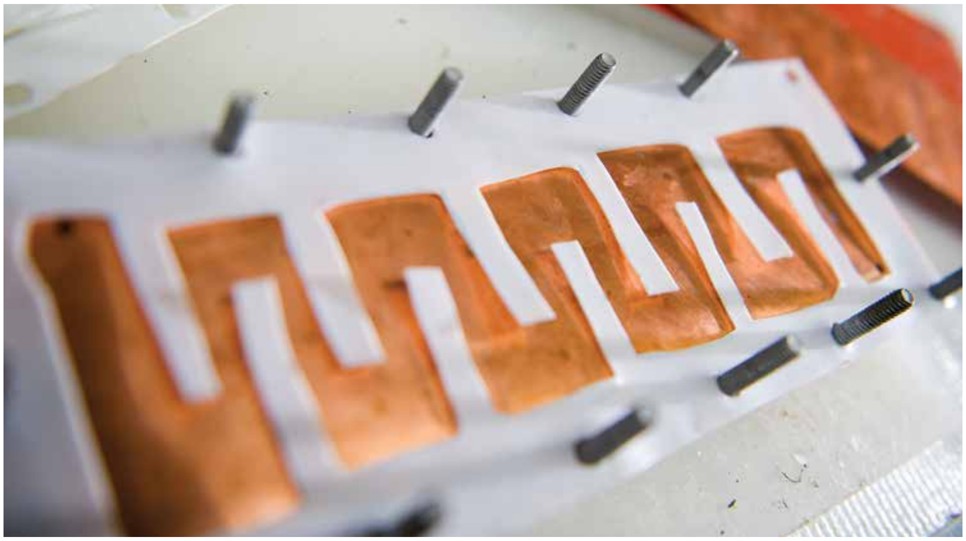
This figure shows the impact of adding copper ions to a CO_2-amine solution. When no copper is present, the amines are fully loaded with CO_2; they are holding all the CO_2 they can. As the copper concentration increases, copper loading of the amines increases, and CO_2 loading decreases. Ultimately, the amines are 100% loaded with copper, and all the CO_2 has been released into the solution.

Effect of current on CO_2 capture



This diagram shows the effect of variations in current within the prototype electrochemical cell on the rate at which CO_2 leaves the absorber. As the input current goes up and down over time, the amount of CO_2 in the output stream follows the same trend. This result demonstrates that current controls the level of CO_2 capture in the system.

Photo: Stuart Darsch



The researchers use this flow channel to guide the amine solution along the copper surfaces inside their electrochemical cell. If the channel were straight, the solution would flow through the cell too quickly. The serpentine shape slows the flow down, increasing the time the solution is in contact with the copper so as to maximize the transfer of copper ions.

consumption of our prototype is far from the lower limit that should be possible with this technology," says Aly Eltayeb, a graduate student in chemical engineering who is now working on the project.

Right now, the bench-scale system—operating at room temperature and pressure—uses about 100 kilojoules (kJ) of energy to capture a mole of CO_2. That level is higher than that achieved with today's thermal scrubbing processes, which require (depending on the installation) roughly 60 kJ per mole of CO_2 captured and compressed. However, the theoretical analyses suggest that optimizing the EMAR system can bring its energy requirement (excluding compression) down toward the 15 kJ per mole limit of the technology. At that point, it will require only 25% of a plant's electrical output. Also, it should be twice as effective as a thermal scrubber at removing CO_2 from the amines. As a result, only a third as much amine solution will need to be recirculated, so the absorber—the most capital-intensive unit in a CO_2 capture plant—can be smaller. And the pressure of the exiting CO_2 stream will be high enough that only half as much energy-consuming compression will be needed. Finally, the EMAR process runs at a lower temperature than a thermal scrubber does, so there's less thermal degradation of the amine over time.

What about cost? For benchmarks, the researchers turned to the US Department of Energy (DOE). According to DOE estimates, the cost of using current thermal capture systems is about \$61 per ton of CO_2 captured. (Costs are in 2012 dollars and will vary at different installations.) To make carbon capture economically competitive, DOE has set a target of \$40 per ton by 2025, with the cost dropping to \$10 per ton over the following 10 years. The MIT researchers' "back-of-the-envelope" calculations on the EMAR process suggest a cost of \$45–\$55 per ton of CO_2 captured—not far above DOE's 2025 target. While the EMAR process may not provide a significant cost advantage over a thermal system in new construction, the estimated cost of EMAR combined with the ease of its installation would mean that retrofitting carbon capture on existing power plants and industrial facilities could become a reality.

Next steps

The researchers are now planning to design and build larger-scale systems in which they can prove—and improve—the system's performance. They'll operate the equipment at higher temperatures and pressures and over longer running times to confirm that the process is robust and stable, even with the constant reversal of direction. They are also considering other materials. They started with amines and copper because of the proven ability of the former to capture CO_2 and the well-understood electrochemistry of the latter. But they are now examining other possible combinations for their two-molecule approach. While optimizing, scaling up, and preparing the EMAR process for deployment will require significant work, the MIT team believes that the technology has the potential to be ready for widespread commercialization within the next decade.

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By Nancy W. Stauffer, MITEI

This research was supported by Siemens AG and by the US Department of Energy through the Advanced Research Projects Agency–Energy. Further information can be found in:

M.C. Stern. *Electrochemically-Mediated Amine Regeneration for Carbon Dioxide Separations*. PhD thesis, MIT Department of Chemical Engineering, 2013.

M.C. Stern and T.A. Hatton. "Bench-scale demonstration of CO_2 capture with electrochemically-mediated amine regeneration." *RSC Advances*, vol. 4, pages 5906–5914, 2014.

M.C. Stern, F. Simeon, H. Herzog, and T.A. Hatton. "Post-combustion carbon dioxide capture using electrochemically mediated amine regeneration." *Energy and Environmental Science*, vol. 6, pages 2505–2517, 2013.

New approach to emissions auditing

More honest reports, lower emissions

In a two-year study of environmental auditing in India, Nicholas Ryan (above, MIT PhD '12, now of Harvard and JPAL), Esther Duflo (opposite page, of MIT), Michael Greenstone (MIT), and Rohini Pande (Harvard) found that independent auditors gave more accurate reports on pollution than did auditors hired by firms—and in response, highly polluting plants cut their emissions.

This research was supported in part by the MIT Center for Energy and Environmental Policy Research. For a full list of sponsors, see page 27 .

Photo: Stuart Darsch

An MIT-Harvard study has provided the first-ever evidence of the impact of removing the conflict of interest that arises when regulated firms hire their own auditors—a common practice in many industries. The researchers selected nearly 500 polluting industrial plants in India, and the state's environmental regulatory body changed the rules for half of them: It randomly assigned auditors to plants, paid them a set fee, and double-checked a sampling of audit reports. Among the striking results: Almost a third of the standard audits falsely reported legal levels of emissions—but under the new rules, the number of dishonest reports dropped by 80%. Best of all, plants responded to the new system by cutting pollution. At least in this case, reform of third-party auditing could lead to more effective regulation.

In many parts of the world, rapid industrial development relieves poverty but brings serious air and water pollution. The state of Gujarat in western India is a good example. After two decades of rapid growth in productivity, Gujarat now generates about a fifth of India's manufacturing output—but the region's rivers are heavily polluted, and the air in its cities is harmful to human health.

In 1996, the Gujarat Pollution Control Board (GPCB)—the state's environmental regulatory body—attempted to curb emissions from its 20,000 industrial facilities by instituting a third-party audit system in which an external auditing firm measures air and water emissions at each plant three times a year and submits an annual report to the GPCB. In response to reported transgressions, the GPCB punishes violators at varying levels of severity—from issuing warnings and fines to cutting off water and electricity. Even so, high pollution has persisted.

In 2009, this problem came to the attention of a group of MIT and Harvard researchers affiliated with the Abdul Latif Jameel Poverty Action Lab, or J-PAL, a research network housed within MIT's Department of Economics. In initial conversations, the researchers learned that the GPCB believed that the current audit system produced unreliable information. The suspected source of the problem? The polluting firms hire the companies that audit their firms' operations, so there's a built-in conflict of interest for the auditors. If they skew their findings to suit the firms, they're more likely to get hired again—and the firms avoid any threat of being penalized for excessive emissions.

"Allowing the entity being audited to hire its own auditor seems a strange arrangement, but it's common practice—pervasive in corporate financial reporting, the global debt-rating system, health and safety regulation, and many other areas," says Nicholas Ryan PhD '12, now a Prize Fellow in Economics at Harvard and J-PAL. Despite periodic calls for reform in various settings, no changes have been enacted to make third-party auditors more independent.

Using Gujarat as a case study, the J-PAL team decided to take the first quantitative look at the third-party auditing system, including the sources and magnitude of problems and their impact on compliance. "While third-party auditing might seem difficult to assess objectively, in J-PAL we specialize in performing such studies," says Esther Duflo, the Abdul Latif Jameel Professor of Poverty Alleviation and Development Economics and a founder and director of J-PAL. "We use rigorous scientific methods to help us understand exactly what causes such programs to have limited effectiveness and what strategies can make them more effective."

Assessing the problem

Key to J-PAL studies are randomized controlled trials. Often used in testing pharmaceuticals, the technique involves applying changed conditions—whether a new medicine or a new regulatory procedure—to one of two otherwise identical groups and then comparing the outcomes for the two groups. Working closely with the GPCB, the J-PAL researchers set up the following two-year field experiment to run in Ahmedabad and Surat, Gujarat's two largest cities.

First they identified a sample of 473 industrial plants. Then they randomly assigned 233 plants to serve as the "treatment" group and kept the remaining 240 as the "control" group. The control firms continued to hire and pay their own auditors, while the treatment firms were subject to a new auditing procedure. Each treatment firm was randomly assigned an auditor, and the assigned auditor was paid a flat fee from a central pool to perform the audit. In 20% of all cases (selected at random), the auditor's visit was followed within a few weeks by an unannounced visit from a "backchecker"—an independent company that performed the same measurements, thereby checking the accuracy of the auditor's report. Finally, at the beginning of the second year, the auditors were notified that their pay would be linked to the accuracy of their reports, as measured by the backcheckers' reports.

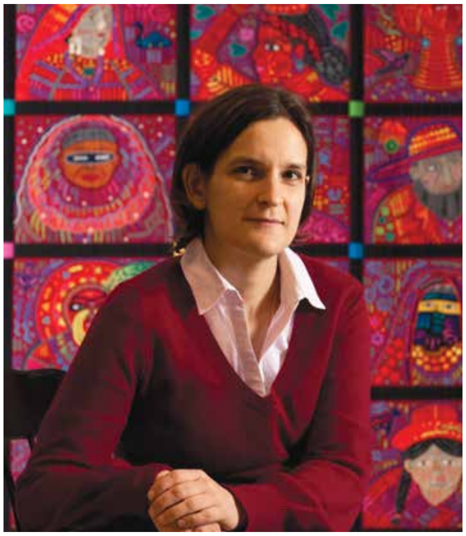
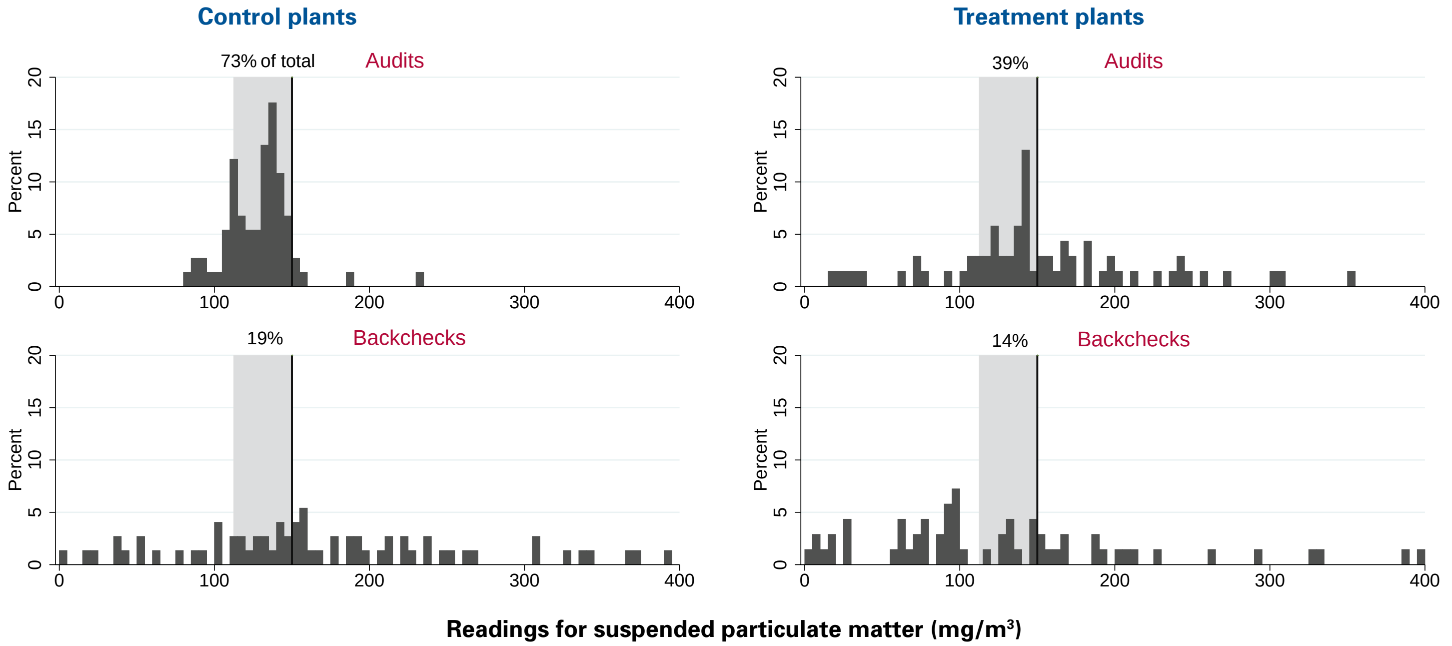


Photo: Peter Tenzer

Esther Duflo, the Abdul Latif Jameel Professor of Poverty Alleviation and Development Economics and a founder and director of J-PAL.

The new arrangement altered the incentives of all parties. "With the new procedure, the auditor has no reason to misrepresent the findings to benefit the plant because the plant has no influence over the auditor's subsequent assignments," says Ryan. "Set fees for the audits are important here, so assigned auditors can't extort firms, and the auditor receives extra pay for doing a good job." Best of all, faced with the possibility of an honest audit, the

Measurements of particulate pollution



These figures show distributions of measurements of suspended particulate matter by auditors at control plants (top left) and treatment plants (top right) and corresponding measurements taken by backcheckers (bottom left and right). The vertical line at 150 mg/m^3 marks the regulatory limit; the gray area shows the region between 75% and 100% of that limit. Auditor measurements at the control plants bunch within the gray area, indicating that they meet the restrictions—but just barely. Backcheck measurements at the same plants are distributed more widely, with many well above the limit. Audit measurements at the treatment plants are more spread out, though some bunching just below the limit is still evident. The modified auditing system significantly reduces—but does not eliminate—false reporting.

plants should be more motivated to clean up their emissions to avoid being penalized by the regulator.

Outcomes

Results of the experiment confirm that false reporting is common in the control group, where auditors are hired by firms. For all pollutants, 29% of the audits in the control group reported that emissions were below legal limits when in fact they weren't. And they systematically reported plant emissions just below the legal limit—levels that are presumably less likely to attract regulatory attention than would be reports showing compliance by a wide margin.

Auditors for plants in the treatment group reported more truthfully. When the treatment auditing method was used, inaccurate reports of plants complying with the law dropped by about 80%. "So it's not that the auditors are now perfectly telling the truth, but they're more than three-quarters of the way there," says Ryan.

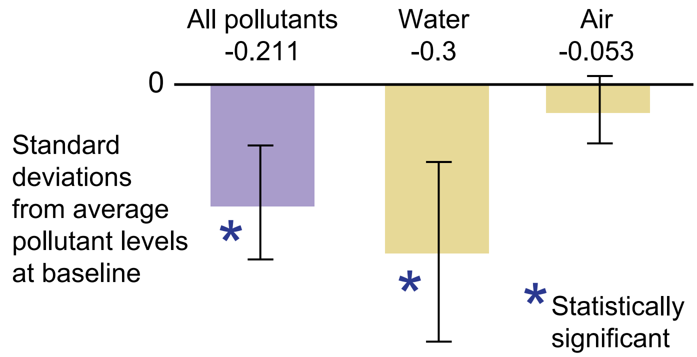
A review of the behavior of auditors who worked under both regimes shows that they reported pollution more accurately at treatment plants than they did at control plants that they were auditing at the same time. That observation suggests that the increased accuracy was due to the new audit system. Another factor may be how much the auditors were paid. The fixed fee under the modified system was 40,000 rupees—according to the regulator, enough to cover the cost of performing the measurements plus a small profit. In contrast, auditors who negotiate their own fees are paid on average 24,000 rupees per audit. At that level, they could not conduct all the tests needed for a proper audit.

The figures above present more detailed results for suspended particulate matter (SPM), measured partway through the second year. On each graph, the vertical line marks the regulatory standard of 150 milligrams per cubic meter, and the gray shading shows the region between 75% of the standard and the standard—the zone where false reports might not look too conspicuous.

The two charts on the left show SPM measurements from audit reports (top) and corresponding backchecker reports (bottom) at the control plants. According to the auditors, 93% of all plants are compliant, and 73% of them fall within the gray shaded area just under the pollution standard. Data from the backcheckers look quite different. Here, 59% of the readings exceed the standard—as opposed to just 7% in the audit reports—and there is significant dispersion in the distribution. Only 19% of the plants have readings in that narrow gray band—54 percentage points less than claimed by auditors. Taken together, these data provide striking evidence that auditors fabricate SPM data so that plants look narrowly compliant with the regulatory standard.

The right-hand charts show measurements by auditors at the treatment plants (top) and their backcheckers (bottom). The distributions of the audit and backcheck data now look more alike. The increased similarity is especially evident for readings above the standard, which were very sparse among the control audits. In the auditors' data for treatment plants, 39% of the readings are within the gray area just below the standard—well below the 73% in the control group reports. But while the treatment increased truth-telling by auditors, it did not end false reporting. The 39% share of audit readings in the shaded area still exceeds the 14% share in the backcheck measurements.

Reduction in pollution at treatment plants



This chart shows reductions in total pollution and in water and air pollution at treatment plants relative to control plants six months after the end of the audits. The new auditing system brought a significant drop for all pollutants. That reduction is driven by an even larger reduction in water pollution. The estimated effect on air pollution is smaller and not statistically significant. The largest reductions came at the highest polluting plants—the ones that would face the harshest penalties if their actual pollution levels were reported to the authorities.

Changes in pollution

"The ultimate goal of improving auditor honesty is, of course, to motivate individual plants to reduce pollution," says Duflo. And measurements taken six months after the final audits show that the treatment plants did cut their emissions relative to the control plants. The figure on this page shows changes in pollutant levels using units of standard deviation—a method of accounting for all air and water pollutants in a single index. Considering all pollutants, the treatment plants reduced their emissions by a statistically significant 0.211 standard deviations on average. That overall effect was driven by a large decrease in concentrations of water pollutants—a top regulatory priority for the GPCB. The pollution reductions occurred mainly at the highest-polluting plants—the ones that would suffer the harshest penalties if they were caught violating the standards and might end up paying more to deal with regulatory sanctions than they would to abate pollution.

Another question is whether the benefits from such pollution reduction outweigh the extra costs of the new auditing system. Performing a cost-benefit analysis requires putting a monetary value on reductions in pollution. India has not set prices on emissions, so as a first cut, the researchers used emissions prices in China. Based on the data they have available thus far, they calculate a net gain of US$6,000 at each treatment plant. While that result is not definitive, it does suggest that the benefits of the new auditing procedure may outweigh the costs.

Encouraging regulatory change

The findings of the study have already begun to spur change in Gujarat. The GPCB has approved the adoption of a new audit system modeled on the one used in the field experiment. Implementation of the recommended changes awaits approval by the supreme court of Gujarat—the entity that originally issued the call for better regulation that led to adoption of the third-party auditing system in 1996.

Will the Gujarat experiment also motivate reform in other settings? There are enormous differences between auditing financial reports or bond ratings and auditing industrial pollution in Gujarat. But whenever the company being audited hires its own auditor, conflict of interest is present. The researchers hope that regulators and policy makers will at least take notice of their findings. They note that the experiment underscores the value of designing third-party audits so that the first-order incentive is for auditors to tell the truth. And they conclude that—at least in this one instance—it was possible to do so.

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By Nancy W. Stauffer, MITEI

This research was supported by the MIT Center for Energy and Environmental Policy Research, the Harvard Environmental Economics Program, the International Growth Centre, the International Initiative for Impact Evaluation, the National Science Foundation, and the Sustainability Science Program at Harvard. Further information can be found in:

E. Duflo, M. Greenstone, R. Pande, and N. Ryan. "Truth-telling by third-party auditors and the response of polluting firms: Experimental evidence from India." *The Quarterly Journal of Economics*, pages 1499–1545, 2013.

MIT Energy Initiative announces latest seed grant awards

The MIT Energy Initiative (MITEI) has announced its latest round of seed grants to support early-stage innovative energy projects. A total of more than $1.6 million was awarded to 11 projects, each lasting up to two years. With this latest round, the MITEI Seed Fund Program has awarded a total of about $15.8 million, making possible 129 early-stage research projects in 22 departments across campus.

This year's winners—listed on page 30—address a wide range of topics including new methods of designing and using catalysts; assessment of natural gas technologies; novel design concepts for batteries, energy harvesters, and capacitors; and investigations into public opinion on various state energy policies.

As in the past, the call for proposals welcomed submissions on topics across the spectrum of energy and related environmental research, with interdisciplinary research strongly encouraged. In addition, this year's call sought to promote submissions on two particular themes: natural gas monetization and materials for energy. Past themes have included topics as diverse as the role of big data and the energy-water nexus.

In response to the call, MITEI received a total of 49 proposals from across the Institute. Once again, proposals came from well-established energy experts as well as from new faculty who need startup support and others who are applying their expertise in different fields to energy for the first time.

The following paragraphs highlight examples of projects led by new assistant professors now engaged with MITEI through the Seed Fund Program.

Hybrid metal-organic materials for sustainability

Much attention is focused on the development of crystalline and amorphous network materials for gas storage. Assistant Professor Niels Holten-Andersen of materials science and engineering and Assistant Professor Jeremiah Johnson of chemistry are working to combine metallosupramolecular assembly with polymer networks to create a new class of hybrid metal-organic materials. These novel materials will unite the well-controlled physical properties of polymers with the promising functional properties of metal-facilitated self-assembly. The materials will be versatile, robust, and capable of self-healing and "tunable" self-assembly. They can thus be optimized for applications such as carbon capture, wastewater filtration, and natural gas storage, and for use in devices such as fuel cells, rechargeable batteries, and solar cells.

Computational tools for catalyst design

The ability to convert methane gas—a primary component of natural gas—directly to liquid methanol at often-remote recovery sites would dramatically alter how this valuable fuel is stored, transported, and used. However, despite decades of effort, no lab-developed catalyst for achieving that conversion has been commercialized. Building on novel computation techniques, Assistant Professor Heather J. Kulik of chemical engineering is developing an "inverse" molecular catalyst strategy that begins with the desired outcome—stability, efficiency, and selectivity for direct methane conversion—and searches for chemical compounds that yield those characteristics. Once the computational framework is established, Kulik and MIT collaborators will use it to guide experimental catalysis work and to gather feedback for further framework development, including generalization to other critical chemical reactions.

Energy harvesting from ambient vibrations

Energy-harvesting systems may be used to generate electricity for portable electronics, sensors, medical implants, and other small devices by using ambient sources such as walking vibrations and water waves. In such sources, the energy "lives" in a wide range of temporal and spatial scales, so taking full advantage of it requires harvesting from a broad band of frequencies. Assistant Professor Themistoklis Sapsis and Professor Alexander Slocum of mechanical engineering are designing a mechanical system for harvesting energy from such broadband sources that mimics the efficient and robust mechanism that governs energy transfers across different scales in turbulent flows. If successful, these mechanical analogs of turbulence could transform the way energy-harvesting systems are designed, yielding much higher conversion efficiencies than achieved in traditional configurations.

Public opinion and state energy policy

In recent years, many important developments in energy policy—including regulations limiting greenhouse gas emissions and increasing renewable energy production—have occurred at the state level. But little attention has been paid to the role of public opinion in the state energy policy process. To clarify that role, Assistant Professor Christopher Warshaw and Professor Adam Berinsky of political science will measure public opinion on an array of state-level energy policies using existing data and original surveys. In addition, they will examine whether the public holds state elected officials accountable for their energy policy decisions, and whether state policy outcomes are responsive to changes in public opinion. Their findings will provide new insights into the politics of energy policy in the United States.

Evaluating quantum dots as thermoelectric materials

Thermoelectric devices can convert waste heat from car engines, power plants, and other sources directly into electricity. The best thermoelectric materials incorporate performance-enhancing nanoscale features, but fabricating them generally requires expensive methods not cost-effective at scale. As an alternative, Assistant Professor William Tisdale of chemical engineering is evaluating the thermoelectric performance capabilities of colloidal quantum dots (QDs), nanoscale semiconductor crystals whose electronic structure and behavior are defined by particle size and shape. By using novel laboratory techniques to synthesize QD materials, Tisdale will examine how surface chemistry and crystal packing affect charge and heat transport in colloidal QD materials—an understanding that will make possible enhanced thermoelectric performance and the optimization of inexpensive solution-based processes for fabrication of large-area energy conversion devices.

Time-dependent climate impacts of natural gas deployment

Fuels emit a variety of greenhouse gases during their life cycles, and those gases have different radiative efficiencies and removal rates. As a result of those variations and a changing climate, the impact of a technology depends on its time of use—dynamics that are not reflected in static climate metrics like the global warming potential. Assistant Professor Jessika Trancik of engineering systems is developing and testing new, dynamic metrics that can better assess the climate impacts of natural gas and other fuels with significant life-cycle methane emissions. With an initial focus on natural gas deployment in the electricity and transportation sectors, she will then use those metrics to inform the optimization of technology portfolios that allow for maximum energy consumption while meeting climate targets and performance standards imposed by policy.

Funding for the new grants comes chiefly from MITEI's Founding and Sustaining Members, supplemented by funds from John M. Bradley '47, SM '49 and an anonymous donor, and gifts from other generous alumni. Alumni contributions help expand the scope of the MITEI Seed Fund Program and enable participation of faculty from across the Institute.

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By Nancy W. Stauffer, MITEI

Best poster awards

Photo: Justin Knight

At a special poster session, MITEI Director Robert Armstrong (left) presents first prize in the competition for best poster to graduate student Dimitra Achilleos of chemical engineering. Achilleos works with Professors T. Alan Hatton and Gregory Rutledge of chemical engineering.

Once again, in conjunction with this year's seed grant review meeting, MITEI organized a day of oral and poster presentations on completed or nearly completed seed grant research projects.

At a special session, graduate student and postdoctoral researchers presented 12 posters describing research projects funded by MITEI seed grants. Three awards were given for best poster.

Dimitra Achilleos, Chemical Engineering: "Enhanced Pseudocapacitors for Energy Storage and Water Treatment"

Jayson Lynch, Electrical Engineering and Computer Science: "Energy-Efficient Algorithms"

David Cohen-Tanugi, Materials Science and Engineering; Shreya Dave, Mechanical Engineering; and Brendan Smith, Materials Science and Engineering: "Nanomaterials for Water Filtration"

Awards were given for especially noteworthy poster presentations, judged on the basis of content and quality of presentation. The poster session and awards are held twice each year in conjunction with special events for the MITEI members that sponsor the MITEI Seed Fund Program.

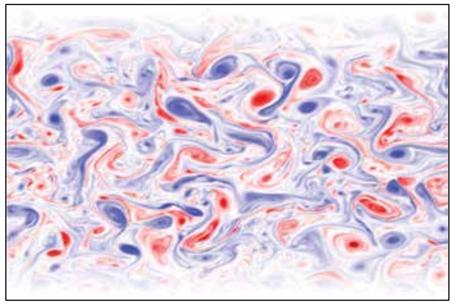
Recipients of MITEI seed grants, spring 2014

Assessment of technologies at different scales to monetize natural gas under uncertain and dynamic conditions
Paul Barton
Chemical Engineering

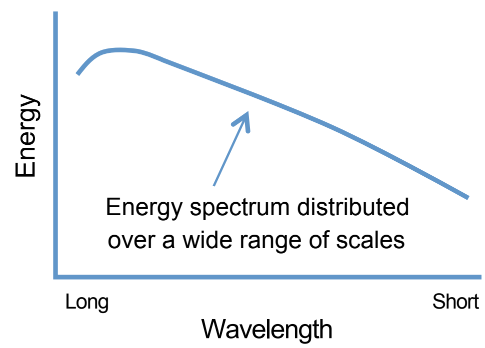
Dual-mode lithium-bromine seawater battery
Martin Bazant
Chemical Engineering
Cullen Buie
Mechanical Engineering

In-cylinder catalysis for ATR: Piston driven chemical reactors
Leslie Bromberg
Plasma Science and Fusion Center
William Green
Chemical Engineering
Wai Cheng
Mechanical Engineering
John Brisson
Mechanical Engineering

Energy transfer in turbulent flows: a model for designing energy-harvesting systems



Turbulent flow



When flows are turbulent, they contain numerous eddies with differing lengths (see above left). As a result, energy can be dissipated simultaneously at many wavelengths (above right), leading to highly efficient energy transfer. Professors Themistoklis Sapsis and Alexander Slocum are designing novel energy-harvesting devices that mimic that natural energy-transfer process, thereby gathering more of the energy available in ambient vibrations such as footfalls **(see page 28).**

Integrated photovoltaic–electrochemical devices to reduce CO_2 for fuel production
Tonio Buonassisi
Mechanical Engineering
Yang Shao-Horn
Mechanical Engineering

Nanostructured high-performance electrostatic capacitors
John Hart
Mechanical Engineering

Hybrid metal-organic materials based on gelation and self-assembly: A new class of materials for sustainability
Niels Holten-Andersen
Materials Science and Engineering
Jeremiah Johnson
Chemistry

New computational tools for direct methane-to-methanol catalyst design
Heather Kulik
Chemical Engineering

Efficient nonlinear energy harvesting from broad-band vibrational sources by mimicking turbulent energy transfer mechanisms
Themistoklis Sapsis
Mechanical Engineering
Alexander Slocum
Mechanical Engineering

Quantum confined materials for thermoelectrics
William Tisdale
Chemical Engineering

Evaluating time-dependent climate impacts of natural gas deployment
Jessika Trancik
Engineering Systems Division

Public opinion and state energy policy
Christopher Warshaw
Political Science
Adam Berinsky
Political Science

Kerry Emanuel: Bringing global warming science from the classroom to the world

Climate change is widely recognized as one of the foremost challenges of this century—one with major repercussions for energy, health, agriculture, and more. Kerry Emanuel, MIT's Cecil and Ida Green Professor of Atmospheric Science, therefore feels it is his duty as a citizen and scientist to educate a broad audience on the possible impacts of climate change.

Emanuel is no stranger to the task. For decades, he has educated students, politicians, the media, and even climate skeptics about the science behind climate change. Named one of *Time* magazine's 100 most influential people of 2006, Emanuel recently wrote a book geared toward educating the public on the subject: *What We Know About Climate Change.* He is also a co-founder and director of the Lorenz Center, a climate think tank housed within MIT's Department of Earth, Atmospheric, and Planetary Sciences.

In spring 2014, Emanuel took his role as public educator one step further with the launch of 12.340x Global Warming Science, a new massive open online course (MOOC) from MIT's edX platform that aims to provide a solid scientific foundation for understanding what is really happening with climate change.

The class is aimed at sophomores and juniors from all over the world, in particular, those who have taken electrodynamics, classical mechanics, and some thermodynamics. It's a serious science course, says Emanuel, which distinguishes it from the handful of other online courses currently being taught beyond MIT on the subject of climate change, most of which have a large policy component.

Photo: Helen Hill, MIT

Kerry Emanuel, MIT's Cecil and Ida Green Professor of Atmospheric Science.

Emanuel's approach to teaching the class maintains a clear boundary between the science and the policy of climate change. "Part of the problem is all the publicity on global warming has sent out a message that global warming is highly politicized and has nothing to do with science," he said in a recent interview. "Nothing could be further from the truth."

Emanuel is pleased with the number of students who have shown an interest in the course: More than 10,000 are registered this semester.

He says one of the benefits of the online class is that students can sign up and take the class wherever they live. This semester, he has students from all over the world, including India, Bangladesh, and several African countries.

"It allows me to reach people who might be very bright, very engaged, possibly future leaders in the field, who otherwise don't have the opportunity to take a real college course at a real college because of financial, political, or other reasons," Emanuel says. "This opens up a world to them. If they're motivated, I think they can get just as much, if not more, out of the edX platform as someone taking it in the classroom."

In addition to helping Emanuel reach future leaders in the field who don't have the means to attend MIT, the online course has special features intended to enhance the learning experience beyond what a traditional physical classroom can support. One of those features is an online discussion and help forum where students working on problem sets can ask other students or teaching assistants for help. The answers to questions are then voted on by other participants, providing a natural system of selecting the best comments.

Another notable feature of the class is the opportunity for students to work with a simple, interactive climate model that takes inputs such as solar radiation and atmospheric greenhouse gas content and calculates the temperatures of the Earth's surface and atmosphere. Users can change variables such as the intensity of sunlight, the time of year, the greenhouse gas concentrations, and more to see how they affect climate change and learn by comparing scenarios they generate themselves.

What has stunned Emanuel about the edX class is that it has spurred interest in the physical classroom version of Global Warming Science—a class within the Energy Studies Minor that Emanuel and his co-teacher, MIT Professor of Physics and Planetary Science Sara Seager, decided not to offer this spring after enrollments had been low for several years.

"Ironically, it seems that the MOOC is drawing more MIT students to have an interest in the classroom course," Emanuel says, surmising that he will probably offer the physical classroom version of the class again next year.

Striking balance

Throughout his time educating politicians and the public about climate change, Emanuel has found himself side-by-side with climate skeptics on multiple occasions. Most recently, he was invited to give a talk at an event hosted by conservative Christians, who often find themselves at odds with other conservative groups because of their yearning to protect nature.

To address the concerns of climate skeptics in the room, Emanuel did what he normally does when in such situations.

"You can't give them a climate education in 30 minutes," he says. "But what you can do is talk to them about the way scientists look at the problem, from a societal standpoint, and that's by framing the problem in terms of risk assessment and management....How much insurance are you willing to pay out to avoid a low probability but very, very high impact event?"

Emanuel also encourages Democrats and Republicans alike to fight the fights worth fighting—the ones that are rational and need action from lawmakers. He gives nuclear power as one example of a fight that leaders should take up. Last year, Emanuel and three other top climate scientists wrote an open letter to world leaders in support of the development of safer nuclear power systems.

"I'll say to [conservative skeptics], if you want to fight the left, don't fight this battle, fight other battles. You should be out there fighting for nuclear power, which the left is opposed to, irrationally. You should be out there fighting to get research on carbon sequestration," Emanuel says. "I'd rather see someone fighting those battles than trying to deny that there's a problem, because those battles might become a bipartisan, intelligent conversation about our mixture of energy sources. But if we keep fighting the old fight, nobody is going to do anything at all."

He comments, "I'm always horrified when ideology trumps evidence and reason."

Emanuel has always been guided by a strict adherence to reason. When he was growing up in the 1960s and 70s, he found that those who argued irrationally tended to be on the left. So he became a Republican. But over the last decade or so, he switched to become a registered independent.

"All the excesses, as far as I can see, are on the right now. I didn't change so much. They changed," Emanuel says.

But it wasn't politics that attracted Emanuel to the challenge of climate change to begin with, and it surely won't be politics that keeps him battling for more public awareness. As always, Emanuel remains focused on the science and hopes decision makers will as well.

"We have people wholly ignorant of science who are making important decisions in this country. And their constituents aren't necessarily any better educated on this subject. That's going to be the downfall of us," Emanuel says. "I do feel a duty as a citizen to try to get education on the subject to a much broader audience."

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By Vicki Ekstrom, MITEI

Energy alumni: Where are they now?

Photo: Michelle Norris

Cristina Botero PhD '14

When Cristina Botero first started carbon capture and storage research as a graduate student at the University of Erlangen in Germany, MIT Energy Initiative researcher Howard Herzog's name kept coming up. When Botero was accepted into the mechanical engineering PhD program at MIT, her first call was to Herzog. She soon became part of the MIT-BP Advanced Conversion Program, which focuses on the thermochemical conversion of coal and biomass to synthetic fuels. Working with Professor Ahmed Ghoniem and Herzog, Botero proposed and patented a novel coal feeding system that uses liquid CO_2—instead of water—to feed coal slurry into a high-pressure vessel. Botero now works as a research engineer for BP's Conversion Technology Center and helps oversee the MIT-BP program.

Why did you decide to work for a major oil and gas company?

I guess you could call me a "tree hugger," so I never thought I would choose to do so! But the reality is that we don't know if renewables will ever replace fossil fuels and, in the meantime, oil and gas companies will continue utilizing fossil resources. So what better place to pursue a career in energy and make an impact than a major oil and gas firm? In addition to being actively involved with renewable technology development, the oil and gas sector relies on people like me to find better, cleaner ways of utilizing traditional fossil resources. Furthermore, they offer multiple career development opportunities and a strong leverage on the direction of our energy future.

Apart from technical understanding, what other useful skills did you learn while you were at MIT?

I would highlight self-confidence as a major area of learning for me. MIT is known to be a "no praise" zone and, to survive, you have to trust what you do and keep going regardless of what other people tell you—or don't! Being the best often means being the only one who doesn't give up.

Also, I used to think that working hard and staying focused was the best way to be successful. At MIT I realized that the ability to network with the right people and to literally "sell" our ideas is at least as important. This is very difficult to accept when you are a techie at MIT, but it also happens to be the ideal place to do it. The person chatting with you during dinner may become the next US Secretary of Energy.

What advice would you give researchers just starting out?

Don't rush through your education. Take the time to get involved with industry while at MIT, even if your goal is to stay in academia. The added value of an internship by far exceeds the time expenditure. I had multiple industrial experiences at wonderful places like Daimler, GE, Fraunhofer, and BP, which not only helped me find what I'm passionate about (energy!) but also shaped the way I do my research and interact with people. I learned to stay focused while keeping the big picture always in mind, which at the detail-oriented world of MIT is an especially important asset to have.

Photo: Tristan Weir

Lara Pierpoint SM '08, PhD '11

When Lara Pierpoint came to MIT as a graduate student in nuclear engineering and engineering systems, Professor Ernest Moniz advised her to become involved in the MIT Energy Club. Later, when he became Pierpoint's advisor, he joked that she had two full-time jobs: running the Energy Club, of which she became president, and getting her PhD. Pierpoint's hard work and the lessons she learned through her experiences at MIT paid off. She is now working for Moniz as a special advisor to the Energy Policy and Systems Analysis Office at the US Department of Energy, after a brief stint in the Senate Energy and Natural Resources Committee.

What motivates you to work in the energy space?

It comes down to climate change. Climate change is a frightening problem. I've always been in love with nature, and the notion that future generations won't be able to experience it the way I have really inspires me to do what I do. But I'm also fascinated by the complexity of energy systems and how challenging the problem is—the fact that there is a set of incumbent technologies and infrastructure, and yet we're trying to make transformational changes in how we consume and produce energy. It requires a lot of technological, policy, and business understanding.

How are you applying what you learned at MIT to your role in government?

I learned from working on The Future of the Nuclear Fuel Cycle study how to coordinate a big, complex study with many groups of analysts and an external advisory board. Having that experience in coordinating people around a set of energy policy recommendations is helping now as I work on the Quadrennial Energy Review.

My experiences with the Energy Club also taught me important lessons. I became involved with the club because—while I wanted to focus on nuclear—I didn't want to lose sight of the broader energy picture. At the club, everyone has a specialty, and we all learned from each other. So I came out of MIT with a more comprehensive view of the energy world. I also learned a lot about leadership and how to inspire people to be involved.

What led you toward a career in government, and why do you feel it is important for scientists to engage?

In college I took a class called Science and Society. Up until that point, I had thought I was a math and science geek. But I realized how much I loved policy and the unique challenge of communicating science and technology issues.

With tight government budgets, scientists need to make the case for more funding. It's also important to make sure science is digested and used within the policy process appropriately. For example, with climate change there is a lot of scientific uncertainty. But that uncertainty doesn't mean we shouldn't take action to mitigate and adapt to climate change. Conveying messages like this effectively is a major challenge. So for young researchers, it's really important to start understanding and engaging in government processes to ensure strong and productive connections between policy development and our science and technology enterprises.

Photo courtesy of Yogesh Ramadass

Yogesh Ramadass SM ’06, PhD ’09

Raised in Chennai, India, Yogesh Ramadass came to the United States to get his master’s and PhD degrees from MIT. Now he’s applying his MIT research at Texas Instruments, where he interned as a student. While at MIT, Ramadass worked in Professor Anantha Chandrakasan’s lab studying power converters for ultra-low power electronics. It wasn’t long until this research deepened to go from using low energy to no energy—or ambient energy that exists naturally in the world around us. Ramadass has since gone on to productize some of the research he started at MIT.

What led you to a career in math and science?

When I was growing up, there weren’t a lot of opportunities outside of math and science. Studying those subjects was how you could get a good job, and naturally, those subjects were highly regarded within society. The combination of social perception and my inclination towards analytical subjects led me towards math and science.

What does it mean to use ambient energy to power electronics? Give me an example in theory and how it’s being put into practice at Texas Instruments.

Modern electronic circuits are able to work at very low power levels. One of the goals in our research in Dr. Chandrakasan’s lab was to get rid of the battery entirely and rely on ambient energy. One could envision a home with sensors throughout it monitoring room temperatures, humidity levels, etc., and communicating with your thermostat, air conditioner, and other electronics. These sensors could each be powered by the light or heat in the room—coming from overhead lights, HVAC vents, and other sources. Most of my research focused on how to extract energy efficiently from ambient sources and power electronics. The research done at MIT was very beneficial in helping build a portfolio of energy-harvesting products at Texas Instruments.

You’re now a mentor to graduate student interns. Why is this mentorship so important?

When I was a graduate student, I learned a lot from people in industry through internships and industry collaborations at MIT. I learned then how important an industry perspective is to providing direction within the research projects, especially in the field of circuit design. Graduate students come up with a lot of good ideas, but it’s essential that they understand where the ideas might fit in and what kinds of problems they need to target. The practicality aspect that gets passed on from industry is very important. That’s the kind of insight I hope to provide to students through mentorship and research collaboration.

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By Vicki Ekstrom, MITEI

Morals matter: New class explores energy and ethics

It's not every day that a graduate student has a key role in designing an MIT class, and certainly not one as novel as The Ethics of Energy Policy. For this new class, due to launch in fall 2015, Nathan Lee, researcher for the MIT Energy Initiative (MITEI) and master's candidate in the Technology and Policy Program, is partnering with Lucas Stanczyk, assistant professor in the Department of Political Science.

There are many contentious ethical problems underlying energy policy, says Lee, but "nowhere in MIT's curriculum is there an opportunity for students to address these questions directly." The Ethics of Energy Policy aims to fill this gap. "The idea for the class came from the two of us discussing ethical issues raised by climate change," says Stanczyk, who taught Lee in a graduate class on political theory. "We started to see that this was one of those very big policy problems that faces us with important ethical dimensions that we tend not to teach at the undergraduate level."

Today, as the team outlines the class syllabus, collecting readings and identifying relevant case studies, an ambitious agenda is emerging: a rigorous class in applied ethics and philosophical theory grounded in real-world problems. The class, whose development is funded by a grant from the S.D. Bechtel, Jr. Foundation to MITEI and which is envisioned as part of the Energy Studies Minor, is intended to draw not only engineering undergraduates who plan to work in the energy industry and graduate students who research energy policy issues, but a more general audience, too.

"The class is for anyone who deals with ethical dilemmas related to energy and the environment in their daily lives," says Lee. "We hope to provide the opportunity for people to reflect on how their own values lead to judgments about these issues—as professionals, as consumers, and as citizens." And given that "a lot of people at MIT are going to be CEOs of companies someday," he adds, the instructors would especially like the class to provide a useful framework for thinking specifically about ethical dilemmas confronting business.

Through a combination of lectures and discussions, in-class exercises, and essays, The Ethics of Energy Policy will tackle a range of contemporary topics pointing to the moral dilemmas central to today's energy and environmental issues: whether the environment is inherently valuable or only because people place value on it; whether climate change generates moral obligations to reduce emissions at the national level, and if so, how nations should share the required burdens and sacrifices; and whether we as individuals and societies have a responsibility to save natural resources for future generations. This last dilemma lies at the core of Lee's own research. It is a problem, he is finding, that offers a rich source of material for the evolving ethics class.

"Global capitalism is lifting hundreds of millions of people out of poverty at unprecedented rates, and the exploitation of fossil fuels is part of that," states Lee. "Most people would agree that this is an admirable endeavor. But there is a tradeoff because the more coal plants that get built now, the worse off some people will be in the future—especially in the poorest countries least able to adapt to climate change." The question for the energy ethics class might be: "Do development goals for today's poor potentially come at the cost of tomorrow's poor and, if so, how should we navigate this tradeoff?"

Revealing hidden assumptions

One key objective for the class will be to reveal the frequently unstated ethical assumptions that underlie current energy policy discussions and to determine when these assumptions are morally reasonable or appropriate. "I suspect there will be some surprises," says Stanczyk, as students closely examine standard methods of evaluating energy and environmental policies.

The primary tool for evaluating climate change abatement policies and energy regulations is cost-benefit analysis. But this economic lens, suggests Stanczyk, "takes for granted certain basic prior questions about the values at stake." Says Lee, "When using economics as a basis for formulating public policy, you are operating within a certain philosophy about what matters and what doesn't. We want to take a step back from that, and ask what should be included as matters of public concern, and what weight these different considerations should have." To put it bluntly, he continues, "Public policy from beginning to end is a values game…and we need to be conscious of what these values are."

It is this deliberative—even "meta"—analysis of energy policy that will distinguish the new class from other MIT offerings on the subject. Lee promises that with Stanczyk, whose main area of research concerns the normative standards used to evaluate basic social institutions, learning analytic methods won't be offputtingly

Photo: Justin Knight

Assistant Professor Lucas Stanczyk of political science (left) and Nathan Lee, graduate student in the Technology and Policy Program, are now developing The Ethics of Energy Policy, a new class scheduled to launch in fall 2015.

abstract. "He's one of the most accessible philosophers I've ever met," says Lee. "He made me realize that ethics does not have to be fluffy hand waving, that it can be as rigorous as the study of materials science or economics."

Lee himself brings to the class a solid foundation in the technology and policy arenas, with an undergraduate degree in materials science and engineering from the University of Pennsylvania, work experience with ExxonMobil's corporate strategic research wing, and climate change policy posts at the White House National Economic Council and the Department of Energy. He arrived at MIT after wading deep professionally and personally into debates on the social cost of carbon. "I thought the climate change debate was sorely in need of a more systematic and transparent discussion of the competing values involved," he states. Lee came to believe that stepping back from the often fraught discourse on energy policy and seeking the moral underpinnings to these discussions was essential to moving the public debate forward.

"Our effort is to bring an interdisciplinary expertise to bear on the policy, economic, and philosophical aspects of energy and environmental problems," says Stanczyk. "We're a good duo," Lee adds. "We will strike a balance in the class between the philosophical and applied worlds." The Ethics of Energy Policy is a milestone for both, and likely one for MIT. "These issues of energy, the environment, and sustainability are arguably the most divisive issues of the 21st century," Lee asserts. "We hope this will provide an opportunity for a structured conversation about the role values play in these issues."

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By Leda Zimmerman, MITEI correspondent

MIT community samples rich menu of 2014 Energy IAP offerings

Date night with a soldering iron, a community fair, and meet-ups with industry experts proved irresistible draws during this winter's Energy Independent Activities Period 2014. Sponsored by the MIT Energy Initiative (MITEI) during January and February, the Energy IAP was designed to "reach out past the typical energy community with activities open and accessible to everybody," according to Ethan Feuer, MITEI's student activities coordinator.

In addition to such credit-worthy classes as Delivering Energy at Scale: Science, Technology, and Sustainable Development, Energy IAP 2014 featured hands-on, student-led, interactive workshops; visits to local businesses; and informal networking events. "We believed that IAP would be a great opportunity to expand our community, and we realized we had to get out there with the kind of programs people would really want to attend," said Feuer.

An important component of MITEI's "big tent" approach was the first-ever competition for mini-grants to support student-run IAP activities. A class taught by graduate students on mesh-less approaches to computational fluid dynamics was one of the winning proposals. Another winner: a carnival complete with bike-powered smoothie makers and renewable bottle bowling, intended to bring together MIT's many energy clubs for the first time.

"It's cool to do hands-on things. That's how you really learn," said Reese Caliman '17, a linguistics major, attending a third mini-grant winning event: the Solar Panel Cell Phone Charger Building workshop run by Fossil-Free MIT. The prospect of manipulating tetchy soldering irons and fragile silicon cells for three evening hours did not deter the dozens of students gathered in the Lab for Engineering Materials. Huddled over his wand, Justin Miller, a fifth-year graduate student in mechanical engineering, admitted, "It was slow going at first, but now I've got the hang of it." And to Mirim Yoo '16 of electrical engineering and computer science, the reward of walking away with a "device that actually works without blowing my phone up" compensated for the difficult hands-on, electrical engineering challenge.

Photos: Justin Knight

At an IAP workshop organized by Fossil Free MIT and sponsored by MITEI, students learn how to assemble solar cells and build battery chargers for their cell phones. The event was supported by a mini-grant awarded in MITEI's first-ever competition for student-led IAP energy activities.

For Fossil-Free MIT, the event showcasing solar power provided the perfect opportunity to generate interest in sustainable energy sources. "We thought it would be fun," said Joel Jean, a third-year graduate student in electrical engineering and a 2011–2012 Siemens-MIT Energy Fellow. "It's also a way to get people together and thinking about climate change and renewable energy." Some students came predisposed to do just that. "I came because I'm from Kenya, and this is really applicable there," said Jerop Kipruto '17. "We have a lot of sunlight, and I just want to know how to build a solar cell."

Close-up on energy careers

Energy IAP 2014 also featured the forum Energy Careers Spotlight: A Day in the Life, which brought in more than 50 participants. "We took a different angle with our career panel this year," said Christie Ko, MITEI's assistant director for member relations. "It was more intimate, featuring more local energy companies and organizations, and it included networking opportunities for participants."

For some of the attendees, learning in detail about the work lives of the six panelists proved eye-opening. "I was surprised by the breadth of careers in energy, from basic research and startups, to architecture, finance, and business," said one forum participant, Chelsea Edwards '17. "It was also exciting to see that you can get started working on energy as an undergraduate and potentially go directly to having an impact."

Among the speakers Edwards singled out were two recent MIT graduates who minored in energy studies and now serve as key personnel at local energy startups: Martha Gross '12 of materials science and engineering, a scientist at Ambri, the maker of liquid metal batteries, and Tim Grejtak '10 of mechanical engineering, an engineer at the solar energy firm Sun Catalytix.

Typical startup workdays often proceed at a relentless pace, Gross cautioned her listeners, but, she said, "I am constantly working on stuff I'm interested in." Grejtak counseled would-be entrepreneurs to "be loud. If anybody asks for something to do in a lab, even if you don't know what you're doing, pipe up. And don't be worried about it going right the first time, since it rarely does."

These nitty-gritty accounts were a revelation for Sayalee Mahajan, fourth-year graduate student focused on thermoelectric systems: "I didn't have any idea of what startups do. It was the first time I explicitly saw what people who work there do every day and what kind of challenges they face."

One theme that emerged during the panel was the importance of seizing opportunities. Panelist Drew Cameron '10 of chemical and biological engineering, now a senior quantitative risk analyst for Constellation Energy, found his way into the energy industry while an undergraduate through a series of internships at Exelon. Harvey Michaels, a lecturer in the Department of

At the IAP workshop, graduate student Neha Mehta (left) and Akhil Nistala '17 solder together solar panels—the first step in assembling their solar-powered cell phone chargers.

Urban Studies and Planning, discussed the best way to take advantage of the new and expanding "opportunity space" of energy efficiency: "Show some leadership," he advised, and make a compelling elevator pitch "about something that could be different from the way it is now."

Flexible career paths

One panelist recounted to rapt listeners how her career nearly foundered on self-doubt. Michele Ostraat, research center leader at Aramco Services Company, confided that 15 years ago she would have found it "physically impossible to get up and speak in front of this room." She was so terrified of flying that she "could not get on a plane." Determined to shed these "serious career inhibitors," Ostraat placed herself "in positions I knew would make me uncomfortable" and eventually learned to conquer her fears. Ostraat also described the potentially stifling influence of colleagues on her professional journey. At one point she had to insist on being considered for a coveted assignment in Saudi Arabia, in the face of her managers' belief she would feel uncomfortable there as a woman. "Follow your passion," she counseled, "and do not let other people make career assumptions for you."

Audience members found encouragement in Ostraat's anecdotes and in her career, which, like other panelists', altered trajectory a number of times. "You actually have chemical engineers working in mechanical engineering, or mechanical engineering students working in biology," said Kristian Fennessy, candidate for a BSA in building technology. "As an architecture major, which is kind of a small field with lots of competition to get jobs, it's good to know I can apply to jobs outside my field and find a footing, a passion, that I'm really interested in."

Other forum participants drew additional takeaways. "The most interesting thing I learned today was that … you have to have a certain flexibility and willingness to go into other fields—and not just dabble in them but become good at them," Fiona Grant '17 commented. "I'm a freshman; I'm thinking materials science," added Victoria Petrova '17. "I realized it doesn't really matter what major you are, you can still go into whatever you want. There are a million different paths to pursue in energy."

At this event, Michele Ostraat made several connections with strong MIT candidates for internships and full-time positions. As a result, Timothy Kucharski—then an MIT postdoctoral research associate—joined her team on April 23, 2014, as a research scientist with Aramco Research Center–Boston, part of Aramco Services Company, a Founding Member of MITEI.

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By Leda Zimmerman, MITEI correspondent

MIT faculty energize launch of Skoltech curriculum

The first-ever classes taught at Skolkovo Institute of Science and Technology (Skoltech) brought an MIT-inspired energy curriculum to Russia in fall 2013 while offering MIT faculty the chance to try new ways of teaching.

Founded in 2011 in collaboration with MIT, Skoltech takes an innovative, experience-oriented approach to education that represents a radical departure for Russian education, which is strong in scientific principles but weak on application, according to Konstantin Turitsyn, the Esther and Harold E. Edgerton Assistant Professor in mechanical engineering at MIT.

"Technology has developed, whereas [the Russian] curriculum has stayed the same," said Turitsyn, who was educated in Russia himself. "That's fine in fields like physics and math that haven't changed that much, but it's a problem for fields related to technology, which is rapidly changing."

To address this deficit and jump-start cutting-edge research and innovation in Russia, Skoltech features a cross-disciplinary curriculum organized along five research areas of critical interest to the country: biomedicine, energy, information technology (IT), nuclear science, and space. Skoltech's energy and IT curricula launched last fall.

"The different organization of Skoltech—where instead of traditional departments, the tracks are structured around some specific problems—that allows you to approach the material in a different way," Turitsyn said. "This was an opportunity to experiment."

Photo: Justin Knight

Amy Glasmeier, professor of economic geography and regional planning, teaches her new Geography of the Global Economy subject at MIT. The subject has a special emphasis on energy systems in transition—including Russia, China, and the United States—and is a direct outgrowth of the class Glasmeier developed and taught at Skoltech in fall 2013.

"Students might erroneously think it's easier to operate in the structure that we have at Skoltech, that the usual strictures that exist in Russia are more difficult, but I think the reverse is probably true," said Amy Glasmeier, professor of economic geography and regional planning and former head of MIT's Department of Urban Studies and Planning. "The Skoltech energy classes last fall required integrating a range of points of view to address complex problems. This is infinitely challenging for both students and faculty," said Glasmeier, who also co-chairs the MIT Energy Initiative's Education Task Force.

Project-based learning

Skoltech's inaugural cohort of students matriculated last academic year, taking their first classes abroad at partner schools, including MIT. Last fall therefore marked the first rollout of the novel Skoltech curriculum, which MIT helped to develop.

Both Glasmeier and Turitsyn taught classes during the fall term and said Skoltech's focus on approaching problems from a systems perspective with an emphasis on hands-on learning is a major advantage of teaching there. "Even for math-intensive classes, you can do projects and make them fun for students," Turitsyn said. "I didn't realize that before."

For example, Turitsyn asked his students to examine a technology, describe its fundamental principles, and then discuss how the technology could be improved. "That turned out to be the highlight of the class," he said. "Students enjoyed this process of bridging the gap between their knowledge of basic scientific principles and actual real-life problems."

Turitsyn taught Energy Physics and Technology, a subject designed to provide students with a foundation in modern energy technologies. For students on the energy track, Turitsyn's course was followed by Glasmeier's class in Global Energy, Decisions, Markets, and Policy, which was intended to illustrate how those technologies fit into the larger social and economic context.

Glasmeier admitted she initially had some apprehension that the experienced scientists and engineers in Skoltech's student body might not be interested in exploring energy issues from a social science perspective. "I found a really different experience entirely," she said. "The students used the class to make connections in their own minds between the experiences that they had had at school, at work, and in real life. It gave them an aperture much larger than the ones they had in terms of how the world works."

'No room for error'

Each class taught at Skoltech is just eight weeks long, divided into six weeks of instruction, one week of assessment, and one week of application, a model that presented both challenges and opportunities to the MIT faculty members.

"If classes are well-organized, it can be a very efficient system," Glasmeier said, noting that the intended sequence enables students to gain skills, learn to apply them, and finally execute a large, collaborative project that synthesizes the material to address a real-world problem.

In Glasmeier's class, for example, students worked on designing a new energy system for China that would reduce that country's dependence on coal. The course culminated with students presenting their findings to Russian energy experts and entrepreneurs at the end of the weeklong application period. "It is very intensive for faculty to do—when you do a six-day project eight hours a day," Glasmeier said. "But the development of capability you see take place in the students is also worth it," she said, adding that the final presentation was extremely well received.

MIT faculty also had to adjust to the compressed time frame at Skoltech. "When you go to a six-week class, you get rid of the redundancy that exists in every class, and that's basically the handoff from one class to the next," Glasmeier said, noting that she had to dive right into core material and rely more heavily than usual on students having a foundation of skills from other classes. "It's much more fun for faculty… but I think it's more difficult. There's no room for error."

While coordinating this handoff presented challenges for the instructors in Skoltech's first term, both Glasmeier and Turitsyn had high hopes for fine-tuning the process in the years ahead. "Courses are never done perfectly the first time, [but] there's a huge opportunity for a lot of coherence," Turitsyn said. Since it's impossible to cover all energy technologies in one six-week class, for example, he intends to focus in the future on the specific technologies that will be needed most by students continuing in Skoltech's energy curriculum, he added.

Ultimately, Glasmeier and Turitsyn both said the experience of working at Skoltech was inspiring and they hope to teach there again in fall 2014. "All the students were really driven by the desire to change the world," Turitsyn said. "It is quite an accomplishment that MIT was able to bring this culture to Russia."

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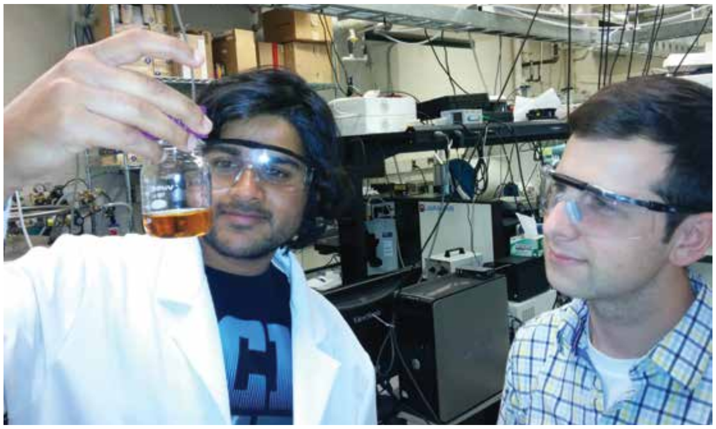
By Kathryn M. O'Neill, MITEI correspondent

Tata Center students seek innovative, affordable solutions to real-world problems in India

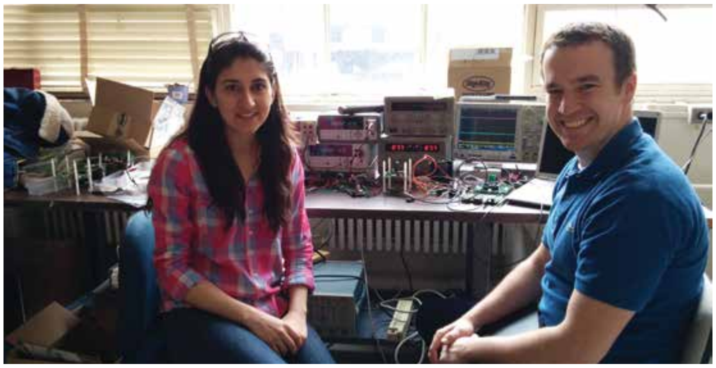
In January 2014, 49 graduate students from the Tata Center for Technology and Design spent four weeks meeting with companies, community members, and policy makers in many parts of India. Their assignment: to identify a specific need or challenge; outline a technically, culturally, and economically viable solution; and team up with a local partner for ongoing collaboration. The Tata Fellows and their MIT faculty advisors are now undertaking projects focusing on energy, water, healthcare, agriculture, and housing. Four of the new energy-related projects are described on this page.

Photo: Giuseppe Romano, MIT



Priyank Kumar (left) and Dr. John McGann, both of materials science and engineering, are synthesizing solar thermal fuels that can provide low-cost, on-demand heat for cooking and other applications. They use specially designed molecules that change shape when exposed to sunlight, assuming a high-energy configuration until they are "jumpstarted" by a small jolt of heat or electricity. They then snap back to their original configuration, releasing heat in the process.

Photo courtesy of the researchers

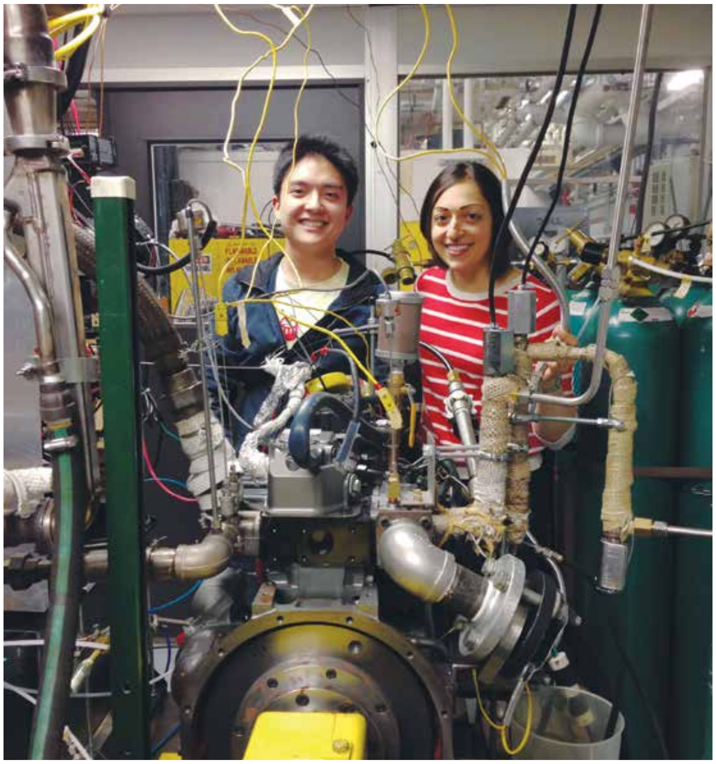


Wardah Inam of electrical engineering and computer science (left) and Daniel Strawser of mechanical engineering are developing uLink, a low-cost, highly scalable power conversion and routing device. The uLink units are used to interconnect households that have excess generating capacity with neighboring households that need it, thereby continuously matching supply with demand. This reduces the need for battery storage and lowers the cost of power for everyone.

Photo: Natasha Wright, MIT

Drip irrigation systems reduce water use and increase crop yields compared to flood irrigation, but they require costly energy for high-pressure pumping. Katherine Taylor of mechanical engineering is designing flexible tubes with controlled shapes and material properties that allow the system to operate at much lower pressures, reducing pumping power and energy consumption. With this technology, solar-powered drip irrigation could become an affordable option for smallholder farmers across the developing world.

Photo courtesy of the researchers



Emmanuel Lim of mechanical engineering (left) and Angela Acocella of engineering systems are developing a small-scale, low-cost process for converting methane gas from organic waste into clean-burning liquid fuels such as dimethyl ether for cooking and heating. Here, they pose with their experimental setup—a conventional internal combustion engine adapted to compress and oxidize methane, producing hydrogen-rich gas, which is later synthesized to liquids.

MIT, Harvard to co-host international sustainability conference

This June, MIT and Harvard University will jointly host the International Sustainable Campus Network (ISCN) conference—an annual gathering of university officers, faculty, and others working to address critical challenges in sustainability both on campus and beyond.

"This is an essential gathering for the field of campus sustainability practitioners in that it gives us time to pause as a global community to exchange ideas and seek input and design scalable solutions for our common challenges," said Julie Newman, MIT's director of sustainability.

The conference, titled Pushing Boundaries: Leveraging Collective Action for Global Impact, will engage experts drawn from the 50 ISCN member institutions worldwide—including universities in Australia, Italy, Japan, Singapore, Sweden, the United States, and elsewhere—to consider how to develop sustainability efforts with global impact through innovation, collective action, and an emphasis on scalable projects.

"We want to be able to both share some of the expertise within our university with an international audience and learn from approaches coming out of peer institutions," said Steven Lanou, deputy director of the MIT Office of Sustainability.

The conference is intended to advance principles identified in the Sustainable Campus Charter, a pledge signed by MIT and 25 other major universities in 2011 to improve sustainability, foster energy efficiency, and reduce waste on campus. Initiated by the Global University Leaders Forum (GULF), a community of university presidents convened by the World Economic Forum to take on pressing global problems, the charter currently has 50 signatories—including (in addition to MIT) Brown, Johns Hopkins, Stanford, and Yale in the United States; Oxford in the United Kingdom; and Tsinghua University in China.

ISCN
International Sustainable Campus Network

The conference is targeting no more than 150 participants to keep the discussions focused and outcomes tangible. It will begin at MIT on June 1, 2014, with a pre-conference workshop for sustainability practitioners that will focus on exploring the future of campus offices devoted to sustainability. "Many offices were created over the last 10 years. It's time now to take stock and recalibrate," Lanou said. "What might the next generation look like and seek to accomplish? We are inviting people to explore that, and challenge them to help shape the future."

The main conference, June 2–4, 2014, will consist of plenary sessions devoted to the four conference themes: pushing boundaries, collective action, impacting globally, and measuring outcomes.

"MIT has positioned itself with Harvard through the ISCN to be a thought leader in the field," said Newman, who serves on the ISCN Steering Committee. Noting that the conference provides an opportunity for international experts in sustainability to develop strategies for addressing universal concerns about water, land, and energy conservation, she added: "This conference renews our sense of common purpose."

While the full speaker list was still being confirmed at press time, MIT Executive Vice President and Treasurer Israel Ruiz and Harvard Executive Vice President Katie Lapp were both expected to address participants on the topic of the role of university/city partnerships to advance sustainability.

The conference will also feature the presentation of awards for sustainable campus projects, and participants will have an opportunity to tour the two host universities. At MIT, the highlight will be a visit to the Institute's two newest green buildings: the MIT Sloan School of Management and the Koch Institute for Integrative Cancer Research, both of which have earned Leadership in Energy and Environmental Design (LEED) Gold certification.

In addition, the ISCN's working groups, which continue collaborative work between conferences, will meet to discuss practical ways to tackle the three ISCN-GULF Sustainable Campus Charter focal areas: buildings and their sustainability impacts; campus-wide planning, goal-setting, and operations; and the integration of research, teaching, facilities, and outreach.

"We are going to step back and reconsider approaches of the past to position our collective efforts going forward," Lanou said. "It's time we looked for more adaptable and scalable models that can be effectively replicated around the world."

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By Kathryn M. O'Neill, MITEI correspondent

MIT Generator launches campus sustainability projects

With nothing but sticky notes and poster boards, MIT students at a three-hour brainstorming session this winter designed and launched six new campus sustainability projects—taking on challenges ranging from composting to carbon emissions.

The MIT Generator event held February 26, 2014, brought nearly 40 students together with MIT facilities and sustainability staff to find practical ways to advance the Institute's goals of integrating sustainability into all facets of operations.

"I thought it was amazing—a very MIT way to solve problems," said Jonathan Krones SB '07, a PhD student in the Engineering Systems Division (ESD), and president of Sustainability@MIT (newly renamed the MIT Sustainability Club), which organized the event along with the MIT Energy Club and the MIT Water Club. "Student projects are a powerful step toward culture change at the Institute."

Students first heard a short presentation on MIT's Office of Sustainability by Director Julie Newman, then quickly got to work exploring their own ideas for improving sustainability in seven categories: energy and climate; food; materials and waste; water; community building; transportation; and other.

Simon Choong, PhD student in chemical engineering and strategic advisor to the MIT Water Club, proposed working to rid the campus of bottled water to cut waste. Caroline Howe, an MCP student in urban studies and planning, advocated for more composting in dorms. The co-chair of the Graduate Student Council's Sustainability Subcommittee, Howe also expressed interest in finding ways to reduce the amount

Photos: Justin Knight

Students at the MIT Generator brainstorm ideas for making the campus more sustainable in the area of materials and waste.

of furniture discarded each year by off-campus students.

ICF-MIT Energy Fellow Michael Davidson, a master's degree candidate in ESD's Technology and Policy Program, said simply: "I'm looking for the biggest bang for the buck on campus." Davidson, whose research centers on modeling renewables integration into the power grid, said he hopes to see MIT provide more comprehensive data on energy use so that students can search for efficiency improvements.

Working at tables arranged by category, the students first developed project ideas in real time to present to the group as a whole. Then participants were invited to team up to pursue endeavors of interest to them. Newman was on hand to provide expert advice, as were Steven Lanou, deputy director of the Office of Sustainability, Peter Cooper, manager of sustainable engineering and utility planning at MIT Facilities, and Ruth T. Davis, manager for communications and sustainability at MIT Facilities.

By the end of the evening, the students had formed six project teams, each with its own action plan. They were:

- **MIT energy data "hackathon"**—working with MIT Facilities to make data on energy and water use in MIT buildings more accessible via a data challenge or hackathon.
- **Green catering**—teaming with purchasers and caterers to reduce the packaging waste generated by catering at MIT, starting with the MIT Sloan School of Management.
- **Tech trash**—improving campus waste bin labeling and signage to increase the amount of waste that is either recycled or composted.

Simon Choong, PhD student in chemical engineering, shares ideas from his small group's discussion on water conservation with other participants at the MIT Generator.

As the MIT Generator gets under way, organizer Jonathan Krones, left, discusses the plan for the evening with Claudio Hail, a graduate student in mechanical engineering.

- **Storm water reuse**—investigating the feasibility of capturing storm water and using it for cooling in the MIT Cogeneration Plant.
- **Tonnes matching**—using a "matching gift" program model, this project would ask members of the MIT community to reduce their own greenhouse gas emissions, with MIT pledging to match those reductions.
- **Sustainability mixers**—organizing monthly get-togethers for those interested in issues of sustainability and providing continued support for the community-building effort begun at the Generator.

Each team was then charged with creating a plan for the semester, identifying funding needs and sources, and finding project partners in the administration and faculty. Teams that made significant progress were invited to share their work with the MIT community and the broader professional sustainability community at the sixth annual MIT Sustainability Summit (sustainabilitysummit.mit.edu), which took place May 3–4 at the MIT Media Lab.

A history of service to MIT

The MIT Generator was first held in 2006—the same year the Institute launched the MIT Energy Initiative—and was organized by two PhD students who have since joined the MIT faculty—Jason Jay PhD '10, a lecturer in the MIT Sloan School of Management, and Elsa Olivetti PhD '07, an assistant professor of materials science and engineering.

Over the years, several useful projects have emerged from the event, including an effort to turn waste cooking oil into biodiesel fuel, a campaign to turn off lights, and a map of campus energy use. "Students often challenge us to look at existing problems in new and innovative ways," Lanou said. "The energy map is an example: It presents information in a way that literally illuminates the challenge with glowing red buildings."

Krones, who participated in the inaugural MIT Generator as an undergraduate, said he thought the time was ripe to reprise the event, last held in 2011. "Since coming back to MIT, I have seen student interest in topics of sustainability on a sharp rise. … At the same time, we've had institutional changes around this topic—for example, the new Office of Sustainability, which is a really magnificent step by the administration and a very real commitment to establishing MIT as a leader in sustainability."

The Generator received support from the MIT Energy Initiative, the MIT Office of Sustainability, and the Sustainability Initiative at MIT Sloan.

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By Kathryn M. O'Neill, MITEI correspondent

MIT researchers describe "energy game changers" at CERAWeek 2014


Photos: Gary Fong/Genesis Photos

MIT and IHS contributors to the keynote session "A Glimpse Over the Horizon: Energy Game Changers from the MIT Energy Initiative" included (left to right) Donald Sadoway, Alexander Slocum, Daniel Yergin, Angela Belcher, Louis Carranza, Robert Armstrong, Vladimir Bulović, and Jamey Rosenfield (IHS senior vice president).

Each year, IHS CERAWeek (ceraweek.com) brings together an international group of industry, policy, technology, and financial leaders for one of the world's preeminent energy conferences. The MIT Energy Initiative (MITEI) was the sole academic institution invited to partner in IHS CERAWeek 2014. MIT researchers played leading roles in several sessions throughout the week.

The highlight event was a keynote session on March 6, 2014, that spotlighted cutting-edge research by four MIT energy researchers: Professor Angela Belcher spoke on transportation fuel made from converted methane, Professor Donald Sadoway on liquid metal batteries, Professor Vladimir Bulović on transparent solar cells, and Professor Alexander Slocum on floating wind turbines combined with energy storage.

Led by MITEI Director Robert Armstrong and moderated by IHS Chairman Daniel Yergin, the keynote session—"A Glimpse Over the Horizon: Energy Game Changers from the MIT Energy Initiative"—underscored the important role universities play in the innovation pipeline as incubators of talent and technology.

One explanation for MIT's unusual success in playing this role is its tradition of broad collaboration across disciplines, which MITEI helps to facilitate, said Armstrong. Belcher, the W.M. Keck Professor of Energy, echoed that sentiment.

"In terms of creativity and pushing new ideas forward, for me it's always been about collaborations. That's been something that's so easy to do at MIT," Belcher said. "You can walk across the hall or across campus and you'll find someone to whom you can say, 'I have this crazy idea.' And they'll say, 'Yes, and here's a way to make it better.' I think the exchange of ideas and the collaborative interaction have been very valuable to my career."

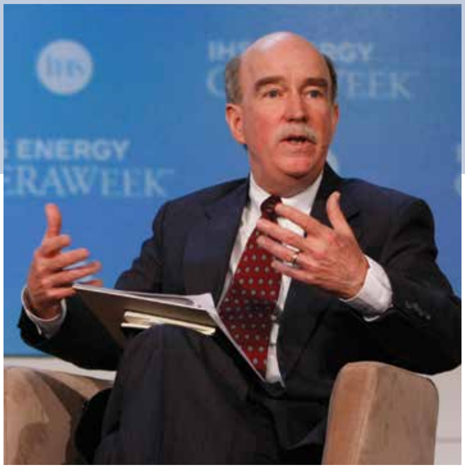
Armstrong and all four panelists also agreed that MIT students are another driving force.

"We admit a brand new set of people each year who come in and are very skeptical of what we're doing and ask lots of hard questions," said Armstrong. "That helps us to keep a fresh view of what we do in research."

Sadoway, the John F. Elliott Professor of Materials Chemistry, said the students encourage professors to think bigger: "A lot of the motivation for tackling important causes has come from the students. Young people today are interested in careers with meaning.... They ask us to work on problems that have huge impacts. They want to know, 'What is the ripple effect?' And that triggers me to look for tougher problems."

Slocum, the Neil and Jane Pappalardo Professor of Mechanical Engineering, commented on the importance of working as a team. "We're all in there shoulder to shoulder...and the freshman is encouraged to ask the *herr doktor professor,* 'Why is that so? That doesn't make any sense!' And I scratch my head and say, 'Gee, I don't know. Let's go back and check!'"

Once these students graduate, they go out into the world and make a difference, said Bulović, the Fariborz Maseeh (1990) Professor of Emerging Technology and the MIT School of Engineering's associate dean for innovation. "Universities have two products: knowledge and people, and our best product is people. [Alumni] are the best thing we make," he said.



Robert Armstrong, MITEI director, notes that working closely with industry collaborators helps MIT faculty identify and pursue research problems that will have a high impact on society's needs.

University-industry collaboration

While "A Glimpse Over the Horizon" focused on the important role of universities in driving innovation, a dinner on March 5 centered on the significant challenges involved in moving innovations out of the lab and into the marketplace. The event explored the role of collective intelligence and crowd sourcing; changing models for innovation; the shifting roles of companies, universities, and public and private capital; and strategies to more effectively identify and scale up next-generation breakthrough energy technologies.

The need for universities to collaborate with industry was a main topic of both the dinner and the following day's keynote panel.

"Our job often ends up being to discover and to train," said Bulović. "The discovery can be done even better when we work with industry....Those are the best connections to the real world because we finally are able to understand what it is that the company needs and what it is that we can solve for them. I'm convinced from what I've seen from my 14 years at MIT that we can solve any problem. We just need to know what the problem is."

During the keynote session, Angela Belcher, the W.M. Keck Professor of Energy, describes how her MIT research group draws on biology and biological processes to create self-assembling solar cells and batteries as well as clean transportation fuels.

Because of industry's important role in helping researchers design technologies that are more competitive in the marketplace, MITEI made industry collaboration a founding principle—one based on a long tradition at MIT. With help from industry, MIT has developed a culture of turning technologies into products. The four researchers from the Thursday panel alone have founded seven startups and hold more than 200 patents.

MIT researchers also gave their expert insight and analysis on several panels throughout the week. Topics addressed included shale gas and associated environmental concerns; public attitudes toward unconventional oil and gas activity; competition between gas and oil for transportation; and mitigation of operational risks and building resiliency within the energy system.

MITEI Associate Director Louis Carranza commented, "Our objective for the conference was simple: to draw attention to the faculty and their research, to MITEI and to MIT. We wanted to show how the work that's done here is very much rooted in the real world and to demonstrate that MIT is providing leadership across a range of energy challenges—and we wanted to inspire."

For more details plus videos from the conference, go to mitei.mit.edu/news/ihs-ceraweek-2014-mit-researchers-present-energy-game-changers.

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By Vicki Ekstrom, MITEI

MITEI analysis: Grid reliability and the role of natural gas

The reliability of the electricity grid is a serious concern for the United States and one that is being amplified by the system's recent increased reliance on natural gas–fired generation. Over the last decade, the share of natural gas-generated electricity has doubled. Its use is expected to continue to increase as regulators look to reduce carbon emissions by replacing coal with gas, which provides the same amount of power with half the emissions. Additionally, natural gas is a key backup for intermittent renewables such as wind and solar power.

If the role of natural gas in providing our nation's power is to increase further, there must be greater flexibility and better integration between the natural gas and electricity markets, according to a new MIT Energy Initiative (MITEI) analysis. The report discusses the challenges that arise from the growing interdependency of natural gas infrastructure and the electricity system and presents possible solutions for the policy, investment, and energy communities. It is based on a 2013 MITEI symposium.

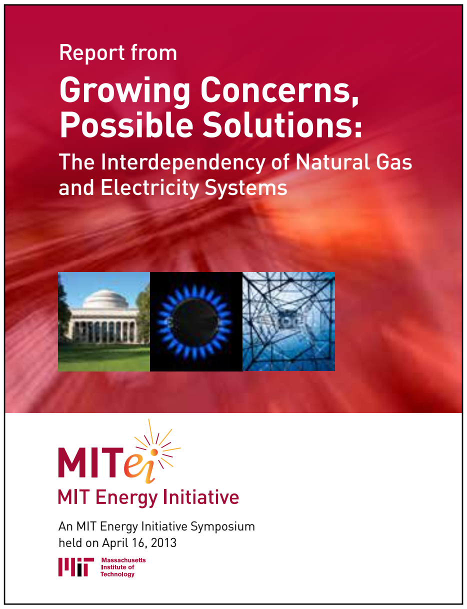
"Substantial policy changes, particularly in the energy sector, don't happen overnight. That's why the industry needs a portfolio of solutions, at both the regional and federal levels, to mitigate short-term challenges while laying the groundwork for long-term change," says Richard Schmalensee, the Howard W. Johnson Professor of Economics and Management Emeritus at the MIT Sloan School of Management, who wrote a report overview for policymakers.

The report notes several special challenges that natural gas presents when it is used for electric power. Unlike coal, where onsite storage is possible, natural gas-fueled plants have limited to no storage capacity and are entirely reliant on pipelines for fuel delivery. Because of geographic constraints, regulatory hurdles, and economic barriers, underground storage and LNG facilities will likely not become a major presence. Additionally, while coal can be delivered by rail from essentially anywhere in almost any quantity, natural gas is limited to the capacity of the given pipelines. To increase deliverability, existing pipelines need to be expanded or new pipelines need to be built. Both options present regulatory hurdles.

"Pipeline constraints can cause dispatch difficulty and in some cases even outages in systems heavily reliant on natural gas," says Francis O'Sullivan, director of research for MITEI and a main author of the report. "Natural gas is a just-in-time fuel, exacerbating the challenges between it and the electricity sector. But there are steps that can be taken to add in resiliency and reduce the risks that power won't be available when it's needed most."

To provide more predictable and reliable power at natural gas plants, the report suggests incentivizing dual-fuel capabilities at new power plants, using fuels with separate supply chains. Additionally, given a growing need to meet demand in real time with little or no storage, the report advises improving the coordination and communication between the natural gas and electricity markets.

"Currently, the two markets operate on different schedules, leading to quantity uncertainty for generators, price increases for consumers, and reliability risks for the grid," O'Sullivan says.



"More effort needs to be made to sync the electricity market with the national gas market, especially when it comes to the market schedules."

Schmalensee agrees.

"The supply and demand landscape is rapidly changing. To meet these changing needs, both the natural gas and electricity sectors need to adapt," says Schmalensee. He notes that the problems, and in turn the solutions, that each region faces depend on local markets, regulations, and political will. "While federal actions could help address some overarching challenges, what's really needed is a portfolio of solutions to address regional challenges."

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By Vicki Ekstrom, MITEI

To download a copy of the report, go to mitei.mit.edu/publications/reports-studies/growing-concerns-possible-solutions.

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 129 seed grant projects across the campus as well as fellowships for nearly 300 graduate students and postdoctoral fellows in 20 MIT departments and divisions.

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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; and outreach activities, including seminars and colloquia.

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New building will be a hub for campus-wide nanoscale research

Starting in 2018, the 200,000-square-foot building in the artist's rendering shown above will provide central cleanroom, imaging, and prototyping facilities for MIT researchers who work at the nanoscale to address challenges in energy, health, computing, and more. Located at the heart of campus, the building—called MIT.nano—will support the activities of some 2,000 researchers, including hundreds who are using nanoscale materials, processes, devices, and systems to make game-changing advances in the field of energy. In keeping with the Institute's commitment to sustainability, MIT.nano is being developed with many energy-saving features, including creatively designed air-filtering systems that will maintain cleanroom standards while minimizing energy consumption.
Image courtesy of Wilson Architects