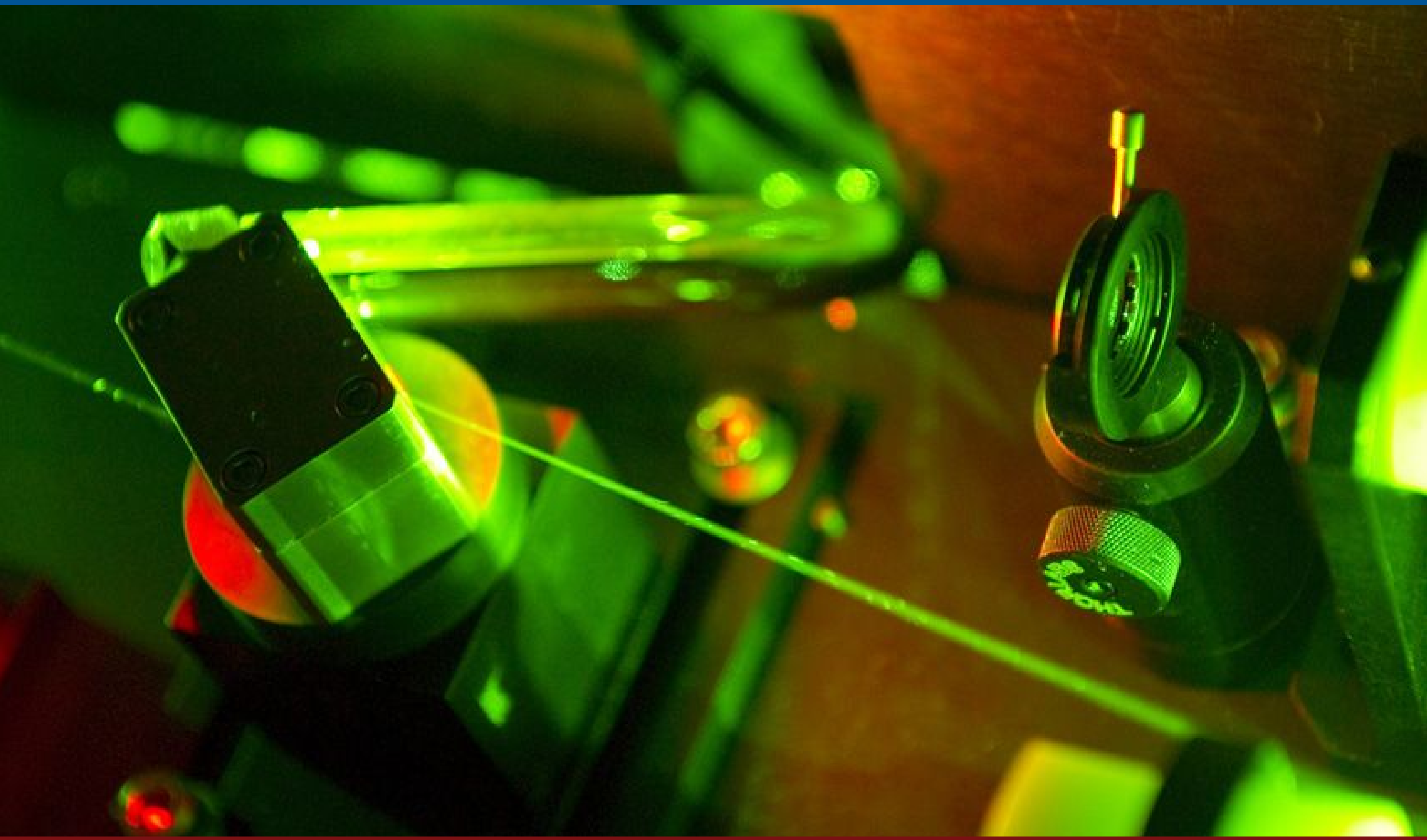
Energy Futures

MIT ENERGY INITIATIVE · SPRING 2010



New Eni-MIT center brings high-tech tools to solar research

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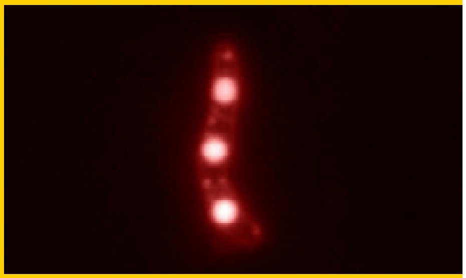

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Energy Futures

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MITEI MEMBERS

Update on the MIT Energy Initiative

Dear Friends,

Three words capture the focus of MITEI's work since our last update in fall 2009—innovation, education, and outreach. All three support our core mission: to help speed transformation of the global energy system to a low-carbon future and to help improve today's energy systems as a bridge to that end.

The importance of innovation was underscored by December's Copenhagen conference, where the world's leaders met to address global climate change. The goal of achieving a binding international treaty for limiting greenhouse gas emissions was not realized. Indeed, some believe that—post-Copenhagen—this goal appears even further away. That outcome provides additional impetus for MITEI's work on synergistic technology, business-model, and policy innovation that will lower the cost of clean, low-carbon energy options and accelerate their diffusion into the marketplace.

During the last semester, MITEI worked with its members and MIT faculty to "fill the innovation pipeline" in multiple ways. MIT faculty garnered more than 10% of the second round of US Department of Energy ARPA-E awards, which are intended to move clean technologies with high impact potential from the laboratory to private capital investment over a few years (see page 20). The MITEI Founding and Sustaining Member programs are now beginning to generate results and make them public. For example, work supported by Founding Member Eni has led to new biologically constructed catalysts for water splitting, and research funded by Founding Member BP has yielded a patent for a gasification system that achieves high efficiency while separating carbon dioxide for easy capture. We continue to welcome new MITEI members such as Sustaining Member Weatherford and several affiliate members.

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

Farther "upstream" in the pipeline, MITEI awarded a new round of seed grants, bringing the total to 67 novel and early-stage innovation projects funded principally by our members, with additional support from donors (see page 21). Once again, the seed grants ushered new faculty into MITEI participation, among them Assistant Professors Cynthia Rudin (Management), who will advance machine learning for electric system reliability, and Evelyn Wang (Mechanical Engineering), who will examine nanofilm-based thermal management for concentrated solar systems. We estimate that nearly 25% of MIT's faculty are now engaged with MITEI in some capacity.

Research awards from a separate seed fund program have been made under the auspices of the Low Carbon Energy University Alliance, a research collaboration among MIT, Tsinghua University in China, and Cambridge University in the United Kingdom (see page 22). This issue of *Energy Futures* presents further description of these and other research activities, including detailed results from five earlier MITEI seed grant projects (see the feature stories starting on page 6).

Energy education at MIT is being significantly enhanced by another source of support: philanthropy. Two substantial gifts, one from the S.D. Bechtel, Jr. Foundation and the other from an anonymous alumnus, are advancing the development of MIT's novel energy minor. Many incoming freshmen for next fall indicated an interest in the energy minor, and these gifts are enabling the creation of energy classes, projects, and teaching materials that will impact students and faculty both within and beyond MIT (see page 27).

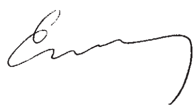
MITEI's campus energy management program has benefited from both philanthropy and a first-of-its-kind utility partnership. The Silverman Evergreen Energy Fund, established by Jeffrey Silverman '68 in 2009, is being used to improve energy efficiency on campus and includes opportunities for capturing the savings from these measures and reinvesting them in technologies and activities that further reduce energy demand on campus. That effort was subsequently enhanced by a significant gift from David desJardins '83 (see page 31). In May, MIT and its electric utility, NSTAR, announced an ambitious three-year partnership to reduce MIT's electricity use by 34 million kilowatt-hours, or 15%, through innovative efficiency and conservation activities; substantial student, faculty, and staff engagement; and the piloting of new technologies and approaches.

MITEI's outreach continues to provide industry leaders, government policy-makers, and other interested parties with technically grounded analysis and information. Examples of outreach to advance critical understanding include *An Action Plan for Cars,* produced by a team led by Professor John Heywood (Mechanical Engineering—see page 40), and a symposium on the electrification of the transportation system, sponsored by four MITEI associate members. In addition, later this year we expect to release the results of multi-year, multidisciplinary analyses of the future of natural gas, of nuclear fuel cycles, and of solar energy.

We also support "inreach" to the campus. A recent featured visitor was His Serene Highness Prince Albert II of Monaco, who discussed his Antarctic trek and the importance of that continent as a "canary in the coal mine" for the global impacts of climate change. Campus forums facilitate community discussions of critical energy topics. Notable was the "The Road from Copenhagen" forum at which MIT Professors Henry Jacoby (Management), Edward Steinfeld (Political Science), and Michael Greenstone (Economics) were joined by Harvard Professors Robert Stavins (Government) and Stephen Ansolabehere (Political Science) to lead a discussion of the actions taken at Copenhagen and their implications for the energy future (see page 36).

The support, hard work, and commitment of all of MITEI's friends and participants are what makes this level of activity possible, and we are grateful for all that you do. We hope that you enjoy this fifth edition of *Energy Futures* as a snapshot of some of the outcomes that will help shape our energy future.

Sincerely,



Professor Ernest J. Moniz
MITEI Director

Professor Robert C. Armstrong
MITEI Deputy Director

June 2010

Photos: Justin Knight

Paolo Scaroni, left, CEO of the Italian energy company Eni S.p.A., and MIT President Susan Hockfield cut the ribbon to celebrate the opening of the Eni-MIT Solar Frontiers Center, headquartered on the MIT campus. (More on page 4.)

During a presentation to the MIT Energy Club on December 9, 2009, Arun Majumdar, director of the Advanced Research Projects Agency-Energy (ARPA-E), announced the creation of the ARPA-E Fellows Program for postdoctoral students and recent PhD graduates. He later addressed an invitation-only MIT Energy Initiative Salon for MITEI members, faculty, and local dignitaries. (More at web.mit.edu/mitei/news/spotlights/majumdar-announce.html.)

On April 13, His Serene Highness Prince Albert II of Monaco visited MIT to share his observations on the potential impacts of global climate change, based on his visits to both the North and South Poles. The prince later attended a salon hosted by the MIT Energy Initiative in his honor at the MIT Museum. (More at web.mit.edu/mitei/news/spotlights/continent-warning.html.)

New Eni-MIT center brings high-tech tools to solar research

Eni CEO Paolo Scaroni and MIT President Susan Hockfield at a press conference held during the inauguration of the Eni-MIT Solar Frontiers Center.

The Eni-MIT Solar Frontiers Center (SFC) unveiled facilities May 4 that will provide researchers around the Institute unprecedented opportunities to test new materials, integrate their work, and pinpoint new directions for groundbreaking advances in solar energy.

The new laboratories and meeting space in Building 13 mark the next step in an ongoing partnership between the Italian energy company Eni S.p.A. and MIT. In early 2008, the two began a far-reaching collaboration aimed at transforming global energy systems through advanced solar energy technologies. The new facilities are expected to speed the progress of MIT's solar technology advances and to evaluate and validate their potential in the marketplace.

"If only 10% of what I have seen in MIT laboratories materializes, it will change the world," said Eni S.p.A. CEO Paolo Scaroni at ribbon-cutting ceremonies at MIT. Scaroni said solar power is a promising choice to help replace hydrocarbon-based fuels in the coming century. Eni, a founding member of the MIT Energy Initiative (MITEI) and a supporter of solar-related research across MIT, intends to lead the fields of innovation and advanced technologies in renewable energy, he said.

"The pairing of Eni's long-term strategic vision and MIT's incredible capacity for innovation has the potential to fundamentally transform how the world produces and consumes energy," said MIT President Susan Hockfield.

Hockfield, Scaroni, and Ernest J. Moniz, director of MITEI and the Cecil and Ida Green Professor of Physics and Engineering Systems, spoke at ceremonies inaugurating the SFC's new Photovoltaics Characterization Laboratory. "Having a central hands-on facility where students can gather for an interactive exchange of information is invaluable for the MIT solar research community," said SFC co-director Vladimir Bulović, professor in the Department of Electrical Engineering and Computer Science.

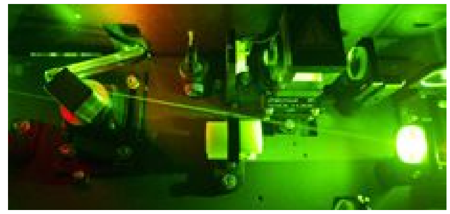
In addition to the SFC, Eni supports projects in energy research at MIT on traditional hydrocarbons, methane hydrates, global climate change, and transportation options. The alliance with MIT has a duration of five years and involves a financial commitment from Eni for $50 million in total, equally distributed between the Solar Frontiers program and other MITEI projects.

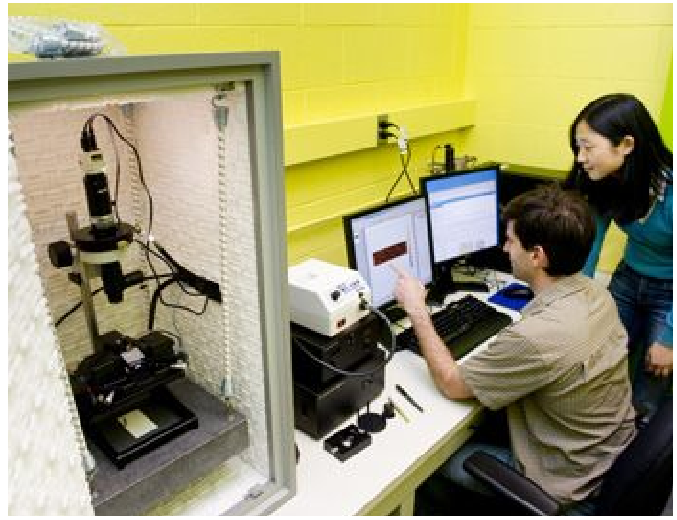
The Eni-MIT Solar Frontiers research program focuses on initiatives ranging from the development of photovoltaic (PV) devices to designing solar plants that are economical to build and operate.

"What Eni has brought to the table is an unprecedented ability to make testing and evaluation assessments about materials and instruments in a standard way," said Daniel G. Nocera, the Henry Dreyfus Professor of Energy, professor of chemistry, and co-director of the SFC. "The research initiated two years ago with the inauguration of the center is now maturing. There are tremendous numbers of MIT students working in concert with Eni with a heavy emphasis on solar energy capture and conversion."

More than 20 MIT faculty and 40 graduate students will use the new labs to develop and test solar devices and materials—some that capture sunlight on their own and some that boost the performance of existing silicon-based structures. The sun's energy can be

Left to right: Salvatore Meli, executive vice president, Research and Technological Innovation, Eni; Ernest Moniz, director of the MIT Energy Initiative (MITEI); Umberto Vergine, senior executive vice president, Studies and Researches, Eni; Melanie Kenderdine, executive director, MITEI; Nicola De Blasio, vice president for R&D International Development, Eni, and MIT visiting scientist; and Robert Armstrong, deputy director, MITEI. Moniz and Vergine are holding up solar cells deposited on paper substrates with electrodes shaped as logos of Eni and MIT.





Photos: Justin Knight

Above left: Professor Vladimir Bulović (right), SFC co-director, explains to Eni CEO Paolo Scaroni the coating process that Professor Karen Gleason's and his group used to deposit on paper a solar cell that has an "Eni"-shaped electrode. Above center: Graduate students Jill Rowehl (left) of materials science and engineering and Patrick Brown of physics use the new ultra-fast laser—shown above right in close-up—to examine how electrons in nanomaterials for solar cells behave when blasted by pulsed light of well-defined wavelengths. Right: Postdoctoral associates Alexi Arango (left) and Ni Zhao of the Research Laboratory of Electronics use the new SFC atomic-force microscope to study the surface texture of a nanostructured thin film.

captured and stored in fuels and batteries, while efficiently converting the sun's rays into electrical current involves the innovative adoption of PV materials. Capture, conversion, and storage must work together to make solar energy a viable global power source.

"We now have a place where people working around campus in mechanical engineering, chemistry, materials science, electrical engineering, and other departments can perform a standard assessment of the performance of their inventions. This capability is missing in solar energy research performed in separate laboratories or with off-site collaborators that all use different assessment standards and tools. These components must work together to be effective," Nocera said.

Maximizing returns

The Photovoltaics Characterization Laboratory will provide:

- specialized equipment such as powerful lasers to conduct precise solar measurements under controlled environmental conditions;
- a standard method of device testing that will enable researchers to share data measured under identical conditions across different device platforms;
- an atomic-force microscope with the ability to measure the electronic structure of nanostructured PV cells and the electronic behavior within them at the level of individual atoms and molecules; and
- thin-film device growth and fabrication capabilities not otherwise available to SFC researchers on campus.

"With these tools, we can discern the fast dynamics of photons and electrons within solar cells, we can identify which processes are working and which are not, and then produce the next set of devices using only the most effective structures," Bulović said. "Measuring the electronic phenomena within nanostructured materials is the key for informing the design of improved devices."

Partnerships across disciplines

The new laboratory and conference space builds on partnerships among Eni and MIT researchers, Nocera said. The photovoltaics lab's dedicated research equipment is expected to enhance effective hybrid solutions in separate but related fields of interdisciplinary solar energy research at MIT, he said. "We've had a lot of great results. The next step is to integrate, and that's what the lab is allowing us to do. It makes a lot of sense that this is coming on line now at this stage of research, when we're at a point of system integration, focused on how we actually make a device that embodies the progress in multiple laboratories."

"What's unique about the lab is that it brings Eni and MIT people together on common ground, taking different projects and integrating them along a path toward forward-looking technology," Nocera said. "That's the exciting thing for me."

• • •

By Deborah Halber, MITEI correspondent

Tailored lighting: Reducing wasted watts

Imagine walking down a dimly lit hall and having lights above you get bright as you pass and then go dim again. If you stand still, the lights stay on—no need to wave your arms around. After you leave, the lights go off, saving energy now often wasted on lighting unoccupied spaces.

Key to this scenario is a new MIT "proximity detector" that uses a fluorescent lamp's own electric field to determine when someone is present. The detector easily fits into existing or new light fixtures, with no need for extra power or specially installed control networks. Since each light has a detector, the system can turn on one or a few lights in an overhead bank of fluorescents, tailoring the lighting to the locations of individuals in the room.

The potential energy savings of such tailored lighting could be considerable, especially in the residential and commercial sectors, where operating lights consumes about a third of all the electricity used. That high consumption is a concern to Steven Leeb, professor of electrical and mechanical engineering and a MacVicar Faculty Fellow. To demonstrate, he points to his office ceiling, where 400 to 800 watts of lighting is running all the time. "That's an appalling number if you think, for example, that a 400-watt radio station could serve a small town," he says.

He and graduate students John Cooley and Al-Thaddeus Avestruz and undergraduate Daniel Vickery, all of electrical engineering and computer science, are therefore trying to find opportunities to take those fixtures and watts and use them to provide other functions—with no interruption or distortion in the primary function of delivering light. "It's an approach we call dual use," Leeb says. "We take energy or information from an electrical appliance and use it for another purpose. In this case, we wouldn't change the quality of the light but would add another feature that might help save energy."

The feature they are adding is the ability to detect the presence of people nearby. They could use that information to control heating and air conditioning systems based on occupancy or to act as a security system to look for intruders. But their primary focus has been on using it to shut off unnecessary lights—in particular, fluorescent and other "gas-discharge" lamps that produce about half of the artificial light in the United States in all sectors.

Using motion sensors to detect occupancy and control lighting is hardly a new idea, but current systems have several drawbacks. They typically involve a wired network of controllers that is difficult and expensive to install and requires extra electricity to operate. To minimize expense, a single motion sensor may control all the lights in an area—an inefficient approach if the room is large and sparsely occupied. Finally, they depend on motion rather than presence, so if occupants remain still for too long, the lights may turn off.

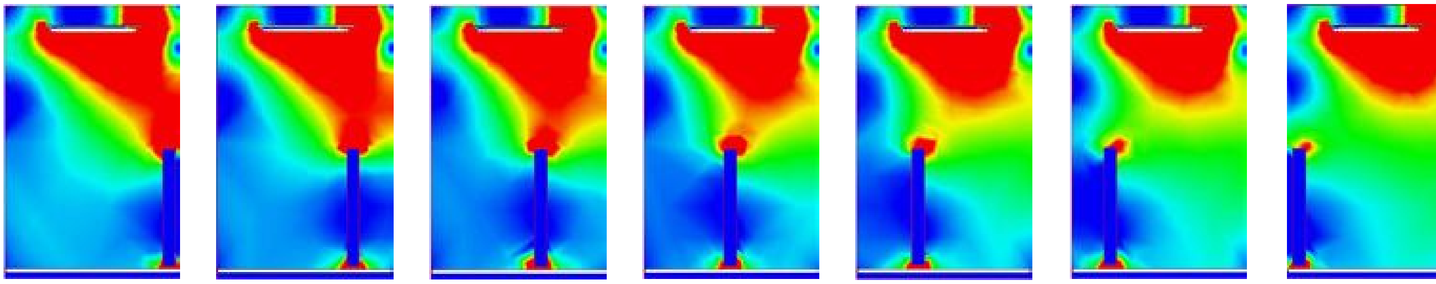
With their new device, Leeb and his students address all those problems, and they do it by using as their detector a naturally occurring phenomenon—the electric field that permeates the space around an operating electric-discharge lamp. Put a person in that space, and the electric field changes. The change is tiny but detectable.

Monitoring natural interactions

The key is that we are all slightly capacitive, that is, we can hold and conduct electric charge—a fact that Leeb demonstrates with a simple example. Think of walking across a carpet, touching a doorknob, and getting a shock. As you walk along, says Leeb, you scrape up electrons and accumulate charge. Touching the doorknob "closes the circuit," creating a return path for that charge, and electrons jump to the knob as a spark. You've been discharged.

When a person enters the electric field around a fluorescent lamp, he or she becomes part of a very complicated circuit that involves interactions between the person and the lamp, the lamp and the walls, the walls and the ground, the ground and the person, and more. So the electric field can be viewed as the result of a complex circuit that is connected from every conductor to every other conductor. Therefore, as one conductor—the person—moves around, the electric field in the area changes.

The students designed and built a device that can detect such changes in the electric field and control the light accordingly. Their detector—a simple circuit board—replaces the conventional lamp ballast and is connected to two electrodes mounted several feet apart on the cover of the light fixture. Measuring an electric field requires finding the voltage simultaneously at two points—here the two electrodes—and then calculating the difference between them. By monitoring that difference over time, the students' device can detect small changes in the electric field when a person walks by.



Images: courtesy Steven Leeb, MIT

These images are the result of a computer simulation of the researchers' proximity detector in action. The vertical dark-blue bar is a six-foot-tall conductive column representing a person. The bright horizontal bar at the top represents the fluorescent lamp. The colors indicate the calculated strength of the electric field around the lamp. In the series of photos, the "person" walks from right to left below the lamp, in the process causing a significant disturbance in the electric field. The images on page 8 show what happens when a real person follows the same pathway in front of a prototype detector.

Included in the device is a "software layer"—computer programming that interprets the observed changes. For example, it knows to reject certain types of changes as false and therefore not relevant. It knows when to turn the light full on or back to dim. And it knows when a person is present but standing still—or is standing exactly between the electrodes so that the difference in their measurements is zero. The key: the person cannot get to the middle without going by one of the ends, and the detector remembers.

"It's very clever about the changes it looks for," says Leeb. And he stresses that it is perfectly safe. "We haven't changed the light at all or changed the interaction between any object in the room and the light," he says. "All we've done is put in a detector."

Simulations and demonstrations

Computer simulations of the device have produced images such as those shown above. The lamp is at the top, and the vertical bar at the bottom is a six-foot-tall conductive column representing a person. The colors represent the strength of the electric field in the region of the lamp. The series of images shows how the "person" walking under the lamp disturbs the electric field.

The research team has constructed two prototype detectors. One hangs vertically inside a two-bulb fixture for testing in a real-world configuration, while the other is mounted horizontally and can easily be moved for experimentation and demonstration.

Tests with the horizontal prototype confirm its ability to detect a person walking by. The photos and figure on page 8 present sample results. As the person walks by the lamp, the voltage difference measured by the detector goes up. It then goes back down, returning to neutral—here about –62 millivolts—when he reaches the mid-point. The voltage difference goes down as he passes by the other half of the lamp and then back up toward neutral as he leaves. The system begins to detect the person at a distance of 8 to 12 feet—plenty of time for the lamp to brighten and create a pool of light to guide the way.

The researchers have also tried using their device with dimming ballasts. The detection system demonstrates high sensitivity even when the lamp is dimmed to just 1.3% of its maximum power. That outcome implies a 98.7% power savings for each lamp while it is dimmed.

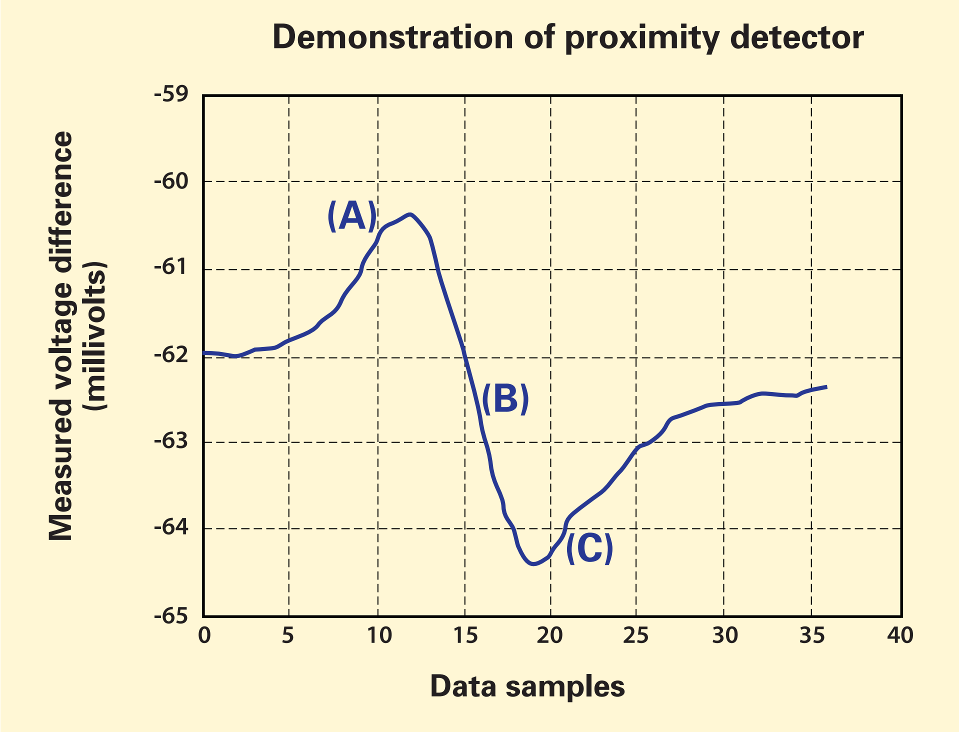
Looking to the future

They are now working on a wireless link that will enable communications between adjacent lamps so that a single lamp can command a cluster of auto-dimming lamps. Such command lamps could be distributed throughout a space to achieve a desired lighting scheme.

They are investigating two schemes for large rooms with many overhead fluorescents. In one scheme, all the lights are turned on but dimmed, and each one contains the proximity-sensing electronics. If an occupant is detected below any lamp, that lamp turns full on until the person moves away. In the other scheme, only some of the lights in an array are left on for sensing. The others are turned off but are linked by a wireless network to the ones with sensors. If a sensor in a light detects an occupant, it turns on the adjoining lights. Critical to this scheme is careful spacing of the lights with the sensors to get full coverage of the room, leaving no "blind spots" where a person would not be detected.

"Giving fluorescent lights the ability to respond to the presence of people is just the first step," says Leeb. "Now we're working to define lighting profiles for specific settings that will ensure the comfort and safety of the occupants

These photos show project director Professor Steven Leeb walking in front of a prototype fluorescent lamp equipped with the proximity detector. The curve below shows the output voltage from the detector, with letters marking positions corresponding to the photos. As Leeb walks by, the output goes up and then down, returning to neutral (about –62 millivolts) when he reaches the midpoint. The output then goes down as he passes the other half of the lamp and finally back up toward neutral as he leaves. While the change in voltage is small, the device sends a clear message that somebody is nearby.



while minimizing energy consumption. We're also looking at adding photosensors that will control the levels of lighting as appropriate to the time of day or ambient light. And we're working to extend our approach to solid-state lighting based on LEDs. The energy savings should be significant."

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By Nancy W. Stauffer, MITEI

This research was supported by a seed grant from the MIT Energy Initiative, by the US Department of Energy, and by the Grainger Foundation. More information can be found in:

J. Cooley, A. Avestruz, and S. Leeb. *An Autonomous Distributed Demand-side Energy Management Network Using Fluorescent Lamps*. IEEE Power Electronics Specialists Conference, Rhodes, Greece, June 2008.

J. Cooley, A. Avestruz, S. Leeb, and L. Norford. *A Fluorescent Lamp with Integral Proximity Sensor for Building Energy Management.* IEEE Power Electronics Specialists Conference, Orlando, Florida, June 2007.

Engineering fat-making bacteria: A road to plentiful biodiesel

An MIT team is getting to know a little-studied bacterium that consumes materials ranging from soil contaminants to corn husks and stores them as globules of fat ideal for making biofuels. Using a variety of approaches, the researchers have been gaining insights into the biological processes and genetic pathways that control that conversion, enabling them to further enhance the bacterium's fat-making ability.

Best of all, they are converting the fat into fuels that—unlike ethanol—contain enough energy per liter to be used in trucks, trains, ships, and even airplanes. "We're already making fat from our bacteria into jet fuel," says Anthony Sinskey, professor of biology and director of the research. "We're going to fly an airplane on it!"

As the nation struggles to replace fossil fuels used in transportation, much attention has focused on ethanol and hydrogen. But Sinskey's team is instead aiming for biodiesel, a fuel with several advantages. It has a much higher energy density than ethanol has (see the chart above right). It does not have the national security issues—or the pollutant emissions—associated with diesel made from petroleum. And unlike hydrogen, it is a "drop-in" fuel. "We already have the infrastructure for transporting, storing, and pumping biodiesel and the vehicle engines that can burn it," says Sinskey.

Most people making biodiesel start with a fat called triacylglycerol, or TAG. Familiar sources of TAGs include leftovers from deep fat fryers and grease traps, fats from meat rendering, and vegetable oils. The conversion to biodiesel is so simple that people are doing it in their garages and barns, according to Daniel MacEachran, a postdoctoral associate in the Department of Biology. As a bonus, TAGs can also be converted into jet fuel. "But we're never going to power the country or the world on grease traps and animal renderings," says MacEachran. Growing algae on biomass is another non-food approach to producing TAGs, but the technology is still under development, and there are problems to be solved.

Energy values for various transportation fuels

• Ethanol	22–24	MJ/liter
• Gasoline	32–35	MJ/liter
• Petro-diesel	36.4	MJ/liter
• Biodiesel	33–36	MJ/liter

Bioenergy Feedstock Development Program, Oak Ridge National Laboratory

Fat-producing bacteria

Another natural source of TAGs is bacteria. Give bacteria lots of carbon (crop waste and the like) and not much nitrogen, and they will store excess carbon for future use. In about 90% of bacteria, the stored carbon is in the form of a polymer, which some members of the Sinskey Lab are using to make "bioplastics."

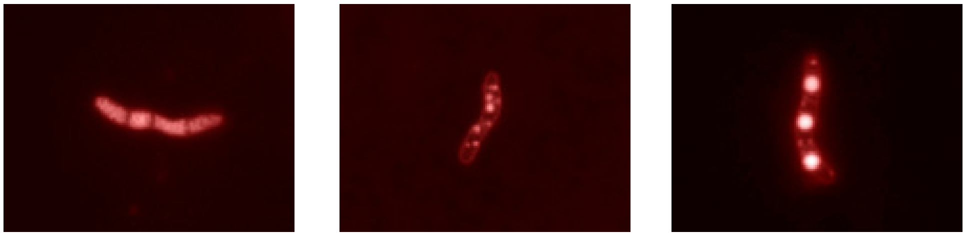
But a small group of bacteria instead stores the carbon in the form of TAGs, and one of them that does it really well is *Rhodococcus opacus.* This bacterium is not well understood and is more difficult to work with than, say, *E. coli.* But it grows quickly; it is not pathogenic; and it produces remarkable quantities of TAGs—in some tests, as much as 75% of its dry weight. Moreover, it can metabolize a wide range of carbon sources. Indeed, it was first found growing on hydrocarbon contaminants in sand at a gas works facility in Germany. "So these bacteria not only survive but actually thrive on compounds that would kill most other organisms," says MacEachran.

Expanding their appetites

In the ideal fermentation process, *Rhodococcus* would quickly and completely consume mixtures of carbon "feedstocks" and produce large quantities of TAGs. But there are some things that even this bacterium does not eat. One of them is xylose, a key constituent—along with glucose—of the cell walls of plants. If *Rhodococcus* bacteria are going to consume cellulosic sources such as corn stover and switchgrass, they need to metabolize xylose as well as glucose.

To achieve that goal, Kazuhiko Kurosawa, a research scientist in biology, turned to genetic engineering. He took carefully chosen genes from bacteria that naturally metabolize xylose and inserted them into *Rhodococcus*. The result: a strain of *Rhodococcus* that metabolizes xylose to produce TAGs. Better still, this new strain consumes glucose and xylose at the same time and at about the same rate. Most bacteria, if presented with two carbon sources, will consume first one and then the other, with a lag in growth as they switch gears in the middle. Because Kurosawa's organism "co-utilizes" xylose and glucose, there is no pause to switch gears, so the overall rates of growth and fat production are dramatically higher—and all the feedstock is consumed.

In addition, the bacterium makes about the same amount of TAGs on the mixture as it does on glucose or xylose alone, and the composition of the TAGs is the same. "So there must be



Images: courtesy of Daniel MacEachran, MIT

An MIT team has been working to understand the genetic pathways whereby the bacterium *Rhodococcus* converts crop waste and other carbon materials into large quantities of fat—or "lipids"—ideal for making biodiesel and jet fuel. Here, they show the effect on lipid formation of a gene they isolated and dubbed *tadA*. In each case, the lipids glow with a fluorescent dye. The left-hand image shows a natural, unaltered *Rhodococcus* bacterium. The bacterium in the middle image lacks the *tadA* gene, while the one in the right-hand image has excess *tadA*. It appears that this gene's primary role is not in making lipids but rather in controlling how they are stored.

some common intermediate that's formed from all carbon feedstocks, and that intermediate—not the feedstock itself—controls the TAGs synthesis," says Sinskey. "That's an interesting phenomenon."

Identifying fat-making genes

Another approach to increasing *Rhodococcus's* ability to metabolize carbon and make fat is to work with the bacterium's own genes. The challenge there is to determine which genes play a role in producing and storing TAGs and to define exactly what each gene or set of genes does. As a critical first step, Jason Holder, postdoctoral associate in biology, sequenced the genome of *Rhodococcus opacus,* identifying all of the DNA and more than 7,000 genes that make up its chromosome.

MacEachran then developed a genetic screening technique to locate the genes of interest. The technique involves the use of a "transposon," a short stretch of DNA that can integrate anywhere among the genes on a chromosome. The presence of the transposon disrupts the function of whatever gene it happens to land in. So if a *Rhodococcus* bacterium is exposed to a transposon and then stops or slows its production of TAGs, the transposon has landed in a gene essential for TAG metabolism. Sequencing the DNA of that bacterium will show where the transposon—with its recognizable DNA—is located and therefore which gene has been affected.

But many genes are likely to play a role in TAG metabolism, so MacEachran developed a "high-throughput" screening technique. He uses a transposon that carries resistance to the antibiotic kanamycin. He takes a batch of bacteria—billions of individual cells—and mixes them with a batch of transposons. Most of the bacteria cells will remain unchanged, but a small fraction will pick up a transposon. When the cells are exposed to kanamycin, only those containing a transposon will be immune to the kanamycin and so will live.

In a painstaking process, the researchers then separate the remaining cells, spread them out on a plate with glucose, and let them divide and replicate to form distinct colonies. Each colony will contain tens of thousands of identical cells, every one with a transposon in the same location in its genome. The colonies are next grown under carefully optimized high-carbon, low-nitrogen conditions and then stained with a chemical dye that is readily absorbed by fat. Most of the colonies become dark—a sign that the transposon has not interfered with their production of TAGs. But a few will remain pale. In those colonies, the transposon has lodged in and disrupted a gene that plays some critical role in the formation of TAGs.

Key genes: What do they do?

That screening technique has permitted the researchers to identify a set of genes that affect TAG formation. "But now we have to do the hard science of characterizing each gene and figuring out exactly what role it plays in TAG metabolism," says MacEachran.

He has been particularly intrigued by a gene he calls "*tadA*" (from "TAG accumulation defective"). Genes similar to the *tadA* gene have been found in several other organisms that also make fat, but its exact function is unknown. "No one else has worked on *tadA* before, so we're moving into new territory," says MacEachran.

To get a closer look at *tadA*, he uses a technique called fluorescent microscopy combined with a dye called Nile red. Within a bacterium, TAGs are contained in large spherical structures known as lipid bodies. Those lipids readily take up Nile red and become fluorescent, thus easily differentiated from the rest of the cell under the microscope.

The images above show three types of *Rhodococcus* bacteria, each with its lipid bodies appearing as glowing spheres. At the left is the "wild type," a natural, unaltered *Rhodococcus* bacterium. The lipids are fairly uniform in size and distribution. The bacterium in the middle image lacks the *tadA* gene. Now there are both small and large lipids, and rather than being uniformly distributed, they appear stuck to the walls. The right-hand image shows a bacterium that contains lots of extra *tadA* gene. Now there are massive lipid bodies that sit right down the middle of the cell.

Taken together, these observations suggest that the *tadA* gene's primary role may not be in making fat but rather in storing it. "Losing the *tadA* gene seems to mess up the organism's ability to assemble the lipids properly," says MacEachran. "And having too much of it produces big, single lipid bodies. So we believe that this gene produces a protein that acts as sort of a shepherd to pull all of the lipid bodies together into fewer, larger bodies."

Continuing investigations

The researchers are continuing to gain insights into the workings of their bacterium. Studies of "neighbors" of *tadA* show that those genes also influence lipid body structure, each one in a slightly different way. And analyses of similar genes in other organisms suggest a model for certain *Rhodococcus* genes that may help lipid bodies attach to one another and coalesce. Further screening has identified genes involved in the actual production of TAGs.

The feedstock studies also continue. The researchers have now tested almost 200 carbon sources, looking for low-cost, high-yield ones that could improve process economics. They have identified specific components in feedstocks that inhibit cell growth and interfere with TAG production. And they have engineered a strain of *Rhodococcus* that metabolizes glycerol, a waste product of biodiesel production. With the engineered strain, the glycerol could be recycled as a feedstock for more biodiesel production.

Finally, Sinskey and his team are working with industry to develop TAG-extraction methods that will yield highly enriched TAG fractions and low concentrations of products known to interfere with the conversion of TAGs into biodiesel. In addition, they are examining chemical and biological catalysts for converting TAGs to fuels and are working to scale up production.

If all goes as planned, Sinskey estimates that within a few years the *Rhodococcus*-based biofuels will be commercially available as a viable, sustainable alternative to today's petroleum-based transportation fuels.

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By Nancy W. Stauffer, MITEI

This research was funded by a seed grant from the MIT Energy Initiative; by Shell International Exploration & Production, Inc.; and by Logos Technologies, Inc. More information can be found in:

K. Kurosawa, P. Boccazzi, N. de Almeida, and A. Sinskey. "High glucose cultivation of *Rhodococcus opacus* PD630 in batch-culture for biodiesel production," *Journal of Biotechnology*, in press 2010.

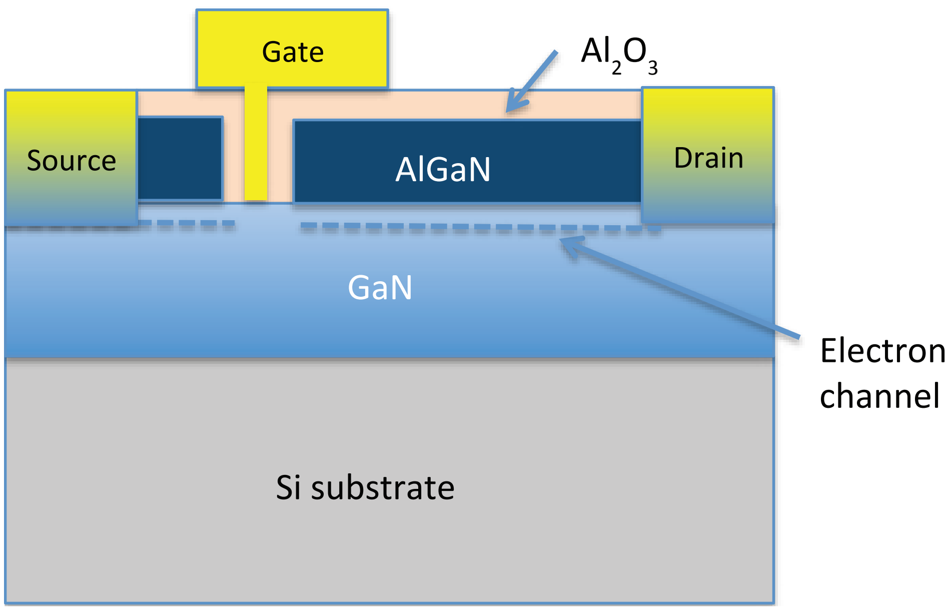
Improving the transistor: Small device, big energy savings

MIT researchers have designed a new transistor that could significantly reduce wasted electricity whenever voltage must be modified, for example, when recharging a laptop or hooking solar panels into the power grid. Widespread use of the novel transistor could cut US electricity consumption as well as give new life to emerging energy technologies ranging from electric cars and solar cells to revolutionary power generation and transmission systems.

Power electronics are used to change the form of electrical energy to match a given need. In particular, many new electronic devices and energy technologies require switching alternating current (AC) to direct current (DC) or vice versa. For example, batteries and solar cells deal only in DC. Therefore, recharging a laptop or cell phone battery requires changing the AC electricity coming from the wall outlet to DC. Conversely, connecting solar cells to the power grid and running the motor in an electric car both require converting DC to AC. At a larger scale, high-voltage DC transmission lines can transfer large amounts of power with lower electrical losses than AC lines can, but their use is now limited because converting DC to AC is expensive.

"Power electronics are used in many different places in our lives," says Tomás Palacios, assistant professor of electrical engineering and computer science. "But any time you transform electricity, there are always energy losses—and with today's devices, those losses are high." If we could reduce the losses in all power electronic circuits, Palacios says, we could save between 10% and 20% of the total electricity now used in the United States. And if we could make the power electronics small, we could integrate them into the equipment that needs them. Small, efficient power electronics that could switch AC to DC and back again would be a game-changer for electric cars, power grids, renewable energy technologies—indeed, for the world's ability to meet the overall energy challenge.

MIT's novel gallium nitride power transistor



This schematic shows a novel MIT transistor based on the semiconductor gallium nitride (GaN). Electrons enter via the source terminal (upper left), flow through the layer of GaN, and exit via the drain terminal (upper right). A small electrical charge on the gate terminal (center top) regulates the flow. To reduce costs, the transistor is built on an inexpensive silicon (Si) substrate. Other design features prevent electrons from escaping within the device, so electrical losses are low. And when there is no charge on the gate, the electrons stop flowing—a critical safety feature not typical of other GaN transistor designs now being considered. (See text for details.)

To help improve power electronics, Palacios and graduate student Bin Lu of electrical engineering and computer science are working on one of the key components—the transistor. This basic building block can serve as either a switch or an amplifier; it can turn on and off or increase or decrease the current flowing in an electronic circuit.

A transistor consists of several layers of semiconductor linked to the circuit by three terminals. The electrons that carry the electric current enter the transistor through the first terminal (called the source). They then travel through a region of the semiconductor called the channel and exit via the second terminal (the drain). A small electrical charge on the third terminal (the gate) influences the channel's ability to conduct electricity. A transistor thus uses a small charge to regulate the flow of a large current.

How well the transistor performs depends in large part on two properties of the semiconductor. First, it must have low resistance so electrons can flow through it with ease. Any impediment to that flow produces heat, which translates into wasted electricity. Second, the semiconductor must be able to handle high voltages without "breaking down," that is, without allowing the current to jump from the source to the drain as a spark. If the breakdown voltage of the semiconductor is high, the source and drain can be located close to one another without sparking; as a result, the transistor can be smaller, which permits the overall power circuit to be smaller and more efficient.

According to Palacios, the desired properties can be found in a family of compounds and alloys based on nitride semiconductors. Gallium nitride (GaN), for example, is a relatively new semiconductor that has a resistance 100 to 1,000 times lower than the best semiconductors now being used commercially. In addition, its breakdown voltage can be 10 times higher than in conventional devices.

However, despite their promise, GaN-based transistors for power electronics are not yet commercially available. Palacios cites three problems with the designs now being considered. First, the best devices to date are grown on a substrate of silicon carbide, an extremely expensive material. Second, in those devices, electrons can escape from the channel via the gate terminal, thereby being lost from the circuit. And finally, if there is no charge on the gate, electrons continue to flow through the transistor. That characteristic—known as being "normally on"—is a safety hazard. If, for example, the gate stops functioning while a laptop is recharging, household current could flow at full voltage into the computer and quickly destroy it.

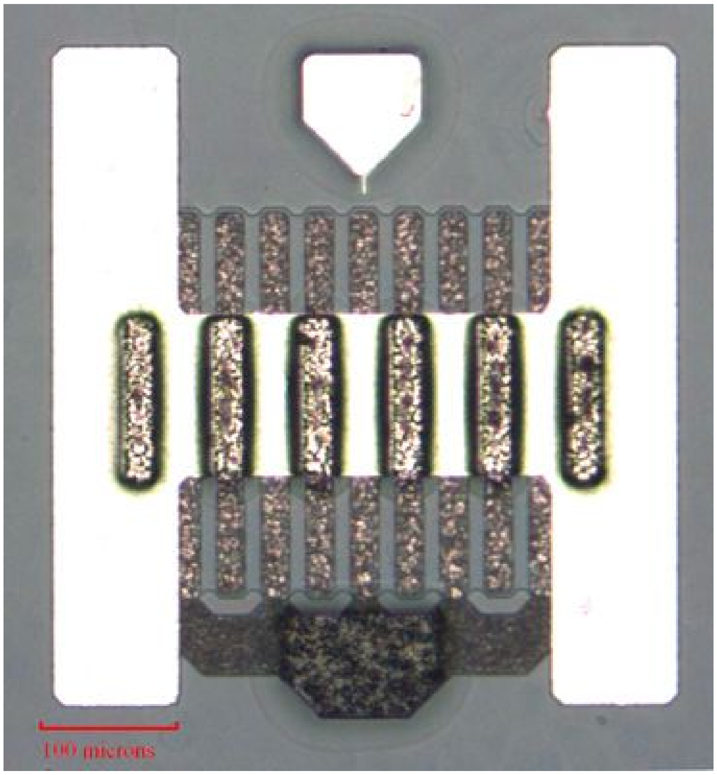


Photo: Daniel Piedra G, MIT

Top-view optical micrograph of one of the gallium nitride power transistors fabricated at MIT.

The MIT design

Palacios and his team therefore set three goals for their GaN transistor: to use a less expensive substrate, to keep resistance low while preventing electrons from escaping via the gate, and to make a device that is "normally off." They have now achieved all of those goals.

Their design is shown on page 12. Electrons—indicated by blue dashes—enter through the source at the upper left, pass through the GaN semiconductor, and exit through the drain at the upper right. The amount of charge on the gate at the top regulates the flow of electrons from the source to the drain.

Specific features address the researchers' three goals. To bring down costs, they build their transistor on a silicon substrate similar to that used by much of today's electronics industry. It is inexpensive and can be manufactured using standard technology for making commercial silicon chips.

To lower the resistance in the GaN channel, the researchers put a layer of aluminum gallium nitride (AlGaN) on top of the GaN. That layer produces a high density of electrons in the GaN just below the GaN/AlGaN interface, easing the flow of current through the channel and reducing the total resistance of the device. "The electrons really like to move through the GaN very close to that interface," says Palacios. In addition, to prevent electrons from going into the gate contact, they add a thin layer of a dielectric—aluminum oxide (Al_2O_3), a highly insulating material that completely stops the flow of electrons to the gate.

Finally, they have developed a new fabrication technology—called "dual-gate technology"—to make the transistor normally off. Traditional approaches to achieving normally off transistors involve thinning down the AlGaN layer under the gate. That change reduces the electron density in the GaN channel to the point that electrons will not flow in the absence of charge on the gate. However, that approach introduces very high resistance, which leads to heating and thus energy losses in the device.

To overcome this problem, the MIT researchers make the gate "T" shaped and then omit the AlGaN layer completely from a very narrow region beneath the foot of the T (see the drawing on page 12). Because no AlGaN is deposited in that region, no electrons are left near the interface; and when there is no charge on the gate, current no longer flows. But the removed section of AlGaN is less than 100 nm—just wide enough to create the normally off conditions but still so narrow that it does not significantly increase the resistance of the transistor. And because the thin layer of Al_2O_3 insulator separates the gate from the channel in that region, when electrons do flow, they cannot escape to the gate.

Fabricating prototypes

Palacios and his team have now successfully achieved each step needed to fabricate their novel transistor. They have developed methods of using thin layers of GaN on silicon wafers, of depositing the Al_2O_3 insulator, and of fabricating normally off transistors using the new dual-gate technology. Tests of initial prototypes confirm that their device is normally off and that electrons are effectively confined to the channel near the GaN-AlGaN interface. "In fact, our preliminary measurements show that the electrons move along that channel 10 times faster than they do in other power devices," says Palacios.

Encouraged by results to date, Palacios is already in discussion with other MIT researchers who might benefit from the small, efficient power electronics made possible by the new GaN transistor. Among the possibilities: new circuit designs for high-efficiency inverters and converters for the power industry, power modules for hybrid-vehicle and fuel-cell technologies, and—because of their tolerance for high temperatures—high-performance power electronics for new solar concentrators.

"With our new devices we should be able to maximize and optimize power conversion and add more intelligence to current and new power systems at a wide range of voltage levels," says Palacios. "Transistors and power systems are ubiquitous, so the potential for saving energy and developing and implementing new energy technologies is substantial."

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By Nancy W. Stauffer, MITEI

This research was funded by a seed grant from the MIT Energy Initiative and by the US Department of Energy. Further information can be found in:

B. Lu and T. Palacios. "New enhancement-mode GaN HEMT based on dipole-Engineering." *IEEE Electron Device Letters*, forthcoming 2010.

B. Lu, E. Piner, and T. Palacios. *High-Performance Dual-Gate AlGaN/GaN Enhancement-Mode Transistor.* Presented at the 37th International Symposium on Compound Semiconductors (ISCS), Kagawa, Japan, May 31–June 4, 2010.

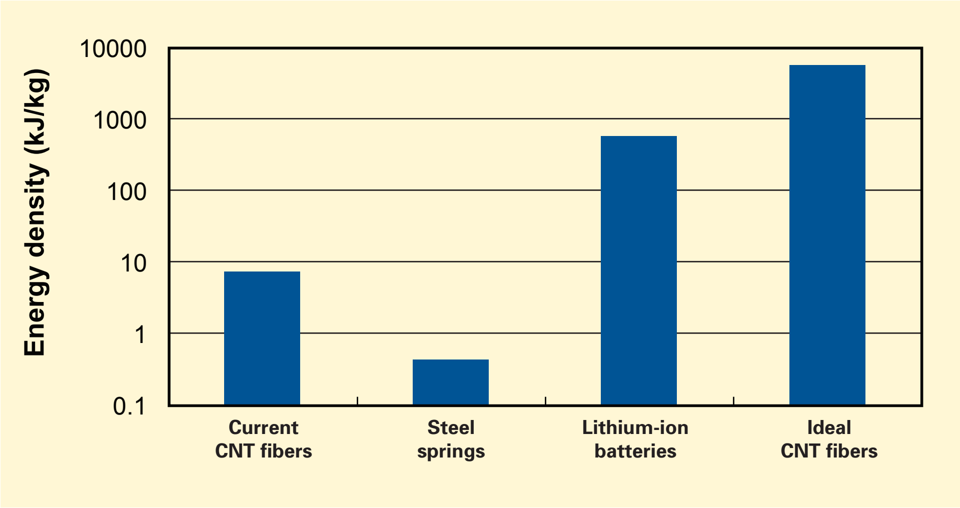
Small springs could provide big power

New research by MIT scientists suggests that carbon nanotubes—tube-shaped molecules of pure carbon—could be formed into tiny springs capable of storing as much energy, pound for pound, as state-of-the-art lithium-ion batteries, and potentially more durably and reliably.

Imagine, for example, an emergency backup power supply or alarm system that can be left in place for many years without losing its "charge," portable mechanical tools like leaf blowers for yard clean-up that work without the noise and fumes of small gasoline engines, or devices to be sent down oil wells or into other harsh environments where the performance of ordinary batteries would be degraded by temperature extremes. That is the kind of potential that carbon nanotube springs could hold, according to Carol Livermore, associate professor of mechanical engineering. Carbon nanotube springs, she found, can potentially store far more energy for their weight than steel springs can (see the chart on this page).

Indeed, theoretical analysis performed by Livermore, graduate student Frances Hill of mechanical engineering, and research affiliate Timothy Havel SM '07 showed that the carbon nanotube springs could ultimately have an energy density—a measure of the amount of energy that can be stored in a given weight of material—more than 1,000 times that of steel springs and comparable to that of the best lithium-ion batteries. Laboratory tests by the same team plus A. John Hart SM '02, PhD '06 demonstrated that the nanotubes really can exceed the energy storage potential of steel.

Energy density of selected energy storage devices



The bar on the left shows the energy density of "current" carbon nanotube (CNT) fibers now being prepared and tested by MIT researchers. The bar at the far right shows the energy density of "ideal" CNT fibers, as predicted by their analytical studies. As the central bars show, the energy density of the researchers' CNT springs already exceeds that of steel springs and may eventually exceed that of typical lithium-ion batteries—with the added advantage of potentially higher durability and reliability.

With a snap or a tick-tock

For some applications, springs can have advantages over other ways of storing energy, Livermore explains. Unlike batteries, for example, springs can deliver the stored energy effectively either in a rapid, intense burst or slowly and steadily over a long period—as exemplified by the difference between the spring in a mousetrap and in a windup clock. Also, unlike batteries, stored energy in springs normally does not slowly leak away over time; a mousetrap can remain poised to snap for years without dissipating any of its energy.

For that reason, such systems might lend themselves to applications for emergency backup systems. With batteries, such devices need to be tested frequently to make sure they still have full power, and the batteries must be replaced or recharged when they run down. But with a spring-based system, in principle "you could stick it on the wall and forget it," Livermore says.

Carbon nanotube springs also have the advantage that they are relatively unaffected by differences in temperature and other environmental factors, whereas batteries need to be optimized for a particular set of conditions, usually to operate at normal room temperature. Nanotube springs might thus find applications in extreme conditions, such as for devices to be used in an oil borehole subjected to high temperature and pressure, or on space vehicles where temperature can fluctuate between extreme heat and extreme cold.

"They should also be able to charge and recharge many times without a loss of performance," Livermore says, although the actual performance over time still needs to be tested.

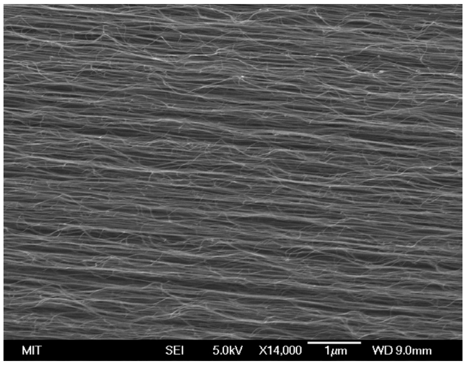


Image: courtesy of Frances Hill G, MIT

The springs tested in this work consist of fibers made of densely packed arrays of carbon nanotubes, harvested from multi-walled carbon nanotube forests grown by thermal chemical vapor deposition. This scanning electron microscope image shows the long, aligned arrays of carbon nanotubes that make up each fiber. Each carbon nanotube has an outer diameter of 10 nm and four to five inner shells.

She says that the springs made from these minuscule tubes might find their first uses in large devices rather than in micro-electromechanical devices. For one thing, the best uses of such springs may be in cases where the energy is stored mechanically and then used to drive a mechanical load, rather than converting it to electricity first.

Any system that requires conversion from mechanical energy to electrical and back again, using a generator and then a motor, will lose some of its energy in the process through friction and other processes that produce waste heat. For example, a regenerative braking system that stores energy as a bicycle coasts downhill and then releases that energy to boost power while going uphill might be more efficient if it stores and releases its energy from a spring instead of an electrical system, she says. In addition to the direct energy losses, about half the weight of such electromechanical systems currently is in the motor-generator used for the conversion—something that would not be needed in a purely mechanical system.

Harvesting carbon nanotubes

To make their springs, the researchers use carbon nanotube "forests." Each forest contains billions of carbon nanotubes grown vertically upward from a flat, one-square-centimeter silicon substrate by thermal chemical vapor deposition. From this forest, they peel off a small strand, creating a fiber of a few million aligned nanotubes. To make the fiber more stable, they increase its density by placing a drop of acetone or toluene on it. As the liquid evaporates, the nanotubes are drawn together by capillary effects. The researchers then stretch the fiber, thereby storing mechanical energy in the strained carbon bonds of each nanotube. To deliver the stored energy to a desired load, they allow the fiber to contract—either suddenly or slowly—so that it returns to its original length.

One reason the microscopic tubes lend themselves to being made into longer fibers that can make effective springs is that the nanotube molecules themselves have a strong tendency to stick to each other. That makes it relatively easy to spin them into long fibers—much as strands of wool can be spun into yarn—and this is something many researchers around the world are working on. "In fact," Livermore says, the fibers are so sticky that "we had some comical moments when you're trying to get them off your tweezers." But that quality means that ultimately it may be possible to "make something that looks like a carbon nanotube and is as long as you want it to be."

Livermore says that to create devices that come close to achieving the theoretically possible high energy density of the material will require plenty of additional basic research, followed by engineering work. Among other things, the initial lab tests used fibers of carbon nanotubes joined in parallel, but creating a practical energy storage device will require assembling nanotubes into longer and likely thicker fibers without losing their key advantages.

"These scaled-up springs need to be large (i.e., incorporating many carbon nanotubes), but those individual carbon nanotubes need to work well enough together in the overall assembly of tubes for it to have comparable properties to the individual tubes," Livermore says. "This is not easy to do."

Livermore and her team are now working on creating new, higher-performing carbon nanotube springs and on demonstrating their use to drive real loads—feats that would make possible many exciting opportunities for their use as flexible, durable, and reliable energy storage devices.

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By David L. Chandler, MIT News Office, with additional reporting by Nancy W. Stauffer, MITEI

This research was funded by an MIT Energy Initiative seed grant and by Deshpande Center for Technological Innovation Ignition and Innovation grants. Further information can be found in:

F. Hill, T. Havel, A. Hart, and C. Livermore. "Characterizing the failure processes that limit the storage of energy in carbon nanotube springs under tension." *Journal of Micromechanics and Microengineering*, forthcoming 2010.

C. Livermore, F. Hill, and A. Hart. "Storing elastic energy in carbon nanotubes." *Journal of Micromechanics and Microengineering*, September 2009.

C. Livermore, F. Hill, and T. Havel. "Modeling mechanical energy storage in springs based on carbon nanotubes." *Nanotechnology*, June 2009.

Urban metabolism: Helping cities make scarce basic resources go further

Many cities in developing regions of the world are facing critical shortages of water, energy, and other basic resources—and those shortages will rapidly intensify as their populations explode in coming decades. To help alleviate such hardship, MIT researchers are working with leaders in the Ica region of Peru to develop two interacting computational models that will help them find ways to use their limited resources more efficiently and to take best advantage of their abundant natural sources of energy, including sunshine, wind, and waves.

In related work, the MIT team is using the same analytical techniques to study resource flows in ancient cities as a possible window into how our post-fossil-fuels cities may look.

Much discussion is focusing on making cities in the industrialized world sustainable. Buzz words include zero-energy buildings, photovoltaic installations, and plug-in hybrid cars. Such attention is well warranted, according to John Fernández, associate professor of building technology, because over the next three decades, 95% of population growth worldwide is projected to occur in cities, adding another 2.5 billion people to today's 3 billion city dwellers.

But the vast majority of those new city dwellers will live in developing countries, where concern focuses on providing the basics—food, water, housing, and the like. "The greatest growth in urban population will be in the most resource-constrained areas of the world," says Fernández. "The limits that those regions will face are like nothing we will see in the industrialized world. It's a whole different level of discussion."

Faced with "crippling resource limits," planners and engineers in such cities desperately need tools to help them make design, planning, and technology decisions that ensure the most efficient use of the resources they have. Such tools could also help them find ways to make their cities more resilient to shocks such as earthquakes and other crises that may interrupt the flow of goods to a populace likely to live close to the margin in good times.

Focus on Peru

One place with an urgent need for such planning tools is the Ica region of southern Peru. The coastal cities in that region are net exporters of natural resources, including oil, natural gas, and copper, but they are nevertheless extremely poor—and in 2007 they were devastated by a series of earthquakes. In January 2008, teams from MIT began working with researchers and government leaders in Peru to help with the redevelopment process, and two things became clear: managing flows of resources to ensure their most efficient use is critical, and a tool to guide policymakers in achieving that goal would be invaluable.

Accordingly, Fernández has been developing a computational model that will enable leaders in Peru—and in cities worldwide—to see the impacts of possible policy options on the availability of critical resources. He has been working closely with academic researchers, local communities, and government officials in Peru to formulate the essential architecture of the model.

The work builds on a concept known as urban metabolism, which uses a holistic view of the way cities consume resources. "Think of a city as an organism that consumes raw materials, fuel, and water and generates waste," says Fernández. "How does this complex organism use the raw materials that it acquires—and can it use them more efficiently?"

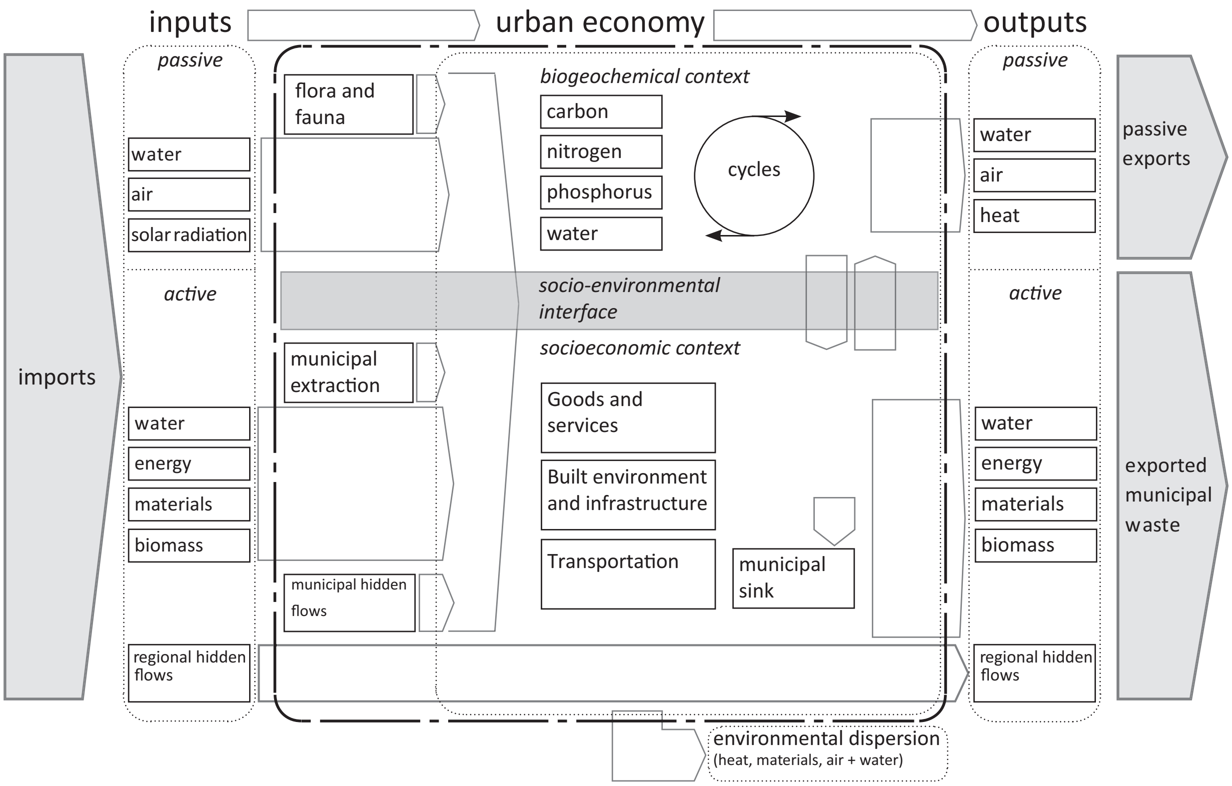
To answer those questions, Fernández and his collaborators use a methodology called materials flow analysis (MFA) to create a physical accounting (in measurable quantities such as weight or volume) of specific resources entering, passing through, and leaving a city and—most important—exactly how they are used within the city limits. A diagram of the MIT model appears on page 18.

The system boundary is the city itself—the "urban economy." The top half is the "biogeochemical context," the bottom half, the "socioeconomic context." The MIT work focuses mainly on the socioeconomic section.

Entering from the left are all the imports. "Active inputs" entering the urban zone are water, energy, materials (fuel and non-fuel), and biomass. Adding to those bulk materials is the "municipal extraction" of sand, gravel, and the like within city bounds. Three fundamental urban activities drive all of those resource flows, namely, goods and services, the built environment and infrastructure, and transportation. Those three activities are the result of anthropogenic action—of people making decisions and acting on them.

Most of the material inputs leave the urban boundary as outputs. The largest portion of materials remaining in the urban space is used in the making of buildings and infrastructure. This addition to the durable stock accounts for the material legacy of our society. Some waste remains in the "municipal sink" as well (for example, material put into landfills), and soot and other pollutants are left behind in the air.

MIT urban materials flow framework



"Environmental dispersion" accounts for natural processes that remove heat, materials, air, and water out of the urban zone.

A final item among the active inputs is "regional hidden flows," which measures resources that simply pass through the city—for example, if the city is a port. Those inputs may produce significant financial flows but no net physical flows of materials.

The top half of the diagram encompasses passive flows through the urban economy—flows not activated by human decisions. The natural inputs include water (groundwater, rain), air, and solar radiation. Those inputs are affected by the behavior of flora and fauna within the city and by natural biogeochemical processes, including the carbon, nitrogen, phosphorus, and water cycles. Passive outputs are water, air, and heat.

In presenting the model framework, Fernández notes the "socio-environmental interface" between the top and the bottom of the diagram. That interface permits passive inputs to move to the active part of the model, and vice versa. "With MFA, we can define how a city can take advantage of passive flows, for example, using solar radiation to run solar-thermal and photovoltaic systems to generate power," says Fernández. "Such uses of passive flows can make a city greener and less dependent on the availability of active flows such as fossil fuels."

Taking a closer look

Identifying the flows and uses of resources in a city is only the first step. The next questions are: Where are the potential savings in this system? And where in this system would intervention be most practical?

To answer those questions, the MIT researchers apply another modeling technique—system dynamics—to specific resources flowing into the three urban activities within the MFA model. System dynamics is designed to handle complex systems that change over time, with interlinked components that influence one another and feedback loops that drive how the system behaves.

One system dynamics model, for example, tracks iron as an input for construction and examines the potential for savings by increasing reclaimed or recycled iron. In the model, iron flows into construction, which—controlled by the demand for housing—generates the housing stock. Iron is embedded in the housing stock until a building is demolished. Then, based on the current price of iron, the iron becomes demolition waste or is reclaimed. The reclaimed iron once again becomes an input for construction—or it can be sent to an iron stockpile within the city.

With such an analysis, policymakers can explore different ways to deliver and maintain raw materials and can assess the possibility of stockpiling resources as a means of making their city more resilient to supply interruptions. "It may not be practical for a lot of materials," notes Fernández. "How do you store material that's useful and valuable now for some possible future occurrence? But having a means of identifying what stocks should be stored and having an explicit program for doing it can be critical."

Next steps—and broadening the view

The MIT team is now working to implement their new model using data for the cities of southern coastal Peru. Getting verifiable and rigorous data on specific resources is proving to be the biggest challenge so far, according to Fernández. He and his collaborators are using every source of data they can find, both formal and informal. In some cases, they extrapolate from national data; in others, they use economic data as a proxy. For example, if an average purchasing power has been defined for a given demographic, they assume that those people buy a certain amount of food, wood, textiles, and so on.

Meanwhile, they are using their analytical framework for other applications. In one project, Artessa Saldivar-Sali, a graduate student in MIT's Department of Architecture, is developing a "typology" of cities and deriving resource profiles for each type. She is surveying 500 cities worldwide, grouping them according to their basic attributes (for example, location, climate, population, and development level), and then developing a resource profile appropriate for all the cities in a given "cluster."

With such a database, policymakers will be able to compare resource flows in their own city with resource flows in other cities in their cluster. If other cities are more resource efficient, they can see not only the potential for improvement but also where the greatest opportunity for making positive change is.

Looking back

In another project, Fernández and his team are using their modeling framework plus archeological data to establish the material and energy flows that served the urban population in an ancient, pre-Incan city called Caral. This 5,000-year-old city, located northwest of present-day Lima, is thought to have been the first large-scale urban center in the Americas. It had a population of many thousands and a sophisticated agricultural economy based on cotton, other plant fiber crops, and textiles.

While it might seem harder to perform MFA for an ancient city than for a modern one, Fernández says that in some ways it is actually easier. "The economy of Caral was much less diverse than today's urban economies are, so there are far fewer products to map. Also, archeologists surveying the site work hard to determine the details of the economy." For example, teams have sifted through waste pits to determine every plant species that was brought in. "That's a whole lot more detail than we can get for a contemporary city of like size in Peru," says Fernández.

He notes that the only good examples we have of truly sustainable cities are the pre-fossil-fuel cities. "Interestingly, results from studying the ancient city of Caral may provide insights into how our post-fossil-fuel, 'sustainable' cities might look in terms of resource flows, houses, products, transportation methods, and so on," he says. "Clues about our pathway forward may be derived from this look backward."

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By Nancy W. Stauffer, MITEI

Research on the urban metabolism of cities—both modern and ancient—in the Ica region of Peru was supported by a seed grant from the MIT Energy Initiative. Additional funding has come from the MIT-Portugal Program. The MITEI seed grant also helped support a two-day workshop in January 2010 at which an international group of people working in urban metabolism began to define common standards and conventions for materials flow analysis. Work to benchmark cities around the world is now being supported by the MIT-Portugal Program. The study of urban metabolism of ancient cities is continuing with seed funding from the Holcim Foundation and funding from an Integrated Research Grant with the Singapore-MIT Alliance for Research and Technology (SMART) Centre. Further information can be found in:

J. Fernández. *Urban Metabolism and a Resource Efficient Built Environment*. Invited lecture. Centre for African Cities, University of Cape Town, South Africa, May 7, 2010.

J. Fernández. *Urban Metabolism of Ancient Caral, Peru.* Presented at the 3rd Forum 2010 Re-Inventing Construction, sponsored by the Holcim Foundation, Mexico City, April 12–17, 2010.

J. Fernández. *Urban Metabolism: Past, Present and Future Resource Flows.* Presented at the Alliance for Global Sustainability Annual Conference, Tokyo, Japan, March 15, 2010.

J. Fernández, P. Ferrão, and L. Rosado. *Unified Methodology for Evaluating Sustainable Consumption Options in an Urban Metabolism Context*. Presented at the International Society of Industrial Ecology Conference, Lisbon, Portugal, June 22, 2009.

ARPA-E clean energy awards: MIT leads again

Once again the US Department of Energy (DOE) has recognized MIT as an engine of energy innovation. On April 29, it awarded $11 million in grants to MIT-led research projects focusing on bacterial production of motor fuels, a novel carbon capture technology, a new "semi-solid flow battery," and teams of microbes that work together to produce biodiesel. According to DOE, those "ambitious research projects could fundamentally change the way the country uses and produces energy."

The new grants are part of the second round of awards from DOE's Advanced Research Projects Agency-Energy (ARPA-E)—funding that is intended to accelerate innovation in clean energy technologies, increase America's competitiveness, and create jobs.

This time, ARPA-E awarded a total of $106 million to 37 energy research projects in 17 states. MIT was the leader on four projects and named a collaborator on one more. An additional three were awarded to other organizations in Massachusetts.

Short descriptions of the four MIT projects with their lead researchers follow. The projects span the three areas of funding defined in the ARPA-E call for proposals: electrofuels—biofuels from electricity; batteries for electrical energy storage in transportation; and innovative materials and processes for advanced carbon capture technologies. The first two proposals were submitted through the MIT Energy Initiative (MITEI).

— Professor Anthony Sinskey of biology and health sciences and technology received $1.7 million to engineer a bacterium that can metabolize hydrogen, carbon dioxide, and oxygen and produce butanol, which can be used as a motor fuel. Key challenges include getting the organism to make abundant amounts of butanol—without then being poisoned by it—and designing a high-performance bioreactor system that can deliver the mix of gases needed for the biological process to occur. The research is being performed in collaboration with Michigan State University.

— Professor Alan Hatton of chemical engineering and Senior Research Engineer Howard Herzog of MITEI received $1 million to develop a new process called electrochemically mediated separation (ECMS) for the post-combustion capture of carbon dioxide at coal-fired power plants. According to DOE's announcement of the awards, the "anticipated benefits include greatly increased energy efficiency for carbon dioxide capture, easier retrofitting of existing coal-fired power plants, and simpler integration with new facilities." Electronics conglomerate Siemens is involved in the research.

— Professor Yet-Ming Chiang of materials science and engineering was awarded $5 million to design a revolutionary semi-solid flow battery for transportation that combines the best characteristics of rechargeable batteries and fuel cells. This new concept could enable lighter, smaller, and cheaper batteries for electric vehicles. According to DOE, the flow battery "potentially could cost less than one-eighth of today's batteries, which could lead to widespread adoption of affordable electric vehicles." Collaborators in the work are Rutgers University and A123 Systems Inc., an MIT spinoff company that develops and manufactures lithium-ion batteries and systems.

— Professor Gregory Stephanopoulos of chemical engineering received $3.2 million to develop a two-stage microbe-based process that would make oil from hydrogen and carbon dioxide, or electricity. In the first stage of the process, an anaerobic organism would utilize hydrogen and carbon dioxide to produce an organic compound, such as acetate. In the second stage, the acetate would be used by an aerobic microbe, which would grow and in the process produce oil that can easily be converted into biodiesel. Harvard University and the University of Delaware are collaborating on the research.

In addition, MIT is named as a collaborator on a project to develop an inexpensive, rechargeable magnesium-ion battery for electric and hybrid-electric vehicle applications. The project was awarded $3.2 million and is led by Pellion Technologies Inc., an MIT spinoff company, with collaboration from Bar-Ilan University as well as MIT.

"The new ARPA-E awards further invigorate MIT's pursuit of the best breakthrough ideas in energy, accelerating advances from the beginning of the innovation pipeline to the end," said Ernest Moniz, director of MITEI and the Cecil and Ida Green Professor of Physics and Engineering Systems. "The technologies chosen for support hold great potential for reducing carbon emissions in both the transportation and the power sectors."

Three awards—all in the area of electrofuels—went to other organizations in Massachusetts, joining the region's

MITEI awards fifth round of seed grants for energy research

growing energy technology innovation cluster. The University of Massachusetts Amherst, with the University of California San Diego and Genomatica, received $1 million for "Electrofuels via direct electron transfer from electrodes to microbes"; Ginkgo BioWorks, with the University of California Berkeley and the University of Washington, received $4 million for "Engineering *E. coli* as an electrofuels chassis for isooctane production"; and Harvard Medical School—Wyss Institute received $4 million for "Engineering a bacterial reverse fuel cell."

"In the first round of ARPA-E awards last October, Massachusetts companies received a larger share of funding—22 percent—than any other state, and, once again with this round, the Commonwealth is showing its colors as a clear leader in clean technology innovation," Energy and Environmental Affairs Secretary Ian Bowles said. "I congratulate MIT and the other Massachusetts ARPA-E winners—all of which are partners in our pursuit of a clean energy future."

In the first round, selected projects included one MIT research lab and five Massachusetts-based companies, four of them MIT spinoffs and one with strong links to MIT.

The new awards were made through the American Recovery and Reinvestment Act, a multibillion-dollar investment intended to stimulate economic growth through innovation, science, and technology. Of that money, $400 million was designated for ARPA-E and will support three rounds of awards.

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By Nancy W. Stauffer, MITEI

Recipients of MITEI seed grants, Spring 2010

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

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

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

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

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

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

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

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

A novel framework for electrical grid maintenance
Cynthia Rudin
Management

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

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

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

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

Tsinghua/Cambridge/MIT alliance awards first research grants

On October 1, 2009, Tsinghua University in China, the University of Cambridge in England, and MIT in the United States joined forces to create the Low Carbon Energy University Alliance (LCEUA). Through this cooperative relationship, the three world-class institutions will conduct collaborative scientific research on low-carbon energy technologies and carry out policy research and analysis on low-carbon energy solutions, with a particular focus on China.

On March 25, 2010, the LCEUA announced its first seed grant awards. The projects and their lead investigators are as follows.

Geo-energy systems simulator: From building scale to city scale (Er-xiang Song, Tsinghua; Kenichi Soga, Cambridge; Andrew Whittle, MIT). District energy systems based on geothermal energy have been available for more than two decades, but applications are generally limited to buildings or small communities. Their feasibility at the city scale requires a new generation of multidisciplinary and multiscale assessment methods. This research will develop tools for examining technology, management, policy, and legislation issues relating to the use of geothermal systems to provide low-carbon, renewable energy at the city scale for heating and cooling buildings and infrastructure. These tools will build confidence in large-scale applications of geothermal systems integrated with urban infrastructure and also will allow comparisons with other candidate technologies such as combined heat and power systems and solar thermal systems.

Technology development for total conversion of sweet sorghum feedstock to biofuels (Shi-Zhong Li, Tsinghua; Paul Dupree, Cambridge; Gregory Stephanopoulos, MIT). Sweet sorghum is an ideal non-food feedstock for ethanol production. To optimize the conversion, this research will improve the efficiency of the fermentation process; investigate the structure of plant cell walls to improve plants for biofuel production; and engineer yeasts that can simultaneously utilize pentose and hexose (constituents of cell walls) and can tolerate high levels of the ethanol produced. The outcome could surpass any cellulosic ethanol technology presently under development due to the utilization of both the soluble sugars and the cellulosic material of the sorghum plant.

Innovative power generation technologies for low-grade energy sources (Min Zhu, Tsinghua; Liping Xu, Cambridge). Industrial production is a major consumer of energy in China, and industrial processes generate huge amounts of waste heat and combustible residual gases with low calorific value. While such low-grade residual gases are often used in steam boilers, much higher efficiency could be achieved in principle by using them in combined cycle gas turbines. One objective of this project is to provide new insights into the design and operation of gas turbine combustors for low-calorific-value gases, in particular, from the point of view of flame fundamentals and combustion stability. Another objective is to explore the potential of organic Rankine cycle engines for efficiently converting waste heat to electric power. These objectives are closely aligned with the Chinese government's policies to extend gas turbine technology and to reduce emissions and save energy.

Biphasic sorbents for carbon mitigation: materials and process development (Guangsheng Luo, Tsinghua; T. Alan Hatton, MIT). Amine scrubbing with selected solvents is an effective means of removing dilute carbon dioxide (CO_2) from flue gas streams of coal-fired power plants—the first step in carbon capture and storage. Using high solvent concentrations would reduce the energy penalty and added cost of such scrubbing but would cause unacceptable equipment corrosion. This project aims to design and engineer sorbents that encapsulate the concentrated amine solution within a highly porous solid support. Because the solution will have minimal contact with equipment surfaces, amine concentrations can be high with no adverse effects. The R&D program includes sorbent development and process engineering and reactor design for the effective capture and regeneration of CO_2.

The awards are US$400,000 for a two-way collaboration and US$600,000 for a three-way collaboration. Project duration is two to three years.

Tsinghua University

University of Cambridge

MIT/Photo: Donna Coveney

TSINGHUA-CAMBRIDGE-MIT ALLIANCE FOR LOW CARBON ENERGY

Why an alliance?

Formation of the LCEUA was motivated by the belief that reducing greenhouse gas emissions requires going to the source. Together, China, the United States, and the European Union are responsible for more than half the world's energy use and associated carbon emissions. Accordingly, the three institutions of science and technology—Tsinghua, Cambridge, and MIT—decided to join forces to establish a cooperative, multiregional program to take on the challenge of climate change.

In its initial stages of operation, the alliance is focusing on economic and policy modeling for a low-carbon future, combustion and carbon capture, low-carbon cities and efficient industry, biofuels, thermal energy conversion, and nuclear power. The first call for proposals, issued in January 2010, elicited 26 proposals in those six research areas, each involving researchers at Tsinghua in collaboration with those at Cambridge or MIT or both.

The LCEUA was initiated with an investment of about US$10 million from the Chinese government to fund core operations including collaborative seed projects. A fundraising committee is now actively seeking to build on this investment. The alliance is managed by a steering committee made up of two members from each university. The steering committee is responsible for reviewing submitted proposals and selecting those to be funded.

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By Nancy W. Stauffer, MITEI

MITEI press briefing showcases energy research

On Friday, March 5, Professor Ernest Moniz, director of the MIT Energy Initiative (MITEI), hosted a press briefing on the latest advances in energy research at MIT. Moniz kicked off the briefing with an overview of MITEI. More than 20 journalists then listened as prominent MIT energy researchers described their work and answered questions from the audience. Topics covered ranged from nanostructured materials and liquid metal batteries to thermopower waves and a new computer simulation program that can show the long-term climate consequences of emissions-reduction proposals. The speakers and their topics are listed below. For videos of the presentations, go to http://web.mit.edu/mitei/news/seminars/press-brief-3-5-10.html.

- **Ernest Moniz**
  Welcome and MITEI overview
- **Marc Baldo**
  Center for Excitonics at MIT: an overview
- **Daniel Nocera**
  Catalyst for a highly manufacturable and inexpensive storage mechanism for solar energy
- **Paula Hammond**
  Materials for energy applications using electrostatic assembly
- **Gang Chen**
  Nanostructured materials for energy applications
- **Michael Strano**
  Discovery and application of thermopower waves
- **John Sterman**
  C-ROADS (Climate Rapid Overview and Decision Support) policy simulation model
- **Luis Ortiz**
  The liquid metal battery, a grid-storage solution for dispatchable renewable energy
- **Michael Greenstone**
  Unequal burdens: predicting the mortality impacts of climate change in the US and India

Moniz named to Blue Ribbon Commission on America's Nuclear Future

Photo: Justin Knight

MIT Energy Initiative Director Ernest Moniz has been named to the Blue Ribbon Commission on America's Nuclear Future, which will provide recommendations for developing a safe, long-term solution to managing the nation's used nuclear fuel and nuclear waste, the US Department of Energy (DOE) announced on January 29.

Moniz currently serves as a member of President Barack Obama's Council of Advisers on Science and Technology (PCAST). Moniz served as DOE undersecretary from October 1997 until January 2001. From 1995 to 1997, he was associate director for science in the Office of Science and Technology Policy in the Executive Office of the President. Moniz is also director of MIT's Laboratory for Energy and the Environment. He is the Cecil and Ida Green Professor of Physics and Engineering Systems at MIT, where he has been on the faculty since 1973. He has served as head of the Department of Physics and as director of the Bates Linear Accelerator Center.

The commission, which will be chaired by former Congressman Lee H. Hamilton and former National Security Advisor Brent Scowcroft, will produce an interim report within 18 months and a final report within 24 months. For more information, go to http://www.energy.gov/news/8584.htm.

New design-build class weaves nature into rural Cambodian school

Rebecca Gould was intrigued by an e-mail describing a new class where she could work with graduate students outside her discipline and do something that could affect people. "We were to design a classroom in rural Cambodia with natural lighting, no air conditioning, natural ventilation, no glass, and low noise level between classrooms," says Gould, a junior in civil engineering. She jumped at the opportunity and signed up for "Design for a Sustainable Future."

"Our class was primarily grad students and people in the architecture department or building technology, so I was working with people who had been out in the field and worked before," adds Gould. "I didn't know how to create a master plan before the class."

During the fall semester, she learned how to analyze a building and design a campus. Then, during Independent Activities Period (IAP) in January, she and her classmates traveled to Cambodia for 15 days to see how well their building plans would work on location and how a structure can be built from scratch—a valuable experience for the undergraduate and graduate students alike.

"Physical building on site is incredible," says Lisa Pauli, a third-year master's student in architecture who had worked for three years in New York as a designer. "In school, we tend to be limited to learning about construction in one or two dimensions. But working on site offers an entirely new understanding of how to pour a concrete slab or level a site."

Andrea Love, a first-year graduate student in architecture who had worked at a sustainable architecture firm for seven years, says she learns better by

Photos: Inês Santos

As part of a sustainable design class, a team of MIT students traveled to Cambodia to test some of the innovative ideas they had developed in the classroom. One challenge was to use available low-cost, low-energy materials wherever possible. Here, school children eat their lunch while sitting on new rammed-earth benches made from soil plus 5% cement binder.

seeing and doing than by reading. "There's a lot you can learn in the field. When you actually try a design in the field to see if it works, it gives you a lot of experience." She adds that since the students were working with local unskilled laborers, they modified their designs to adapt to local skill sets.

During the project, the 15 students in the class and their three instructors collaborated with a Cambodian architecture firm and people from the local school. The MIT group also got some unexpected help on site. The local school kids watching them wet bricks in a small pond soon joined in. "The kids did it, too, in their cute school uniforms," says Pauli.

Project-based learning

The design-build project started as a class run last fall by Marilyne Andersen, associate professor of building technology and a physics engineer; John Ochsendorf, associate professor of building technology and a structural engineer; and J. Meejin Yoon, associate professor in architectural design and a licensed architect. The class was divided into three teams, each tasked with designing a K–12 green school in the province of Siem Reap, home to the famous Angkor Wat temple complex. They also were asked to suggest improvements to an existing school and to build a kitchen for a government-run school nearby.

In the classroom, the students learned to use Lightsolve, MIT's home-grown daylighting simulation program, and Rhinoceros, a commercial 3D modeling program, to help guide their project development. One team also used a computational fluid dynamics program to model and analyze airflows around the buildings in its proposed campus design. "The undergraduates'

In addition to designing alternatives for a new low-energy school campus for 800 students, the MIT students conducted a service project by building a kitchen for a small local school. In the left-hand photo, MIT graduate students in architecture (left to right) Joseph Nunez, Adam Galletly, Zachary Lamb, Yan-Ping Wang, and Lee Dykxhoorn move a concrete cistern into place. In the right-hand photo, Samantha Cohen '11 of civil and environmental engineering lays bricks for the vaulted roof of the pantry.

enthusiasm was through the roof," Pauli says. "They jumped into learning the new software programs." Every design went through many iterations before the teams headed to Cambodia.

"This class illustrates the extraordinary impact that project-based learning has on students at every level," says Donald Lessard, the Epoch Foundation Professor of International Management and co-chair of the Energy Education Task Force. "It's very different from a lecture in room 10-250 and has a positive influence on their motivation and how they learn in the future. They get to know real-world stakeholders and challenges, giving their learning experience new relevance."

The Cambodian school, known as the Jay Pritzker Academy, is funded by Dan Pritzker, an entrepreneur who is building English K–12 college preparatory schools in the country. The schools are free and look for bright students from low-income families in Siem Reap. The aim is to graduate students who could eventually attend MIT or other colleges overseas. Cambodia's educated class was decimated by the ruling Khmer Rouge in the 1970s, leaving behind a largely agricultural and uneducated population.

"The Pritzker Foundation is looking at how to get from humble agriculture to taking SATs," explains Ochsendorf. The Pritzkers reviewed designs prepared by each of the three MIT teams, plus one by a local design company in Cambodia, and may ultimately pick elements from each design for the new school.

Using what nature offers

Ochsendorf says students and the general public know a lot about the performance of cars, but do not think of buildings as having performance in the way they use energy as well. "One of the primary things we hopefully conveyed to [the architecture] students is the notion that building performance should be part of the way they do things," he says.

In Cambodia, the students had to consider the humid, hot climate where temperatures often climb to 100°F, regional taste in design, and the orientation of buildings for cooling. "They had to look at how the environment and limited resources dictate the design of a building," he says.

Using available materials also led to some creative solutions, according to Ochsendorf. In the kitchen built in the government school, the students replaced 30% of the concrete with local ash from burning rice husks to make the floor slab. This is similar to Roman concrete, which is made with volcanic ash, he says. The mixture recycles the ash and makes for a strong concrete, with lower greenhouse gas emissions. Another material innovation was adding a 5% cement binder to soil to make rammed-earth benches.

Ochsendorf hopes the students will carry on with such creative thinking within a given environmental setting because design considerations in a developed, colder area like Massachusetts are much different than in Cambodia's tropical, low-infrastructure environment.

Multidisciplines are key

Yoon says that while there are design-build projects at MIT all the time, they typically don't have the diversity of faculty as well as public service and sustainability aspects of this new class. "I learned so much from my colleagues," she says. "At MIT we teach in side-by-side classrooms, but we don't teach all three disciplines [engineering, building physics, and architecture] at the same time in the same classroom."

Andersen says she noticed how hard it is to work in an interdisciplinary way. "There are language differences. It was

Here, team members finish building the vault that is at the core of the kitchen. A few days later, the school children were served their first meal in the new kitchen.

a success only because the three professors worked together very well," she says.

"Working across disciplines was so important, as was working with the people who work and live there," adds Pauli. "We went through the full cycle of a design." One example was the roof for the new school. "We used digital modeling software to analyze the building and then adjusted our roof overhangs and window openings to create an ideal indoor temperature for the students," says Pauli. To ventilate the clay-tiled roof, the MIT team came up with a layered design of clay tiles, a vapor barrier, corrugated metal, insulation board, an air gap, and more insulation board.

Andersen says she had hoped the class, which was competitive—there were 40 applicants—would have attracted more engineers. "We would have liked to have reached out to a broader range of engineering students by advertising the class earlier, but the very large number of applicants from architecture itself shows that this was the kind of class students were eager to see offered," she says. She judges the class a success because it forced all of the students—the graduate students, who were primarily in architecture, and the undergraduates in civil engineering—to think outside their usual comfort zone. "It was a rich learning experience for both them and us. They had to think cross-boundary and had to incorporate new kinds of design objectives. Ultimately, it enhances creativity," she says. "The hope is they will now see design in a more holistic way."

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By Lori Fortig, MITEI correspondent

This class was supported in part by the Dirk (SB 1975) and Charlene (SB 1979) Kabcenell Foundation.

Two major gifts bolster MIT energy minor

Undergraduate energy education at MIT was transformed this year with the launch of the multidisciplinary, Institute-wide Energy Studies Minor. Now that transformation has the resources it needs to move out of the startup phase, thanks to two major gifts to the MIT Energy Initiative (MITEI): $5.37 million from the S.D. Bechtel, Jr. Foundation and $2.4 million from an anonymous donor.

Those gifts add to the $1 million grant provided by the Dirk (SB 1975) and Charlene (SB 1979) Kabcenell Foundation in June 2007—before the minor was established—to develop new energy-related curricula and strengthen existing programs. To date, the MITEI Energy Education Task Force has put the Kabcenell grant to use in the creation or revision of 10 classes and four workshops spanning the priority areas of the minor: energy science, energy technology and engineering, and energy social science.

One of the original goals of the minor was to transform undergraduate energy education from a diffuse set of offerings to a coherent and coordinated curriculum accessible to all undergraduates. There was a profusion of energy-related classes, but there was no clear pathway for students interested in energy. "MIT has a vast course catalog that can be daunting for any student looking for a class that interests him or her," says senior Christopher Carper. "The curriculum of the Energy Studies Minor points out relevant courses for interested students, regardless of major."

The energy minor is intended to complement any major in any MIT school, in part to encourage students to take classes in disciplines that they may not otherwise explore. That requirement was an eye-opener for Carper, a mechanical engineering major. In choosing an elective from a list of about two dozen possibilities, he settled on an architecture class. It was full of new topics for him—from studying the vapor and thermal permeability of a façade in order to pinpoint condensation risks to determining the effect of a façade's thermal mass on temperature stabilization. "Before taking Introduction to Building Technology, I never understood how applicable mechanical engineering is to sustainable building design," he says.

Focus on project-based learning

Over five years, the gift from the S.D. Bechtel, Jr. Foundation will support the creation and implementation of eight new energy-related classes, half of which will be project-based classes with an emphasis on applied skills. The goal is to ensure that the curriculum covers the widest possible spectrum of energy-related topics and that it is sufficiently flexible to accommodate any interested student. Each year, a call will be issued to all departments for proposals from faculty interested in developing either project-based or traditional classes. "MIT's new energy minor, with its multidisciplinary approach and emphasis on problem-focused learning, is just the kind of education that engineers need to make a difference in energy," says Lauren Dachs, president of the S.D. Bechtel, Jr. Foundation. "We are excited to help the minor move into its next phase of development."

The gift will also be used to identify and renovate project-based teaching space to serve multiple classes and disciplines. Project-based classes may involve activities ranging from feasibility studies and system simula-

Photo: Justin Knight

"D-Lab: Energy" lab instructor Sarah Reed G of mechanical engineering (second from right) and mentor Gwyn Jones, instructor in the Edgerton Center (second from left), discuss material options for a tool that Tyler Liechty '10 (left) and Juliana Velez '11 designed to improve the speed and effectiveness of photovoltaic panel cutting at a Nicaraguan manufacturer of solar cell phone chargers.

Teaching and learning about energy...

tions to the design and construction of prototype devices. Such activities often have needs not met by traditional classrooms—from laboratory equipment and space to simple storage facilities.

Project-based learning is one way the minor helps students develop a broad view of energy and the skills to tackle real-world challenges. Jeffrey Mekler, a senior in aeronautics and astronautics, wanted to get a better understanding of energy alternatives after being involved in a class project on how to improve wind turbine performance. "The minor focused not only on energy technologies but also on the larger social, political, and economic contexts that energy technologies—and perhaps more importantly engineers—must operate in," he says. "My classes encouraged me to think about solutions to our energy challenges that combine technologies with policy and market solutions."

The third component of the gift focuses on sharing the new approaches and materials of the energy minor with faculty, students, and high school teachers. Mechanisms for sharing include MIT's OpenCourseWare (OCW), web resources, and print and electronic textbooks. After three years, 15 classes will be offered on a new OCW "energy platform." With these activities, the support from the S.D. Bechtel, Jr. Foundation will help improve energy education around the globe.

A significant achievement of the energy minor has been to support classes that bring together faculty and students from diverse areas of the Institute. However, that integration creates difficulties because a class spanning disciplines does not fall within any single department's area of responsibility. Faculty leaders are able to engage colleagues from across campus to co-teach their classes, but there is no clear source of funding to support graduate teaching assistants. The anonymous gift has helped establish a fund for that important purpose.

Robert Armstrong, Chevron Professor of Chemical Engineering and deputy director of MITEI, says, "The energy minor is having a transformative effect on our education program and will have a lasting impact on MIT. The two recent gifts are helping us to ensure that the minor is robust and that we can sustain an environment of educational innovation in this important area."

For one of the first MIT students to graduate with the minor, that innovation has both personal and practical implications. "I can only imagine that the Energy Studies Minor will have a positive impact on my career opportunities," says Carper. "It may be the most valuable minor at MIT because of the rapid growth of energy-related industries around the world."

Photo: Justin Knight

Julie Paul '10, a student in "D-Lab: Energy," shows off her team's prototype of a "stove-within-a-stove," an insert fabricated of aluminum sheeting to enable residents of rural Nicaragua to substitute cleaner-burning charcoal for wood as a cooking fuel.

Photo: Justin Knight

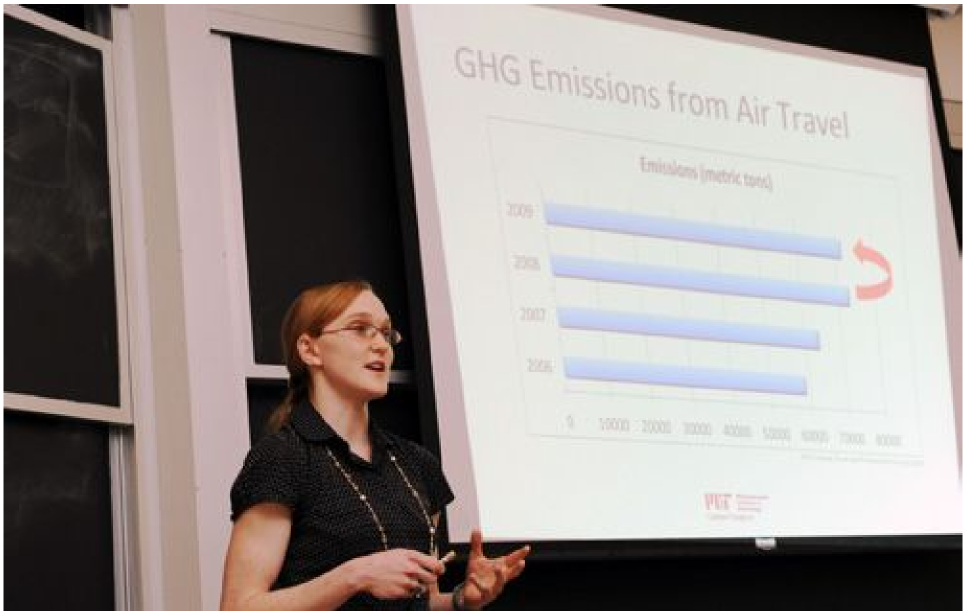
Professor Vladimir Bulović of electrical engineering and computer science describes electron "tunneling," a quantum-mechanical phenomenon that governs charge transport in semiconducting materials used in photovoltaic solar cells, during a lecture in "Electromagnetic Energy: From Motors to Lasers."

...from the lab to the lecture hall

Photo: Justin Knight

Students discuss energy efficiency policies and politics with Professor Judy Layzer of urban studies and planning (at far left) in her new undergraduate seminar, "The Politics of Energy and the Environment."

Photo: © Donna Coveney



Margaret Lloyd '12 reviews findings on travel emissions during her team's presentation of an updated MIT "carbon footprint" study completed during "Projects in Energy," a cross-disciplinary class targeting freshmen and sophomores and supported by the d'Arbeloff Fund for Excellence in Education.

Summer opportunities for energy professionals

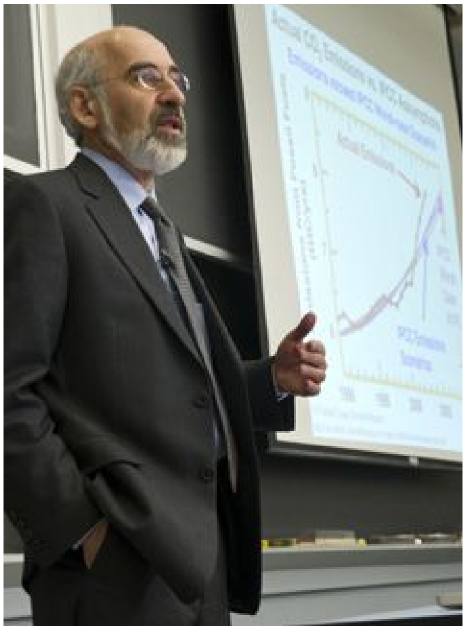
MIT Professional Education—Short Programs offers courses of two to five days in length on the MIT campus during the summer. Short Programs are geared to working professionals in engineering and science, and they attract a worldwide student body with many different interests. Professionals from industry, government, and academia come to learn from MIT experts and bring actionable information back to their organizations. MIT Short Programs reach a broad spectrum of professionals who can communicate industry perspectives. In keeping with the strong interest in energy on as well as off campus, Short Programs will offer the following courses for summer 2010.

- Biofuels from biomass: technology and policy considerations (G. Stephanopoulos)
- Carbon capture and storage: science, technology, and policy (R. Juanes, H. Herzog)
- Clean energy technology: understanding materials limitations and opportunities (G. Ceder, J. Grossman, H. Tuller)
- Design of motors, generators, and drive systems (J. Kirtley, S. Leeb)
- Energy in the context of climate policy: strategic challenges and opportunities (M. Webster)
- Modeling and simulation of transportation networks (M. Ben-Akiva)
- Nuclear plant safety (M. Kazimi, N. Todreas)
- Organic, molecular, and nanostructured electronics: physics and technology (V. Bulović, M. Baldo)
- Present and future internal combustion engines: performance, efficiency, emissions, and fuels (J. Heywood, W. Cheng)
- Solar energy: capturing the sun (D. Nocera)

For more information, visit shortprograms.mit.edu or e-mail shortprograms@mit.edu.

Energy Futures Week 2010

Energy Futures Week 2010 was filled with energy-related events to inspire and educate the MIT community as we look to the future of sustainable energy. The week was part of MIT's Independent Activities Period (IAP) in January, which offers a break from the academic routine of the fall and spring semesters. More than 20 events—including lectures, panel discussions, tours, information sessions, strategy games, and working sessions—ensured that Energy Futures Week embodied the spirit of IAP.



Photos: Justin Knight

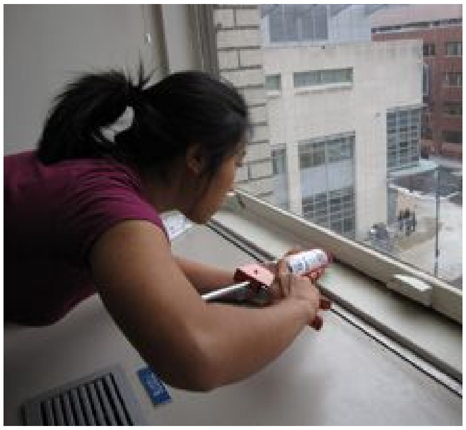


Photo: Jennifer DiMase, MITEI

Above: Professor John Sterman describes C-ROADS, a simulation model that can quickly calculate the climate impacts of specific mitigation proposals. Above right: After Sterman's presentation, participants in the session divided into regional groups, negotiated emissions-reduction proposals, reconvened for plenary presentations, and ran their proposals through the simulation. The US Department of State uses C-ROADS to analyze the climate impacts of various country-level proposals and shared that understanding with other parties to the 2009 UN Climate Change Conference in Copenhagen. See http://climateinteractive.org for more information.

Left: Lucy Fan '12 helps to make Building E52 more energy efficient by applying caulk to a window gap. During this workshop, staff from MIT's Department of Facilities discussed and demonstrated building weatherization techniques.

Clockwise around table from left: Linda Patton of Housing, Ruth Davis of Facilities, Ryan Gray and Peter Norman of the MIT Libraries, and William VanSchalkwyk of the Environment, Health, and Safety Office brainstorm strategies to promote greener practices for the office. The interactive Green Ambassadors workshop provided insights on behavior change research to students and staff from all corners of the Institute. (See page 32 for more on MIT's Green Ambassadors.)

Photos: Justin Knight

Kelly Ran '12 discusses details of the MIT Solar Electric Vehicle Team's latest car, Eleanor, at the student projects showcase during Energy Futures Week. The event featured the work of students active in research and groups on campus that revolve around energy, the environment, and sustainability.

Fund helps energy efficiency bloom across campus

One hurdle colleges and universities face as they try to improve energy efficiency is figuring out how to pay for it. The long-term savings from these kinds of projects can be significant for a large institution—done right, such a plan could save MIT several million dollars on its energy bill each year. But these energy projects require substantial up-front investment, and that can be challenging for schools struggling with budget cuts.

MIT is on a path to meet this challenge, thanks to a $1 million gift from Jeffrey Silverman '68 about one year ago. With this money, the Institute has established a fund to support campus energy and efficiency projects that have rapid "paybacks"—or savings that accrue and then can be reinvested into additional projects.

Silverman was intrigued by this giving opportunity because it allowed him to make a major difference at his alma mater while also leveraging his initial investment so that it could grow and be used in different ways. "The idea of providing the seed money that was going to create savings and then get reinvested into more savings interested me," he said. He was also impressed that the fund was designed so that the savings would be rigorously measured, documented, and verified.

Silverman, a successful commodities trader, first heard about the investment opportunity from Theresa M. Stone, MIT's executive vice president and treasurer, who also co-chairs the Campus Energy Task Force. The task force was established by the MIT Energy Initiative to help MIT "walk the talk" on energy use. Stone budgeted $500,000 in seed money in 2008 to promote energy conservation work in response to a review by the Department of Facilities and a student team from the MIT Sloan School of Management's Laboratory for Sustainable Business. That review determined that the Institute could save about $6 million each year—or 10% of its annual energy bill—through conservation projects that have quick paybacks. Stone's team then developed a list of appropriate payback projects, estimating they would cost MIT $14 million in one upfront investment.

Silverman was eager to contribute to Stone's effort, and so in April 2009 he formed the Silverman Evergreen Energy Fund. David desJardins '83, a consultant and investor who is also passionate about campus energy issues, has since donated an additional $500,000 to the effort.

"The gifts made by Jeff and David marked votes of confidence in our commitment to implement disciplined, measurable improvements designed to improve campus energy efficiency," Stone says. "Their seed money continues to bear fruit for the MIT community and for those who value our example."

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

Another major focus of the Silverman fund has been to recalibrate the nearly 200 fume hoods in the Dreyfus Chemistry Building (Building 18). Fume hoods are massive ventilation devices that protect researchers from potential chemical exposure by sucking up air and exhausting it outside—and they require a lot of energy. A significant amount of this energy consumption can be reduced by lowering the volume of air that moves through the hoods while still providing the same level of protection. This project cost about $430,000 and will save about $160,000 annually.

The savings from the first round of projects financed by the Silverman fund will be reinvested into a second round of energy conservation work. These additional projects will most likely include more lighting retrofits and fume hood work. They could also involve strategies for reducing heating, ventilation, and air-conditioning needs in unoccupied spaces. After this second round of investments is deployed, Stone will examine the fund's effectiveness in meeting the Institute's goals for payback opportunities.

Information on other innovative campus energy programs at MIT and a newly released task force update report are available at http://web.mit.edu/mitei/campus.

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By Morgan Bettex, MIT News Office

MIT ambassadors spread the word on ways to "walk the talk"

Jessica E. Garrett was already giving her Edgerton Center colleagues tips on going green—take the stairs, bring reusable containers to the lunch trucks, turn off lights—when she found out about a new Campus Energy Task Force program aimed at promoting sustainable practices on campus. Now, when she jokingly makes her co-workers earn the right to display "I walk the talk" postcards on their office doors, Garrett is performing her duty as a Green Ambassador.

The Green Ambassadors program creates and empowers a network of student, staff, and faculty volunteers to promote sustainable practices. Energy conservation, green purchasing, alternative transportation—the sky's the limit, so long as it makes MIT a little greener.

"The Green Ambassadors program seeks to help establish MIT as a model of community-engaged sustainability through strengthening our sustainability community, providing and sharing critical information and knowledge, driving 'place-based' action, supporting collaboration, and sharing best practices," says Steven M. Lanou, deputy director for environmental sustainability and a member of the Campus Energy Task Force of the MIT Energy Initiative.

There are currently 172 Green Ambassadors across campus. One of them is Peter H. Fisher, professor of physics. "I try to keep people off airplanes. I move printers to where they are inconvenient so people print less. I put the recycling bin near the desk and the regular wastebasket on the other side of the room," he says. "Central is my belief that living well and living sustainably are deeply related."

The Green Ambassadors program helps individuals share information and enables best practices that can make a difference. "At a basic level, Green Ambassadors show by example the choices and practices that can be adopted to have an impact," Lanou says. His office coordinates the development of outreach and educational material as well as networking tools. Lanou's staff, along with an active and engaged steering committee of student and staff volunteers, hosts events to strengthen the network and helps Green Ambassadors identify "greening" opportunities.

Expanding on past success

The Green Ambassadors program is an outgrowth of campus working groups in recycling and other initiatives that have been in existence for as long as 10 years, according to Niamh Kelly, assistant officer for the Environment, Health, and Safety Office (EHS), who has been working with Lanou to develop the program.

Students who helped set the stage for the program include Pamela Lundin, graduate student in chemistry, and Jialan Wang, graduate student in financial economics. Founders of the student group "Closing the Loop," Lundin and Wang spearheaded a recent pilot project that slashed after-hours electricity use in Buildings 16 and 56.

"There have been 'greening' initiatives on campus for a long time, but without a name," Kelly says. "The ambassadors program is a little broader than previous efforts because it includes elements such as purchasing and green events—and is sponsored by an Institute-wide initiative."

In response to requests such as "What can we do in our office?" Kelly and Lanou took their show on the road with presentations that have since turned into handouts about topics such as how to increase energy efficiency and recycling and how to set computers, monitors, and printers on energy-saving modes. Using their own N52 officemates as guinea pigs, Kelly and Lanou post sustainability-related news on bulletin boards, print double-sided, and vanquish screen savers, Kelly says. Lanou plans to post data on how much energy is consumed daily by the EHS copy machines, computers, and water coolers.

"As individuals, we often feel powerless to make an impact on global climate change. When an individual switches to a better practice, the impact is multiplied as others learn of and adopt the new practice. When individual action becomes collective action, the aggregate can have a very large cumulative impact," Lanou says.

Breaking down barriers

According to Kat A. Donnelly, an Engineering Systems Division graduate student researching behavior change and energy efficiency who presented her findings at a Green Ambassadors event during Independent Activities Period 2010, one of the reasons people don't conserve energy may be the fact that energy is invisible—there's no feedback from the system on how much we're using.

Donnelly advocates an approach called community-based social marketing, which focuses on behavior change. Equally effective in offices, dormitories, and laboratories, social marketing involves putting yourself in other people's shoes to understand their biases and determine the probability and potential impact of key behavior changes. In this way, she says, Green

Photo: courtesy of Jessica Garrett, MIT

From left, Jessica Garrett and Amy Fitzgerald, instructors in the Edgerton Center, and Paula Cogliano, administrative assistant in the Office of Experiential Learning, bring reusable plastic containers to a lunch truck. Garrett had been advocating such sustainable practices even before she joined the team of Green Ambassadors.

Ambassadors can help uncover barriers to saving energy and design approaches to break down those barriers.

Social marketing relies on incentives and education—tactics now being used by MIT ambassadors. The Campus Energy Task Force has launched educational strategies such as poster and e-mail campaigns that quantify the savings associated with using revolving doors, closing lab fume hoods when not in use, and turning off lights. "We provided some hard data that would answer the questions a typical MIT campus member would ask," Kelly says.

Garrett, the Edgerton Center instructor and Green Ambassador, knows the value of incentives. She publicly acknowledges and congratulates her "green" colleagues at staff meetings—a tactic Donnelly would applaud. "It's cheesy, but it does get people telling me what they are doing and thinking of ways they could make more changes. Amazing what people will do for a free postcard." And, she might add, a chance to help save the planet.

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By Deborah Halber, MITEI correspondent

Students tackle the climate crisis from Cambridge to Copenhagen

While world leaders at the recent United Nations climate summit wrestled with the thorny politics surrounding global agreement, MIT students and their peers from around the world were in perfect accord: They pledged to make their own campuses greener and to spread the word of student-led initiatives that seek to tackle climate change.

Photo: Justin Knight

Katherine Dykes, an MIT graduate student in the Engineering Systems Division, was among the participants at a student-run workshop on greening university campuses, held during the UN Climate Change Conference in Copenhagen in December 2009. Dykes told workshop attendees—more than 60 students from universities worldwide—about MIT's many initiatives to cut campus energy use, reduce environmental impacts, and increase sustainability.

MIT students traveled to Copenhagen during the 2009 UN Climate Change Conference (COP 15) to attend a workshop convened by Yale students partnering with the University of Copenhagen and to organize and attend events through the World Student Community for Sustainable Development (WSC-SD).

The workshop, attended by more than 60 university students from the United States, Canada, Sweden, Denmark, Switzerland, Australia, Japan, and China, explored ways students and their institutions can minimize environmental damage and promote sustainable solutions. The event took place December 13–14 at the University of Copenhagen. In the coming year, university teams, including MIT's, will implement projects on their campuses and report back to the group. The hope is that by sharing best practices, universities can help inspire institutional change beyond their campuses.

Katherine Dykes, Engineering Systems Division graduate student, vice president of the MIT Energy Club, and a student representative on the MIT Energy Initiative's Campus Energy Task Force, presented an overview of MIT's many campus initiatives at the workshop. "It was really great to see the kind of bottom-up efforts that are happening all over the globe, as evidenced by the global participation at the event," she says.

Dykes' presentation addressed the Institute's current status and future directions for "greening MIT." She discussed possible sources of funding for campus-focused initiatives and how to track implementation of those initiatives. Dykes reported to workshop participants on more than 20 MIT activities that range from conserving water, composting food waste, and metering energy use in dorms to retrofitting lighting and heating systems, powering down computers when not in use, and building silver and gold LEED-certified buildings. She plans to spearhead a student effort to assess current and past programs directed at campus energy, environmental, and sustainability issues to identify what, among MIT's many and varied projects, is and isn't working. "I hope that the study we are doing will provide real insight as to how and why our energy and sustainability programs are doing well and provide guidance for future efforts," Dykes says.

She says the best thing about the Copenhagen workshop "was the connections formed between the different university groups. It's a great way to share best practices and keep each other accountable for what we propose to do."

In an effort to gauge how well campus sustainability programs are working, the MIT student team will collaborate with counterparts at Yale and Carnegie

Mellon University on how campuses benchmark and measure the impact of their programs. In this early stage of the study, the actual methods of measuring and monitoring are still being discussed, Dykes says. MITEI's Campus Energy Task Force supported an undergraduate student to assist with the project during spring semester.

Inspiring thought-leaders

Two other students traveled to Copenhagen. As members of Sustainability@MIT, a student umbrella group, Aaron Thom, a senior in civil and environmental engineering, and Katherine E. Potter, a graduate student in earth, atmospheric, and planetary sciences, are automatically affiliated with the WSC-SD. This group brings together student communities working on environmental sustainability all over the globe, so Copenhagen was a prime focal point. From the conference, Potter and Thom "contributed to a blog (http://cop15.wscsd.org/), released an e-book of students' connections to climate change (http://wscsd.org/2009/12/11/resolutions-21-young-leaders-on-climate-change/), and held a get-together uniting students present at COP 15," Potter says.

The WSC-SD e-book, *RE:SOLUTIONS—21 Young Leaders on Climate Change,* showcased 20 innovative student-led projects ranging from a solar-powered open air cinema to reforestation projects, all demonstrating that students worldwide are taking the lead on tackling climate change. The publication aims to "inspire thought-leaders in business, academia, and civil society to acknowledge and support student initiatives," according to the WSC-SD.

John Sterman, the Jay W. Forrester Professor of Management and director of the MIT Sloan School of Management's System Dynamics Group, also attended the Copenhagen conference along with a team from Climate Interactive—a consortium made up of the MIT Sloan group, the Vermont-based Sustainability Institute, the Harvard, Mass.-based software company Ventana Systems, and many MIT alumni. Climate Interactive developed the C-ROADS climate policy simulation model used by the US negotiating team.

"Students such as Katherine Dykes and the others who attended the Copenhagen climate conference not only had a chance to see the international negotiation process up close, but by organizing and speaking at a variety of workshops and side events they were leaders themselves," Sterman says. "Getting out of the lab and engaging with policymakers is a vital part of that 'mens et manus' MIT spirit."

By the end of the conference, after eight draft texts and all-day talks among 115 world leaders, President Barack Obama helped broker a political agreement among China, South Africa, India, Brazil, and the United States. The so-called Copenhagen Accord acknowledges that climate change is one of today's greatest challenges but does not commit countries to specific emissions reductions. Calling the deal a "meaningful agreement," Obama says, "This progress is not enough. We have come a long way, but we have much further to go."

"How inspiring it was to see the masses of professionals, politicians, scientists, and the world community, young and old, descend upon Copenhagen for the climate talks," Potter says. "There was no doubt that the world sees the need for action—no piddly debate over the reality of it all." MIT students and their counterparts from around the world showed that when it comes to mediating the world's climate woes, universities' actions are like their words: loud and clear.

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By Deborah Halber, MITEI correspondent

A silver lining to the Copenhagen cloud?

Although December's UN Climate Change Conference in Copenhagen was widely portrayed as a failure, some speakers at an MIT panel discussion on Friday, February 5, suggested that its results actually represent real progress in the world's efforts to head off the dangers of climate change—and that in fact the results may have been better, in the long run, than an outcome that most people would have considered a "success" at the time.

The Copenhagen conference "has elicited some strong reactions, both positive and negative," said MIT Energy Initiative Director Ernest J. Moniz as he introduced the panelists for the event, called "The Road from Copenhagen." Officially known as the COP 15 conference (15th Conference of the Parties), some have taken to calling it "Copout 15," he said. "At a minimum, it was an interesting process."

Robert Stavins, professor of business and government at Harvard's Kennedy School of Government, opened with a relatively upbeat assessment. "What would have been possible, but I think unfortunate, would have been a signed international agreement" at the conclusion of the conference, he said. "Unfortunate, because the only agreement feasible would have been 'Kyoto on steroids,' " he said—that is, an agreement that perpetuated the structure of the Kyoto Accord signed in 1997 (which called for reductions in emissions by 39 industrialized nations). That agreement had no set requirement for action by emerging economies, and Stavins said that any similar agreement from Copenhagen might have been signed by US representatives at the conference, but would never have been ratified by the US Senate.

What emerged by the end of the Copenhagen process instead, Stavins said, was real, substantive negotiation being carried out directly by heads of state, including President Barack Obama. Stavins called this sort of negotiation "virtually unprecedented." In this case, the high-level talks led to "what I would characterize as a significant political accord," which, he said, addressed the two key deficiencies of Kyoto: It has expanded the agreement to include, so far, nations responsible for more than 80% of all greenhouse gas emissions, and it extended the timeframe covered by the agreement from 2012 to 2050.

Michael Greenstone, the 3M Professor of Environmental Economics at MIT, listed all the reasons the United States ought to change its policy on climate change. Greenstone, who just returned to MIT after a year as chief economist on the Council of Economic Advisers at the White House, said that projections of the impact of the measures now being discussed suggest that these proposals will barely make a dent in the problem. He also said that a target of stabilizing carbon dioxide levels in the atmosphere at 450 parts per million, as some have proposed, is not politically feasible. And he complained that current proposals to achieve emissions reductions rely on measures that cannot be verified.

"Current technologies to monitor reductions are very poor," he said. He suggested several policy measures to address these issues. He recommended a shift of research and development funding away from new energy sources and toward lowering the emissions of existing fossil-fuel power plants, and developing carbon sequestration technologies and geoengineering systems to mitigate the effects of increased greenhouse gases; devoting "incredible resources" toward developing technologies for accurately measuring emissions; and emphasizing the development of a true global market for carbon trading.

Steven Ansolabehere, professor of political science at MIT and Harvard, said the Supreme Court decision last year that gave the Environmental Protection Agency (EPA) the power to regulate greenhouse gases has "changed the game" politically. "My economist friends tell me it's the worst way" for emissions to be regulated, rather than having it done through legislation, he said, "but politically, it changes the status quo." Before, if Congress failed to take action, there would be no regulation of greenhouse gases; now, if Congress doesn't act, the EPA could require much more sudden and drastic changes such as immediately shutting down coal plants that are heavy emitters of carbon dioxide. As a result, he said, that puts pressure on Congress and makes it more likely that a bill will be passed this year.

Edward Steinfeld, director of the MIT-China program and associate professor of political science, said that a crucial component of any global agreements emerging from the Copenhagen conference will be the role of China, the burgeoning economic giant that is likely to soon displace the United States as the biggest emitter of greenhouse gases. In analyzing China's energy and climate policies, he said, there is a disconnect between political rhetoric opposing emissions limits and what's actually happening there. This on-the-ground reality "gives us grounds for more optimism than the political side does," he said.

Photo: Justin Knight

From top to bottom, Ernest J. Moniz, Robert Stavins, Michael Greenstone, Steven Ansolabehere, Edward Steinfeld, and Henry Jacoby at the panel discussion, "The Road from Copenhagen."

"In the Chinese energy sector today, right across the board," he said, "we are seeing jaw-dropping investments being made in new technology and the replacement of old infrastructure with new" using cutting-edge technology. "There is a recognition there that climate change is happening, and that China is vulnerable" to its effects.

Henry Jacoby, co-director of MIT's Joint Program on the Science and Policy of Global Change and professor of management at MIT's Sloan School of Management, said that despite the downbeat reports about the outcome of the Copenhagen meeting, "it's important not to lose heart." While many people had hoped for stronger action or more ambitious targets for curbing emissions, he said, any action at all is worthwhile "because almost anything we do plays a part in reducing the risk" of severe consequences from climate change.

If all the pledges made by various nations before and after the Copenhagen meeting were met, "we would stabilize emissions by 2020," he said. While atmospheric concentrations would continue to rise, "we would begin to turn the corner" toward leveling it off. However, he added, in order to avert the most damaging impacts, the amount of money pledged by the industrialized nations to help finance energy improvements in the developing world would need to be increased by four to five times.

On the positive side, he said, the earlier any action is taken, the greater its effects. The proposals for emissions reductions resulting from the Copenhagen meeting, he said, change the median odds for temperature rise in this century from a potentially devastating 5 to 6 degrees F if no action is taken to a more manageable 2 to 2.5 degrees.

"That's my maximum optimism," he said.

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By David L. Chandler, MIT News Office

For a video of the entire two-hour panel discussion, go to http://web.mit.edu/mitei/news/video.html.

Americans on climate change: Still concerned, less support for major action, finds MIT survey

In a recent MIT survey, Americans expressed less urgency about dealing with climate change than they did three years ago—but still far more than they did six years ago.

"Despite the back-off since the 2006 survey, we've come a long way in public support for doing something about climate change since the first survey in 2003," says Howard Herzog, senior research engineer in the MIT Energy Initiative. Indeed, about half the 2009 respondents believed that the United States should join an international treaty aimed at reducing greenhouse gas (GHG) emissions.

The new survey shows two other striking changes. For the first time there is a correlation between political party and views, with Democrats consistently ranking the climate change problem as more serious than Republicans and Independents do. And there is a significant increase in people's awareness of carbon capture and storage (CCS)—a climate-change-mitigation technology that calls for capturing carbon dioxide emissions from power plants and other large sources and injecting them into geologic formations for long-term storage.

That last finding is of particular interest to Herzog and his colleagues, who have been working on CCS since the late 1980s. They undertook the first public survey in 2003 primarily to find out what people thought about CCS. At that time, their research had demonstrated the technologic and economic promise of CCS, but public recognition and acceptance of the technology were a concern.

The group has now conducted three surveys—in September of 2003, 2006, and 2009—to find out what the public thinks about CCS in particular and climate change and environmental issues in general. Each survey included about 20 questions focusing on the environment, global warming, and a variety of climate-change-mitigation technologies.

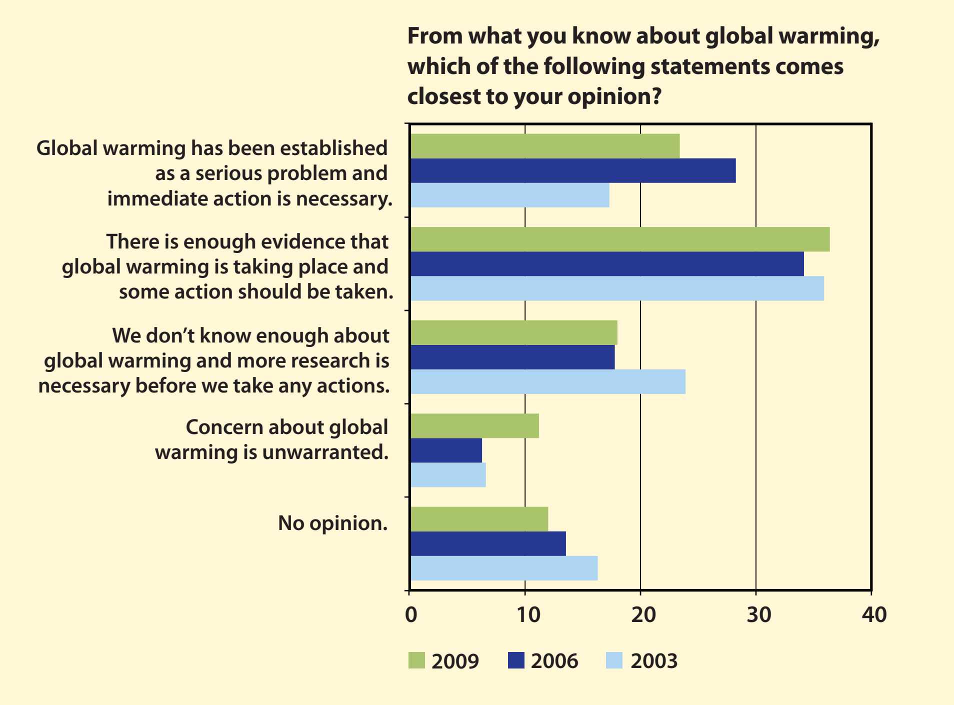
In designing and administering the surveys, the research team collaborated with Knowledge Networks, a company that specializes in Internet-based public opinion surveys. More than 1,200 people answered each survey (with no overlap among the three groups of respondents). Samantha F. O'Keefe, an MIT graduate student in civil and environmental engineering, has been working with Herzog to analyze the 2009 survey responses.

Results from the three surveys provide insights into how public awareness, concern, and understanding have changed—or not changed—during the past six years.

Global warming continues to be ranked first in a list of 10 environmental concerns, but the environment in general still ranks near the middle of a list of 22 "most important issues facing the US today." The economy, health care, and unemployment are the top three concerns—no doubt a reflection of the recent economic downturn and health care debate.

Several sets of responses show the recent decline in urgency about tackling climate change. For example, the

From what you know about global warming...



In a recent MIT survey, Americans expressed less urgency about dealing with climate change than they did three years ago—but still far more than they did six years ago. About half of the 2009 respondents believed that the United States should join an international treaty aimed at reducing greenhouse gas emissions.

fraction of people who feel that immediate action to solve global warming is necessary is now 23%—lower than in 2006 (28%) but still higher than in 2003 (17%). In terms of willingness to pay extra on their electricity bill to "solve" global warming, in 2006 people agreed to pay on average $21 more per month, but in 2009 that number dropped down to $14—roughly the value observed in the 2003 survey.

Nevertheless, 60% of the 2009 respondents said that the federal government should be doing more to deal with global warming—a value down 10 percentage points from 2006 but still a significant fraction of the population. Moreover, almost half the people surveyed in 2009 said that the United States should join other industrialized nations in an international treaty that calls for cutting back GHG emissions from power plants and cars—even after being told that "some people say this will hurt the economy."

"That was somewhat surprising," says Herzog. "Even though the population has backed off a little in terms of calling for urgent action…I think there's still popular support for doing something about climate change but probably not for taking the drastic actions that some people are calling for. The question is not so much about whether people are in favor or not in favor of taking action but more about the magnitude and the pace."

In terms of demographic trends, the 2009 survey was the first to show a correlation between views on the severity of the global warming problem and the political party of the respondent. In the recent survey, Democrats overwhelmingly ranked climate change as either "serious" or "somewhat serious." In contrast, Republican responses were distributed among "somewhat serious," "uncertain," and "concern is unwarranted," while Independent responses were evenly spread across all choices. "It appears that the issue has become more politicized than it was in the past," says Herzog.

Technology awareness

In the section of the survey measuring awareness of technologies related to climate change, hybrid cars and solar and wind energy continued to top the list of "what people have heard about in the past year." But awareness of CCS increased significantly since the previous surveys. The fraction of people recognizing the term "carbon capture and sequestration" was 4% in 2003, 5% in 2006, and 17% in 2009.

Why the big increase in name recognition? "There's been a significant increase in press coverage of CCS in the past three years," says Herzog. "It's been talked about in congressional bills, and even the US president has mentioned the technology." Interestingly, better-educated and wealthier people were more likely than others to have heard of CCS. Indeed, respondents earning $100,000 per year were four times more likely to have heard of CCS than those making less than $25,000.

But respondents still were not ready to accept CCS as a viable option for addressing climate change. Asked if they would include CCS in a climate change plan, about 25% of the people responded favorably and about 25% were opposed, but fully 50% were not sure. That response is consistent with another question in which many respondents were not sure which environmental concerns CCS would address. Despite the increased name recognition, many people are still unclear about the details of CCS.

Herzog is pleased with the increased recognition of CCS. He stresses that the climate change problem "is not going to go away," so research should continue on technologies such as CCS. "I think more and more people see it as a technology that's going to be important in the longer term," he says. "And we're getting increasing numbers of e-mails and other inquiries from a broad spectrum of sources, from educational institutions to industry to governmental officials, all wanting to know more about it."

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By Nancy W. Stauffer, MITEI

This research was supported by the MIT Carbon Sequestration Initiative (http://sequestration.mit.edu/CSI/index.html). More details about the 2009 survey along with links to the previous surveys are available at http://sequestration.mit.edu/research/survey2009.html.

MIT team recommends strategy for reducing automotive fuel use, emissions

Cutting petroleum use and greenhouse gas (GHG) emissions in all of America's cars and light trucks is a critical but daunting task. Now, an MIT report outlines a set of policies that could accomplish that goal in the next few decades. Working together, the policies would give all stakeholders incentives to do their part.

Manufacturers would be required to make more fuel-efficient cars, and consumers would be encouraged to buy them and then drive them in a fuel-efficient manner. Meanwhile, the nation would develop a comprehensive strategy on fuels setting long-term targets, with care taken to account for the life-cycle emissions as well as production, distribution, and vehicle requirements for each possible fuel.

"If we're serious about reducing petroleum consumption and GHG emissions, we need to look at the whole system—at everyone who makes, buys, and uses vehicles and their associated fuels," says John Heywood, professor in MIT's Department of Mechanical Engineering. "All the pieces are interrelated, and we need them to work together. For example, tighter regulations can push industry toward higher fuel economy, but then we need to create incentives for consumers to buy those cars, which may be smaller, lighter, and more expensive than they're used to."

For policymakers in Washington, taking a systems view is difficult because of the politics involved. Interest groups are constantly converging or diverging into separate camps and lobbying for separate policies. The result, says Heywood, is confusion in the policy debate and adoption of isolated initiatives that focus on specific fuels, car technologies, and so on.

To help demonstrate how a systems approach could work, Heywood turned to 10 of his graduate students in the Sloan Automotive Laboratory, each of whom is immersed in studying some aspect of the transportation problem—from selected technology and fuels options to consumer behavior to the impacts of specific policies and more. A year ago, Heywood issued this group a challenge: Drawing on their individual knowledge and expertise, they should together come up with a sensible, effective, and realistic policy portfolio—*An Action Plan for Cars.*

The students held a series of meetings, and ultimately each participant contributed to one section of the report, drawing on his or her own experience supplemented by information from other transportation and energy sources. Guided by Heywood and feedback from several outside experts, graduate students Valerie Karplus and Donald MacKenzie of MIT's Engineering Systems Division integrated the sections into a 24-page document that outlines a set of interacting policies that the MIT team believes can significantly reduce petroleum use and emissions in America's cars and light trucks.

Getting fuel-efficient vehicles on the road

The first group of policies aims to reduce the fuel consumption of new vehicles. The report recommends that the Corporate Average Fuel Economy (CAFE) standards for the fuel economy of new cars continue to tighten—well beyond the 2016 target of 34.1 mpg—and that manufacturers be given ample lead time to plan for those increases. Two other policies would create consumer incentives. One would establish a "feebate" system under which buyers of new cars would get a rebate if they chose fuel-efficient models—or pay a fee if they went for gas-guzzlers. The exact payment would depend on how many miles per gallon the purchased model is above or below a set fuel economy. The other policy in this group would increase taxes on motor fuels by 10 cents per gallon each year for at least the next 10 years.

Those three policies would produce a synergistic effect, with manufacturers producing more efficient cars and consumers demanding them, motivated by immediate and long-term savings. To make rising fuel taxes more palatable, drivers would see reductions on their income taxes or payroll taxes. But some of the revenue would be used to improve the US transportation infrastructure. "Our roads and bridges are in real need of maintenance and improvement," says Heywood. "This would provide much-needed money to get them back in shape."

Educating vehicle buyers and drivers

The next pair of policies is designed to help consumers buy and drive more wisely by giving them more information. Although labeling provisions exist, it is not always clear what the cited ratings mean. In general, the fuel economy listed on stickers or in advertisements is for highway driving, when most vehicles are at their most fuel efficient. New rules should call for a clear presentation of fuel economies for both highway and city driving so that car buyers can make more informed choices.

The second policy aims to teach people how to avoid driving behaviors that waste fuel. Driving at a steady, comfortable speed and avoiding rapid braking and accelerating can reduce fuel use by 10% or more compared with more

Primary Target	Recommendation
Vehicle fuel economy	• Continue to tighten CAFE standards beyond 2016 target of 34.1 mpg, providing ample lead time • Implement a feebate system that adjusts new vehicle prices in proportion to fuel consumption • Raise the tax on motor fuels by 10 cents per gallon each year, for at least 10 years
Driver behavior	• Improve and standardize fuel economy labels on new vehicles and car-buying websites • Establish driver education programs to inform consumers how to reduce fuel consumption through behavior
Fuel supply	• Evaluate all fuels on the basis of full life-cycle GHG emissions • Develop national strategy for alternative fuels with involvement of all stakeholders • Address need for production capacity, distribution infrastructure, and compatible vehicles simultaneously

Main features of the policy portfolio presented in MIT's *An Action Plan for Cars.*

aggressive driving behaviors. "Perhaps it isn't a glamorous way to reduce consumption, but it's relatively low cost—and it's scalable," says Karplus. "Every driver on the road can do it. They'll use less fuel, save money, and reduce emissions, all at the same time." Information can be distributed in advertisements and incorporated into drivers' education programs so that new generations of drivers will develop fuel-conserving habits.

Fuels for the future

The final set of recommendations focuses on fuels. Heywood notes that current initiatives, laws, and requirements are "piecemeal," with no coherence or clear sense of purpose. However, he also believes that it is "inappropriate and premature to say something about how specific fuels are being treated or should be treated—with subsidies, import duties, and so on. We're missing a lot of basic information." The team's recommendations therefore take a broader view of how to move forward on the fuels side.

After intense discussion and debate, the MIT team reached consensus on three critical points. First, all transportation fuels—petroleum-based as well as alternative fuels—should be evaluated on the basis of their full life-cycle GHG emissions. "While that may seem obvious, the devil is in the details on this one," says Karplus. She cites several examples. Growing biofuels in place of food crops in Iowa may push up food imports from Brazil, where the need for added agricultural land could lead to destruction of rainforest, an important carbon sink. Electric vehicles emit no tailpipe emissions, but recharging their batteries may increase electricity generation from GHG-emitting power plants. "And the list goes on," says Karplus. "If we're really looking for ways to reduce GHG emissions, we have to be careful about how we do the accounting."

The second recommendation calls for developing a coordinated national strategy for alternative fuels. This high-level, overarching strategy should define clear targets and then—based on careful consideration of all the options—identify fuels and technologies that can best contribute to meeting the goals of displacing petroleum and reducing GHG emissions. Developing a successful strategy will require full participation of the now-splintered interest groups that support biofuels, electric cars, hydrogen, natural gas, and so on.

Finally, any national fuels strategy should include policies that address the need for developing fuel production capacity, distribution infrastructure, and compatible vehicles at the same time. Focusing on only one or even two of those challenges will not yield the intended reductions in petroleum use and emissions. In addition, current subsidies, mandates, and import tariffs (for example, on ethanol) should be examined to make sure that they are consistent with the national fuels strategy.

Moving ahead

Heywood stresses that the report does not attempt to write specific legislation or regulation or to define end objectives too tightly because we need to better understand the full impacts of our choices. The report is instead meant to demonstrate a set of integrated policies that can help us "define where we want to get to, decide whether a given path shows potential for getting us there, and then plan so that we can both get moving and get wiser."

"We're hoping our report serves as a first step, a starting point to spur thinking about how you can achieve policies that are going to work together in a synergistic way," adds Karplus. "We aren't necessarily saying to adopt this set of policies exactly as written, but we're demonstrating how Washington can think about policies in a way that considers how they might best work together."

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By Nancy W. Stauffer, MITEI

This study was supported in part by the MIT Energy Initiative. Go to http://web.mit.edu/mitei/research/studies.html to download a copy of *An Action Plan for Cars: The Policies Needed to Reduce US Petroleum Consumption and Greenhouse Gas Emissions*.

Lisbon's buildings get more energy efficient, thanks to MIT students

Three graduate students at MIT—one from Portugal and two from the United States—are seeking to boost the energy efficiency of Lisbon's buildings. They've estimated that as many as 800,000 structures, ranging from modern high-rises to two-century-old buildings, would benefit from some form of intervention.

The students are linked by their affiliation with Leon Glicksman, MIT professor of architecture and mechanical engineering. Glicksman brought the students together almost two years ago to walk through Lisbon's neighborhoods and brainstorm about ways to dovetail their separate research interests to help the city benefit from energy-saving interventions.

In Portugal, buildings are responsible for more than 30% of total energy use. In Lisbon, the figure is almost twice that and is expected to grow significantly in the coming years. "This makes a compelling case for the need to retrofit existing building stock," says Nuno Clímaco Pereira, a Lisbon native who is a PhD candidate in the MIT-Portugal Program and is based at Instituto Superior Técnico (IST) in Portugal. He is currently in residence at MIT.

While Pereira used models to predict the cost savings of different retrofitting options over time, MIT mechanical engineering graduate student Stephen Ray created a new tool for people around the world to investigate the energy-saving potential of different types of roofs. MIT building technology graduate student Carrie Brown is using data from Lisbon in models she designed for assessing energy-efficient retrofits and options such as the addition of solar panels to buildings.

Photo: courtesy of Carrie Brown G, MIT

Left to right: Stephen Ray and Carrie Brown of MIT and Nuno Clímaco Pereira of the Instituto Superior Técnico in Portugal received a "best poster" award at the January 2009 annual meeting of the Alliance for Global Sustainability in Zürich. Their winning poster, titled "Retrofit Options for Increasing Energy Efficiency in the Existing Building Stock—Lisbon Case Study," explained the trio's research on ways in which Lisbon might reduce energy consumption in its building stock.

All three are affiliated with MIT-Portugal, a nearly four-year-old collaboration between MIT and universities, laboratories, and industry in Portugal that was launched by the Portuguese Ministry of Science, Technology, and Higher Education to strengthen the country's knowledge base and international competitiveness.

The time is ripe for the students' initiative: Rising energy prices and government efficiency incentives are creating a promising climate for energy retrofitting. "A lot of information is starting to be available on how energy-efficient buildings perform. This will drive the implementation of retrofits," Pereira says.

History meets efficiency

Pereira is doing a case study of poorly constructed residential buildings that ring the city. He estimates that a quarter of them need medium to high levels of attention. He's looking at the projected benefits of insulating their walls and roofs, adding natural ventilation systems to take advantage of ocean breezes, and shading and upgrading their windows to block some of Lisbon's relentless sunshine.

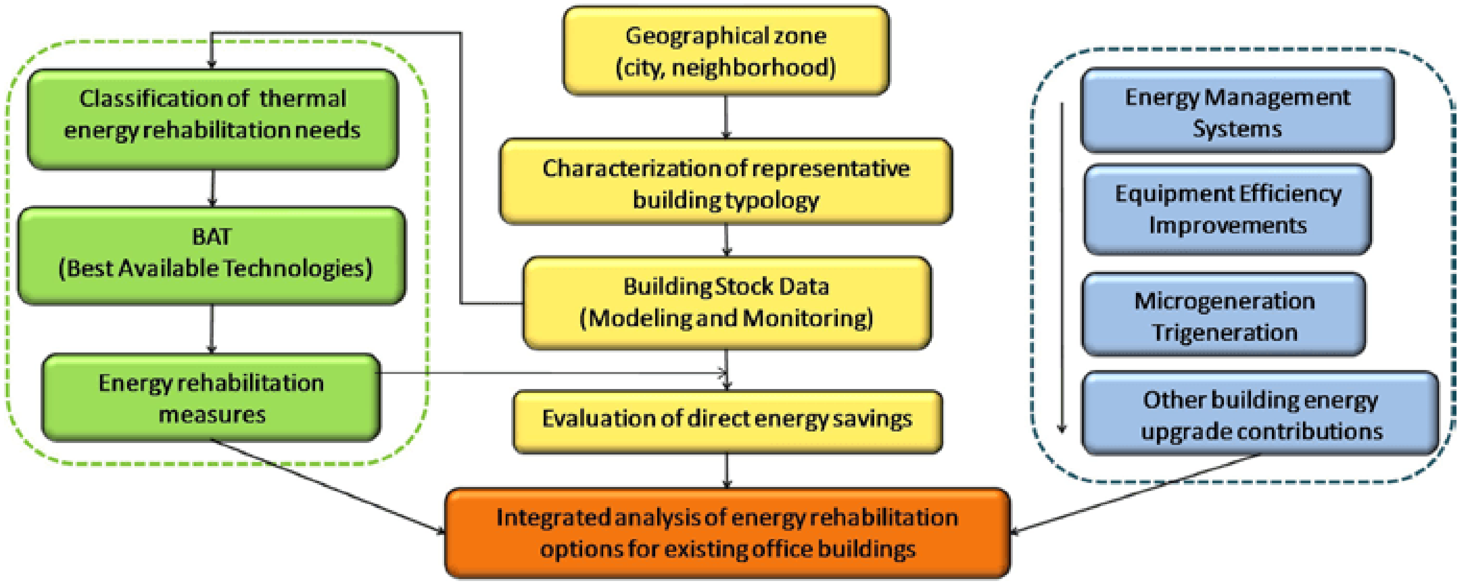
Amazingly, due to their thick walls, buildings designed immediately after Lisbon's devastating 1755 earthquake are not as wasteful as some newer structures. Still, Pereira calculated that adding insulation, double glazing windows, and taking advantage of natural ventilation could halve the energy consumption of the vaulted-ceiling, tiled buildings known as Pombalinos.

Pereira hopes to define the best available retrofit options for both modern and historic buildings, assess the potential for energy reductions citywide, and develop a methodology for large-scale rehabilitation throughout Portugal. He will develop implementation strategies with Lisbon city officials and the Lisbon Municipal Energy Agency.

Ray, whose doctoral research focuses on natural ventilation in commercial buildings, investigated the energy-saving potential of various roof types. He also created a new software module to supplement an existing online design tool, the MIT Design Advisor, thus providing engineers and architects worldwide with the ability to mimic his analysis of Lisbon roofs.

"We found most buildings in Lisbon could actually save more energy by adding insulation to the traditional red ceramic tile roofs instead of installing a new roof," Ray says. However, modern buildings with flat black roofs would fare better with cool or green roofs, he says, which reduce roof temperatures and solar heat gains.

Energy rehabilitation methodology—an extract from the students' award-winning poster



Brown, whose work focuses on assessing technology choices in the built environment, says options for sustainable buildings include a variety of demand-side efficiency measures such as added insulation and better windows. Supply-side renewable options include adding photovoltaics as an energy source.

"While there are many options to reduce energy used in buildings, it is often difficult to determine which are the most appropriate technologies to implement," she says. "I'm really interested in helping people figure out what changes they can make with the least amount of money that can give them the biggest energy savings."

Global connections

Although Ray and Brown are not directly enrolled in MIT-Portugal, the program partially funds their research. In 2009, Ray organized a workshop for students in the MIT-Portugal Sustainable Energy Systems (SES) group interested in pursuing buildings-related research. "After that workshop, it was clear that Nuno, Carrie, and I had work that was interrelated," Ray says. The three designed a poster presenting the scope of their work in Lisbon. The poster was selected as one of the six best posters at the Alliance for Global Sustainability's annual meeting in 2009.

A central goal of the MIT-Portugal Program is to demonstrate that an investment in science, technology, and higher education can have a positive, lasting impact on the economy. To that end, MIT-Portugal has created cutting-edge PhD and master's-style programs involving eight Portuguese universities and research institutions. Each semester, several MIT-Portugal students and faculty visit MIT to do research in leading laboratories at the Institute. "These connections help MIT in its efforts to be a global university," Glicksman says. Through workshops and teleconferences, Pereira, Brown, and Ray have given and heard feedback on their respective projects as well as those under way in MIT-Portugal's entire SES group.

Ray is enthusiastic about the international connections he has made through the program. "I appreciate the chance to collaborate with the future leaders of sustainable energy in Portugal," he says, and he predicts that the relationships he has developed will continue throughout his career.

"There is a lot of interest in green technologies for buildings, but too often it seems such technologies and their benefits are poorly understood," Ray says. By increasing awareness, understanding, and information about the choices available, the MIT students' work has the potential to reach well beyond Lisbon city limits.

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By Deborah Halber, MITEI correspondent

Martin Fellows, 2010–2011

The Martin Family Society of Fellows for Sustainability, established at MIT in 1996 through the generous support of the Martin Family Foundation, fosters graduate-level research, education, and collaboration in sustainability. The society supports and connects MIT's top graduate students in environmental studies and fosters opportunities for multidisciplinary cooperation in both the short and long term.

Regina Clewlow
Engineering Systems Division
Examining intercity demand for high-speed rail and air transportation and potential long-range scenarios under climate policies

Madhu Dutta-Koehler
Urban Studies and Planning
Developing planning strategies for climate change adaptation for rapidly growing cities of the global south

Katherine Dykes
Engineering Systems Division
Developing a model for wind energy diffusion into the utility system with particular attention to issues associated with integration

Anita Ganesan
Earth, Atmospheric, and Planetary Sciences
Examining regional monitoring of greenhouse gas emissions in India

David Griffith
Civil and Environmental Engineering (with Woods Hole Oceanographic Institution)
Quantifying the inputs and fate of steroidal estrogens in Massachusetts Bay

Roberto Guerrero Compeán
Urban Studies and Planning
Exploring effects of anti-poverty programs on household behavior toward climatic risks in rural areas

Rhonda Jordan
Engineering Systems Division
Developing an electrification planning methodology that incorporates demand characteristics unique to the developing world

Woei Ling Leow
Engineering Systems Division
Developing algorithms for managing home electricity use in a smart grid

Samar Malek
Civil and Environmental Engineering
Developing new understanding of and design tools for grid shells for sustainable buildings

Bryan Palmintier
Engineering Systems Division
Designing sustainable electric systems with significant renewable and demand-side resources by modeling intra-daily dynamics, uncertainty, and constraints during long-range planning

Jeff Rominger
Civil and Environmental Engineering
Investigating the physical controls of nutrient uptake in aquatic vegetation

Nicholas Ryan
Economics
Measuring the scope for profitably saving energy in small, energy-intensive Indian factories and testing the efficacy of the Clean Development Mechanism in reducing carbon emissions

Sourabh Saha
Mechanical Engineering
Developing probe-based nano-manufacturing tools and processes for nano-applications

Todd Senecal
Chemistry
Examining the catalytic introduction of trifluoromethyl groups into organic molecules

Xing Sheng
Materials Science and Engineering
Exploring optical and electronic design to improve the performance of thin film photovoltaic and light-emitting devices

Yasuhiro Shirasaki
Electrical Engineering and Computer Science
Developing energy-efficient colloidal quantum dot light-emitting diodes for display and lighting applications

Gaj Sivandran
Civil and Environmental Engineering
Examining plant-water interactions in dryland systems, where water is the limiting resource to ecosystem function

Lily Song
Urban Studies and Planning
Examining community-utility partnerships for taking building energy efficiency retrofits to scale

Mattijs van Maasakkers
Urban Studies and Planning
Studying the emergence of ecosystem services in river basin management: sources of scientific legitimacy in environmental decision making

Yi Zhu
Urban Studies and Planning
Developing an urban information system for transportation and land use modeling, travel behavior, and urban sustainable transportation strategy

MITEI Founding and Sustaining members

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

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SUSTAINING PUBLIC MEMBER

Portuguese Science and Technology Foundation

Members as of June 15, 2010

MITEI Associate and Affiliate members

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

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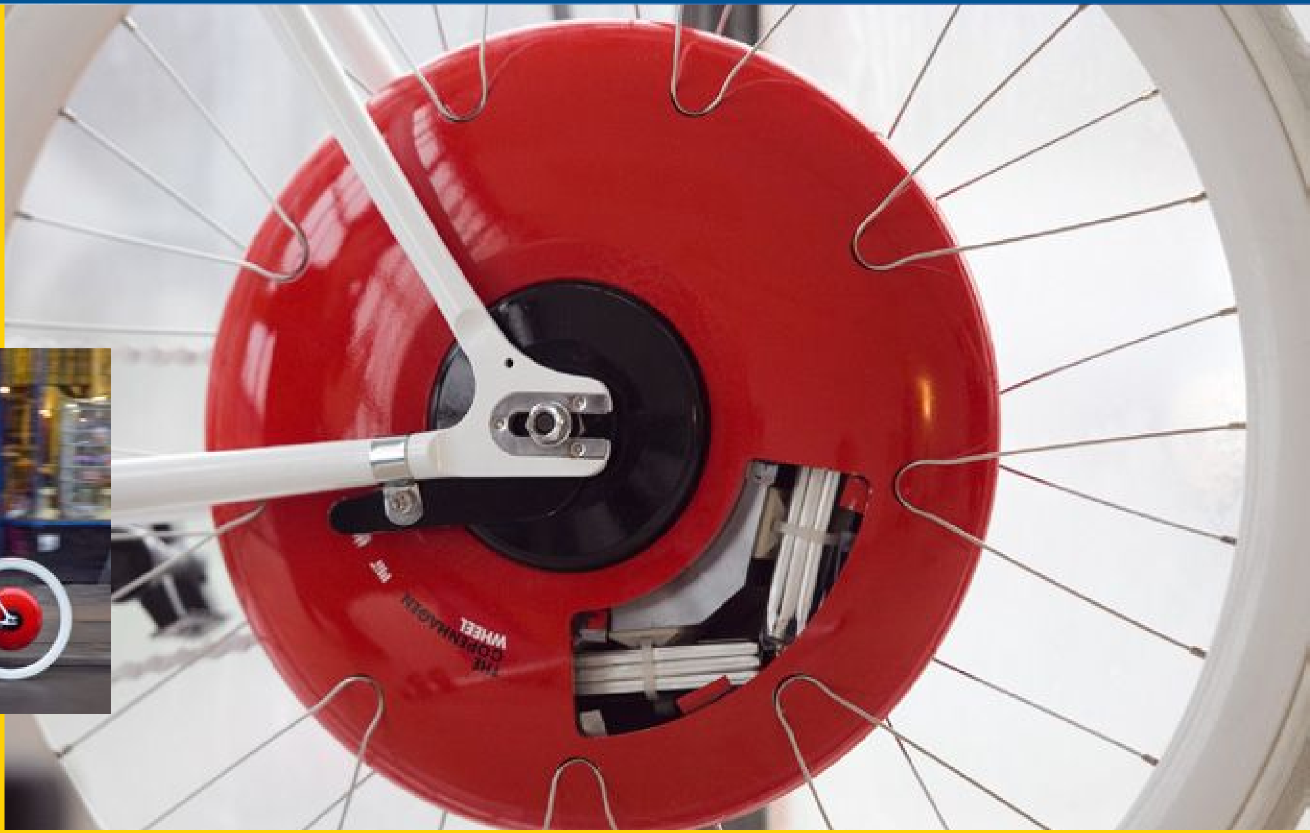

Photos: courtesy of the SENSEable City Lab

At the Copenhagen climate change conference in December 2009, MIT researchers demonstrated a revolutionary bicycle wheel that transforms existing bikes into hybrid electric bikes and promotes cycling by improving the riding experience. The wheel stores energy whenever the rider brakes and then uses that power to provide a boost for climbing hills or maneuvering in traffic. Assisted by a smart phone, the wheel can track speed, direction, and distance traveled; pollution levels; road conditions; and even the proximity of the rider's friends. Dubbed the Copenhagen Wheel, it was developed by Carlo Ratti, associate professor of the practice in MIT's Department of Urban Studies and Planning and director of the SENSEable City Laboratory, and his team. The wheel can easily be mounted on any standard bike. More at http://senseable.mit.edu/copenhagenwheel/.