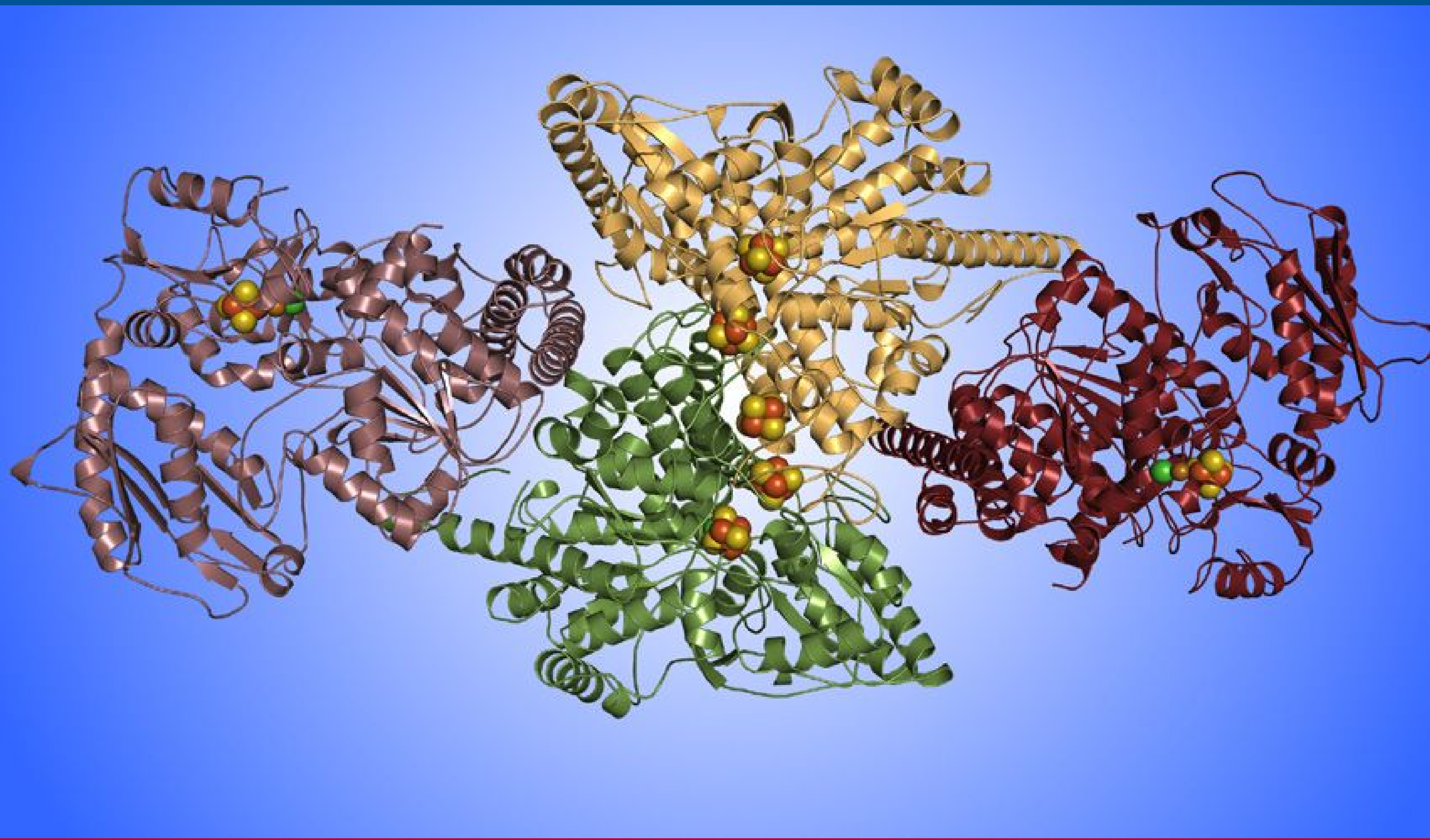
Energy Futures

MIT ENERGY INITIATIVE
AUTUMN 2009



Carbon-capturing enzyme: MIT chemists learn from nature

IN THIS ISSUE

Energy Futures

Energy Futures is published twice yearly by the MIT Energy Initiative. It reports on research results and energy-related activities across the Institute. To subscribe, send your address to stauffer@mit.edu.

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ISSN 1942-4671
(Online ISSN 1942-468X)

MIT Energy Initiative
The MIT Energy Initiative is designed to accelerate energy innovation by integrating the Institute's cutting-edge capabilities in science, engineering, management, planning, and policy.

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Cover diagram: Yan Kung, MIT
Design: Tim Blackburn
Printing: Puritan Press, Inc.
PSB 09.10.0580

Printed on paper containing 30% post-consumer recycled content, with the balance coming from responsibly managed sources.

Update on the MIT Energy Initiative

Dear Friends,

We live in interesting times! Energy issues and associated environmental challenges continue to hold center stage as the world community transitions from preparing for the UN climate change talks in Copenhagen ("COP-15") to mapping the road *from* Copenhagen.

Nowhere was the centrality of these issues more in evidence than at MIT in October, when the Institute had the distinct honor of hosting President Barack Obama for a tour of campus energy research laboratories, briefings from MIT energy faculty, and an address on energy at Kresge Auditorium. In his talk, the President countered the "pessimism" of those who believe there is little we can do to address climate change risks by expressing strong support for the role of technology and innovation in meeting the challenge. You can read more about the President's visit on page 4 of this issue of *Energy Futures* and access a video of the entire event at the MITEI website (web.mit.edu/mitei).

The administration backed up the President's faith in the "American spirit of innovation" with its announcement of the winners for the first round of awards from the new Advanced Research Projects Agency-Energy (ARPA-E). MIT and recent MIT spinoffs in the Boston area were recipients of 5 of the 37 awards for potentially transformative energy technologies. Massachusetts received the largest combined dollar amount of any state in the nation, demonstrating again MIT's continuing tradition of driving economic growth. For more details, turn to page 26.

Achieving an actionable global consensus on a path forward for mitigating climate change risks will be arduous. Closer to home, Washington is engaged in complex legislative trade-offs to balance regional energy interests, economic impacts, and environmental imperatives. These global and national efforts are occurring against a backdrop of significant economic uncertainty and anxiety, lower energy prices, and flat consumption. Such near-term trends diminish the political will to transform the global energy marketplace, even as greenhouse gas emissions continue to accumulate in the atmosphere, making it essential that we accelerate that transformation. There is an increasingly urgent need for low-carbon energy technologies that meet economic tests in both developed and developing countries and for policies aligned with their introduction at scale.

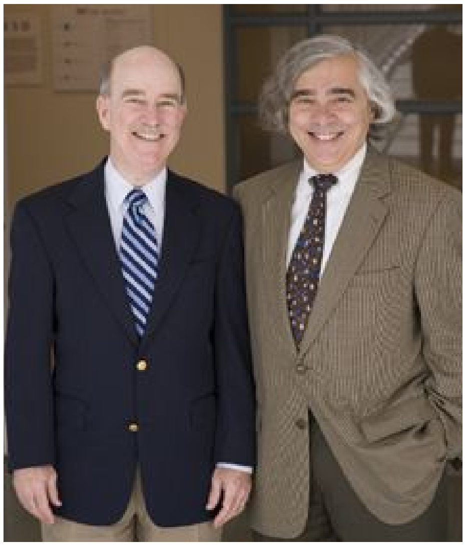
Photo: Justin Knight

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.

This imperative is clearly recognized by the many companies, foundations, government programs, and MIT alumni and friends who continue to support MITEI's research, education, campus energy, and outreach programs in these economically challenging times. This steady support is essential for pursuing our research and educational missions.

This year, we were pleased to welcome 22 new MITEI members, provide 47 new graduate fellowships to 20 departments, and support 24 early-stage seed fund projects. Results from five of our earlier seed fund projects—one from each of MIT's schools—are chronicled in the research section of this issue starting on page 6. These projects highlight both the diversity of energy challenges we face and the need for high-impact solutions from a variety of disciplines.

The sponsored research projects supported by MITEI members reside in 13 departments and four laboratories. Taken together, these projects make up an extraordinary set of investments in the energy future and are just what is needed for the long road from Copenhagen.

Dramatic increases in government support for significant and sustained energy-related research programs at universities also have created new opportunities for MIT faculty and students. These have come about through a convergence of new administration priorities, congressional focus, and the economic stimulus package. MIT is now home to two new Energy Frontier Research Centers (EFRCs) funded by the US Department of Energy (DOE) Office of Science (see page 25). MIT is also a collaborator on four others. Selected after a highly competitive solicitation, the EFRCs are designed to provide science-based solutions to some of the most difficult and intractable energy challenges. MITEI coordinated the campus-wide response to this opportunity and looks forward as novel DOE programs—additional rounds of ARPA-E awards funded through the stimulus package and the Energy Innovation Hubs proposed by the Obama administration—are advanced. Other agencies, such as the Department of Defense and the National Science Foundation, are also increasing energy-related project support.

On the outreach front, we continue to help bring technically grounded analysis to bear on national and international discussions about energy and R&D policies. MITEI members have joined with us to support a new symposium series on timely energy topics, with a goal of informing policy circles about technical realities. The first symposium was on the retrofit of coal plants for CO_2 emissions reduction (see page 42), and the next will be on the electrification of the transportation system. Also, four major interdisciplinary integrative studies—the Future of Solar Energy, the Future of Natural Gas, the Future of Nuclear Fuel Cycles, and the Future of the Electric Grid—are at various stages of their two-year journeys.

MITEI's Energy Education Task Force reached a significant milestone by establishing the Institute-wide Energy Studies Minor for undergraduates (see page 29). The design of this program drew on the expertise of 16 faculty members from 14 departments to develop a curriculum that includes 10 new and redesigned courses. MITEI's commitment to undergraduate research was also expanded to include support for 16 Undergraduate Research Opportunities Program (UROP) students during the past summer (see page 31). Another great sign for the future of energy education at MIT: almost a third of the 50 new faculty members hired in fall 2009 have research interests directly related to energy.

Finally, in recognition of the global nature of energy and climate challenges, we are moving toward enhanced cooperation with corresponding institutions in the major emerging economies and in developing countries. Together with Cambridge University, we recently entered into a Low Carbon Energy University Alliance agreement with Tsinghua University. Planning is in the early stages for several other international initiatives.

MITEI has been built on the continued hard work of its staff, MIT faculty and students, and the engagement of its members, the broader energy technology and policy community, and alumni and friends. We are grateful for your support and value your continued interest and input. We hope you enjoy this fourth edition of *Energy Futures.*

Sincerely,

Professor Ernest J. Moniz
MITEI Director

Professor Robert C. Armstrong
MITEI Deputy Director

December 2009

Photos: Justin Knight

During his October 23 energy address at MIT, President Barack Obama called on the nation to lead the world in developing new, efficient, clean energy technologies. After visiting several MIT energy labs, he said, "Extraordinary research [is] being conducted at this Institute." (More on page 4.)

At a MITEI colloquium on October 7, Frances Beinecke, president of the Natural Resources Defense Council and a member of MITEI's external advisory board, described signs of global warming, including melting Arctic sea ice, rising sea levels, and increasing acidity of the sea waters. She urged rapid passage of climate legislation. (More at web.mit.edu/mitei/news/spotlights/beinecke.html.)

At a MITEI colloquium on October 29, Tony Hayward, CEO of BP and a member of MITEI's external advisory board, stressed that there is no magic solution to the world energy situation and that government involvement will be needed to resolve the energy/climate dilemma. (More at web.mit.edu/mitei/news/spotlights/many-answers.html.)

President Barack Obama at MIT: Gives clean energy speech, tours energy labs

Professor Paula Hammond's week at MIT started out like any other—teaching, meeting with students, working on her research. It ended with Hammond and her colleague Professor Angela Belcher briefing President Barack Obama on a novel approach to energy storage—batteries that can be grown, not manufactured.

Hammond and Belcher were part of a team of energy researchers at MIT who met with the President on his visit to the MIT campus on October 23. Obama also heard from Professors Alex Slocum and Marc Baldo and toured the laboratory of Professor Vladimir Bulović. They were joined in the briefings by two graduate students working with Hammond and Belcher, Rebecca Lynn Ladewski and Lt. Col. F. John Burpo, who has completed his second tour in Iraq and was an Eni-MIT Energy Fellow in 2008–2009.

Hammond had this to say about the President: "He put everyone in the room at ease the moment he walked into the lab. As Angie and I explained different aspects of the science, he would stop us and ask specific questions about the technology....He wanted to know when these innovations would become companies, startups, and ultimately new jobs. It was clear that the President knew the importance of science and engineering both for its practical contributions and its downstream economic value."

Belcher noted the President's quick mind and quick wit. Her answer to Obama's query about her ability to do a billion experiments simultaneously—"yes we can"—prompted the President to respond, "Hey, that's my campaign slogan."

President Obama greets members of the audience after his speech. Of his visit to MIT he said: "You just get excited being here and seeing these extraordinary young people.... It taps into something essential about America." He asserted that the nation has "always been about discovery. It's in our DNA."

MIT President Susan Hockfield, Governor Deval Patrick, Senator John Kerry, and Professor Ernest Moniz, director of the MIT Energy Initiative (MITEI), joined the President on his tour. After hearing from MIT faculty about several promising research projects in renewable energy, storage, and efficiency, President Obama delivered an address on American leadership in clean energy.

Hockfield opened the event, emphasizing the importance of increased and sustained funding for energy research and development. She noted that President Obama's stimulus package and other funding priorities underscore "his forceful support of federal funding for energy R&D."

Moniz introduced the President to a packed audience at Kresge Auditorium. Attendees included numerous local, state, and federal officials and clean-tech entrepreneurs, in addition to many MIT faculty, students, and staff. Welcoming the President to MIT, Moniz said, "The President's commitment to integrating sound science and critical analysis into the formulation and implementation of policy across the board is profoundly important—and indeed essential for moving us to a sustainable energy future."

Moniz added, "The President has re-established the United States as a member of the community of nations that are committed to meeting the linked challenges of climate change, economic development, and security."

In his address, Obama praised MIT's commitment to energy research, singling out the MIT Energy Initiative and making a strong call for the nation to lead the world in the development of new, efficient, and clean energy technologies. The President's aspiration: "Nations everywhere are racing to develop new ways to produce and use energy. The nation that wins this competition will be the nation that leads the global economy. I'm convinced of that. And I want America to be that nation."

Describing his tour earlier in the day, the President said, "Extraordinary research [is] being conducted at this Institute." An appropriate exclamation point to this sentence was the President's signature on equipment in Bulović's lab that said, "Great work!" (See photo on back cover.)

Here is an overview of the research that inspired President Obama's praise.

Solar. Baldo of electrical engineering and computer science demonstrated his work on luminescent solar concentrators, which collect sunlight for solar cells. These concentrators reduce the number of solar cells needed for a given energy output, thereby reducing the cost of solar-generated electricity. The luminescent concentrators can be mounted on rooftops and other space- and weight-sensitive locations that cannot support conventional solar concentrators. Baldo's research is funded by the US Department of Energy.

Wind. Slocum of mechanical engineering demonstrated an offshore renewable energy system (ORES) in which excess power from a wind turbine pumps water out of a storage volume anchored to the seabed. ORES operates by having water flow past a turbine into the storage volume, creating an inverse lake on the bottom of the ocean. This storage system has two purposes: it enables offshore power generation when the wind is not blowing and power is needed; and it can be used for mooring a floating wind turbine. Storage is a key enabling technology for intermittent renewable energy sources such as wind. This research was funded by a seed grant from MITEI.

In his introduction, Professor Ernest Moniz, director of MITEI, praised President Obama, stating: "The President has expanded our energy vision and is focused on creating the conditions for energy innovation to flourish across the country—at a faster pace, at a scale large enough to match the challenge."

Batteries and solar cells. Hammond of chemical engineering and Belcher of materials science and engineering and bioengineering demonstrated high-power batteries and thin-film solar cells that were grown and assembled at room temperature using biological processes. The materials involved are inexpensive and nontoxic, and the processing techniques are low-cost, water-based, and readily commercialized. Their approach addresses one of the main challenges in generating highly efficient solar cells: combining different material components so that they interact with each other on the nanometer-length scale. Their assembled batteries have the same power performance as the very best state-of-the-art batteries. When scaled, these materials—and, more importantly, the next generation of materials—could be used for computers or plug-in hybrid vehicles. Their research is funded by the National Science Foundation, Eni, MITEI, and the Army Research Office.

LED technology. Bulović of electrical engineering and computer science demonstrated quantum dot lighting, which is a potential replacement for existing incandescent or fluorescent bulbs that combines warm, rich color with the high efficiency of LED technology. The remarkably high white-light efficiency of this device is combined with a life span of more than 20 years, which could change the paradigm of lighting technology. These lights can be fabricated in a simple molding process, enabling manufacturability and large-scale deployment. Artificial lighting consumes 8% of all US energy and 22% of US electricity. The efficiency of present light sources can be doubled or even tripled with the LED white light sources that Bulović and colleagues are developing.

Photos: Justin Knight

In her welcoming comments, MIT President Susan Hockfield said, "That President Obama has come to MIT to talk about America's potential to lead in clean energy is a tribute to the groundbreaking work of our faculty and students, including many in this room."

This research was performed jointly with Professor Moungi Bawendi of chemistry and was sponsored by the National Science Foundation through MIT's Center for Materials Science and Engineering, the Army Research Laboratory through MIT's Institute for Soldier Nanotechnologies, and the Presidential Early Career Award for Scientists and Engineers. The lighting samples Bulović showed were fabricated by QD Vision of Watertown, MA, an MIT startup founded by Bawendi and Bulović's graduate students.

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By Melanie Kenderdine and Rebecca Marshall-Howarth, MITEI

For links to a webcast of President Obama's address and printed copies of his address and of introductory remarks by President Hockfield and Professor Moniz, please go to web.mit.edu/mitei/news/spotlights/obama.html.

Carbon-capturing enzyme: MIT chemists learn from nature

Each year, microorganisms containing a certain enzyme remove an estimated 100 million tons of the pollutant carbon monoxide (CO) from the environment. Now, MIT researchers have new insights into how they go about it—happy news for inorganic chemists who have long been trying to synthesize compounds that can do the same thing without the living creature.

"Microorganisms such as bacteria can do lots of chemistry that people would like to do," says Catherine L. Drennan, professor of chemistry and a Howard Hughes Medical Institute investigator. "They can form and break carbon bonds, split nitrogen, and break apart hydrogen and oxygen—all things that we can't do or can do only with great difficulty."

Key to the microorganisms' ability to perform such feats are large, powerful enzymes that catalyze (speed up) reactions. For many decades, researchers worldwide have been working to replicate that chemistry using smaller molecules in an artificial rather than natural setting. Success could mean the ability to make hydrogen for fuel cells, to remove the greenhouse gas carbon dioxide (CO_2) from the atmosphere, to clean up CO in polluted urban areas, and more.

But the researchers' best efforts are frequently unsuccessful—and Drennan is not surprised. "If we're going to copy what microorganisms are doing, we need to have a clear understanding of how they do it—at the molecular level," she says. She and her research group aim to develop that understanding by actually observing the physical structure of the key molecules involved and seeing how they change when a reaction takes place.

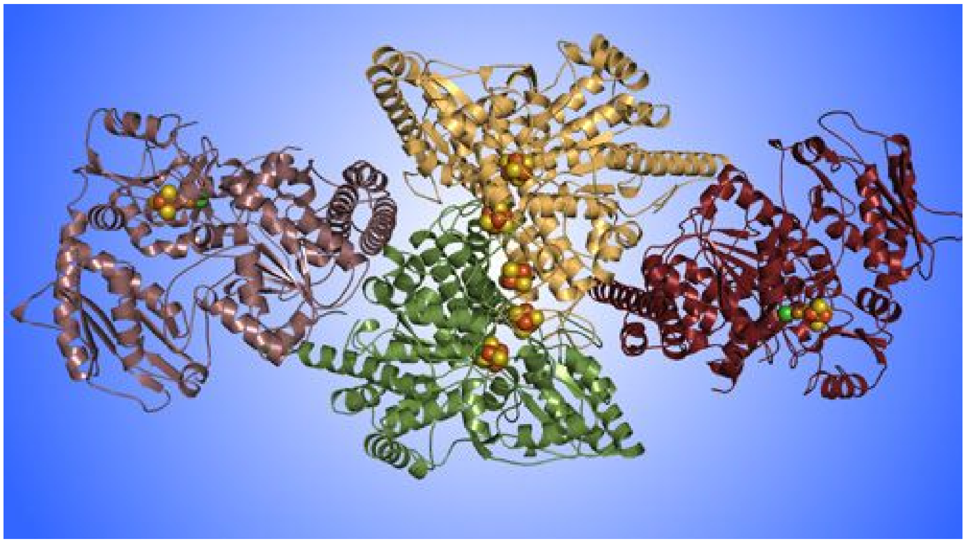
Recently, her work has focused on an enzyme that—depending on its changeable structure—can take up CO and release CO_2, or take up CO_2 and release CO, or use the CO to make a form of acetate that plays a key role in metabolism. "Unlike humans, these organisms are very flexible," says Drennan. "They'll take whatever is around them and find a way to live on it."

To start, she has been investigating the reaction whereby CO is picked up by the enzyme, where it reacts with water to form CO_2. That chemistry can be traced to a small section within the enzyme known as the C-cluster—an unusual and possibly quite ancient combination of metals and inorganic compounds including iron, nickel, and sulfur.

To help inorganic chemists replicate the abilities of the C-cluster, Drennan has been exploring its structural details. Using crystalline enzyme samples, she has looked at where the atoms are located, how they are oriented, and where empty sites are needed for other atoms to attach and catalyze chemical reactions.

Using X-rays to "see" atoms

Atoms are too small to see with an optical microscope, so Drennan turns to X-rays, which have a wavelength a thousand times shorter than that of visible light and comparable to the spacing of atoms in a crystal. The technique she uses, called X-ray crystallography, involves beaming X-rays through a crystal sample. Atoms in the sample diffract the X-rays, creating a diffraction pattern that a crystallographer—with the help of mathematical methods—converts into an electron density map and



Diagrams: Yan Kung G, MIT

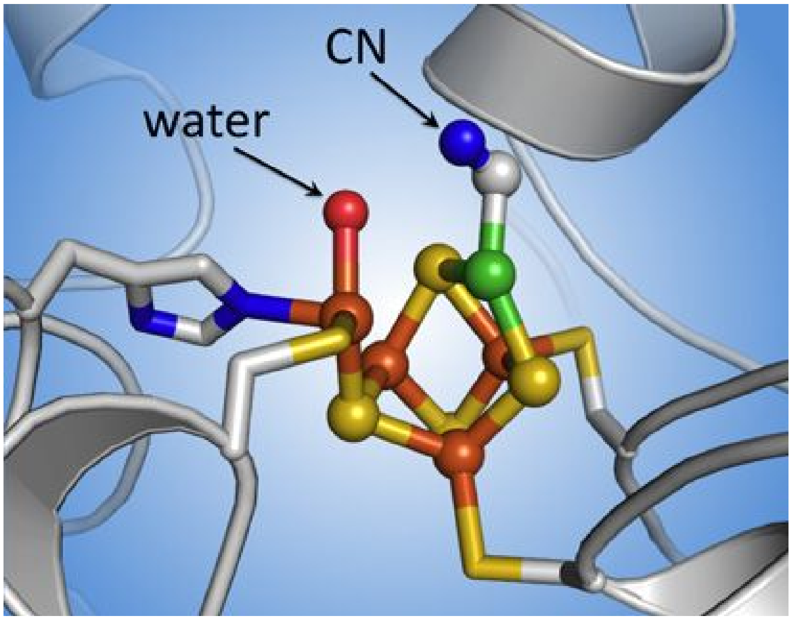
This diagram shows the overall structure of an enzyme that enables microorganisms to capture large quantities of carbon dioxide (CO_2) and carbon monoxide (CO) from the environment. Using X-ray crystallography, MIT researchers have solved the enzyme's three-dimensional structure to atomic resolution. The colors in this "ribbon" diagram indicate the four protein chains that make up the enzyme. The grouped spheres are clusters of metal atoms that play key roles in the carbon chemistry.

ultimately to an image, or "snapshot," that shows where the atoms in the sample are located.

For these studies, Drennan receives samples of the enzyme from collaborator Stephen Ragsdale at the University of Michigan Medical School, who has a laboratory specially equipped to grow the microorganism of interest. The microorganisms grow rapidly at room temperature, and the enzyme is abundant and stable—except that the metal clusters are sensitive to oxygen, so all work takes place in chambers filled with argon or nitrogen.

Keeping their enzymes away from oxygen is a minor inconvenience compared with the challenges involved in using X-ray crystallography to study them. First, the researchers must get the enzyme to form a crystal—a task that Drennan deems the "hard part," which can take many years of trying different materials and methods.
In this case, her team uses salt at high concentrations to force the enzyme molecules out of solution and into a crystalline state. The individual enzymes line up in a regularly repeating pattern in a three-dimensional crystal, presenting enough sample to be analyzed.

The next challenge is to stop the reaction just before it happens. "With X-ray crystallography you only get snapshots in time," says Drennan. "If you give the enzyme everything it needs for the reaction, it'll react—and your snapshot will show the end result but not how it happened." Tests showed that providing the enzyme with cyanide (CN) rather than CO does the trick. CN is similar to CO in structure and will bind at the same site where the CO would bind—but it won't react. The enzyme will be poised for action but frozen in time.



Based on their analyses, the researchers determined the above structure of the C-cluster, a metal cluster within the enzyme that captures CO, which then reacts with water to form CO_2. In these experiments, cyanide (CN) was used as a stand-in for CO because it would bind at the same site as CO would but not react. The structure therefore shows where CO and water molecules are bound to the metal cluster just before the reaction occurs. Knowing where the atoms bind—and where empty binding sites are located—will help guide inorganic chemists as they manipulate materials to mimic the C-cluster's removal of CO.

Atomic-level insights

Their experiments worked well. They now have a clear image of the arrangement of the metal atoms in the C-cluster just prior to the reaction. They can see where the CO would bind, and they know the location of the nearby water molecule that participates in the reaction. From those observations, they can predict how the reaction would proceed.

The researchers' results settled a long-standing debate about the presence or absence of a single sulfur atom. Another group has argued that there is a sulfur atom at the site where the CN latched on. But Drennan's results suggest that if a sulfur atom were there, it would block the CO from binding. Most experts in the field now agree that the "active" form of the C-cluster has no sulfur in that position—a finding significant for inorganic chemists as they manipulate materials to mimic the cluster's CO-removal action.

Results from Holger Dobbek and his research group at the Max-Planck-Institut für Biochemie (Germany) both verify and supplement the MIT findings. That group produced an image of the C-cluster with a CO_2 molecule in place—a structure that can be interpreted as a post-reaction counterpart to Drennan's pre-reaction images with CN (the stand-in for CO). Indeed, the structures from the two groups superimpose remarkably well, and in neither case is the disputed sulfur atom in evidence. "So at an atomic resolution, we have images that enable us to understand one of the important chemical reactions that happens on this metal site," says Drennan. "It's really very exciting."

Drennan and her colleagues are now investigating other metal clusters in the same enzyme, in particular, one that controls the acetate-forming reactions. But, she warns, there is always the chance that—even getting the right structure—human-made copies of the metal clusters may not work. For example, it may be impossible to make a small version that is stable but still flexible enough to do chemistry. (In the CO reaction, for example, the carbon atom needs to rotate to react with the water.) Or the reaction may require other elements in the enzyme, not just the metals. As a result, it may be necessary to use the whole enzyme or perhaps even the whole microorganism to achieve the desired effect.

From a commercial perspective, this particular enzyme is attractive because it can be made in large quantities and at room temperature. The only downside is having to keep it away from oxygen—a problem Drennan thinks she can fix. "I think I know the source of the problem with oxygen," she says. "We may be able to redesign the enzyme to make it more stable in an oxygen environment."

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By Nancy Stauffer, MITEI

This research was funded by the National Institutes of Health and by a seed grant from the MIT Energy Initiative. More information can be found in:

Y. Kung, T. Doukov, J. Seravalli, S. Ragsdale, and C. Drennan. "Crystallographic snapshots of cyanide- and water-bound C-clusters from bifunctional carbon monoxide dehydrogenase/acetyl-CoA synthase." *Biochemistry*, vol. 48, no. 31, 2009, pp. 7432–7440.

Enlisting bacteria to make better biofuels for vehicles

Using specially programmed bacteria, MIT researchers have produced biofuels that—unlike ethanol—contain almost as much energy per volume as gasoline does and can be used in today's vehicles and pipelines without threat of corrosion. In related work, the researchers have found materials that can effectively remove the product as it forms—a critical role as the product can be toxic to the bacteria that are making it.

The search for biomass-derived fuels for transportation has led to new interest in ethanol. Indeed, annual demand for ethanol tripled between 2000 and 2006. But ethanol is not well suited to the task. Pure ethanol has only 60% the energy density of gasoline, so traveling a given distance requires more ethanol than gasoline. Also, ethanol tends to absorb water, so it can potentially cause corrosion in the current US petroleum infrastructure.

The focus on ethanol raises concerns for Kristala Jones Prather, the Joseph R. Mares (1924) Assistant Professor of Chemical Engineering. "We shouldn't do ethanol just because we know how to do ethanol," she says. "If we're going to have a long-term investment and real commitment to using biomass-derived fuels, then we should take the time to find alternatives that make sense—molecules that have the best physical and chemical characteristics and will be compatible with today's cars, pipelines, and other infrastructure."

Prather points to butanol as a potentially better option. Its thermodynamic and physical properties are much like those of gasoline; it has 95% the energy density of gasoline; and it is much less miscible with water. An even better molecule may be pentanol, which has still higher energy density and more favorable properties. "As a general rule, energy density goes up with the number of carbon atoms in a molecule," she says. "Ethanol has two, butanol has four, and pentanol has five."

As a first step toward production of higher-carbon biofuels, Prather and her colleagues have been focusing on butanol. A bacterium called *Clostridium acetobutylicum* can ferment renewable substrates such as glucose to form butanol. But *Clostridium* is not always stable, and at a relatively low concentration the butanol it produces is toxic to the bacterium. People have tried to improve the butanol production efficiency of *Clostridium* but without real success.

Prather is therefore turning to other bacteria—ones that do not naturally make butanol but might with some genetic engineering. "Given the genes that cause *Clostridium* to produce butanol, some other bacterium might produce larger quantities and might be more stable," she says.

Work thus far has focused on three organisms: *E. coli*, *Bacillus subtilis*, and *Pseudomonas putida*. (Each of these organisms has been used safely in industrial processes.) Though other investigators have studied butanol production from *E. coli,* Prather and her colleagues believe that the other two bacteria have not previously been used for this purpose. As a starting material they use glycerol, which is closely related to the sugars in cellulose and is a byproduct of biodiesel production so is now becoming abundantly available.

The fermentation to produce butanol requires a series of six enzymatic reactions, each one involving the products of the previous reaction plus a specific enzyme. So to reconstruct the "butanol synthesis pathway" in their three "host" organisms, they inserted all of the genes that encode for those enzymes—genes foreign to the new organisms. "And we got them all to make butanol," Prather says.

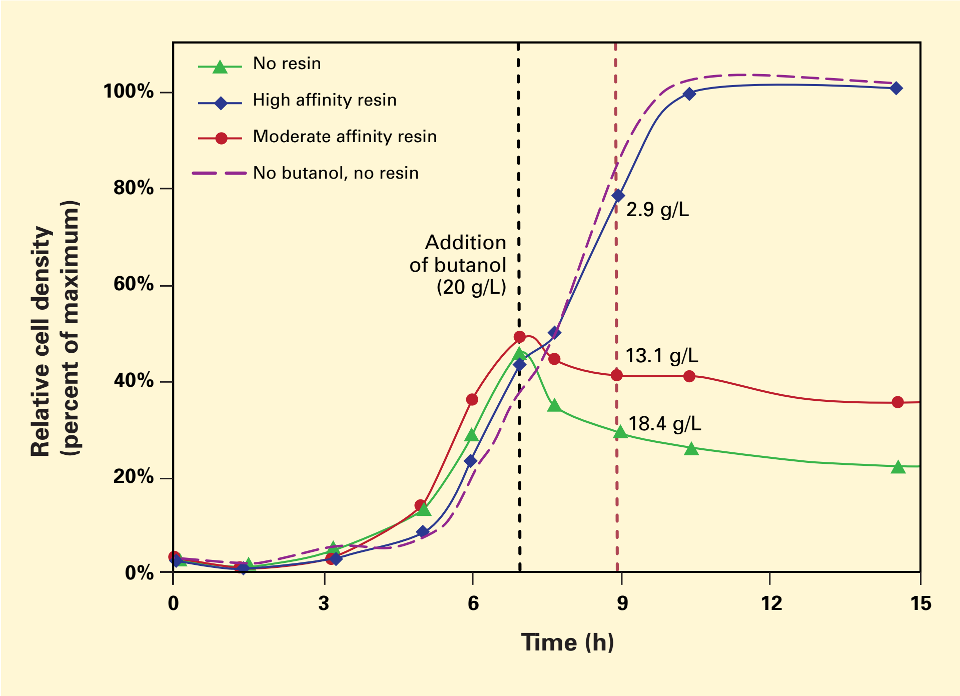
Lessons learned

Those findings demonstrate that a variety of organisms can be used to produce butanol—among them, organisms that previously were considered without potential. According to the literature, one of the enzymes in the researchers' butanol pathway does not function in the presence of oxygen. But their genetically altered *Pseudomonas*—an organism that requires oxygen to grow—generated 10 times more butanol than previously achieved in an oxygen environment.

The researchers have been able to characterize most of the steps in their butanol synthesis pathway. One observation of note is that truncating the steps partway through the series yields products that are not fuels but are of value to the chemical industry. Also, based on their findings, the researchers have new ideas about how to produce even more desirable molecules—ones that contain more carbon atoms and better properties for use as a biofuel.

While all three of their host organisms produced butanol, they did not make a lot of it. But that does not trouble Prather. "We're pretty sure the problem is that our enzymes aren't very good," she says. "But the world is a big place, and there's lots of biological diversity out there. With persistence and some technological innovation, we should be able to find better alternatives."

Protecting butanol-producing organisms from toxicity



Graph: David R. Nielsen

This graph demonstrates the ability of polymer resin beads to adsorb butanol, thereby protecting the bacteria that are making it from its toxicity. In a culture without beads (triangles), the addition of concentrated butanol at 7 hours stops the growth of butanol-producing *E. coli*. When beads of a material with moderate affinity to butanol are present (circles), cell growth also stops but at a higher level. When the beads have a high affinity to butanol (diamonds), cell growth continues even after the butanol is added. Indeed, growth follows almost the same pathway exhibited by cells in a control experiment without the added butanol or the resin beads (dashed line). Measurements of butanol concentrations at 9 hours confirm the effectiveness of the high-affinity beads in removing butanol from the system.

To help in that process, Prather is looking to collaborate with Bruce Tidor, MIT professor of biological engineering and computer science. Tidor is formulating computational methods for predicting the impacts of specific enzymes on organisms and systems. "Getting guidance on which enzymes will give us the desired outcome will be enormously helpful," says Prather. "Access to better enzymes will allow us to broaden the repertoire of molecules that we can make—whether fuels or valuable chemicals."

Practical concerns

The final component of the work focuses on another practical problem: the chemicals that the bacteria make can harm and even kill them. "It's been nearly 100 years since a butanol-producing fermentation was first discovered and commercialized," says David R. Nielsen, a postdoctoral fellow in chemical engineering who works with Prather. "But the development of economically viable systems has been limited largely because even fairly low concentrations of butanol inhibit organisms that naturally produce butanol from producing more."

To solve that problem, he has been looking at ways to remove the butanol from the product mix as soon as it forms. He has been experimenting with the use of small beads of polymer resins that selectively adsorb butanol in solutions.

In one set of experiments, he tested the effectiveness of two of those resins in removing butanol from growing cultures. As a model organism, he used the bacterium *E. coli*, genetically engineered to make butanol and cultured in glucose. He measured the bacteria's growth over time (in cell density per volume), with and without the addition of butanol (20 g/L) after 7 hours. For reference, he also ran a control experiment that shows how the cells grow without the added butanol or the resin beads. (In that experiment, growth levels off at about 10 hours because the cells have run out of their growth substrate, glucose.)

Results are shown in the figure on page 9. In the sample with no resin beads (triangles), the bacteria stopped growing as soon as the butanol was added, and cell density then declined over time. In samples containing beads with a moderate affinity to butanol (circles), growth also stopped on addition of the butanol but at a somewhat higher cell density. But in the samples containing the high-affinity beads (diamonds), the bacteria continued to grow, following almost the same pathway as samples grown without the added butanol (dashed line). Measurements of butanol concentrations at 9 hours—2 hours after addition of the butanol—show that only the high-affinity beads reduced the butanol to well below 10 g/L, the level at which the researchers begin to observe impacts on the growth and viability of *E. coli* in other experiments.

In other work, Nielsen measured how much butanol *Clostridium* produced in samples with and without the added resin beads. In the absence of the beads, the bacteria produced 170 mg of butanol. But when the beads were present, butanol production was as high as 487 mg—nearly a tripling of the product. Because the beads successfully removed the butanol from the solution, the cells were not inhibited in their production.

Further analysis shows that the butanol-laden polymer beads can easily be separated from the rest of the culture, the butanol removed by vaporization, and the beads reinserted into subsequent cultures—at least three times with no degradation in performance. Preliminary estimates suggest that removing the butanol from the beads should take roughly 80% less energy than expended when using a conventional distillation process.

One limitation of Nielsen's study was that he used only commercially available materials. "In future work we'd like to tailor the chemical and physical characteristics of polymers to best deal with specific molecules of interest," he says. Developing a library of "designer" polymers would be an expensive undertaking, but it would provide powerful tools for the in situ recovery of products—a useful capability for researchers who are developing new organisms and novel processes for making biofuels and other valuable chemicals.

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By Nancy Stauffer, MITEI

This research was supported by the Synthetic Biology Engineering Research Center funded by the National Science Foundation as well as by a seed grant from the MIT Energy Initiative. David R. Nielsen received fellowship assistance from the Natural Sciences and Engineering Research Council of Canada. More information can be found in:

H-C. Tseng, C. Martin, D. Nielsen, and K. Prather. "Metabolic engineering and *Escherichia coli* for enhanced production (R)- and (S)-3-hydroxybutyrate." *Applied and Environmental Microbiology,* May 2009, pp. 3137–3145.

D. Nielsen, E. Leonard, S-H. Yoon, H-C. Tseng, C. Yuan, and K. Prather. "Engineering alternative butanol production platforms in heterologous bacteria." *Metabolic Engineering*, 2009, doi:10.1016/j.ymben.2009.05.003.

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Clean coal: New plant design promises carbon capture, efficiency, no atmospheric emissions

MIT researchers have designed a novel coal-fired power plant that can capture essentially all of its carbon dioxide (CO_2) and other atmospheric emissions; can produce more water than it consumes; and is more fuel efficient than any comparable coal plant now running or being planned, with or without carbon capture. The new plant, which combines coal gasification and solid oxide fuel cells (SOFCs), will be expensive to build; but if new federal policies put even a low price on carbon emissions, the new design would become cost competitive.

"Large-scale implementation of our design should be possible within a few years," says researcher Paul I. Barton, professor of chemical engineering. "Where to store the captured CO_2 and how much storage space is available are still major issues. I see our design as part of a medium-term solution that will let us keep using coal while we develop carbon-free energy technologies."

The world's reliance on coal to meet its energy needs is expected to continue for some time. But today's coal-fired power plants generate significant quantities of greenhouse gases. In the United States, for example, such power plants are responsible for fully a third of the nation's total CO_2 emissions from fossil fuel use. As the worldwide construction and use of coal-fired plants continue to grow rapidly, finding a way to restrict those emissions is critical. As described in the 2007 MIT study *The Future of Coal* (web.mit.edu/coal/), the answer lies in capturing CO_2 from power plants and other sources and then storing it in deep geological basins—a technology known as carbon capture and sequestration (CCS).

Capturing the CO_2 is, however, a challenge. In conventional coal-fired power plants—including those now being built in China—pulverized coal is burned in air, generating electricity plus exhaust that contains CO_2, water, and nitrogen. But separating relatively small amounts of CO_2 from nitrogen is extremely energy intensive. To reduce the energy intensity, the integrated gasification combined cycle (IGCC) process—an option favored by many experts—removes the CO_2 before combustion occurs. Coal is gasified, the CO_2 is removed by absorption, and hydrogen combustion in air powers an electricity-generating gas turbine. However, the equipment used to absorb and regenerate the CO_2 is massive, expensive, and energy consuming.

A year ago, Barton and his colleague Thomas A. Adams II, a postdoctoral associate in chemical engineering, decided to try a different approach: generating electricity without ever mixing the air and the fuel. "I'd been working with solid oxide fuel cells and suddenly realized that those fuel cells can do just what we need: mix oxygen with the fuel but keep the rest of the air—including the nitrogen—separated," Barton says.

"By replacing the combustion section of the power plant with the SOFC, we can actually change the entire system so that we're able to recover the CO_2 very easily," says Adams. Moreover, the electricity is generated by electrochemical reactions, a process that is inherently more efficient than burning fuel to power a turbine.

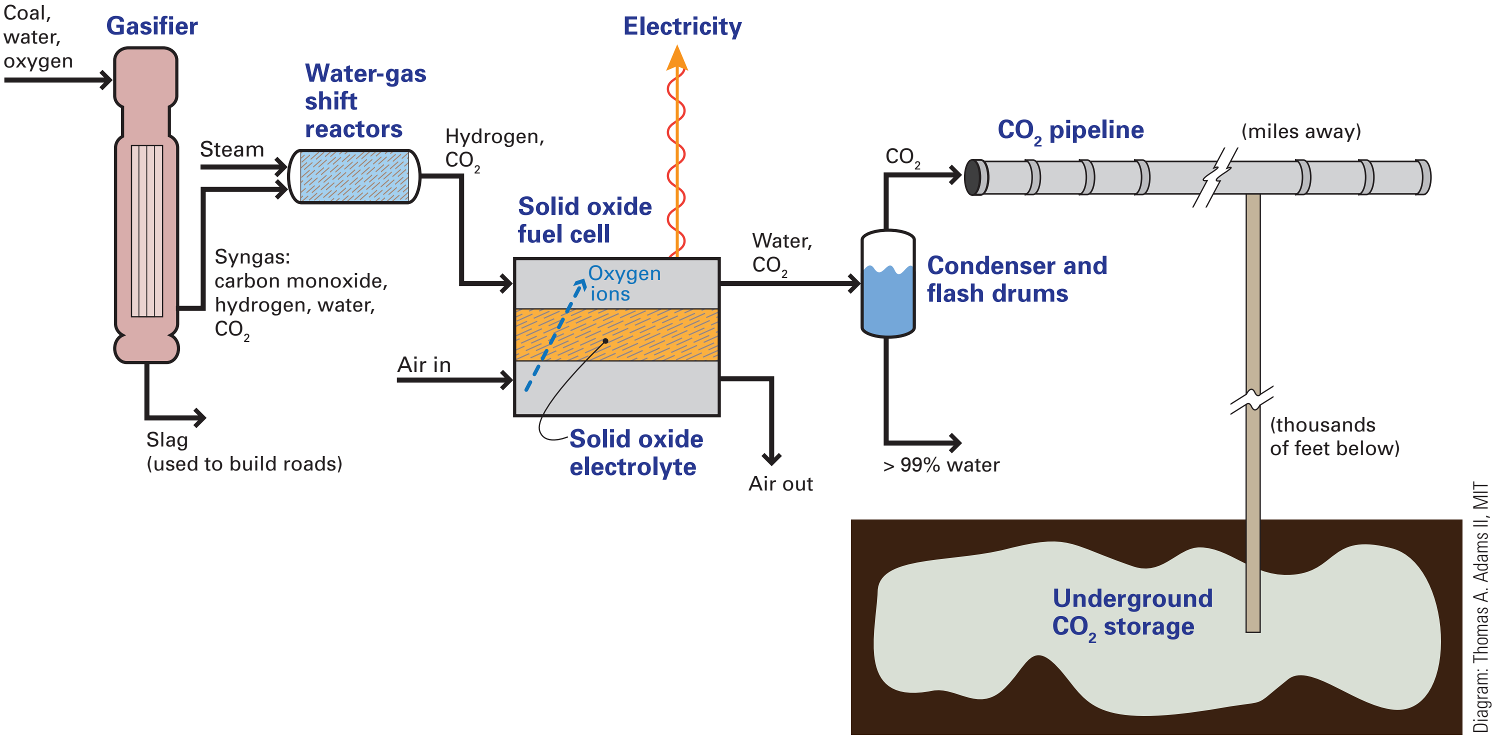
The MIT design is shown on page 12. The first few steps are the same as in the IGCC process. Coal plus water and oxygen enter a gasifier, where they are converted to "syngas," a mixture that is largely carbon monoxide, hydrogen, water, and CO_2. Next comes the water-gas shift reaction, which produces hydrogen gas and more CO_2. In the IGCC process those products would then enter the absorption system, but in Barton and Adams's design they instead enter an SOFC.

Like all fuel cells, the SOFC consists of two chambers—here separated not by a porous membrane but rather by a solid oxide electrolyte. Products of the water-gas shift reaction enter one chamber (the anode side) while air is injected into the other (the cathode side). In most fuel cells, the fuel would then migrate through a membrane to the air on the other side. But in an SOFC, oxygen ions are conducted in the reverse direction through the solid electrolyte to the fuel, leaving the rest of the air behind. The oxygen and fuel react, generating electricity and a waste stream consisting largely of CO_2 and water vapor. Those products then enter a condenser and a series of "flash drums," where changes in temperature and pressure cause liquid water to settle to the bottom and CO_2 vapor to rise to the top, where it enters a pipeline. On the other side of the fuel cell, the exhaust stream is simply air, somewhat depleted in oxygen.

Innovations and benefits

Other researchers have proposed systems that combine coal gasification and fuel cells. But the MIT SOFC design includes two innovations. First is the inclusion of the water-gas shift reaction. Without that step, carbon monoxide goes directly into the fuel cell. Over time, black carbon deposits will build up and interfere with fuel cell operation. While MIT's SOFC process can be built with existing technology, other designs will have to wait until carbon-resistant fuel cell materials can be tested and demonstrated.

Solid oxide fuel cell power plant



The new MIT design replaces the combustion section of a conventional power plant with a solid oxide fuel cell. Benefits include easy recovery of carbon dioxide, removal of all atmospheric pollutants, little or no water consumption, and high plant efficiency.

Another major innovation—useful in many types of processes—is an improved method of separating the CO_2 and water. According to Adams, the general assumption that a sudden drop in temperature will achieve a clean separation is incorrect because of the high pressures prevailing in gasification/fuel cell systems. Unless the CO_2 and water vapor mixture is at atmospheric pressure, the drop in temperature will leave excessive CO_2 in the liquid water that forms. But a drop to atmospheric pressure will leave water in the CO_2—a corrosive mixture that can damage the pipeline. Worse still, it will take considerable energy to compress the CO_2 back up to the high pressure needed for injection into the pipeline. So Adams prepared a new design involving a condenser and a series of flash drums, each one at a lower pressure than the one before it. The system requires little energy to operate, and the products will be nearly pure streams of water and of CO_2—with most of the CO_2 still at high pressure.

The researchers have performed detailed simulations of their SOFC process, and the potential benefits it offers are many. The SOFC plant should capture more than 99.95% of the carbon in the coal as CO_2, which is well above the often-sought goal of 90% CO_2 capture. Indeed, the total atmospheric emissions from the SOFC system are essentially zero, says Adams.

A second benefit of the process is its high efficiency. Using simulations plus surveys of existing plants, the researchers estimated efficiencies for traditional pulverized coal (PC), IGCC, and SOFC plants, without and with carbon capture. The cooling strategy used affects overall efficiency, so the analyses considered two options: cooling towers (a system in which water is consumed for cooling) and air cooling (a system that uses air instead of water).

Assuming cooling towers but no carbon capture, the SOFC-based power plant achieves about 45% efficiency—significantly higher than a PC plant at 36%–39% and an IGCC at 38%–41%.

(These numbers depend on the type of coal used and how it is gasified, among other factors.) When CCS capability is included, the PC efficiency drops by 9–12 percentage points and the IGCC by 4–7, while the SOFC efficiency is reduced by less than 1 percentage point. Even with the water-saving air-cooling system, the SOFC plant is more efficient than the other options, with or without carbon capture.

Another benefit of the SOFC is its minimal water consumption. Assuming the use of cooling towers, conventional PC plants consuming about 5,500 tonnes of coal per day (roughly 600–700 MW of power output, depending on the technology) use as much as 11 billion liters of water per year—a serious problem in regions where water is a valuable, fought-over commodity. An IGCC plant requires 30% less fresh water, while the SOFC plant requires nearly 50% less.

But the real reduction comes with air cooling. Indeed, using air cooling, the SOFC can be a net water producer. Even after recycling water to meet all the needs of the plant, there will be a surplus of about 1 billion liters per year—and according to Adams's calculations, that water should be almost pure enough to drink.

Costs and timing

The researchers are still working to develop reliable cost estimates for their SOFC power plant—a task made difficult by still-evolving cost projections for the SOFC fuel cell technology. Building the SOFC plant will be expensive, but the high efficiency and resulting low operating costs may combine to make the overall cost of generating electricity lower with the SOFC technology than with the IGCC.

If both technologies incorporate carbon capture, the SOFC is the economic winner. And if a cap-and-trade policy goes into effect, the SOFC process would be economically competitive at carbon prices of \$5–\$10 per tonne—much lower than the roughly \$50–\$60 per tonne now being discussed in Congress and being rejected as too high by most power companies.

Although large-scale solid oxide fuel cells have not yet been built, companies are now competing to produce a 1 MW fuel cell unit—a goal that Adams thinks will be achieved in the next two years. These units can easily be stacked and interconnected to produce a 500 MW power plant. "Instead of having a few gigantic gas turbines, you'd have hundreds of these fuel cell units in stacks and rows," says Adams. "And if a few of the fuel cells failed, you wouldn't have to shut down the plant, as you would if the main gas turbine in your plant malfunctioned."

"We're really excited about this new design," says Adams. "We've crunched all the numbers to the point that we can be confident that we can actually do this in practice."

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By Nancy Stauffer, MITEI

This research was supported by BP under the BP-MIT Advanced Conversion Research Program. The program is part of the agreement under which BP became the inaugural Founding member of the MIT Energy Initiative.

Profile: The Eni-MIT Solar Frontiers Center

The Eni-MIT Solar Frontiers Center (SFC), established in July 2008, is the centerpiece of a close collaboration between Eni and MIT that was formalized in February 2008 when Eni became a Founding member of the MIT Energy Initiative (MITEI). SFC research focuses on developing advanced solar technologies, with projects ranging from novel photovoltaic materials to solar hydrogen production to the design of optimized solar power plants. Snapshots of ongoing SFC projects begin in the next column.

The research activities of the SFC are overseen by its co-directors, Vladimir Bulović, the KDD Associate Professor of Communications and Technology in the Department of Electrical Engineering and Computer Science, and Daniel G. Nocera, the Henry Dreyfus Professor of Energy and professor of chemistry. Eni's on-campus representative is MIT Visiting Scientist Nicola De Blasio, vice president for R&D International Development.

The SFC recently announced the appointment of Clifton G. Fonstad Jr., the Vitesse Professor of Electrical Engineering, as executive director. Fonstad is responsible for organizing the center's on-campus activities, including setting up an ongoing seminar series and identifying and running other outreach events. He is also participating in MIT-Eni discussions about establishing shared research facilities on campus.

In addition to the SFC, Eni supports MIT research projects that span the energy spectrum from traditional oil and gas to methane hydrates to global change to transportation options.

Research projects in the SFC

Nanostructured thin-film photovoltaics

Vladimir Bulović, *Electrical Engineering and Computer Science*
Moungi Bawendi, *Chemistry*
Silvija Gradečak, *Materials Science and Engineering*
Francesco Stellacci, *Materials Science and Engineering*
Michael Strano, *Chemical Engineering*
Timothy Swager, *Chemistry*

This project aims to develop techniques for fabricating low-cost photovoltaic (PV) devices at room temperature over large areas that can achieve 12% conversion efficiency. The devices consist of thin films of quantum dots, polymers, organic molecules, metal oxides, or other materials controlled at the nanoscale. In some cases, the PV cells have multiple layers, each tuned to capture a specific portion of the solar spectrum and assembled to minimize energy loss within the cell. Some versions are synthetic structures that mimic natural biological functions such as self-assembly and self-repair. The overall result should be robust thin-film PV devices that combine efficient performance, low-cost manufacturing, and long lifetimes.

Materials genome: Materials design for solar energy technology

Gerbrand Ceder, *Materials Science and Engineering*
Nicola Marzari, *Materials Science and Engineering*
Donald Sadoway, *Materials Science and Engineering*
Troy Van Voorhis, *Chemistry*

The development of new technologies for solar energy capture and storage depends critically on the development of new, innovative materials—a process that is typically extremely slow. To help accelerate that process, this project is formulating a computational methodology for predicting the electronic, structural, and thermodynamic properties of materials for solar energy capture and storage. The new methodology combined with an environment for virtual design and testing will permit hundreds to thousands of materials and structures to be rapidly and systematically evaluated for their potential performance in devices. Collaborating experimental teams working on Eni-MIT projects will use the new methodology to accelerate the design of viable materials and devices for solar energy. While this project focuses on solar technology, the methodology will prove valuable to materials innovation well beyond that field.

Paper-thin solar cells

Karen Gleason, *Chemical Engineering*
Tonio Buonassisi, *Mechanical Engineering*
Vladimir Bulović, *Electrical Engineering and Computer Science*
Jing Kong, *Electrical Engineering and Computer Science*
Michael Strano, *Chemical Engineering*

Polymers provide extraordinary opportunities for creating conducting and semi-conducting thin films that can be integrated into flexible, paper-thin devices. This work uses new, scalable chemical vapor deposition techniques—developed at MIT—to fabricate solvent-free polymer thin films and use them in combination with inorganic materials to create prototypes of efficient and environmentally stable PVs. Using these novel deposition methods, the research team will systematically tune properties of the deposited thin films; create coatings of uniform thickness over large areas, including the irregular surfaces of flexible substrates; and achieve high purity of materials and precise interface definition. This low-cost, low-temperature, low-energy-consumption technique can also be used to deposit films that are integrated into devices in which layers of nanomaterials combine to boost efficiency.

Self-assembly of nanomaterials for low-cost, flexible, large-area solar cells
Paula Hammond, *Chemical Engineering*
Angela Belcher, *Biological Engineering and Materials Science and Engineering*

Thin, lightweight solar cells that can be incorporated at low cost on various substrates, particularly flexible substrates such as plastic films or fabrics, are promising for commercial applications for portable or easily deployable power sources as well as stationary energy needs. Promising options are organic and organic-inorganic hybrid devices such as dye-sensitized solar cells and bulk hetero-junction cells. However, achieving the full potential of such devices requires engineering them with nanometer-level control to optimize the interfaces and materials properties for high power efficiencies. This project will construct such devices using bio-inspired self-assembly methods, inexpensive materials, and low-cost, facile processing techniques that can be readily commercialized. The techniques can be applied to both large, macroscale systems and microfabricated structures on surfaces.

Photo: Justin Knight

Left to right, Nicola De Blasio, vice president for R&D International Development at Eni and MIT visiting scientist; Professor Ernest Moniz, director of the MIT Energy Initiative; and Professor Clifton Fonstad Jr., executive director of the Solar Frontiers Center.

Water splitting: The artificial leaf
Daniel Nocera, *Chemistry*
Christopher Cummins, *Chemistry*
Klavs Jensen, *Chemical Engineering*
Yang Shao-Horn, *Mechanical Engineering*

This project addresses one of the outstanding "holy grails" of science in the 21st century—the efficient and economical storage of solar energy in the form of fuels. The goal is to imitate photosynthesis, the process by which plants separate water into hydrogen and oxygen using solar light as the energy input. The proposed device uses a PV to capture and convert absorbed light into charge-separated holes and electrons. Specially designed catalysts will capture the holes and electrons and use them to transform water into its chemical constituents, hydrogen and oxygen. The energy of those products will be released in a fuel cell, which recombines the hydrogen and oxygen to form water to start the process again. This advance will deliver water—with solar light as an input—as a renewable, environmentally benign storage vehicle for the future.

Maximizing return on investment in solar thermal plants
Alexander Slocum, *Mechanical Engineering*

This project will create a novel parabolic trough concentrated solar power (CSP) system that is economical to build, install, and operate, allowing a higher return on investment compared to a conventional CSP plant. It uses stamped metal trough sections with a reflective coating, where the trough itself acts as the structure. Small electric motors rotate the troughs to keep them pointed at the sun. For storage, a conventional nitrate salt tank system can be heated by thermal oil from the receiver tubes.

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Energy-efficient lighting: Bringing in daylight while controlling heat and glare

Architects and designers could significantly reduce the future energy needs of their new and renovated buildings by using novel window systems that bring in more daylight, filter out heat, control glare, and more. But detailed information about such systems can be hard to find and even harder to understand. MIT researchers are now developing an online "search and selection" tool that will contain readily understandable information on well over a hundred window systems and a navigation tool that will guide users to those that best suit their current project.

Buildings consume more than a third of all the energy used in the United States, and 25%–40% of that third is used for lighting. Increasing the use of natural lighting (daylighting) in place of electric lighting could bring significant energy savings. "Depending on the situation, a good daylighting strategy can reduce the need for energy-consuming electric lighting by 20% to 80%, according to current research literature," says Marilyne Andersen, associate professor of architecture and a member of MIT's Building Technology Program.

But it is not so simple. With the daylight can come solar radiation and glare, which can make occupants uncomfortable enough to turn up the air conditioner or pull down the shades and turn on the lights.

Many new "fenestration systems" have been designed to solve those problems, but they are not widely used, largely because architects and designers have a hard time finding out about them, according to Andersen. In the past, architects were actively engaged in the development of building systems and materials. But in recent decades, such systems and materials have relied more and more on sophisticated technological advances. As a result, the characteristics and performance of new products are often described in technical publications using numerical data—not well suited to architects and designers, who are used to working with more visual representations.

Andersen's colleague Rosa Urbano—an architect, PhD candidate at Escuela Técnica Superior de Arquitectura de Madrid, and visiting student in MIT's Department of Architecture—experienced this problem firsthand. "At the beginning of my research I had to work on a façade project and didn't know what advanced light-control materials to use," says Urbano. "When I started to read, I realized that all the information was not only widely dispersed but also generally cryptic and hard to understand if you are not a physicist."

Together Andersen and Urbano decided that they would pull information on light and "sun-control" products together and present it in a way that architects and designers can use. Their tool, called Database of Light Interacting Technologies for Envelopes, or D-LITE (www.d-lite.org/), includes a comprehensive directory that—when data entry is completed—will contain extensive information on 160 products.

To make the information user-friendly, they have developed visual methods of expressing technical aspects and performance data—a presentation that is intuitive and well matched to the decisions that an architect is likely to make in a realistic design process. Finally, they have created an interactive navigation tool that can guide a user to a limited set of options that are suitable for the project at hand.

Navigating the database

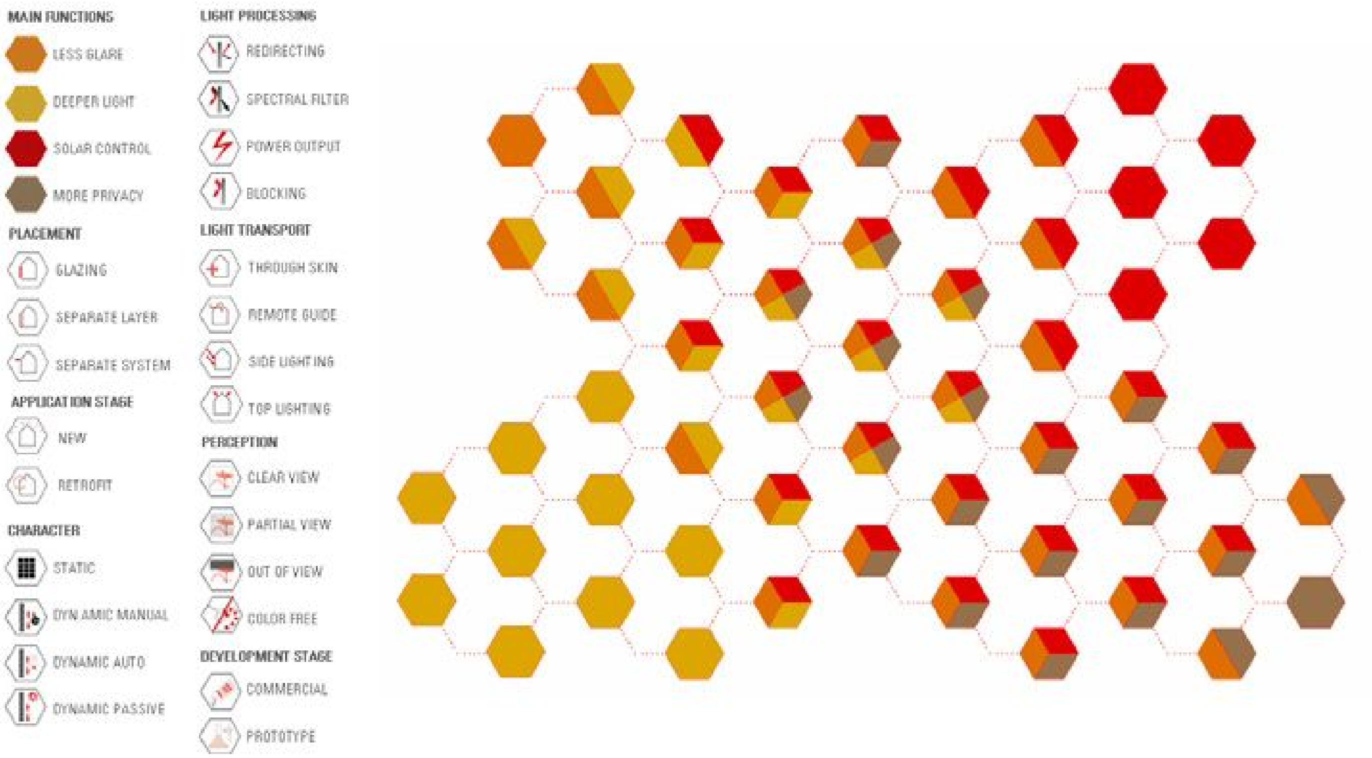
The figure to the right shows the "search interface" for navigating the database. The buttons in the two columns at the left act as filters to narrow down the available options. The "main functions" choices address the likely reasons that a designer would be considering an advanced fenestration system rather than standard double-glazed windows. They may want to reduce glare, get daylight to come farther into the room, control solar heating, ensure the occupants' privacy—or they may want to achieve a combination of those goals. The rest of the two-column list contains other aesthetic and practical considerations that the architect can select as important in his or her current project.

Each of the 53 hexagons at the right represents a family of products that fulfill the same set of filters and have similar function and application characteristics. The colors of the hexagons show which of the main functions the products in that family fulfill.

To begin, the user makes selections among the functions and filters. As search filters get activated, hexagons representing products that do not meet the needs are eliminated from the matrix. "The more requirements the user stipulates, the more accurate the outcome will be, hence the more suitable for the particular application," says Andersen.

Having completed the selection process, the user can click on any of the hexagons that remain and get a pop-up window presenting pictures of several products that qualify. By clicking one of those pictures, the user gets to the description page for a single light-interacting product, replete with

Search interface that enables users to find suitable products in the Database of Light Interacting Technologies for Envelopes (D-LITE)



information presented in a highly visual and intuitive fashion.

The page includes a detailed description of the product; links to the companies or research institutes that developed and supply it; and drawings that show how it looks, how it works, and how it should be installed. Where possible, case studies show examples of projects where the product has been used, with descriptions, photos, and links to the architectural firms or designers involved. Finally, an interactive graph enables the user to compare the selected product to others in the matrix on such measures as cost, light transmission, light reflection, thermal behavior, and power consumption or production.

A highlight of the product description page is a series of photos showing how the window system affects light entering a room. To take the photos, the MIT researchers used special equipment in the MIT Daylighting Lab that enables them to test scale models with incoming light replicating the sun at three positions. On the website, the user can click on the photos to see how the angle of incidence—25, 50, or 75 degrees—affects the pathway of the incoming light, sometimes aiming it downward and sometimes sending it deep into the room.

Photos from one such test appear on page 18. In this series, the left and center photos show light entering a window at the left of the room. The angle of incidence is 50 degrees. In the left photo, the window contains clear glass as a reference case. In the center photo, the window is a sample of a product provided by its manufacturer. The change in the distribution of light within the room is striking.

The right-hand photo shows the view looking through the window system at a tree. With this product, the tree appears quite clear. However, with other products it can look hazy or distorted. Although that information is important to a designer, it is seldom available because capturing it in a computer simulation is difficult. With the database, a designer can get a firsthand look at the "view out."

Performance of advanced window system in scale model

The information page for each window system in the database includes a series of photos showing the product's impact on the distribution of incoming light in a scale model room. In the samples above, the left photo shows the reference case with clear glass and an incident sun angle of 50 degrees. The center photo shows the same conditions but with the light entering through a sample product provided by a manufacturer. The right-hand photo shows the view out through the sample product.

"We hope that our database and search tool will lead to wider use of advanced window systems, which can save energy, reduce emissions, and ensure the comfort and well-being of building occupants," says Urbano. "And by making the search easy, we hope to encourage architects and designers to start planning their lighting from the beginning so it's well integrated into the overall design process."

Other perspectives, opportunities

D-LITE is just one avenue that Andersen and her students are pursuing to encourage the use of advanced window systems. They are also developing Lightsolve (daylighting.mit.edu/research.php), an interactive simulation tool for analyzing and increasing the daylighting potential of project-specific design decisions, such as window type, arrangement, shading strategy, and material choice. Taking into account the location-specific climate and changes in light throughout the year, the simulation generates information that will help designers achieve the delicate balance between illumination and visual and thermal comfort. The researchers are also working to develop new performance metrics and calculation methods that will enable architects and others to generate realistic estimates of the potential for advanced window systems to reduce energy use for lighting, heating, and cooling as well as to produce other benefits such as visual and thermal comfort, health, and productivity.

Finally, in collaboration with the MIT Museum, Andersen and Urbano have been developing a novel concept for a museum exhibition that will let architects, designers, and the general public experience firsthand a variety of state-of-the-art façade technologies for advanced daylighting control. The exhibition will consist of a series of round enclosures housing installations of these materials. Visitors will be able to walk through the space, interacting with the technologies while learning the basic principles of daylighting and its potential for saving energy and increasing sustainability. "People will be able to experience and compare the effects of many new systems on light for the first time," says Urbano. "Light is very perceptual, and this exhibition will provide people with an immersive and sensible experience."

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By Nancy Stauffer, MITEI

Research on D-LITE was supported by MIT, the Fulbright Program, Harvard University's Committee on General Scholarships, a seed grant from the MIT Energy Initiative, and the Fundación Caja Madrid. MITEI seed funds are also supporting the work to develop new performance metrics for assessing the energy-savings potential of leading-edge façade technologies. More information is available on the Building Technology Program at bt.mit.edu/ and on the Daylighting Lab at daylighting.mit.edu/.

Cleaner stoves, better health in rural India

Early results from an MIT-led study confirm that a program providing clean cooking stoves to thousands of families in India is improving the respiratory health of women and children. By venting smoke and unburned particles outdoors, the new stoves reduce indoor air pollution, a leading cause of illness and death in poor rural regions of many developing countries.

On-the-ground work in India identified two ways to improve the program's effectiveness: by changing the stove design to reduce the high frequency of breakage and by identifying a "good user" in each village who can teach other villagers how to use and maintain their new stoves properly.

"The study's findings will be particularly important for policy makers because it is an assessment of a real program that already exists and could be scaled up or easily replicated," notes project leader Esther Duflo, the Abdul Latif Jameel Professor of Poverty Alleviation and Development Economics at MIT.

Half the world's population continues to rely on firewood, dung, and crop residue for cooking and heating. In poor countries, up to 95% of people use those fuels, frequently burning them in traditional cooking stoves inside their homes with little ventilation. The result is dangerously high levels of indoor air pollution that pose a serious health threat, especially for women and children, who spend considerable time near the cooking stove.

To combat that problem, many organizations and governments advocate the distribution of improved cooking stoves. In India, for example, Gram Vikas, a rural development organization, began a stove distribution program in 2006 in Orissa, one of the poorest states in the country. The "smokeless" stoves in their program have been shown to burn less fuel than traditional stoves do, and they include a chimney that vents the smoke outdoors.

Photos: courtesy of Stephen Ray G, MIT

In poor rural regions of India, traditional cooking stoves (left) burning firewood or dung inside homes with little ventilation cause dangerously high levels of indoor air pollution. To prevent such pollution and associated health impacts, a rural development organization has been providing smokeless stoves to thousands of families since 2006. The new stove—shown above right with simmering food—is molded out of local mud and includes a chimney that vents pollutants outdoors.

"In principle, you'd think that just putting a chimney in and taking the pollution outside would help a lot," says Duflo. "That's the technology solution to the problem. But does it actually do any good? Do people use the stoves and maintain them properly? And is there actually any impact on health?"

Designing and performing controlled field experiments to answer such questions is a specialty of the Abdul Latif Jameel Poverty Action Laboratory (J-PAL) at MIT. Co-founded by Duflo in 2003, J-PAL seeks to provide scientific evidence that can help assess and potentially improve policies to combat poverty. "To shape good policy, we must understand what causes the problems we're trying to cure and which cures work," notes Duflo, who in September received a 2009 MacArthur Fellowship—the so-called "genius" grant—for her innovative approach to helping alleviate poverty worldwide.

To evaluate the effectiveness of the cooking stove program, Duflo is working with Rema N. Hanna, assistant professor of public policy at the John F. Kennedy School of Government, Harvard University, and Michael B. Greenstone, the 3M Professor of Economics at MIT and now chief economist of the White House Council of Economic Advisers. They are teaming up with collaborators at Gram Vikas and at the Institute for Financial Management and Research (IFMR) in Chennai, the home of J-PAL's research partner for south Asia.

Scientific evidence of better health

To establish a baseline, Gram Vikas and the Centre for Microfinance at the IFMR surveyed almost 2,400 households in 40 villages in Orissa. The survey, performed between January and July 2006, included a range of questions about wealth and income, stove design and use, and people's health status during the previous 30 days. Each person was given a short physical examination, including measurements of various lung functions using a spirometer and a carbon monoxide (CO) analyzer.

Representatives from Gram Vikas test the lung functions of a child in a village in Orissa, India, where clean cooking stoves have been distributed to some families. Results from such tests are among the scientific data that MIT researchers are using to determine whether the stove distribution program is actually improving people's health. Early results from their analyses are encouraging.

In analyzing the collected data, Duflo, Hanna, and Greenstone found evidence of a very high incidence of respiratory illness. About one-third of the adults and half of the children had experienced symptoms of respiratory illness in the 30 days preceding the survey, with 10% of the adults and 20% of the children having had a serious cough.

The analysis showed a strong correlation between using a stove with high emissions and improper ventilation and having symptoms of respiratory illness. However, the researchers could not say conclusively that the negative health impacts were due solely to the polluting stoves. Households that choose to use a clean stove are also likely to be wealthier, to eat better, and to be more health conscious—factors that would also contribute to better health.

To disentangle those effects, J-PAL is using an approach called randomized testing. It works as follows. Take a large group of people and randomly choose some of them to receive (for example) clean stoves. After a period of time, test the health of everyone. With a large enough study population, the two groups will be statistically indistinguishable—except that the one group will have had the new cooking stoves. As a result, any observed difference in health can be attributed to use of the improved stoves.

The distribution of smokeless cooking stoves by Gram Vitas presented an ideal opportunity to perform this type of testing. Within a given village, the organization distributes stoves based on a lottery. Winners in the first lottery received their stoves in 2006, winners in the second round in 2008, and the remaining third of the villagers are getting them now. Because the three groups are fundamentally the same, households in the third group can serve as a comparison for households in the first group.

In 2008, Gram Vikas and the Centre for Microfinance performed a follow-up survey. Although Duflo and her colleagues are still analyzing data from both surveys, preliminary results on the health impacts of the new stoves are encouraging. In this study, the concentration of CO in the breath serves as a measure of recent exposure to air pollution from biomass combustion. (Because the study area has few vehicles, industrial plants, or other sources of such pollution, the researchers can assume that elevated CO in the breath is due to cooking stove emissions.) Initial findings show that women who have the clean stoves are less likely to have high CO readings than are women who do not—and the difference is statistically significant.

Practical steps for greater benefits

The 2008 survey also points to some practical problems that can be addressed to make the stove program more effective. For example, of all the stoves that were installed, only 60% were still in good operating condition. The rest had broken.

To investigate that problem, Stephen Ray, an MIT graduate student in mechanical engineering, spent the summer at Gram Vikas examining stoves. "After visiting numerous villages and observing lots of stoves, I started seeing patterns in how they were breaking," said Ray. "Most often the chimneys were broken. They'd been knocked down by children or animals, or they'd come apart while being cleaned. So there'd be a broken pipe sticking out of the stove, sending all of the smoke and other emissions right into the kitchen." Typically the problem was lack of support. The chimneys—some of them 10 feet tall—were made of multiple sections held together only by a clay compound.

Based on his observations, Ray came up with design changes that would help. For example, when making a new stove, he suggested running bamboo poles down the back of the chimney and into the clay at the back of the stove. For already installed stoves he developed several designs for attaching the chimney to support structures such as the wall of the house. Before he left India, he was able to retrofit a number of stoves; and six months later they were still in good working order.

Another problem identified in the survey was that people who had smokeless stoves did not always use and maintain them properly. For example, they might put a pot on only one of the stove's two openings, leaving the second one uncovered so that smoke could escape. Sometimes they did not clean the chimney, and it became clogged. And sometimes they just continued to use their traditional stove, arguing that those stoves cooked faster and required less fuel.

The collaborators are now developing a "good user" system in which they identify one woman in each village who knows how to use and maintain the stove properly and is willing to teach others to do the same. The good user also identifies and reports problems with the stoves to Gram Vikas.

Duflo says there is still much work to be done. In addition to analyzing the data from both surveys for health impacts, she also wants to examine the program's effects on economic well-being. "If people are in better health, households should have to spend less money on medical care, and they should be more productive, with adults missing fewer days of work and children missing fewer days of school," she says. "Knowing the economic benefits as well as costs of this program will help policy makers as they consider how aid money can be used most efficiently and what kinds of programs can have long-term positive effects in the developing world."

Stephen Ray, an MIT graduate student in mechanical engineering, spent a summer examining smokeless cooking stoves in people's homes to see why they had such a tendency to break. He found that most often the chimney had collapsed (left). To correct the problem, he developed design changes that would help support the chimney, such as running bamboo poles down the back (right) or attaching it to the wall of the house.

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By Nancy Stauffer, MITEI

This research was funded by a seed grant from the MIT Energy Initiative; Institut Veolia Environnement; and ICICI Social Initiative Group. More information can be found in:

E. Duflo, M. Greenstone, and R. Hanna. "Indoor air pollution, health and economic well-being." *Surveys and Perspectives Integrating Environment & Society,* v. 1, no. 1, January 1, 2008, pp. 1–9.

E. Duflo, M. Greenstone, and R. Hanna. "Cooking stoves, indoor air pollution and respiratory health in rural Orissa." *Economic & Political Weekly,* v. 43, no. 32, pp. 71–76, 2008.

Harnessing the world's collective intelligence to deal with climate change

MIT researchers are asking you to help devise a plan for dealing with climate change.

At their online forum, you can review the impacts of plans now being discussed and debated internationally—and you can try to design a plan that might be better.

Based on assumptions in your plan, you can run computer simulations to test its impact on global temperature and sea level and determine its economic costs and benefits out to 2100. You can also take part in organized debates with others and ultimately vote on which plans you believe would be most effective and most feasible.

No matter your level of expertise, you would be helping MIT achieve its goal: to harness the world's collective human intelligence and computer power to address what is viewed by many as the world's most important and challenging problem today.

Collective intelligence

Researchers worldwide are tackling climate change in various ways, but the problem is so vast and complex that no individual or group can have all the solutions or even understand it all. Moreover, traditional methods of communicating—conferences, journal articles, public media, and so on—are not capable of gathering and synthesizing the distributed knowledge accurately and quickly.

Thomas W. Malone, the Patrick J. McGovern Professor of Management, believes that it is time to address the climate change problem using collective intelligence. "We need to connect people and computers so that collectively they act more intelligently than any person, group, or computer has ever done before," he says.

Making such connections is now possible on an unprecedented scale, and the outcome can be powerful. To illustrate, Malone cites not only Wikipedia and Linux but also popular Internet sites where the combined wisdom of thousands of users has proved surprisingly accurate at predicting the outcomes of future elections, sporting events, and more.

To apply collective intelligence to the climate change problem, Malone, who is director of MIT's Center for Collective Intelligence (CCI); Robert Laubacher, CCI's acting executive director; and their CCI colleagues have developed an online forum called the Climate Collaboratorium (www.climatecollaboratorium.org), a combination of software tools on a website and a broad community of people who use them, including policy makers, businesspeople, educators, students, activists, and other concerned citizens.

Computer models

Key to the Collaboratorium is the notion of "radically open computer modeling." Many computer models are now available that can simulate key processes and relationships pertaining to climate change. However, most have been written and used by small groups of people who decide what assumptions to make, what possibilities to examine, and how to interpret the results.

The MIT team is developing a library of such models that users can run, trying out their own assumptions and generating results that other visitors can examine and evaluate. Over time, the team hopes that many visitors to the website will add more models and modify models that are already there.

For example, the first web-accessible, interactive simulation model in the Collaboratorium was C-LEARN—a model developed by John Sterman, the Jay W. Forrester Professor of Management, graduate student Juan Martin, and their colleagues in a consortium called Climate Interactive.

To try out a plan with C-LEARN, users select target values for future greenhouse gas (GHG) emissions over the coming decades in three regions of the world: industrial countries; large, rapidly developing countries; and other developing countries. Users also set future changes in land use that will affect GHG removal. Specifically, they define the rate of deforestation (cutting trees for development or agriculture) and the rate of afforestation (planting trees to create new forests). For each set of values, C-LEARN calculates the resulting changes in atmospheric concentrations of GHGs and in temperature and sea level to the year 2100 and displays them on the same page where users enter their inputs.

Through other models incorporated in the site, users can also assess the economics of their choices. For instance, for a given plan, how much will we have to invest to reduce emissions, and—on the other side of the balance sheet—how much will we save by not having to repair or adapt to the damage that would have occurred had we not taken action? The Collaboratorium quantifies such economic trade-offs by drawing on results from existing large-scale models—without actually running them.

For example, several research groups have used their major models to

Sample page from the Climate Collaboratorium

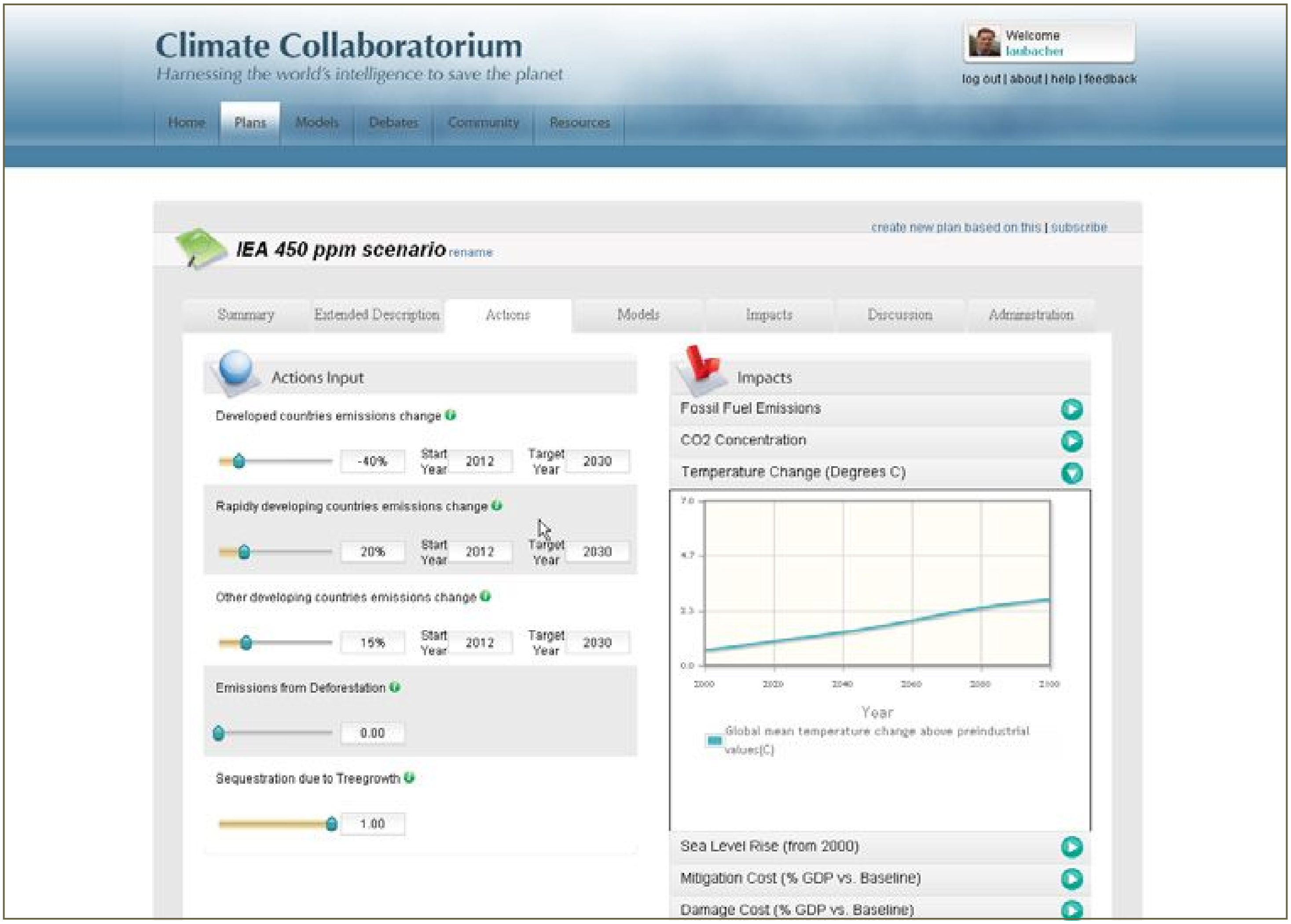

Image: Joshua Introne, MIT

This plan, based on the International Energy Agency's 450 ppm scenario, shows the actions (left column) and projected impacts (right column), as calculated by the Collaboratorium's simulation models. Note that the user can easily change the actions and see how the impacts change—or make up an entirely new plan.

examine different stabilization targets for atmospheric carbon dioxide (450 ppm, 550 ppm, and so on). The models determined the emissions levels and policies that would be required to meet each target and then calculated the resulting drop in gross domestic product (GDP) associated with each stabilization level as compared to "business as usual" (the continuation of current emission trends).

Laubacher and the Collaboratorium team used the results from these model runs to create "response surfaces"—simplified models that can quickly show the relationship between selected stabilization levels and the reduction in GDP associated with each and then mathematically interpolate between those discrete points so that users can choose any values they like.

Using the same approach with results from other models, the researchers also produced response surfaces that show the GDP losses that can be prevented by avoiding the damage associated with specific increases in temperature. With those tools, users of the Collaboratorium can get fast, approximate predictions of the economic costs and benefits of any proposed plan.

The Collaboratorium also addresses non-economic issues that must be considered when judging climate plans. Drawing on qualitative results from studies by the Intergovernmental Panel on Climate Change and others, the researchers prepared tables that show the impacts of each degree of warming on water supply, agriculture, coral reefs, and other factors in different regions of the world.

"With those capabilities, people are using the Collaboratorium to assess the impacts and trade-offs of the plans and proposals being discussed at the UN climate talks in Copenhagen," says Laubacher. Moreover, notes Malone, with thousands of people trying out different combinations of assumptions and possible actions, the Collaboratorium may actually yield better solutions than those now on the table.

Discuss, debate, vote

Like most online forums, the Collaboratorium hosts open, informal discussion among its visitors. But it also provides a "debate summary," which offers a concise look at key issues and different positions on them. The design is based on "argument mapping," an approach developed by team member Mark Klein, CCI principal research associate. Discussion is organized around issues, positions, and arguments.

To illustrate, one key issue is, how should we divide up the emissions reduction task among the different regions of the world? Positions posted by users might include making the same percentage reduction everywhere, achieving the same per capita use everywhere, and having the developed countries cut emissions before the developing countries do. Users can then post arguments for and against those positions, based on scientific studies, economic evidence, moral grounds, and the like.

The site organizes the discussion to be productive and systematic. "Every point or argument has a location, and once it's there, there's no point in saying it again," says Malone. "This approach reduces counterproductive behaviors like repeating comments and changing the subject, which make many online discussion forums unhelpful."

The combination of accessible models and constructive debate permits users to explore issues and possibilities in great depth, but even with these tools in place, there is still a risk that the exercise would never converge on a result. The Collaboratorium therefore lets people express their preferences by voting.

They can vote for or against specific plans that are posted, including those being discussed in Copenhagen. And they can vote for or against comments made by other visitors. On scientific issues—for example, what fraction of carbon dioxide emissions ends up in the upper atmosphere—participating experts may sometimes agree on the "right" answer. When they don't, other participants can learn from their discussion and debate.

Permitting people to vote provides a powerful means of focusing in on possibilities that are the most plausible or most promising. "We refer to this approach as 'electronic democracy on steroids' because it lets many, many people express their opinions about even fairly detailed issues if they care to," says Malone.

If they do not care to, they will be able to appoint others to vote on their behalf. An individual might, for example, give his or her proxy to the National Academy of Sciences for scientific issues and to the Sierra Club for political issues—but retain the right to vote as an individual on issues related to the division of responsibility between industrial and developing countries.

Building the online community

The researchers spent considerable time and effort recruiting, motivating, and organizing the Collaboratorium's first contributors and moderators. Since the website's launch in November 2009, the number of participants has grown. But the pressure is on to engage an ever larger community of both experts and non-experts—large enough to achieve the wisdom of collective intelligence.

"In the extreme form," says Malone, "you can imagine the Climate Collaboratorium as a kind of societal institution where many tens or even hundreds of thousands of people around the world are actively involved, contributing information, expressing their opinions, and helping to formulate the best possible plan for the world to deal with climate change."

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By Nancy Stauffer, MITEI

This research was supported by a seed grant from the MIT Energy Initiative. Other sponsors included Sustainability@MIT and the Argosy Foundation. More information can be found at cci.mit.edu/research/climate.html and in the following publications:

T. Malone and M. Klein. "Harnessing collective intelligence to address global climate change." *Innovations*, summer 2007, pp. 15–26 (www.mitpressjournals.org/doi/abs/10.1162/itgg.2007.2.3.15).

T. Malone, R. Laubacher, J. Introne, M. Klein, H. Abelson, J. Sterman, and G. Olson. *The Climate Collaboratorium: Project Overview*, MIT Center for Collective Intelligence Working Paper No. 2009-003 (cci.mit.edu/publications/CCIwp2009-03.pdf).

DOE establishes two Energy Frontier Research Centers at MIT

MIT is home to two of 46 new multi-million-dollar Energy Frontier Research Centers (EFRCs), the White House announced on April 27, 2009. Of the universities selected, only MIT will be leading two such centers.

The EFRCs, which will pursue basic scientific research on energy, are being established by the US Department of Energy (DOE) Office of Science at universities, national laboratories, nonprofit organizations, and private firms across the nation.

The EFRC program will provide $19 million to fund the Center for Excitonics at MIT, which is directed by Marc A. Baldo, associate professor of electrical engineering and a principal investigator in the Research Laboratory for Electronics. This center aims to understand excited states known as excitons, which consist of a bound electron and a positively charged hole. Excitons underpin the operation of a new generation of solar cells and solid state lighting technologies. The researchers will investigate the fundamental properties of excitons in complex nanostructures. This EFRC includes collaborations with scientists at Harvard University and Brookhaven National Laboratory.

The EFRC program also plans to supply $17.5 million to fund the Solid-State Solar-Thermal Energy Conversion Center at MIT, which is directed by Gang Chen, the Carl Richard Soderberg Professor of Power Engineering, director of the Pappalardo Micro and Nano Engineering Laboratories, and a principal investigator in the Materials Processing Center. This EFRC aims to advance the fundamental scientific understanding of thermoelectric and thermo-photovoltaic materials and to develop novel materials and devices to harvest energy from the sun and terrestrial heat sources. Researchers will study the fundamentals of photon, phonon, and charge carrier interactions in thermoelectric materials and will also use photonic crystals and metamaterials to manipulate the solar and thermal radiation spectrum in an attempt to provide an ideal match to the bandgap of photovoltaic materials. This EFRC includes collaborations with scientists at Boston College, Oak Ridge National Laboratory, and Brookhaven National Laboratory.

MIT is also a collaborator on four other EFRCs: the Center for Nanoscale Control of Geologic Carbon Dioxide at Lawrence Berkeley National Laboratory; the Energy Frontier Research Center for Combustion Science at Princeton University; the Center on Extreme Environment-Tolerant Materials via Atomic Scale Design of Interfaces at Los Alamos National Laboratory; and the Northeastern Chemical Energy Storage Center at the State University of New York, Stony Brook.

An unprecedented federal commitment

"As global energy demand grows over this century, there is an urgent need to reduce our dependence on fossil fuels and imported oil and curtail greenhouse gas emissions," said US Secretary of Energy Steven Chu. "Meeting this challenge will require significant scientific advances. These centers will mobilize the enormous talents and skills of our nation's scientific workforce in pursuit of the breakthroughs that are essential to make alternative and renewable energy truly viable as large-scale replacements for fossil fuels."

The 46 EFRCs, each to be funded at $2 million to $5 million per year for a planned initial five-year period, were selected from a pool of some 260 applications received in response to a solicitation from the DOE Office of Science in 2008. Selection was based on a rigorous merit review process using outside panels of scientific experts.

Professor Ernest J. Moniz, director of the MIT Energy Initiative (MITEI), noted, "We at MIT are extremely pleased to have been awarded leadership of two EFRCs and to be named as sub-awardee for four more. The EFRC program reflects an unprecedented federal commitment to the basic research needed for continuing energy technology innovation and was built upon an exemplary process that engaged the national scientific community to set priorities."

The DOE solicitation had specified that any institution could submit no more than three proposals, so MITEI developed and implemented an internal review process for MIT. MITEI informed MIT faculty about the opportunity, solicited concept papers from interested faculty teams, and worked with Vice President for Research Claude Canizares and the deans of science and engineering to select and strengthen the three MIT submissions.

Of the 46 EFRCs selected, 31 are led by universities, 12 by DOE national laboratories, two by nonprofit organizations, and one by a corporate research laboratory. Sixteen EFRCs, including Baldo's, are funded through the American Recovery and Reinvestment Act, with the objective of creating jobs and promoting economic recovery in addition to laying the foundation for future energy technologies. Numerous postdoctoral, graduate student, and technical staff positions will be created to support the work of the EFRCs.

MIT: An engine of energy innovation

Question: What do liquid-metal batteries, water-splitting catalysts, wafers from molten silicon, nanotube-enhanced ultracapacitors, and plant cell wall-degrading enzymes have in common?

Answer: These novel clean energy technologies were recently deemed to be potentially "transformative" by the US Department of Energy (DOE). The technologies are the focus of research awards by DOE's new Advanced Research Projects Agency-Energy (ARPA-E). These awards—which support key links in the energy value chain—highlight the critical role MIT plays as an engine of energy innovation.

Photo: Salvador Barriga G, MIT

Professor Donald Sadoway (right), recipient of one of DOE's ARPA-E awards, and graduate student David Bradwell, both of the Department of Materials Science and Engineering, are working on liquid metal batteries, a technology that could make possible grid-scale energy storage.

The selected projects were for one MIT research lab and four startups with strong links to MIT. The successful proposals—submitted by MIT Professor Donald Sadoway of materials science and engineering, Sun Catalytix, 1366 Technologies, FastCAP Systems, and Agrivida—will receive combined funding of $24.8 million from the new program's inaugural round of funding. A sixth Massachusetts awardee, FloDesign Wind Turbine Corporation, was an earlier recipient of an MIT prize for energy entrepreneurs.

Sadoway's "Liquid Metal Grid-Scale Batteries" project was described by DOE as a technology that "could revolutionize the way electricity is used and produced on the grid, enabling round-the-clock power from America's wind and solar power resources." Sadoway's proposal, funded at $6.9 million, would use low-cost, domestically available liquid metals to store energy at grid-scale. When he learned of the award, Sadoway said, "This is fantastic news. These new funds will allow us to accelerate the rate of discovery." He noted that the funds will "enable us to enlarge our team and to expand our collaboration with other researchers on campus. The addition of new and complementary skills to the project will help us move this novel energy-storage concept to a reality."

Another successful project, submitted by Sun Catalytix Corporation, a startup that emerged from MIT, has the potential to "greatly enhance the efficiency of splitting water into hydrogen and oxygen," according to DOE. The company will receive $4 million to continue its groundbreaking work on the development of a catalyst that mimics a plant's storage system, with the potential to be a key enabler for liquid fuel-based distributed energy-storage systems. Sun Catalytix, started by MIT Professor Daniel Nocera of chemistry in 2008, is focused on commercializing catalyst technology originally developed in Nocera's laboratory at MIT.

1366 Technologies Inc.—a startup initially launched from the lab of MIT Professor Emanuel Sachs of mechanical engineering and the only photovoltaics company to receive a stamp of approval from ARPA-E—was selected to receive $4 million to pursue the development of high-efficiency monocrystalline-equivalent silicon wafers directly from molten silicon. These wafers have the "potential to halve the installed cost of solar photovoltaics." Professor Tonio Buonassisi's Laboratory for Photovoltaic Research will team with 1366 to support the project. 1366 Technologies was formed in 2008, and its board of directors consists entirely of MIT alumni.

Research that underpins the proposal of FastCAP Systems—another startup whose genesis was in MIT-generated research—began at the Laboratory for Electromagnetic and Electronic Systems (LEES) in 2003 under the direction of Professor Joel Schindall of electrical engineering and computer science. The novel ultracapacitors being developed approach the energy density of conventional batteries but do not similarly degrade. According to Schindall, they have an essentially indefinite cycle life. DOE, in its selection of the $5.3 million project, noted that it could "greatly reduce the cost of hybrid and electric vehicles and of grid-scale storage." FastCAP was formed in 2009 by MIT alumni Riccardo Signorelli and John Cooley. Schindall and LEES will partner on the project. The MIT Energy Initiative provided a seed grant for Schindall's work on ultracapacitors.

Agrivida—yet another startup with strong ties to MIT—was selected to receive a $4.6 million grant from ARPA-E to develop the ability to grow cell wall-degrading enzymes within plants that are activated after harvest. DOE selected this project because "the technology has the potential to dramatically reduce the cost of cellulosic biofuels and chemicals." Agrivida was formed in 2003 by MIT alumni Michael Raab and Jeremy Johnson. At least five other MIT alumni are involved in the company, which routinely hires MIT students as summer interns. Agrivida is an agricultural biotechnology company developing energy crops designed to produce chemicals, fuels, and bioproducts from non-food cellulosic biomass.

Finally, FloDesign Wind Turbine Corporation of Wilbraham, MA, received an award of more than $8 million to develop an advanced wind turbine, the Mixer Ejector Wind Turbine, or MEWT. While not an MIT spinoff, FloDesign received the MIT Clean Energy Entrepreneurship Prize in 2008, supported by N-STAR and DOE.

The five MIT-affiliated awards and FloDesign were selected from a total of more than 3,600 initial concept papers, of which approximately 300 went on to the proposal stage. Ultimately, DOE selected 37 projects for funding from ARPA-E. In a highly competitive field, MIT demonstrated once again that it is the "go-to" place for developing energy solutions with an eye toward commercialization and the potential to transform how we produce and consume energy.

MIT President Susan Hockfield said, "The ARPA-E awards reflect MIT's track record of inventing inspired solutions to real-world problems, and only reinforce our confidence in the Commonwealth's growing energy technology innovation cluster."

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By Timothy Heidel G and Melanie Kenderdine, MITEI

MITEI awards fourth round of seed grants

In October 2009, the MIT Energy Initiative (MITEI) announced its fourth round of seed grants supporting innovative, early-stage research projects across the Institute. The list of awards at the right demonstrates the creativity and diversity of the funded research.

Total funding in this round of seed grants exceeded $1.7 million. The awards span nine departments, and half of the projects involve collaborations across departments. Once again, many of the awards went to junior faculty and to faculty new to energy-related research.

The response to the call for proposals—issued in mid-July—was as strong as ever, with 55 submissions coming from across the Institute.

Funding for the new grants comes chiefly from MITEI's Founding and Sustaining members (see list on page 48) supplemented by funding from the Chesonis Family Foundation, Doug and Barbara Spreng, the Singapore-MIT programs, and MITEI.

To date, MITEI's seed grant program has supported 54 early-stage research proposals, with total funding of more than $6.5 million. In addition, eight individuals or groups have received ignition grants for junior faculty or planning grants to help generate new ideas.

For a complete listing of the seed grant awards, go to web.mit.edu/mitei/research/seed-funds.html. The research section of this issue (starting on page 6) reports on results from five projects—one in each of the MIT schools—that were funded in the first round of awards in January 2008.

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Recipients of MITEI seed grants, October 2009

Theory of ultrafast Li-ion battery materials
Martin Bazant
Chemical Engineering

Efficient solid-state lighting based on III-nitride nanowires and catalyst engineering
Karl Berggren
Electrical Engineering and Computer Science
Silvija Gradečak
Materials Science and Engineering

Designing new materials for sunlight—thermal energy storage
Jeffrey Grossman
Materials Science and Engineering

Development of nanoparticle-laden molten salts for heat transfer in high-temperature solar and nuclear applications
T. Alan Hatton
Chemical Engineering
Jacopo Buongiorno
Nuclear Science and Engineering

Genetic identification and expression of efficient cellulose degrading complexes from fungi
Chris Kaiser
Biology

Innovation policy, innovation prizes, and the energy economy: analyzing the role of prizes as a policy mechanism for energy innovation
Fiona Murray
Management

Learning from nature: design principles for resilient bioenergy systems
Martin Polz
Civil and Environmental Engineering

Integrated ribbons for solar cell applications
Marin Soljačić
Physics
Yoel Fink
Materials Science and Engineering

Understanding and controlling the flow of thermal energy in nanostructured materials for energy conversion
Edwin Thomas, Martin Maldovan
Materials Science and Engineering

Processing of nanostructures for electrochemical energy storage
Carl Thompson
Materials Science and Engineering
Yang Shao-Horn
Mechanical Engineering, Materials Science and Engineering

Nanoscale hetero-interfaces for reversible solid oxide fuel cells in energy storage
Harry Tuller
Materials Science and Engineering
Bilge Yildiz
Nuclear Science and Engineering

Nanoengineered surfaces for subsea separation of fluid-fluid (oil-water) mixtures
Kripa Varanasi, Gareth McKinley
Mechanical Engineering
Robert Cohen
Chemical Engineering

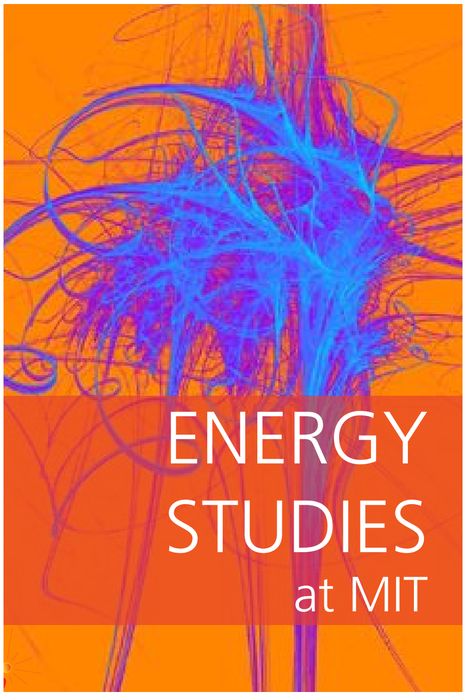
MIT announces new energy minor

Starting this year, all MIT undergraduate students have a new academic option available to them: a minor in energy, which can be combined with any major. The new Energy Studies Minor, unlike most energy concentrations available at other institutions, and unlike any other concentration at MIT, explicitly integrates science, social science, and engineering, and encompasses all five schools at MIT.

Timothy Grejtak '11 could hardly wait to sign up for the new minor, and became the first student to do so—literally minutes after the registration form was finalized in late September. He hopes also to be the first person to graduate with the energy minor, but he has three semesters left so he knows that someone else could beat him to that finish line.

"It's going to be very popular, I have a feeling," says Grejtak, who three years ago started the annual dormitory energy competition at MIT—a two-month contest to see which dorm can lower its electricity usage the most—and has been running it each year. "I know of many students who are very interested" in the energy minor, he says.

The new energy minor is the product of two years of work by the MIT Energy Initiative's Energy Education Task Force, co-chaired by Vladimir Bulović, the KDD Associate Professor of Communications and Technology in the Department of Electrical Engineering and Computer Science, and Donald Lessard, the Epoch Foundation Professor of International Management at the MIT Sloan School of Management, who had a great deal of support from numerous faculty members and administrators to get the new curriculum approved and in place. Bulović notes that "the required core classes and wide array of approved



electives for the energy minor reflect the multidisciplinary nature of energy science, technology, and policy and cover the range of energy challenges, including energy-related climate change, pollution, and associated poverty issues. They also include subjects on energy efficiency and sustainable sources of energy."

Dr. Amanda Graham, who will administer the minor as director of the Education Office for the MIT Energy Initiative, has supported the task force's work on the energy minor since 2007. From the start, she says, it was clear that what they wanted was a balance that included three areas: energy science, energy technology and engineering, and energy social sciences.

So, for example, a solar energy project might require detailed knowledge of the inherent physical limits to the system's possible efficiency (a basic science matter), the specific engineering challenges associated with building the system in a specific design and location (a matter of technology), and the issues associated with gaining the necessary financing, permitting, and public support to allow the project to go forward (matters of policy and economics). This range of disciplines was seen as essential in order to prepare students to deal with the full range of technical, scientific, political, and economic issues that surround most energy-related decisions.

"In order to be proficient in energy, you have to be able to cross over these three areas," Graham says. Those who choose careers in energy policy need to understand the science and technology, to understand what's possible and feasible, she says; and those working on energy technology need an understanding of the political and economic realities that determine what becomes a realistic option for society. "We wanted to make sure the energy minor was suitable to complement any major, in any of the schools."

The faculty task force specifically chose to develop a minor rather than a major in the belief that an MIT student focusing on energy should develop expertise in depth in a specific discipline, and then complement that with the breadth of understanding offered by the energy minor. While there are some other interdisciplinary minors at MIT, they are all based in one or two of the schools. In contrast, the energy minor was conceived from the start as a program that would be accountable to all five schools in order to ensure a multidisciplinary curriculum and enrollment.

New academic structure

The concept was unanimously approved last year by the faculty, which created an experimental new body, the Inter-school Educational Council, to which the new minor reports. A new Energy Minor Oversight Committee, with representation from the five schools, was formed to directly manage the program. At the moment, the energy minor is the only program that has this new reporting structure.

This broad structure makes MIT's program unusual, if not unique, in higher education, says Graham. In other schools that have energy majors or minors, she says, "the programs that I'm aware of are either science- or policy-focused. Ours is distinctive in its three-domain structure."

MIT Dean for Undergraduate Education Daniel Hastings says the new minor "can be regarded as part of the ongoing transformation of the MIT curriculum for the 21st century, in that it creates an option for our students which uses approaches and knowledge from all corners of MIT. This shows the power of MIT working together to harness its activities in service to the world." He adds that the creation of this new program "allows an MIT student to obtain a degree in a major discipline while also learning about and showing competence in one of the pressing problems of our time."

According to Richard Schmalensee, the Howard W. Johnson Professor of Economics and Management and a member of the Energy Minor Oversight Committee, the Energy Studies program "reflects the hard fact that the energy challenge is multi-dimensional. For students, the minor unites people of diverse backgrounds and interests in this important effort. For faculty, it helps us prepare the next generation of leaders at MIT and elsewhere."

As part of the development of the curriculum for the new minor, seven new undergraduate classes were created, and three existing classes were significantly revised. Among the new offerings are a social sciences class called "Energy Decisions, Markets, and Policies," and a new class in Earth, Atmospheric, and Planetary Sciences called "Earth Science, Energy, and the Environment."

The list of electives available for students in the energy minor is "quite long, and we'd like to see that list grow," Bulović says.

A survey of students earlier this year found a high level of interest in the energy minor, with 23% of sophomores and 19% of juniors saying they had some interest in it.

Grejtak, who is majoring in mechanical engineering with a focus on energy conversion engineering, likes the fact that the new minor provides a structure to enhance that major with courses dealing with the economics and policy of energy. "It goes through the whole gamut, and that's one of the reasons I think it's such a great idea," he says.

He hopes to find work developing complete energy systems, including working on the political aspects to make them socially feasible, the economics to make them practical, and the engineering to make them successful. "There are many ways of tackling problems in energy," he says, "and this is a multi-pronged approach."

"Energy is such an important topic now—it's the largest crisis that my generation will face," he says. "It's going to be a major problem for us, and this energy minor acknowledges that and gives us a way to be qualified to address these problems."

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By David L. Chandler, MIT News Office, with reporting by Sarah Wright, MITEI correspondent

Summer UROPs cut across disciplines to address real-world energy issues

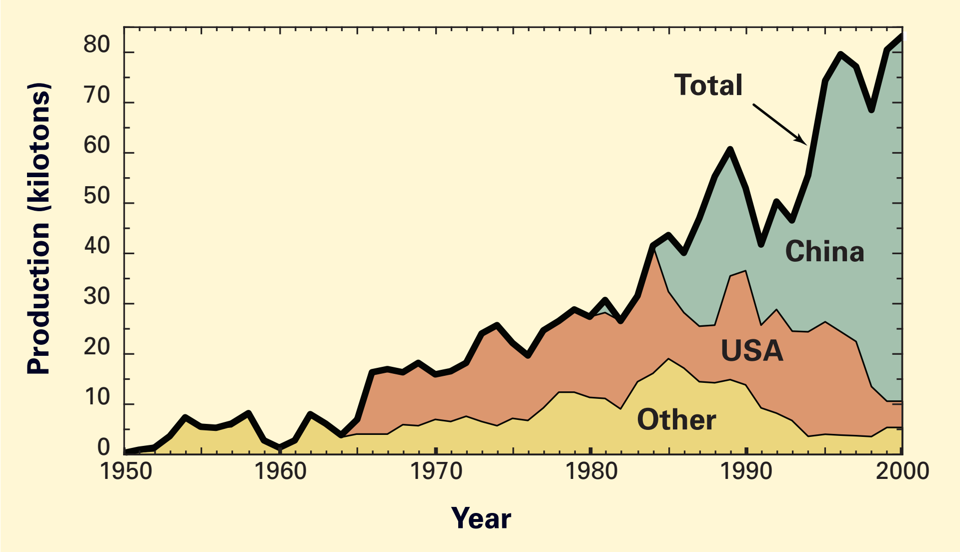
Elizabeth Turner's childhood interest in rocks could easily turn into a career. A senior in environmental engineering with a focus on geology, Turner '10 plans to continue a summer research project on the use of rare elements in new energy technologies by writing a series of articles focused on individual elements.

"I am interested in policy and geology," says Turner, whose father is a geologist, and who likes to rock climb and hike. "I really like this research. I've written two papers and hope to write three or four more."

Student enthusiasm and cross-disciplinary research characterize this summer's Undergraduate Research Opportunities Program (UROP) projects supported by the MIT Energy Initiative (MITEI), with funds coming from four MITEI Affiliate members, a private donor, and the MIT Future of Natural Gas study. Fifteen UROP students and one intern from seven MIT departments worked on 12 research projects (see box on page 33). In many cases, the student and his or her faculty advisor were from different MIT schools, ensuring the interdisciplinary nature of the experience. Topics addressed included solar energy, electric vehicles, oil and natural gas costs, carbon sequestration, and tools for assessing climate change policies.

"Diversity is the most impressive feature of this summer's group of UROPs, which involved students and faculty from across MIT," says Robert C. Armstrong, deputy director of MITEI and the Chevron Professor of Chemical Engineering. "This reflects the complex and interdisciplinary character of the energy field." The UROPs also can have far-reaching impact outside the MIT community, he says.

Global production of rare earth oxides, 1950–2000



The rare earth elements, studied along with other energy-critical elements by UROP student Elizabeth Turner, are key to energy technologies including batteries, photovoltaics, and magnets. The graph above shows the global production of such elements (in their oxide form) from the United States, China, and all other countries combined. While the US was once largely self-sufficient, it has become increasingly dependent on imports from China—a situation that raises concerns as the US works to develop and commercialize new energy technologies. (Source: *USGS Fact Sheet 087-02*.)

For example, Turner's papers could be used to educate the government and others about the complexity of using rare elements in new energy technologies, according to Robert Jaffe, her faculty advisor on the project and the Jane and Otto Morningstar Professor of Physics at MIT. "She could do this for a living," he says. "MIT students are dynamite."

Turner's UROP project involved combing the scientific literature and newspapers for information on rare elements that are critical to energy technologies, such as lithium for batteries and tellurium for high-efficiency photovoltaics. Turner compiled a list of those materials and then started to examine them in terms of their availability, mineralogy, extraction, reserves, potential for recycling, economics, and scalability. She also began developing a series of case studies on the most critical elements such as tellurium and neodymium (used in magnets), which China is reportedly stockpiling. (See the graph above for trends in global production of rare earth oxides.)

"If we are short on critical materials, we need to find a way to address that availability; otherwise we won't get too far in developing new energy technologies," says William Chao '78, who holds an SB in electrical engineering from MIT and who sponsored five summer UROP projects, including Turner's.

Seeding the next generation

"It is really cool to be able to fund multiple UROP projects in parallel," says Chao. "The UROPs help sow the seeds for the next generation of graduate students."

Graduate school is part of the plan for Julia Day '10, a senior in mechanical engineering. Her UROP project focused on the application of micro- and nano-engineered surfaces to increase the efficiency of existing power plants. Expanding output from those facilities will become increasingly important with the expected rapid growth in demand for electricity in developing countries, which may lack the capital to build new power plants.

Day researched super-hydrophobic (water-repelling) and super-hydrophilic (water-attracting) technologies that can be tailored to improve different parts of steam turbines, condensers, and boilers.

"A UROP is a great way to get involved in research," she says. "My project covered a lot of subjects I am interested in, like manufacturing, micro- and nano-technology, energy, and how to better use energy we already have." She also was excited to work with Kripa Varanasi, d'Arbeloff Assistant Professor of Mechanical Engineering, helping to set up his new lab, develop lab procedures, and devise experiments.

Day was drawn to micro- and nano-applications when she was young, including an interest in quantum physics in high school. "The idea of tiny particles and really looking at how things interact on tiny levels is really cool," she says. "There's a great worldwide potential to help people and save lives. My UROP also had far-reaching implications for the environment. Plus, I could do the geeky stuff that I love. I would like to work on this topic for a long time."

In her post-UROP report, Day says, "One of my favorite parts of the lab is that there is a lot of focus on collaboration, which means that I had the opportunity to form lots of connections with other research groups and professors." She adds that she learned how to be more proactive in getting help and networking with other labs.

Helping urban planners

Grafton Daniels '11 and Christos Samolis '12, both electrical engineering and computer science majors, were able to hone their programming skills—and to learn firsthand how academic research is conducted. The two collaborated on a project attempting to adapt the UrbanSim model to the Lisbon metropolitan area. UrbanSim forms a core component of Opus, the Open Platform for Urban Simulation—an initiative of an international group of researchers working on integrated simulations of land use and travel demand. UrbanSim aims to simulate where households and businesses are likely to move within a city and, for example, help planners ensure that adequate public utilities and other services are available in those areas.

The students examined the software and added comments to the code to help educate newcomers using the program. In addition, they examined ways to improve UrbanSim by including more behaviorally sophisticated models of passenger travel.

"One thing we tried to do was to use a wider sample, to model a whole city," says Samolis. The original software samples 30 possible locations when simulating location choices. The students examined the computational implications of expanding the sample size to thousands of locations or eliminating the sampling approach altogether. The purpose was to increase the theoretical rigor of the approach and improve the forecasting accuracy.

"It's a work in progress," says Christopher Zegras, the students' faculty advisor and the Ford Career Development Assistant Professor, Transportation and Urban Planning, about the efforts to apply UrbanSim and Opus in Portugal. "It's part of a large research project that spans several departments at MIT and a number of Portuguese partner universities." The project is part of the MIT-Portugal Program, and Daniels and Samolis worked with partners at the University of Coimbra in Portugal. The models are now being adapted for pilot application in Lisbon starting in January.

Zegras notes that the students are "in the early stages of their intellectual formation." Their work with UrbanSim and the Opus platform "gets them to think in trans-disciplinary ways and see how one skill is valuable in another area," he says. In addition, in the future they will be able to see the results of their work helping real-world decision makers design transportation and land-development policies and make investments for urban revitalization.

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By Lori Fortig, MITEI correspondent

MITEI Undergraduate Energy Research Projects, Summer 2009

Student name *Department*	Project title	Sponsor	Faculty supervisor(s) *Department(s)*
Yieu Chyan '11 *Chemistry*	**Dibenzocyclooctatetraene-based electronic polymers**	GreengEnergy	Timothy Swager *Chemistry*
Grafton Daniels '11 *Electrical Engineering and Computer Science* Christos Samolis '12 *Electrical Engineering and Computer Science*	**Computer programming for OPUS/UrbanSim enhancements**	Nth Power	Christopher Zegras *Urban Studies and Planning*
Julia Day '10 *Mechanical Engineering*	**Application of micro- and nano-engineered surfaces to increase power plant efficiency**	MIT Energy Initiative	Kripa Varanasi *Mechanical Engineering*
Ian Fischer '12 *Aeronautics and Astronautics*	**Concentrated solar power for Experimental Study Group**	William Chao '78	Alex Slocum *Mechanical Engineering*
Daniel Kelly '12 *Mechanical Engineering* Kwadwo Nyarko '12 *Mechanical Engineering*	**MIT Electric Vehicle Team vehicle modeling and testing**	Natalie Givans '84	Yang Shao-Horn, John Heywood, Wai Cheng *Mechanical Engineering* Yet-Ming Chiang *Materials Science and Engineering*
Haitao Mao '12 *Electrical Engineering and Computer Science* Patrick Yamane '11 *Electrical Engineering and Computer Science*	**Climate Collaboratorium**	William Chao '78	Robert Laubacher *Center for Collective Intelligence* Thomas Malone *Management*
Nikhil Pradhan '09 *Chemical Engineering*	**Climate Collaboratorium intern**	MIT Energy Initiative	Robert Laubacher *Center for Collective Intelligence* Thomas Malone *Management*
Anya Shafiro '10 *Economics*	**Natural Gas Study**	MIT Natural Gas Study	Ernest Moniz, Tony Meggs, Daniel Cohn *MIT Energy Initiative*
Anna Shcherbina '11 *Electrical Engineering and Computer Science*	**Biofilms and carbon sequestration**	William Chao '78	Roman Stocker *Civil and Environmental Engineering*
Josh Siegel '11 *Mechanical Engineering*	**Fuel efficiency monitoring in modern vehicles**	William Chao '78	Sanjay Sarma *Mechanical Engineering*
Elizabeth Turner '10 *Civil and Environmental Engineering*	**Rare elements and scalability of energy technology**	William Chao '78	Robert Jaffe *Physics*
Juliana Velez '11 *Mechanical Engineering*	**Data center cooling**	Millennial Net	Leon Glicksman *Architecture*
Joshua Velson '10 *Chemical Engineering*	**Fermentation of used vegetable oil biodiesel-derived raw glycerin to 1,3-propanediol using *clostridium butyricum***	MIT Energy Initiative	Jean-François Hamel *Chemical Engineering*

MITEI helps pre-frosh get into the flow of energy at MIT

In August, the MIT Energy Initiative Education Office enrolled 24 students in its first Freshman Pre-Orientation Program. The week-long program—called "Discover Energy: Learn, Think, Apply"—featured activities to acquaint new students with the range of energy-related opportunities at MIT, introduce them to important topics within the energy arena, and connect them with the MIT energy and environment student community.

Photo: Amanda Graham, MITEI

Jaclyn Wilson (left) and Kaleb Ayalew estimate their personal "carbon footprints."

Photo: Amanda Graham, MITEI

Peter Cooper (right), manager of sustainability engineering and utility planning in the MIT Department of Facilities, explains MIT's electrical distribution system to students in the basement of the Stata Center during a tour of how energy flows at MIT—from generation to end use.

Photo: Jennifer DiMase '01, MITEI

Matt Alvarado SB '00, PhD '08 leads a walking tour highlighting historical landmarks and pointing out areas that may be inundated according to some climate change scenarios.

Photo: Jennifer DiMase '01, MITEI

To demonstrate fundamental principles of energy flow, Professor Steven Leeb SB '87, SM '89, PhD '93 of electrical engineering and computer science shows Julia Kimmerly (center) and Carlos Greaves how to make a simple battery-powered motor.

Named MIT Energy Fellows, 2009–2010

The Society of Energy Fellows at MIT welcomed 47 new members in September 2009. The Energy Fellows network now totals 87 graduate students and spans 20 MIT departments and divisions. The new graduate fellowships are made possible through the generous support of 17 MITEI member companies.

Photo: Justin Knight

Named Energy Fellows for 2009–2010.

ABB
Matthias Bahlke Electrical Engineering and Computer Science
David Liu Physics

b_TEC
Nan-Wei Gong Media Arts and Sciences
Jae Jin Kim Materials Science and Engineering

Bosch
Sophie Ni Sisi Materials Science and Engineering
Adam Paxson Mechanical Engineering

BP
Andres Cubillos-Ruiz Biology
Pearl Donohoo Engineering Systems Division
Roberto Guerrero-Compean Urban Studies and Planning
Jonathon Harding Chemical Engineering
Christopher Love Mechanical Engineering
Sigurdur Magnusson Civil and Environmental Engineering
Kawika Pierson Management
Joseph Shapiro Economics
Mark Smith Biology
Jason Sussman Materials Science and Engineering
Laken Top Chemistry

Chevron
Phech Colatat Management
Andrew Shroll Mechanical Engineering

Constellation
Ibrahim Toukan Technology and Policy Program

EDF
Saaransh Gulati Nuclear Science and Engineering

Enel
Bhavya Daya Electrical Engineering and Computer Science
Paul Lewis Civil and Environmental Engineering

Eni
Michael Bikard Management
Shamel Merchant Chemical Engineering
Deepak Mishra Biological Engineering
Steven Shimizu Chemical Engineering
Mohit Singh Nuclear Science and Engineering
Geoffrey Supran Materials Science and Engineering
Nathaniel Towery Science, Technology, and Society
Andrew Ullman Chemistry
Di Yang Earth, Atmospheric, and Planetary Sciences
Metodi Zlatinov Aeronautics and Astronautics

Entergy
Maximilian Parness Technology and Policy Program

Hess
Michael Kearney Technology and Policy Program

Lockheed Martin
Tom Heaps-Nelson Engineering Systems Division
Max Solar Materials Science and Engineering

Ormat
Michelle Vogl Mechanical Engineering

Saudi Aramco
Kwabena Bediako Chemistry
David Borrelli Chemical Engineering

Schlumberger
Samantha Gunter Electrical Engineering and Computer Science
Ronan Lonergan Mechanical Engineering

Siemens
Karen Welling Architecture
Brandon Reizman Chemical Engineering

Total
Paul Murphy Engineering Systems Division
Sreeja Nag Earth, Atmospheric, and Planetary Sciences/Engineering Systems Division
Jonas Nahm Political Science

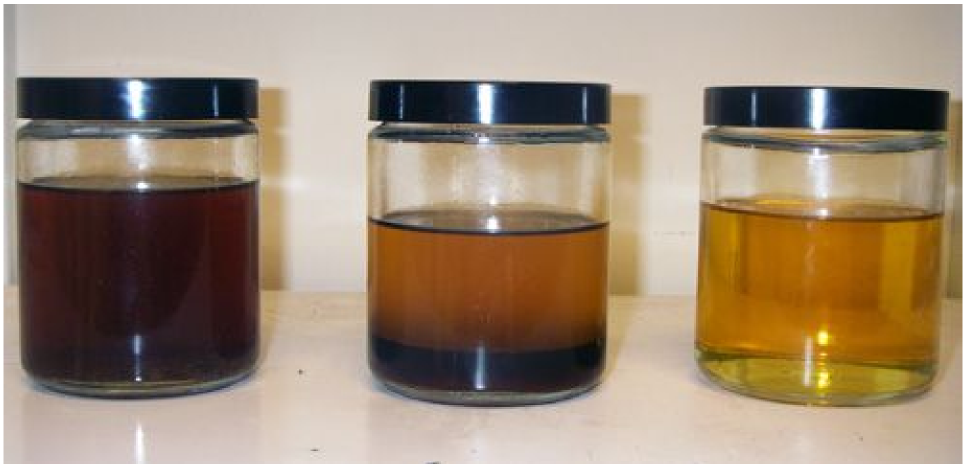
Recycled frying oil to power MIT shuttles

If you catch a whiff of french fries when an MIT shuttle rolls past, it won't be a coincidence. Part of the fuel in its tank may have come out of a kitchen deep fryer just a few weeks earlier.

The student group biodiesel@MIT, formed three years ago, has been working diligently—and often in an uphill effort—to secure the space, equipment, and safety approvals to begin turning leftover cooking oil into fuel that can be blended with regular diesel fuel to help power MIT's fleet of shuttles. That long effort finally came to fruition in August when the group succeeded in making its first batch: 30 gallons of golden-colored fuel. In early September, they finished a second batch.

Before the fuel can actually be poured into the tank of a shuttle bus, though, it has to be tested under standards set by ASTM International (originally known as the American Society for Testing and Materials), an independent safety standards and testing organization, to assure that it's free of contaminants and has the correct flash point for ignition. "If it passes that," says biodiesel@MIT Vice President Kyle Gilpin, a graduate student in Electrical Engineering and Computer Science, "then we will pass it off to Facilities to use in their equipment."

The initial batches, cooked up by Gilpin and Natasha Jensen '12, might go into lawn-mowing equipment, but after this pilot phase the system should be ready to start adding 20% biodiesel to the fuel supply for the campus shuttles. The fuel will be made from used oil collected initially from the Student Center and eventually from all of MIT's dining facilities. When the system is in full swing, producing about one 55-gallon drum of biodiesel per week,



Photos: Kyle Gilpin G, MIT

Biodiesel is produced from waste vegetable oil (left). After initial processing with alcohol and a strong base, the oil is transformed into biodiesel floating on much denser waste glycerol (center). After removing the glycerol, the biodiesel is filtered and washed to produce the light, clear liquid (right) that can be used in place of diesel fuel in many engines.

it should be a win-win for the Institute: It will save up to 20% of fuel costs (the amount of biodiesel that's blended in), since the raw material is free and the labor is donated. At the same time, it will save on the disposal cost and environmental impact of dumping the used cooking oil. And it will even make the exhaust fumes smell better.

The equipment used to process the used oil—which involves first filtering it and then mixing it with methanol and a catalyst—was engineered, designed, and constructed by MBP Bioenergy, a biodiesel production company based in North Conway, NH. Principals Al Landano and Jim Proulx, under contract with the student-led group, have worked with the students and MIT's Environment, Health, and Safety Office (EHS) to install the processor that produces the biodiesel fuel. As part of the contract, MBP will ensure that the fuel from MIT's customized processor is ASTM certified to be used on the road.

As the students actually operate the equipment over the coming months and years, learning to adjust the system as they go along, they may well figure out some methods that could help improve biodiesel manufacturing in general, Gilpin suggests.

The biodiesel@MIT group was formed in 2006 and has been working ever since to draw up detailed plans and get the system installed and running. Two students who have since graduated, Matthew Zedler '07 and Joseph Roy-Mayhew '08, originated the project, and the group is currently led by Sara Barnowski '10.

Finding a place

The hardest part turned out to be finding an appropriate place on campus to install the facility, given the safety issues associated with producing flammable fuel and using some toxic chemicals. Niamh Kelly of EHS has been working closely with the group to help them get the system installed and running in Building NW14.

Gilpin has been an avid advocate for biodiesel. Last summer he made a carefully planned coast-to-coast trip in his diesel engine VW sedan, using 100% biodiesel the whole way. Because suppliers are hard to find in some parts of the country, that often meant having to haul along cans of the stuff in his car. "It was a challenge, but well worth it," he says.

The students hope to study "how best to go about producing the fuel, how to produce it most efficiently, and how best to handle the waste," which can include some toxic materials, he says. "There are a lot of process variations that can be tried."

Eventually, the biodiesel@MIT group, which during the academic year has eight to ten active members, would like to increase production by collecting oil from local restaurants. There's no reason it couldn't be collected from such sources, Gilpin says, although the drums of used oil tend to be "big, heavy, and kind of messy."

The costs of buying and installing the equipment were covered by a $25,000 first prize the group won in 2006 in a competition run by GE and mtvU, called the Ecomagination Challenge. The Campus Sustainability Fund has also provided support by paying students through the Undergraduate Research Opportunities Program to work on the project. The operating costs of the system are relatively small, Gilpin says, mainly for the purchase of the methanol additive. The system "will definitely pay for itself," he says.

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By David L. Chandler, MIT News Office

The MIT biodiesel reactor is capable of processing 70-gallon batches of waste vegetable oil into almost the same amount of biodiesel. Here the main processor tank (top center) contains about 20 gallons of biodiesel that was produced from oil collected in a 55-gallon drum (bottom right) at the Student Center.

Flipping a switch for energy savings

Feeling responsible? Altruistic? How about guilty? MIT students hoping to get people to turn off lights by telling them how much energy they're using aren't too concerned about exactly which emotion does the trick—just as long as that switch gets flipped to "off."

Lights Out 16-56 is a pilot project exploring the effectiveness of computer-aided feedback in changing behavior. In September and October 2008, cameras set up in the Stata Center were trained on Buildings 16 and 56—per square foot, the second- and third-highest energy consumers on campus—to monitor how often lights were left burning after conventional working hours. A computer program analyzed the images and sent weekly e-mails to laboratory staff and students participating in the study with a summary of their rooms' energy use.

The message, for example, might inform the occupants that their lighting was on 20 out of 49 hours, equaling 25 kilowatt-hours and producing 25 pounds of carbon dioxide (CO_2).

Sure enough, after a few weeks of e-mails, all-night lighting in 16 and 56 decreased. Of the 56 north-facing rooms monitored by camera, five rooms with more than two occupants who volunteered to participate in the study showed declines of between 1.4 and 2.4 hours per night between early September and late October, while rooms without study participants showed no decline. "This is very preliminary evidence given the small sample, but it provides some encouragement," says Jialan Wang, a graduate student in financial economics, who helped spearhead the project through the student organization Closing the Loop.

Climate change and economic woes both point to the necessity of scaling back energy consumption. Green buildings outfitted with sustainable materials and energy-efficient fixtures only go so far, because the buck stops with the people who actually turn the devices on and off. Why target lighting? It's easy to tell if lights are burning at night, and relatively easy to measure the energy savings from cutting back on their use.

"Lighting accounts for about one-third of all electricity use on campus, accounting for approximately $8 million a year," says Steven M. Lanou, deputy director for environmental sustainability. "This is a compelling reason for people to turn off their lights."

The Lights Out 16-56 project was supported by staff from the MIT Energy Initiative (MITEI); the Environment, Health, and Safety Headquarters Office; the Department of Facilities; and the Department of Architecture. (The project received approval from the MIT Committee on the Use of Humans as Experimental Subjects to ensure appropriate practices.) It was developed by the student group Closing the Loop, which was founded in 2005 to increase awareness of MIT's resource use by individuals and the community. In addition to lighting, Closing the Loop initiatives have targeted revolving doors, fume hoods, paper conservation, and green purchasing.

For Lights Out, Wang and former intern Shyam Shrinivasan, now at the California Institute of Technology, installed small devices called data loggers to record occupancy and lighting use in Buildings 16 and 56. They canvassed the buildings for participants and set up webcams. Funded by MITEI and MIT's Environmental Programs Office, Shrinivasan worked on the initial algorithm and camera setup. With the help of Stephen S. Intille, a Department of Architecture research scientist, they developed software that analyzed the photos to match windows to rooms and send e-mails to participants (see diagram to the right).

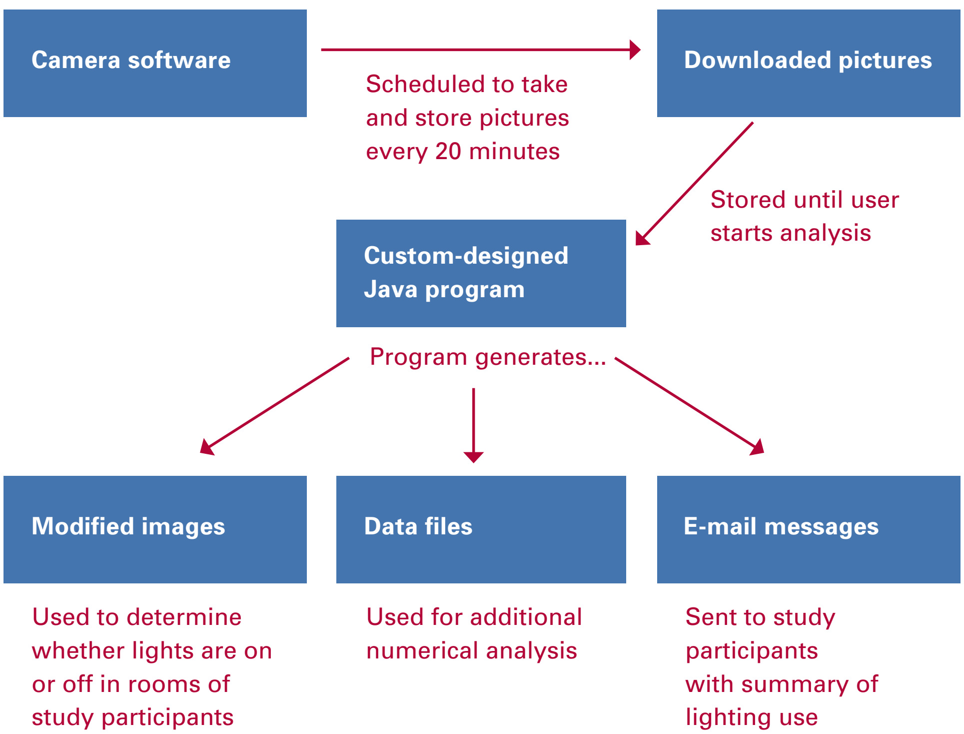
"Research shows that timely, highly tailored messages presented at so-called teachable moments are often well-received and can motivate people to change their behavior," Intille says. "Computer systems may be able to detect these teachable moments automatically and respond in real time."

When the project was turned into an Undergraduate Research Opportunities Program (UROP) study in early 2009, Joshua E. Hester, a junior majoring in civil and environmental engineering, worked on analyzing the data.

Something as simple as being more conscientious about turning off the lights can lead to significant savings, Hester says. Based on preliminary measurements from the data loggers, reducing lighting in unoccupied labs and offices in Buildings 16 and 56 could save about $21,000 and 63 tons of CO_2 emissions annually. Reducing lighting during daylight hours could save a further 160 metric tons annually for every 10% in lighting reduction, he says.

"This study has played a key supporting role in promoting energy efficiency awareness and Institute-wide programs at MIT. Lights Out 16-56 has helped inform and inspire components of the recent greeningMIT awareness campaigns, which are highlighting lighting use in a campus-wide effort to improve

“Lights Out” system layout



environmental sustainability at MIT,” Lanou says. “We strive to use MIT’s campus as a testing ground and learning laboratory for principles and practices that are widely applicable, and this student-led project has been a terrific demonstration of this in action.”

Next steps include exploring the possibility of expanding the Lights Out approach to additional MIT buildings; developing a more sophisticated and tailored feedback system incorporating more visually compelling messages; selective e-mailing to target heavy users; and making web-based data on lighting use available to the public. In the long term, the goal is to install automated lighting occupancy sensors in all campus buildings that shut off lights when rooms are unoccupied, eliminating the need for cameras.

“From our talking to our building occupant recruits in 16 and 56 and presenting this project to many people from all over campus and visitors from around the world, it seems that a lot of people do want to save energy by doing simple things like turning off lights,” Wang says. “But they need to be informed about what behaviors to adopt and what the impact of these behaviors is. They also need feedback on how to improve. Addressing these three points has become Closing the Loop’s approach to encouraging sustainable behavior.”

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By Deborah Halber, MITEI correspondent

Gaining visibility into buildings' real-time energy performance

Although energy use can account for up to 70% of an MIT building's operating cost, exactly where and why that consumption occurs is not obvious. And when a blip in a building's internal workings can lead to even higher costs, it helps to know what's going on, energy-wise, around the clock.

At MIT, Building 68, the biology building, has been the subject of close scrutiny since January. Called continuous commissioning, or data-based commissioning, this monitoring is an ongoing process to resolve building operating problems, improve comfort, and optimize energy use.

"Computer analysis of building data points out operating patterns that fall outside of a determined tolerance level and recommends the affected system components for study by an engineer," says Peter Cooper, manager of sustainability engineering and utility planning. "In this manner, large amounts of data can be evaluated and sifted to allow us to identify potential energy savings opportunities."

In the Building 68 pilot project, the payoff has been significant. In the current fiscal year, more than $3.1 million of the building's $4.5 million operating expense has been for steam, chilled water, and electricity. Based on the first three months of monitoring, annual savings from changes in Building 68 alone are projected to top $360,000.

"This is part of a larger-scale effort coordinated by the MIT Energy Initiative Campus Energy Task Force of greening the MIT campus. The project encompasses facility improvements, student projects, and individual measures by the entire MIT community to increase energy efficiency," says Leon R. Glicksman, professor of building technology and mechanical engineering and co-chair of the Campus Energy Task Force.

Steam consumption in MIT's Building 68

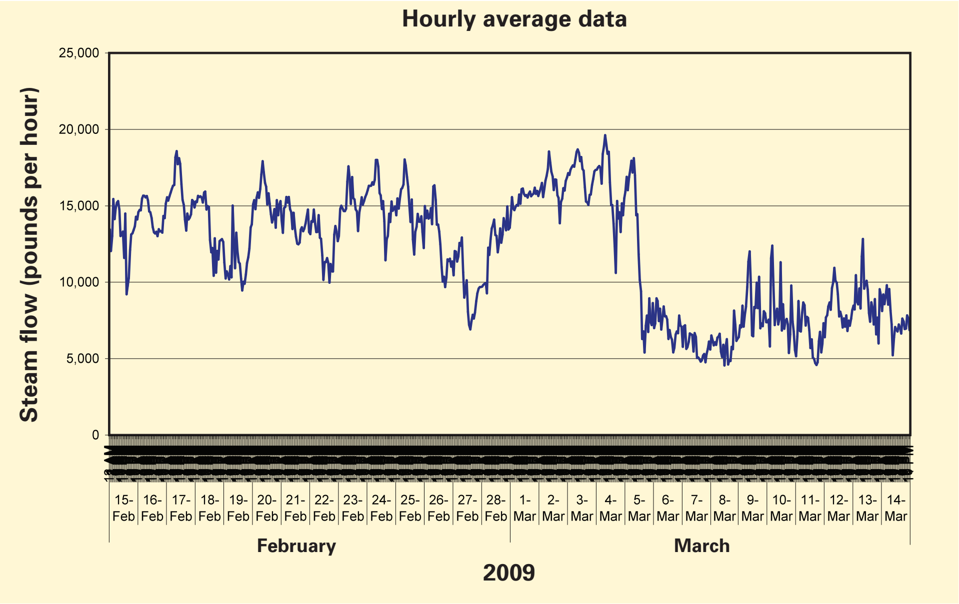

Chart: courtesy of MIT Department of Facilities

Detailed monitoring of the automation system in MIT's Building 68 showed that heating and cooling were occurring simultaneously in three of the large air-handling units. Programming changes to the building's automation system on March 5 reduced both steam and chilled water consumption immediately. The reduction in steam use is evident in the chart above. Based on data from the first three months, the annual savings from the reduction in both steam and chilled water use is projected to be more than $360,000.

"We plan to carefully monitor the energy savings as well as economic payback to inform future measures on campus and provide guidance for other organizations facing the same challenges," he says.

Running hot and cold

Building 68 keeps its laboratories up and running and its occupants comfortable with the help of seven air handlers, two heat exchangers, chilled and hot water pumps, fan coil units, and variable air volume boxes, which help make air-conditioning systems more efficient by regulating the amount of cooling targeted toward specific rooms or areas. All these components represent a lot of complexity, which translates into opportunities for things to go wrong—which is what happened sometime before March 5.

MIT had enlisted the help of Cimetrics, a Boston-based pioneer in building optimization, to install a system that delivers building data over the Internet. Thanks to Cimetrics' monitoring of key operating parameters—541 data points in the building's automation system are read and analyzed every 15 minutes—building operators could see that heating and cooling were occurring simultaneously in three of the large air-handling units.

Programming changes to the building's automation system fixed the simultaneous heating and cooling problem, Photo: David J. Conlon, MIT

Photo: Amanda Graham, MITEI

Left: MIT's Building 68, the biology building, where continuous commissioning led to adjustments in the building's automation system yielding significant energy and cost savings. Right: Typical large heating, ventilating, and air-conditioning equipment that is monitored, analyzed, and optimized by continuous commissioning.

leading to an immediate, dramatic drop in both steam and chilled water use. Repairs to valves and valve operators boosted the poor performance of a heat recovery system—also identified by the data monitoring—and Cooper predicts that setting back heating and cooling temperatures when the building is unoccupied will result in additional savings.

"As energy gets more expensive and retrofits get more complicated, building owners want to know just how their investment in HVAC or lighting controls is paying off in terms of lower operating costs and higher energy savings," says Walter E. Henry, MIT Department of Facilities' director of engineering. "So far, we have applied monitoring technology to Buildings 18, W35, E25, and most recently, 16 and 56. We plan to work our way through other lab buildings, which are the highest energy intensity and most complex of the Institute's buildings.

"We are also incorporating this capability into new construction—the new graduate residence NW35, the new Media Lab and Sloan buildings, the David H. Koch Institute for Integrated Cancer Research—as a performance verification tool during the warranty period and beyond," he says.

Assessing three months of Building 68's utility billing data led to a reduction of 5,047 pounds per hour of steam and 275,910 tons per hour of chilled water from April to June 2009 over the same period in 2008. "We will save more than $360,000 over 12 months if gas prices remain at the current level," Cooper says. "Building 68 was a continuous commissioning success, and we're looking forward to repeating this kind of success story around campus."

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By Deborah Halber, MITEI correspondent

MIT releases report on retrofitting coal-fired power plants for CO_2 capture

On June 23, 2009, in Washington, DC, Professor Ernest Moniz, director of the MIT Energy Initiative (MITEI) and former undersecretary of the US Department of Energy, unveiled a report on reducing carbon dioxide (CO_2) emissions from existing coal plants. The report, based on the findings of an MIT symposium on retrofitting coal-fired power plants, identifies possible next steps for the consideration of policy makers, industry, and others engaged in CO_2 emissions mitigation.

"There is no credible pathway toward prudent greenhouse gas stabilization targets without CO_2 emissions reduction from existing coal power plants. We urgently need technology options for these plants and policies that incentivize implementation," Moniz said. "We may not see a strong CO_2 price signal for many years. In the interim, we need a large, focused federal program to develop and demonstrate commercial-scale technologies."

The March 2009 symposium dealt with retrofitting of existing pulverized coal power plants for CO_2 emissions reduction, with a focus on post-combustion capture. The symposium included 54 subject matter experts from a range of stakeholder groups, including academia, government, public interest groups, and industry. Chatham House rules applied. Participants were provided three commissioned white papers on key issues in advance, and they also benefited from 14 additional papers submitted by symposium participants. They addressed a range of additional technology options for cutting CO_2 emissions, including:

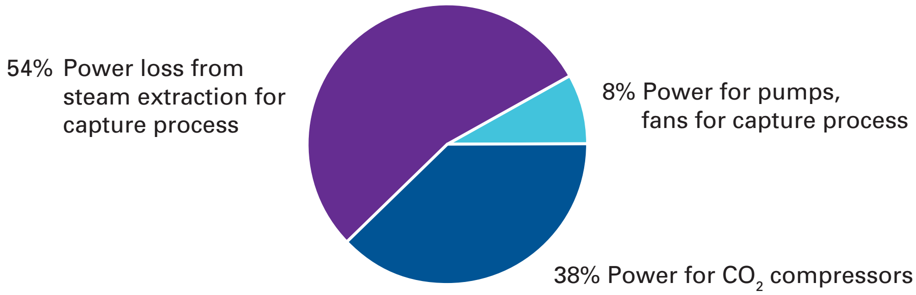
- efficiency retrofits
- co-firing of coal plants with low-carbon fuels
- rebuilding existing subcritical units to ultra-supercritical units with capture
- more extensive rebuilds such as oxy-combustion or integrated gasification combined cycle with CO_2 capture
- poly-generation
- repowering of existing boilers with alternative fuels such as biomass or natural gas

Moniz was joined at the announcement by Wayne Leonard, chairman and CEO of Entergy Corporation, who co-chaired the symposium. Leonard spoke about the core issue for existing plants, noting that they will continue to operate for decades, even as industry turns to carbon-free electric power-generating technologies. "Once built, coal plants are, in most cases, the cheapest source of base load power generation and will not be phased out absent very high CO_2 prices," Leonard said. "It's basic economics."

Key findings of the report are the following.

- Relatively large, high-efficiency coal plants already equipped with desulfurization and nitrogen oxide emissions controls are the best candidates for post-combustion capture retrofit. Such plants make up less than half of the existing fleet. However, specific retrofit projects must pass various site-specific screens, such as available space, increased water supply, and CO_2 off-take options. A fleet-wide, detailed inventory of plants and sites is urgently needed to determine which plants are suitable for retrofitting, rebuilding, or repowering or for partial CO_2 capture solutions tailored to the current plant configuration. This inventory should inform policy makers about the range of options for significant reduction of CO_2 emissions from operating coal plants in different climate policy scenarios.

Parasitic energy losses for CO_2 capture from typical coal power plant



The relative efficiency losses associated with post-combustion CO_2 capture from a typical coal power plant can be as high as 26%. A more specific breakdown of those losses—shown above—helps focus research to improve CO_2 capture efficiency.

- Research and development for existing coal plants should focus on cost reduction of post-combustion capture. This is essential if retrofits are to be affordable in developing countries. An expanded R&D program should also include efficiency upgrades, rebuilds, repowering, poly-generation, and co-firing with biomass. A component for research on CO_2 capture from natural gas power plants should be included. A robust US R&D effort with this scope requires about $1 billion per year for the next decade (not including support for commercial-scale demonstration).
- The federal government should dramatically expand the scale and scope for utility-scale commercial demonstration of coal plants with CO_2 capture, including demonstration of retrofit and rebuild options for existing coal power plants. New government management approaches with greater flexibility and new government funding approaches with greater certainty are a prerequisite for an effective program.
- The world cannot achieve significant reductions in CO_2 emissions, avoiding the most disruptive impacts of climate change, without commitments to reduce emissions from existing coal-fired power plants in the US and China. Bilateral approaches on climate change should be encouraged and supported as a matter of US policy. Joint RD&D programs between the US and China should be supported and funded.

To download copies of the summary, the full report, and related papers and presentations, please go to web.mit.edu/mitei/research/reports.html.

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Major MIT study examines the future of the electric grid

The **Future of the Electric Grid** *study described below is one in a series of interdisciplinary studies undertaken by MIT faculty to explore the contribution that different energy technologies could make to meet future US and global energy needs in a carbon-constrained world. Final reports are available for the 2003* MIT Future of Nuclear Power *study (web.mit.edu/nuclearpower/) and the 2007* MIT Future of Coal *study (web.mit.edu/coal/). Ongoing studies focus on solar energy, natural gas, and nuclear fuel cycles (see* Energy Futures, *autumn 2008, for more information).*

Most projections of desirable future energy systems in the United States and other developed nations involve an expanded role for electricity and therefore for the transmission and distribution functions of the electric grid. In the US, the capacity of today's grid will need to be dramatically expanded, not just to carry more electricity produced by conventional power plants but also to exploit wind and solar generation opportunities, some located far from load centers. New transmission facilities must be built, and current legal and regulatory regimes will almost certainly need to be changed to remove existing barriers to such construction.

As society relies more and more on electric power, ensuring grid reliability and security will become more important—but also more difficult, in part because of the growing role of wind and solar generating systems, the output of which cannot be precisely controlled or forecast to sufficiently inform grid managers. In addition, demand on the grid will change as energy-related technologies advance. Electrification of the transportation sector, for instance, would alter the characteristics of system loads and impose new requirements on the grid.

Simply expanding the capacity of the current grid will not be adequate. Deployment of a more sophisticated and powerful communication and control system—both within the grid and between the grid and key end users such as firms, households, and even individual appliances—will be critical if we are to maintain high reliability and security while making more intensive use of renewable generation.

In September 2009, MIT launched a faculty-led, interdisciplinary study that will examine the substantial issues surrounding the national initiative to enhance the functionality and reliability of the electric grid. The Future of the Electric Grid study will also explore the contribution that an enhanced electric grid can make to meet the growing and changing energy needs of the nation in an efficient and environmentally responsible manner.

The study will provide an objective assessment of the potential benefits of grid expansion as well as of extensive deployment of new and emerging technologies and standards relating to a "smart grid"—a modernized, efficient grid controlled by Information Age technologies. Indeed, a principal goal is to clarify the technical, administrative, regulatory, financial, and societal opportunities and challenges that are presented by the many innovations being proposed under the smart grid banner to optimize our future electrical network and its operation.

The study will also examine regulatory and other policies that could help improve various dimensions of grid performance and accelerate deployment of new and emerging technologies. The role of regional transmission operators and wholesale electricity markets will be addressed. While the study will focus on the United States, it will also examine issues faced by other nations and the lessons their experiences can offer.

Based on its findings, the study will make recommendations about research, development, and demonstration strategies, government policies, and industry actions.

The Future of the Electric Grid study is co-chaired by John Kassakian, professor of electrical engineering and computer science, and Richard Schmalensee, the Howard W. Johnson Professor of Economics and Management and director of the MIT Center for Energy and Environmental Policy Research. The study team includes faculty with expertise in power systems, power electronics, information technology, economics, and energy and environmental policy. A team of student research assistants—some of them uncompensated volunteers—is already hard at work.

The electric grid study has a distinguished outside advisory committee chaired by the Hon. J. Bennett Johnston, former chairman of the Senate Energy and Natural Resources Committee. It is anticipated that this study, like the MIT nuclear and coal studies, will have a significant impact on public policies and private decisions.

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Future of the Electric Grid study team

Khurram Afridi, Electrical Engineering and Computer Science (visiting)

Jerrold M. Grochow, consultant and (retired) MIT vice president for Information Services and Technology

William Hogan, Harvard Kennedy School of Government

Henry Jacoby, Sloan School of Management

John Kassakian, Electrical Engineering and Computer Science, co-chair

James Kirtley, Electrical Engineering and Computer Science

Ignacio Pérez-Arriaga, Engineering Systems Division and Center for Energy and Environmental Policy Research (visiting)

David Perreault, Electrical Engineering and Computer Science

Nancy Rose, Economics

Richard Schmalensee, Sloan School of Management and Department of Economics, co-chair

Gerald Wilson, Electrical Engineering and Computer Science and Mechanical Engineering

Martin Fellows wade into salt marsh ecology

Past and present Martin Fellows visited Thompson Island as part of a September retreat. Students pursuing a wide range of environmental, energy, and sustainability research topics came together to learn about (and get knee deep in!) the Boston Harbor Island's pristine and restored salt marshes. The annual event provides an opportunity for the fellows to share ideas and meet colleagues across disciplinary lines.

Ranger Jennifer Bourque (right) examines a sample of tiny shrimp with Malima Wolf (left), a 2008 Martin Fellow in mechanical engineering, and Carlijn Mulder, a 2009 Martin Fellow in electrical engineering and computer science.

Sara Lincoln, a 2009 Martin Fellow in earth, atmospheric, and planetary sciences, and Casper Martin of the Martin Family Foundation cross over the salt marsh on a monkey bridge in order to protect the land at the water's edge.

Cy Chan (left), a 2009 Martin Fellow in electrical engineering and computer science, and Jennifer Hsiaw (center), a graduate student in civil and environmental engineering, inspect native hermit crabs with Ranger Anna Hines.

Alejandra Menchaca (left), a 2009 Martin Fellow in mechanical engineering, and Katherine Potter, a 2008 Martin Fellow in earth, atmospheric, and planetary sciences, pull a net through Thompson Island's pristine salt marsh to collect samples of aquatic life, including crabs, shrimp, and several species of fish.

Joseph Shapiro, a 2009 Martin Fellow in economics, checks his net for the Asian shore crab, an invasive species in the salt marsh.

Elise Li, a 2008 Martin Fellow in chemistry, prepares to take a picture of the Boston skyline as the Outward Bound Ferry takes retreat attendees to Thompson Island.

Photos: Justin Knight

UROP shines light on energy in rural Africa

MIT junior Peter Lu got more than he bargained for during his summer research project in Lesotho, a mountainous country surrounded by South Africa. Installing a new solar-thermal system for a rural medical clinic involved not only his engineering skills but also some very low-tech work: digging holes and pouring cement to build the system's infrastructure. And that was after spending 36 hours en route by plane and another half day driving into the mountains to get there.

"There was a lot of physical work. But I'm a gym nut," says Lu, a mechanical engineering major. "And the mountains were beautiful." Lu spent the first six weeks of his Undergraduate Research Opportunities Program (UROP) project at MIT performing design reviews of the system's solar power collector and identifying areas where the mechanical ruggedness could be improved. Then, in mid-July he traveled to Lesotho, where he spent another six weeks helping implement the system and training local people on techniques to make the system independently.

Overseeing his work was Matthew Orosz, a PhD candidate in civil and environmental engineering and a recent Martin Family Society of Fellows for Sustainability awardee. As part of that fellowship, Orosz was allowed a UROP student.

"He's outgoing and enthusiastic," Orosz says of Lu. "He did all the work that needed to get done. We worked on various parts of the machine, cut steel, welded, figured out dimensions from a computer-aided design drawing, set up jigs, worked on machine tools, and dug holes for foundations. It was a multidisciplinary project."

UROP student Peter Lu '11 pours cement with mechanical engineers Motlatsi Sekhesa (center) and Tumelo Makhetha, both of whom are with STG International, a nonprofit company formed by MIT PhD student Matthew Orosz.

Lu first heard about the Lesotho project a couple years ago when he read about it on the MIT Energy Initiative (MITEI) website (web.mit.edu/mitei), and then contacted Orosz. Lu's previous UROP, during his sophomore year, focused on improving the thermodynamic efficiency of the solar-thermal system's power-generating heat engines. He continued work on the system through the summer UROP, which was sponsored by the Martin fellowship.

"MIT is riding a new wave of energy research," says Lu. "This project is interesting to me because the systems are mechanical, which has to do with classes I am taking now. And it involves the interaction of energy and the developing world." According to the *CIA World Factbook,* almost 49% of Lesotho's population lives below the poverty level. The country is at a high altitude and gets more than 300 days of sun per year, making it an ideal setting for solar-thermal technology.

Amanda Graham, director of the MITEI Education Office, notes that Lu and Orosz's work in Lesotho demonstrates the potential impact of cross-disciplinary, applied research in energy and the environment. "This Martin Family UROP is a powerful example of how teaming an undergrad with a PhD student in the field can enrich the educational experience while improving the quality of life for others," says Graham, who administers the Martin Fellowship Program for MITEI's Laboratory for Energy and the Environment.

Lu worked side-by-side with Orosz, as well as local and visiting engineers. "Matt has been working on the project for six years. He has an immense technical repertoire and was a fantastic guide," says Lu. "And the local engineers were very skilled. I was thrilled to have such an inspiring crew of individuals to work with." The project involved a local school and engineers in the Pharmong region of Lesotho.

Many of the parts for the system are makeshift. A former Peace Corps volunteer in Lesotho, Orosz got the idea to use a parabolic trough for the solar-thermal system after seeing how it could simultaneously bake 10 loaves of bread for a local community. The parabolic trough focuses sunlight onto a pipe containing a thermal absorption fluid that circulates through a heat-transfer engine where it turns a refrigerant into vapor. The vapor drives a positive displacement expander, which in turn causes a generator to produce thermal and electrical energy. The solar collector array for the medical clinic measures 70 square meters. Orosz said

Photos: courtesy of Peter Lu '11, MIT

Mechanical engineer Tumelo Maketha (left) and MIT graduate student Matthew Orosz in front of the solar collector. Orosz got the idea to use a parabolic trough—which also is ideal for baking 10 loaves of bread simultaneously—during his work in the Peace Corps.

the cogeneration design can recover some of the waste heat, so more of the sun's energy is captured.

Orosz started engineering and design work on the system in 2004 during a D-Lab class with Amy Smith, a senior lecturer in mechanical engineering. "It was the first opportunity to apply my ideas to a prototype," he said. He went to Lesotho during Independent Activities Period (IAP) in January 2005, and returned the next year as well. In 2006 he won a $129,500 World Bank grant for the project. Much of the system was built using ordinary auto parts and plumbing supplies that are available locally and are easy to maintain.

"We developed some components and repurposed others, such as running an air conditioner or compressor backwards," says Orosz. He adds that the system is not a complete prototype and that it still is being tested at MIT. He hopes to return to Lesotho with colleagues during IAP in 2010 to finish the installation. The system will produce around 3 kilowatts of electricity for the rural clinic.

"I gained valuable experience performing engineering work in the absence of mechanized tools and discovered a new appreciation for first-world public infrastructure," Lu wrote in his post-UROP report. "I learned to plan for extended supply shortages and delivery delays, and to synchronize my daily schedule with the sun."

Lu says he got everything he wanted from the trip. "This plays into my interests in mechanical applications for the energy sector. I'd love to continue working with solar-thermal technology, especially on an industrial scale," he says. Lu hopes to work with multi-megawatt solar farms in the future. But he's also leaving the door open to graduate studies. "Having seen what Matt can do—managing both a doctorate degree and a project like this—is inspiring."

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By Lori Fortig, MITEI correspondent

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 54 seed grant projects across the campus as well as fellowships for 87 graduate students in 20 MIT departments and divisions.

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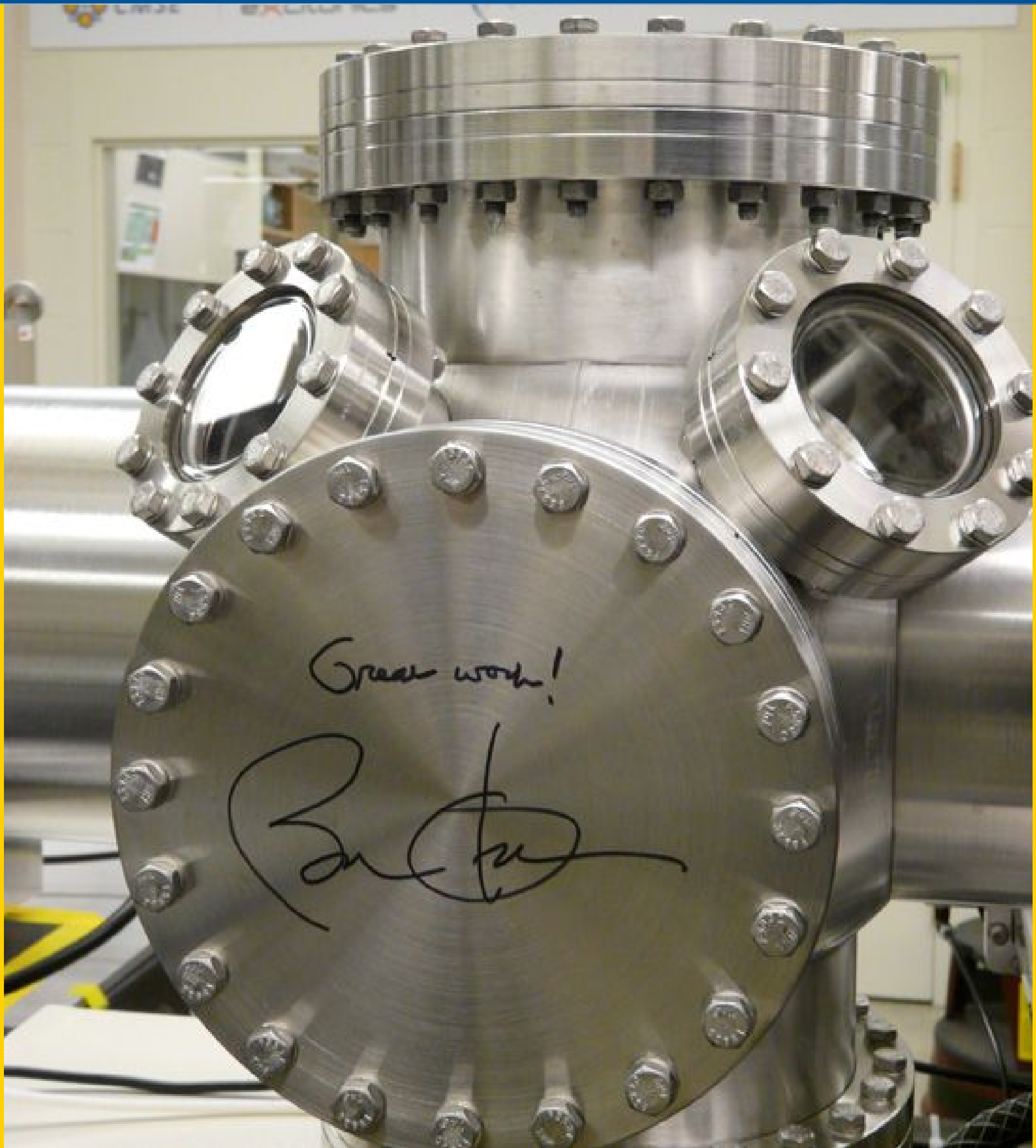

Photo: Geoffrey Supran G, MIT

On October 23, President Barack Obama delivered a major address on clean energy at MIT. But first he toured several research laboratories where MIT faculty briefed him on promising research projects in renewable energy, storage, and efficiency. While in Professor Vladimir Bulović's lab, he signed a piece of equipment along with his assessment of MIT's energy research: "Great work!" **See page 4 for more about his visit.**