Energy Futures

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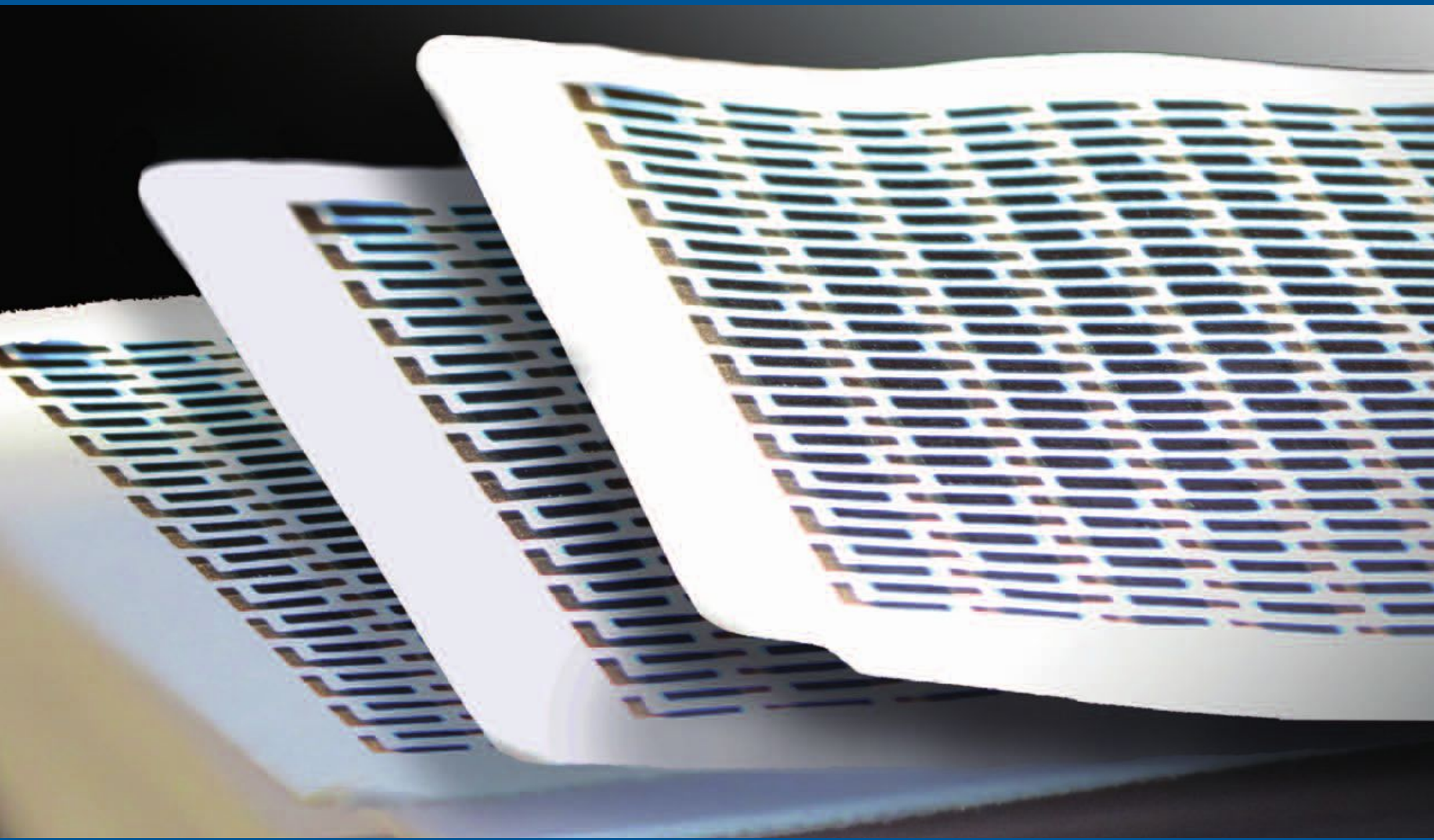
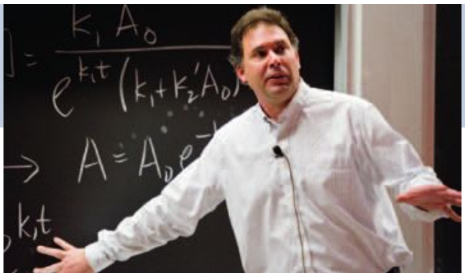
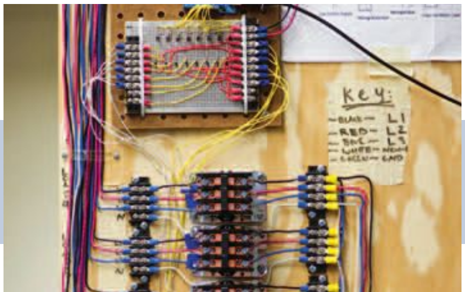


Solar cells printed on paper: Flexible, lightweight, durable

IN THIS ISSUE





Energy Futures

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A LETTER FROM MIT PRESIDENT SUSAN HOCKFIELD

A MESSAGE FROM GEORGE P. SHULTZ

RESEARCH REPORTS

EDUCATION

EDUCATION: FOCUS ON FACULTY

CAMPUS ENERGY ACTIVITIES

OUTREACH

LFEE • Laboratory for Energy and the Environment

MITEI MEMBERS

MITEI at five years, looking forward

Dear Friends,

In the fall of 2006, we launched the MIT Energy Initiative (MITEI)—committing the Institute's expertise and capabilities to help meet the world's energy challenges through research, education, campus energy management, and outreach. As we celebrate the Initiative's fifth anniversary, it seems appropriate to reflect on MITEI's accomplishments, but as importantly, also on its future opportunities to make meaningful contributions to energy sustainability in a rapidly changing energy marketplace.

By design, MITEI's research, analysis, and education activities have focused both on innovations for conventional energy sources and on new technologies that could help transform global energy systems. This dual, adaptive approach has been essential to MITEI's success, promoting the development of high-impact energy technology options in a persistently evolving landscape. Consider how the global energy marketplace has changed in the last five years alone:

- **Economy**
  In 2006, global energy demand was soaring. It has now stagnated, as many regions and nations grapple with a severe economic downturn. And yet oil prices remain stubbornly high for a slow economy, underscoring both concerns about the security of oil supply and the need to develop affordable, scalable alternative transportation fuels.

  The state of the economy has also intensified interest in boosting economic productivity. Research to improve energy efficiency, increase affordable energy supplies, and develop advanced "green tech" manufacturing technologies could help enhance productivity and competitiveness.

- **Policy**
  In the early days of MITEI, we were hopeful that the United States and other key global players would take concrete, concerted steps to reduce greenhouse gas emissions. But progress under the Kyoto Protocol appears to be stalled, and climate legislation failed to pass the US Congress. This lack of consensus argues for greater focus on developing low-carbon technologies that meet multiple policy objectives, not only greenhouse gas mitigation.

- **Research funding**
  The US economic stimulus package funded extensive energy research; now this funding has ended, and the US economic malaise has called into question investments in R&D. The changed economic environment has created uncertainty about funding to drive energy innovation and clean technology deployment.

- **Renewable energy realities**
  Renewable energy technologies now confront the realities of economic stress, high costs, and growing political opposition to mandates or subsidies. Whether through new materials, economies of scale, or new distribution methods, renewable energy research must focus, above all, on cost reduction.

- **Conventional energy realities**
  In 2006, North America was thought to be running out of natural gas. The United States is now the No. 1 gas producer in the world, in large part due to the development of affordable shale gas. Recent assessments suggest that global shale reserves could significantly alter the geopolitics of gas. Understanding this changing dynamic is an essential avenue of analysis; the MITEI-sponsored Future of Natural Gas study has provided an influential voice in that discussion.

  On the other hand, repercussions from the Macondo oil spill are still being felt, and, in the wake of Fukushima, the long-term future of nuclear energy is uncertain. Conventional fuels, however, will be used for decades to come. Mitigating their environmental impacts has been—and should continue to be—a key research focus area at MITEI.

Although the energy landscape has changed dramatically in the last five years, MITEI has maintained remarkable momentum, through a consistent but inherently flexible strategy.

- **Partnerships with industry**
  From the start, MITEI committed to meaningful impacts on the energy marketplace. The enormous capital investments of energy industries position them to help us understand global energy markets, so MITEI sought solid, long-term strategic industry partnerships. For their part, industry players quickly saw how much they had to gain from MIT's enormous research capabilities and infrastructure, capacity for creativity, and track record in developing game-changing technologies and transferring them into the marketplace.

  This industry-linked approach has proved very successful. MITEI now has more than 60 members spanning the innovation value chain, 24 of


Photo: Dominick Reuter

which sponsor research or analysis, and all of which share our commitment to energy innovation, education, and technically grounded policy analysis. MITEI's members support projects in almost all critical areas of energy research, and in all five MIT Schools. Significant areas of focus include advanced solar, energy storage, hydrocarbons, nanotechnology, modeling and simulation of complex systems, and many more. Almost 300 MIT faculty and senior researchers are now engaged in this research—a powerful concentration of intellect, creativity, vision, and commitment.

- **Growing student opportunities**
  To develop the next generation of energy and environmental leaders, MITEI members and sponsors have supported almost 200 graduate fellows in energy in the last five years. MITEI, its members, and other MITEI supporters have also funded a significant number of "UROPs"—students using MIT's Undergraduate Research Opportunities Program to take part in front-line, faculty-directed energy research.

  Reflecting MIT's interest in shaping new energy leaders, just over two years ago MITEI launched the Energy Studies Minor, which allows students to balance their intense focus on a major area of study, from chemistry to mechanical engineering to economics, with an informed appreciation of the multidisciplinary questions that define the world of energy. The minor—already one of the largest at MIT—is attracting more and more students each year, all focused on meeting the world's energy challenges. With generous philanthropic support, we continue to develop, refine, and add to energy course offerings.

  Finally, MITEI is working to establish endowed chairs to attract new senior energy faculty to MIT. This issue of *Energy Futures* includes a profile of Christopher R. Knittel, holder of the new William Barton Rogers Chair in Energy Economics (see page 32).

- **Campus energy efficiency**
  Beyond research and education, MITEI's Campus Energy Task Force (CETF) has helped MIT "walk the talk," to use energy on campus wisely. New conservation and efficiency measures have already saved the Institute millions in energy costs. The CETF is also turning the campus into a learning laboratory for energy conservation and efficiency by supporting a range of student projects—from dorm electricity competitions, to waste heat recovery, to programs that promote energy-saving behavior.

- **Policy outreach**
  Finally, MITEI has advanced a series of comprehensive, multidisciplinary studies, led by MIT faculty: the Future of Nuclear Power; the Future of Coal; the Future of the Nuclear Fuel Cycle; and the Future of Natural Gas. Designed to provide technically grounded analyses to inform strategies for achieving a clean energy future, these multiyear studies have already had significant impact, illustrated most recently when the US Senate Committee on Energy and Natural Resources held a hearing titled *The MIT Future of Natural Gas Study.* Additional Future of… studies are in the works, on the electric grid and solar energy. These studies represent only one of MITEI's outreach efforts, which also include colloquia, a symposium series, a seminar series, and a range of activities for MITEI members, students, faculty, staff, and the public at large.

The Future of…MITEI

Since 2006, MITEI's work has been far-reaching, influential, and inspiring. To prepare for the unpredictable challenges and opportunities of the next five years, MITEI is seeking input from the MIT community and other supporters on the best ways to advance the research, education, outreach, and policy analyses we need to help transform the world's energy future. This continued engagement will ensure that MITEI remains positioned to face the energy challenges ahead.

Sincerely,

Susan Hockfield
MIT President

November 2011

Reflections on US energy challenges

Over the past four decades, the United States has been on an energy roller coaster that has landed us, unnecessarily, in a place that is dangerous to our economy, our national security, and our climate.

In 1959, President Eisenhower, concerned that overdependence on imported oil would be a threat to our national security, imposed a quota of 20% of consumption on imports. The Arab Oil Embargo in 1973 made his case. However, today we import 50% of the oil we use.

And causes for concern have increased. The economic impact of dependence on foreign oil has always been apparent as economic recessions have invariably followed significant oil price increases. President Eisenhower's concern about national security has been greatly heightened in recent times because high prices have funneled large flows of revenue to regimes that do not wish us well. Further, our military clearly needs more energy produced at the point of use.

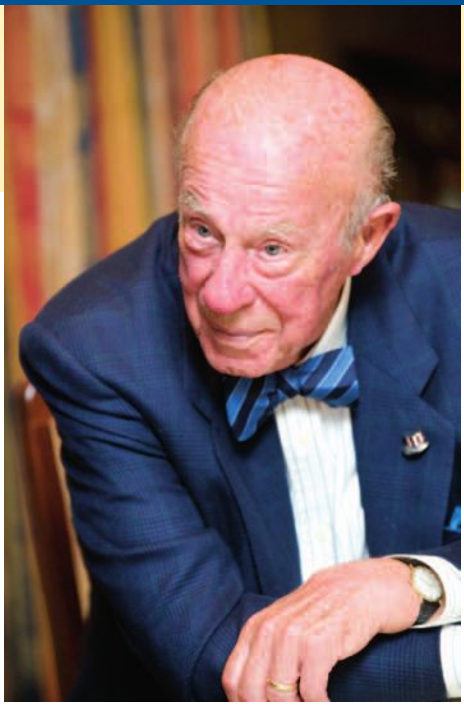
The issue of climate change has been added to our list of concerns. Recognition of the environmental risks created by greenhouse gases has heightened apprehensions about our heavy reliance on oil. And it has brought concerns about the use of coal, which produces much of our electricity, into the policy mix.

Now we have another chance to get it right—to construct an energy policy that meets these issues in a comprehensive way.

Along multiple dimensions, the energy industry is almost unfathomably large. Reasonable estimates indicate that demand for energy may well grow by about 35% or so by 2030. Scalability, an important attribute for any new energy development, can apply to something big, but also to something small that is readily replicable. Over time, significant change is clearly possible. Energy intensity—energy consumed per dollar of GDP—has declined by about 1% per year over the past 200 years, but in response to the oil-price shocks of the 1970s, the rate of decline in energy intensity has nearly tripled.

An effective effort to reduce carbon dioxide (CO_2) emissions or reduce revenues to oil-producing countries must include the developing world. The challenge is that China, India, and other developing countries see limits on CO_2 emissions as limits on economic growth, and, understandably, they will not accept such limits. Efforts to reduce oil consumption and CO_2 emissions must be cost-effective if they are to be adopted in the developing world. Over the long run, technology can have a great impact. Cost-effective technology will naturally be adopted by market forces, without government subsidy, on a global basis. Research into cost-effective conservation measures and clean energy therefore has the potential for significant payoffs.

Energy is a large and critical component of the economy. Getting energy policy wrong and adopting unnecessarily costly, economically inefficient policies will have a significant negative impact on our standard of living. This means that continued efforts to find and develop new sources of oil and gas are essential. And, insofar as the United States is concerned, efforts should be made to develop our own reserves, consistent with proper environmental standards.



Photos: Justin Knight

A native of New York, George P. Shultz graduated from Princeton University in 1942. After serving in the Marine Corps (1942–45), he earned a PhD in industrial economics at MIT. Shultz taught at MIT and the University of Chicago Graduate School of Business, where he became dean in 1962. He was appointed Secretary of Labor in 1969, director of the Office of Management and Budget in 1970, and Secretary of the Treasury in 1972. From 1974 to 1982, he was president of Bechtel Group, Inc. Shultz served as chairman of the President's Economic Policy Advisory Board (1981–82) and Secretary of State (1982–89). He is chairman of the J.P. Morgan Chase International Council, Advisory Council chair of the Precourt Energy Efficiency Center at Stanford University, chairman of the MIT Energy Initiative External Advisory Board, and chairman of the Energy Task Force at the Hoover Institution, Stanford University. Since 1989, he has been a Distinguished Fellow at the Hoover Institution.

Policy options

The United States should use policies to set conditions for the market that maximize the possibility of desirable results. The marketplace has long demonstrated its superior ability to sort out low-cost, high-quality providers of energy and other commodities, so policies should be designed to promote the operation of the market and fight against the effectiveness of anticompetitive forces such as OPEC.

At the same time, the marketplace by itself does not take into account important considerations such as the costs of pollution and climate change. These costs should be assessed in such a way that the market recognizes them. The problems of national security that arise from unreliable energy sources are an externality to the market, so ways must be devised to deal with these problems. Also, the market does not usually support basic research because market participants cannot firmly capture the benefits of the research. Commercial development, of course, is another matter. So non-market sources of support for basic research are needed, and the subtleties of interaction between research and development should be understood—and fruitful means identified—to ease that transition.

Two of these policy areas, supporting basic research and establishing a price for carbon, require more detailed consideration.

Supporting basic research on energy generously and on a sustained basis

An essential attribute when considering energy issues is the ability to think long and to think creatively. We need an energy policy that capitalizes on the traditional American strengths of ingenuity and innovation. Inventive juices, once released, will yield important contributions to solving our energy issues.

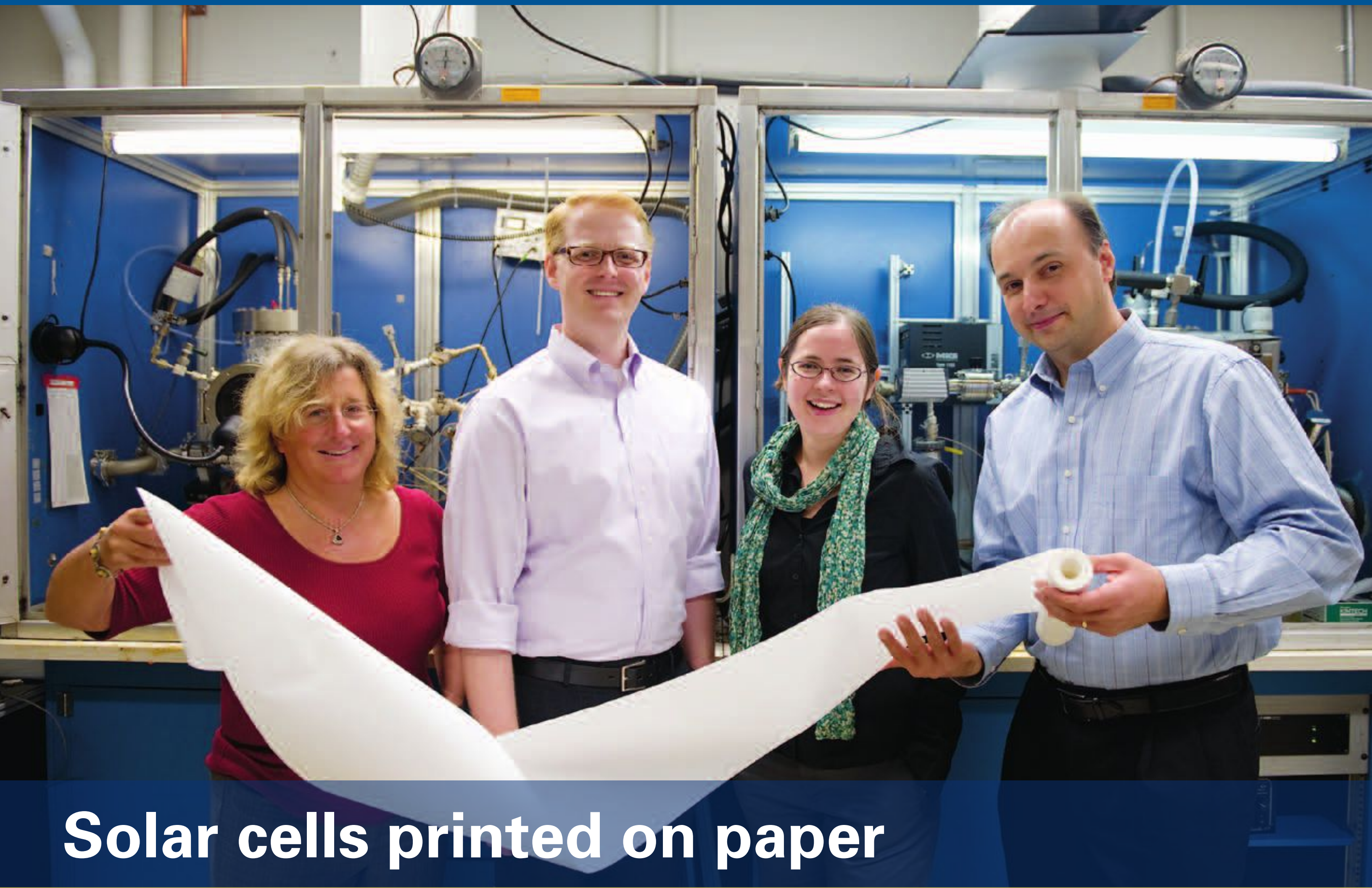
Immediate results are desirable wherever possible, but real game-changers will take some time to emerge and develop. They will most likely result from a heavy emphasis on basic scientific research related to energy.

Government and private foundations need to take primary responsibility for generous and sustained funding of basic research, which is probably the most important undertaking of any prospective energy policy. Recent efforts by major corporations that have joined together to sponsor basic research demonstrate that they understand its fundamental importance. Sustained corporate, foundation, and government support will be an essential source of the game-changing innovations that almost surely lie in our future. MITEI stands as a key effort in the search for game-changers. During MITEI's first five years, I have had the privilege of seeing scientists and engineers at MIT make dramatic progress. The work must continue so that we can get off the roller coaster and find ways to support our national security, economic, and environmental objectives.

George P. Shultz
Chairman
MITEI External Advisory Board

September 26, 2011

Above, from left: George P. Shultz, chair of the MITEI External Advisory Board (EAB); MIT President Susan Hockfield; Jeffrey Immelt, chairman and CEO of GE; and Ernest Moniz, director of MITEI. Immelt, who is now chairman of the President's Council on Jobs and Competitiveness, addressed the EAB and MIT faculty and administration in fall 2009. Below: Shultz with Angela Belcher, the W.M. Keck Professor of Energy in the Departments of Materials Science and Engineering and Biological Engineering.



Solar cells printed on paper

Fold them, ship them, install them with ease

Left to right: Professor Karen Gleason, graduate students Miles Barr and Jill Rowehl, and Professor Vladimir Bulović, working with others at MIT, have developed methods of depositing photovoltaic (PV) cells on sheets of ordinary paper and other inexpensive, lightweight, flexible materials. Inside the vacuum chambers shown behind them, they use a novel process to "vapor print" anodes that are integrally linked to the surface of the paper. In another lab, they use evaporative methods to deposit the remaining layers of the PV cells, producing solar arrays that can—even when folded—power small electronic devices.
Photo: Stuart Darsch

Imagine a future in which solar cells are everywhere around you—on your window shades, in your laptop cover, in your clothing, perhaps even on a folded slip of paper that you carry in your pocket and take out when you want to charge your cell phone or other electronic gadget.

That's the future that several MIT researchers envision. Using a novel process involving moderate temperatures and no liquids, they've printed photovoltaic (PV) cells on tissue paper, printer paper, newsprint, textiles, and even plastic food wrap. They've made solar devices that are low-cost, lightweight, flexible, and durable—features that make them ideal not only for integrating into consumer products but also for shipping to remote regions of the world where energy demand is growing rapidly and there's no power grid in sight.

For PVs to make a real difference to our energy future, they need to pervade people's lives worldwide. But today's PVs are typically fragile and must be moved with care and installed by trained experts to avoid damage. More robust PVs have been made on flexible materials such as plastic, but thus far they have not been entirely successful. Problems have stemmed largely from the anode (the positive electrode), which has a tendency to crack or lift off when the surface it's mounted on is bent. If PVs are to be manufactured and used on a large commercial scale, they must be made on lightweight, flexible materials with anodes that adhere under the most extreme stress—and that are composed of common, inexpensive substances.

Anodes with those features have now been fabricated by Karen K. Gleason, the Alexander and I. Michael Kasser Professor of Chemical Engineering, and her colleague Vladimir Bulović, professor of electrical engineering, with their "Paper PV Team": graduate students Miles C. Barr, Jill A. Rowehl, Jingjing Xu, and Annie Wang; postdoctoral associate Richard R. Lunt; and undergraduate Christopher M. Boyce. The work takes place in the Eni-MIT Solar Frontiers Center, which is co-directed by Bulović and funded by the Italian oil and gas company Eni S.p.A.

Key to their success is a process called oxidative chemical vapor deposition, or oCVD. Invented by Gleason, oCVD is designed especially for making thin films of organic polymers—carbon-containing molecules that are composed of repeating structural units and offer desirable traits including low cost, good electrical conductivity, and good mechanical properties that allow them to be flexed, stretched, and even folded.

The oCVD process is based on conventional CVD, a well-known method of depositing a thin coating of one material on the surface of another (the "substrate"). It involves heating up reactant gases and the substrate in a furnace until the former react and deposit on the latter. But the temperatures and other operating conditions required for CVD are too harsh to use with the organic materials of interest to Gleason. Adding the oxidant and carefully selecting the correct starting materials enable oCVD to operate at "gentler" conditions inside a vacuum chamber.

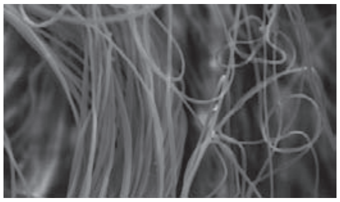
In addition, the oCVD process is completely dry—no liquids allowed. It therefore provides a new capability for making polymers. "Thousands of people synthesize polymers in solution," says Gleason. "We don't really want to compete with them. Instead, we want to do things they can't do"—including making robust anodes out of polymers composed entirely of earth-abundant elements such as carbon, hydrogen, oxygen, and sulfur.

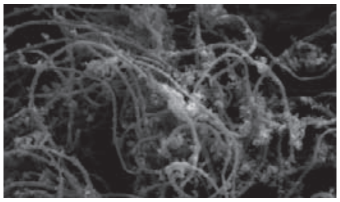
Three processes in one

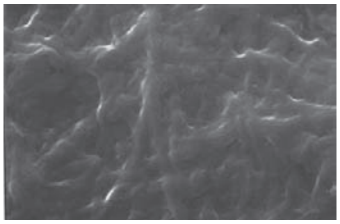
To make their anodes using oCVD, Gleason and her research group start with two reactants: iron chloride, the oxidizing agent, and ethylenedioxythiophene (EDOT), the monomer. The EDOT molecules are the basic building blocks that link together to form long chains of the polymer known as PEDOT.

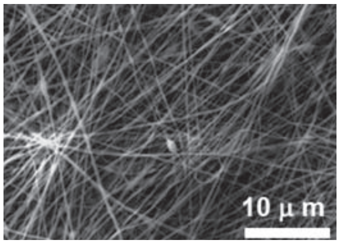
The researchers first prepare the selected substrate by placing on it a

Depositing thin films on fiber mat


Uncoated


Solution


Evaporation



oCVD

Images courtesy of the Gleason Lab

A comparison of three methods of depositing thin films on fiber mat. Top image: The uncoated mat, with its complex fiber structure clearly visible. Second image down: A liquid-based process produces irregular coverage of the fibers. Third image: An evaporation process creates a coating that covers over the fibers. Fourth image: MIT's oxidative chemical vapor deposition (oCVD) process yields a thin film that is "conformal," with the individual fibers still visible. Only the oCVD film will not change the structure, flexibility, or other characteristics of the underlying material.

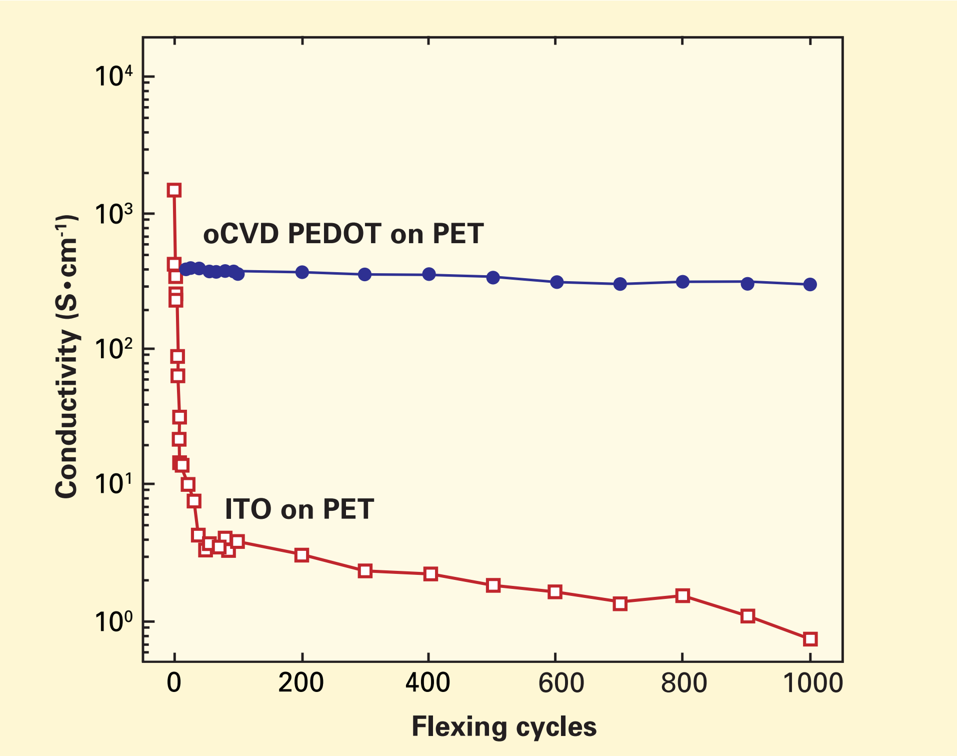
physical mask that can be pulled off to leave the desired pattern. (Think of using stencils to paint a strip of flowers on the wall of a room.) They then spray their two reactants, both in vapor form, onto the surface of the substrate. Three things happen at once. When the iron chloride and EDOT meet on the surface, they react to form PEDOT. At the same time, they form a thin film. And because of the presence of the mask, the film is deposited in the pattern needed to act as an anode.

"If we were working with a solution, we'd do those steps one at a time," says Gleason. "But we can do all of them at the same time—synthesis, film growth, and patterning all in one step. So that gives us three-for-one. We call it vapor printing."

Advantages of vapor printing

The remarkable features of the vapor-printed anodes—including their flexibility and robustness—can be traced to details of the oCVD process. Most notably, oCVD produces an unusually tight adherence between the deposited material and the substrate. The images on page 7 show the results of using three methods of depositing thin films on fiber mat. The first image shows the uncoated mat, with its complex fiber structure. The coating in the second image, created using a liquid-based process, is irregular, with blobs in some areas and no coverage in others. The one in the third image, made with an evaporation process, covers the surface such that individual fibers are no longer distinguishable. The final image shows the outcome using oCVD: a thin film that conforms to the surface so that the individual fibers of the mat are still clearly visible.

Effect of flexing on electrode conductivity



A test of how flexing affects the conductivity of two sample electrodes. One electrode was made by MIT researchers using oxidative chemical vapor deposition (oCVD) of a polymer known as PEDOT. The other is a commercially produced electrode made of indium tin oxide (ITO). The conductivity of the conventional ITO electrode starts out somewhat higher than that of the oCVD electrode, but within the first few flexing cycles it drops dramatically. In contrast, the oCVD electrode displays essentially no loss in conductivity from the first to the 1,000th flexing cycle.

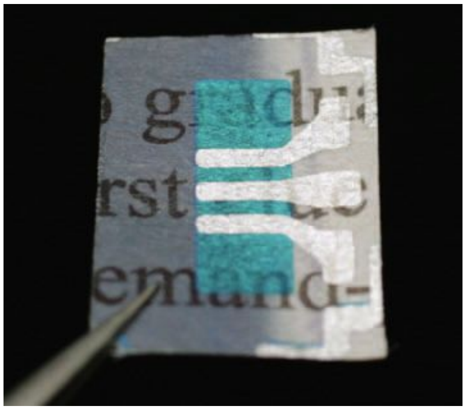
"With oCVD, the deposited material follows the geometry of the substrate," says Gleason. "It's like shrink-wrapping each individual fiber." Thus, with oCVD, an anode can be created on virtually any substrate—even the most fragile paper—without degrading its structure, creating defects, or altering its flexibility or other characteristics.

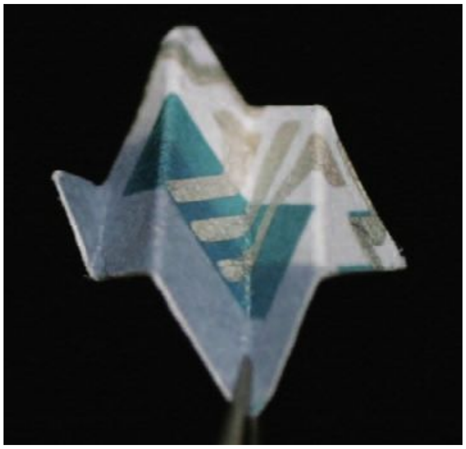
Better still, the deposited film is integrally linked to the surface of the substrate. In oCVD, the oxidant "activates" the surface, creating reactive sites where the monomers can attach—just as they attach to one another during growth of the polymer chains. The polymer chains are therefore "grafted" to the surface, a bit like hairs growing up out of their roots. In contrast, polymer chains that are not grafted lie in a loose jumble on the substrate.

Torture tests

To demonstrate the strength of the adhesion, the researchers performed "torture tests" of samples with grafted and ungrafted coatings. In one test, they immersed the coated samples in an ultrasound bath—an aggressive environment similar to boiling water. After two hours, the grafted coating was still attached, while the ungrafted one had let go. In another test, they used a stencil to create a pattern on two samples. When they lifted the stencil off the grafted sample, the pattern remained intact, with distinct edges. In contrast, with the ungrafted sample, large sections of the coating lifted off with the stencil so that no discernible pattern remained.

Newsprint and copy paper





These photos show single PV cells deposited on newsprint (top) and on copy paper (bottom). The dark gray area is the anode; blue is the photoactive layer; and silver is the cathode coming from the other side. In the top sample, the text of the newspaper is still visible—undisturbed by the dry deposition of the PV materials. The bottom sample is folded, but it still functions.

Even more telling were experiments focusing on flexibility and performance. These tests involved two samples: one a PEDOT electrode prepared using oCVD and the other a commercially produced indium tin oxide (ITO) electrode, both deposited on PET (a thinned-down version of the plastic used in soda bottles). The figure on page 8 shows conductivity measured in the two electrodes as they underwent 1,000 flexing "cycles." The results are striking. The conductivity of the conventional ITO electrode starts out somewhat higher than that of the oCVD electrode, but within the first few flexing cycles, it drops dramatically. In contrast, the oCVD electrode displays essentially no loss in conductivity from the first to the 1,000th flexing cycle.

"A lot of people make electronics on flexible substrates, but then they don't actually flex them," says Gleason. "We flex and fold our samples hundreds of times, and there's essentially no change in their performance."

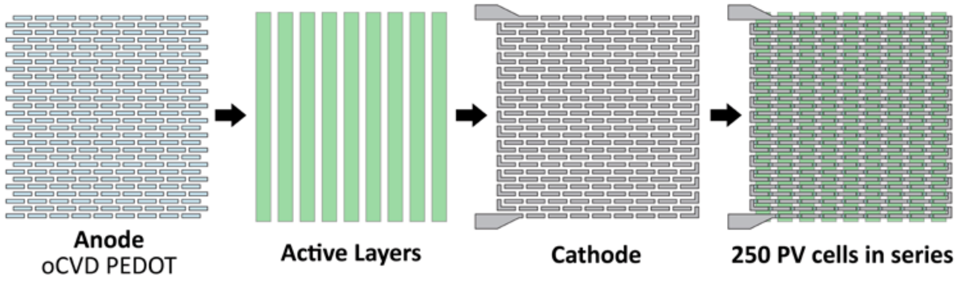
Making complete PV cells and arrays

A working PV cell, of course, requires more than just an anode. Deposition of the remaining components takes place in Bulović's lab. He and his team use evaporation, another dry process but with no chemical reactions involved. They take a material in solid form, heat it until it becomes a gas, and then allow it to condense on the surface of interest. Using that approach, they coat the PEDOT anode with several "photoactive" nanostructured thin films—the layers that absorb light and cause electrons to flow—and then finally the cathode (the negative electrode). The result is a complete PV cell. The photos on this page show single cells printed on newsprint (top) and copy paper (bottom).

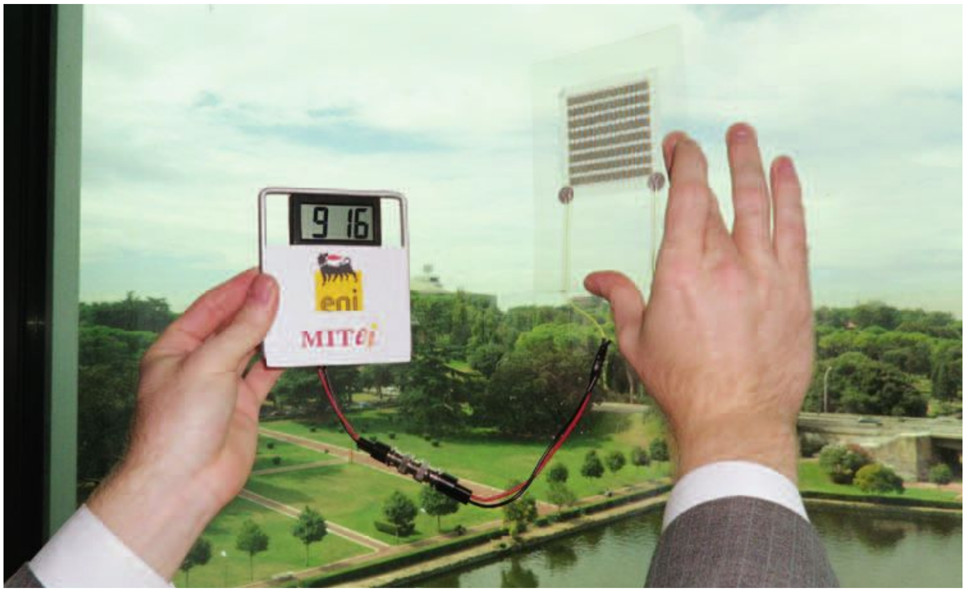
A single PV cell is unlikely to be useful in practice, so the researchers have made PV arrays, using the procedure shown below to lay down many interconnected cells simultaneously. One sample array, shown on page 10, contains 250 PV cells on a 7 cm by 7 cm piece of paper. In ambient light, this array can generate 50 volts and microamps of current, which is much more than enough to power the LCD clock display in the photo. An equivalent array on smooth glass could produce 67 volts—but would get catastrophically damaged if it were flexed and folded, as the array on paper has been. In fact, the sample shown was made in September 2010, and it's still running. Even when the researchers encapsulated it within a 1-micron-thick polymer coating and submerged it in water, it continued to produce power.

Bulović credits the oCVD layer with being the "enabling factor" for making PVs on flexible materials such as paper. "Unlike the substrate itself, the PEDOT layer is amenable to the deposition of the organic thin films that we need to put on top," he says. "As long as the PEDOT doesn't crack or peel off the substrate, the overlying films remain

Printing a PV array



These diagrams show how the researchers create an array of interconnected PV cells. Using their masking technique, they first lay down the anodes; next come the active layers at a 90-degree angle; and finally the silver cathodes—a little offset from the anodes so as to connect each cell to the one next to it. Little L's connect the end of one row to the beginning of the next.



The prototype array shown here contains 250 PV cells on a 7 cm by 7 cm piece of paper laminated in plastic. In natural light on a cloudy day, it generates 50 volts—enough to power the LCD clock display in the photo.

undamaged. And we know the PEDOT layer won't detach from the substrate because it's chemically bonded to it."

Efficiency, cost, and distribution

Thus far, the new PV devices have a light-to-electricity conversion efficiency of only about 1%. But the researchers are working on another PV device composition that they think will push that number up to 4%. Also, they point out that—even at 1% efficiency—their PV arrays on paper can power small electronic devices. And they emphasize that costs could be low. For example, paper is 1,000 times less expensive than traditional glass substrates for the same area and about 100 times less than common plastic substrates. Those numbers become even more impressive when considering that the substrate represents 25%-60% of total material costs in current solar modules.

The ease with which the new PVs can be transported and installed will mean further cost savings and—perhaps more importantly—the possibility of unprecedented dispersion of electric power generation worldwide. Indeed, if all goes as planned, the researchers envision their lightweight PV devices being folded or rolled up and trucked long distances over rough terrain to remote villages. Whether tacked onto roofs, taped on windows, or built into clothing, these devices could serve as the first local source of power to millions of people who have cell phones but no convenient way to charge them.

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By Nancy W. Stauffer, MITEI

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M. Barr, J. Rowehl, R. Lunt, J. Xu, A. Wang, C. Boyce, S. Im, V. Bulović, and K. Gleason. "Direct monolithic integration of organic photovoltaic circuits on unmodified paper." *Advanced Materials*, DOI: 10.1002/adma.201101263, vol. 23, no. 31, pp. 3500–3505, August 16, 2011.

US passenger cars

Designing policies to curb fuel use, GHG emissions

Research Scientist Valerie Karplus (right) has been working with Professor Henry Jacoby (left), Professor John Heywood, Dr. John Reilly, and others to examine different policy approaches to motivating drivers to consume less gasoline in their cars. Using a specially formulated model based on empirical data about people's vehicle purchase and travel behavior, advanced vehicle types (including plug-in hybrids), and more, they looked at the costs and impacts of imposing a gas tax, requiring higher fuel economy in new cars, and mandating the use of advanced biofuels. Her findings provide new insights into designing effective policies that will help the nation move toward its energy security and environmental goals. Photo: Stuart Darsch

For some years, the United States has had regulations in place to cut its growing consumption of gasoline in passenger cars. A new MIT analysis shows that those regulations—which mandate increasing fuel economy in new cars and, more recently, the gradual phasing in of biofuels—are not the most cost-effective way to reduce gasoline use. Indeed, a moderate tax on gasoline could elicit the same reduction at a sixth of the cost. But using a tax to reduce gasoline demand has never proven politically feasible in the United States.

Other results of the analysis show that combining policies may actually reduce cost-effectiveness. For instance, when regulations on vehicle efficiency and fuels are imposed at the same time, the costs are additive but the benefits are not. And combining those passenger vehicle and fuel regulations with a cap-and-trade system would only increase the cost of cutting greenhouse gas (GHG) emissions.

Those findings come from a macroeconomic model with a novel transportation component: it includes detailed information on advanced vehicles and fuels, vehicle ownership and fleet characteristics in different countries or regions, and consumer investment in vehicle fuel efficiency in response to vehicle and fuel prices.

The model's ability to track responses to specific policies at a detailed level yields useful insights for policymakers. Results thus far suggest that, in the case of passenger vehicles, the most politically feasible policies in the United States today also rank among the most costly—and that the challenge for policymakers is to find ways to address this trade-off over time.

Effects of US driving habits

Passenger vehicles generate about 16% of total anthropogenic GHG emissions and consume about 40% of the total petroleum used in the United States—statistics that are troubling for both climate change and energy security reasons. Policy and regulatory measures create constraints and incentives that can influence consumer behavior, but it can be difficult to assess in advance how effective and costly such actions will be in reducing gasoline use and GHG emissions.

Analysts can use macroeconomic models to predict, for example, how increases in gasoline prices will affect fuel use, incomes, and prices of other goods in energy and non-energy sectors as well as how changes in different sectors may interact. And they can use models with detailed descriptions of vehicle technologies and fuels to forecast, say, the energy-efficiency characteristics of plug-in hybrids or the composition of the vehicle stock over time. But assessing the costs and benefits of policies aimed at reducing gasoline use and emissions in passenger cars is best achieved with a model that combines both economics and technology.

"Models used in policy analysis typically do not capture both extensive passenger vehicle system detail and economic feedbacks in an integrated fashion," says Valerie Karplus PhD '11, a research scientist in the MIT Joint Program on the Science and Policy of Global Change. "Most models don't do well at representing how technology and behavior respond to economic signals—but getting that right is critical to understanding the impacts of specific policies."

Developing a technology-rich economic model

To fill that gap, Karplus decided to implement a more detailed transportation component within MIT's Emissions Prediction and Policy Analysis (EPPA) model. This sophisticated macroeconomic model—developed, refined, and applied over the past 20 years by researchers in the Joint Program—tracks global economic activity and associated energy use and GHG emissions. The enhanced transportation component was drawn from work performed in the MIT Future Vehicles and Fuels Program, led by John B. Heywood, professor of mechanical engineering.

Karplus used empirical data to represent technology and fuel options and the behavior of vehicle consumers and drivers. To ensure that the model reflected the latest industry predictions on advanced vehicles and fuels options, she consulted several experts, including Rosemary Albinson, technology and transport strategy advisor in the Research and Technology Group at BP. Based on her wide-ranging experience, Albinson could provide detailed data on advanced vehicle and fuel technologies along with valuable insights into the workings of global markets for ground transportation. "I could explain the differences between how people think about fuel costs in the freight business versus the passenger-car business, and between the developing world and the developed world—and there are distinctive characteristics that need to be modeled differently," says Albinson.

Aided by information from Albinson and others, Karplus made three major changes to the transportation sector of the EPPA model.

- She introduced different types of vehicles (including plug-in hybrid electric vehicles and electric-only vehicles) and fuels (including electricity and advanced biofuels). Those options could then compete with conventional internal combustion engine vehicles and fuels.
- She restructured the vehicle transport sector to capture changes in fuel efficiency and alternative fuel use in new vehicles in response to fuel price changes and policy mandates. She also separately described miles traveled in new and used vehicles.
- Finally, she made changes to address trends in travel demand by calibrating the relationship between per capita income and travel demand by region. The demand for vehicle travel by region varies with per capita income, population growth, geography, availability of substitute modes, and other factors.

Unraveling the impacts of specific policies

Karplus's first task was to establish a baseline. Using the refined EPPA model, she analyzed gasoline use and GHG emissions out to 2050 without any policy or regulatory intervention. Her results show that in the United States between 2010 and 2050, gasoline consumption and GHG emissions would not change much from today's levels, assuming plausible variations in travel demand, cost of efficiency improvements, and availability of alternative-fuel vehicle types.

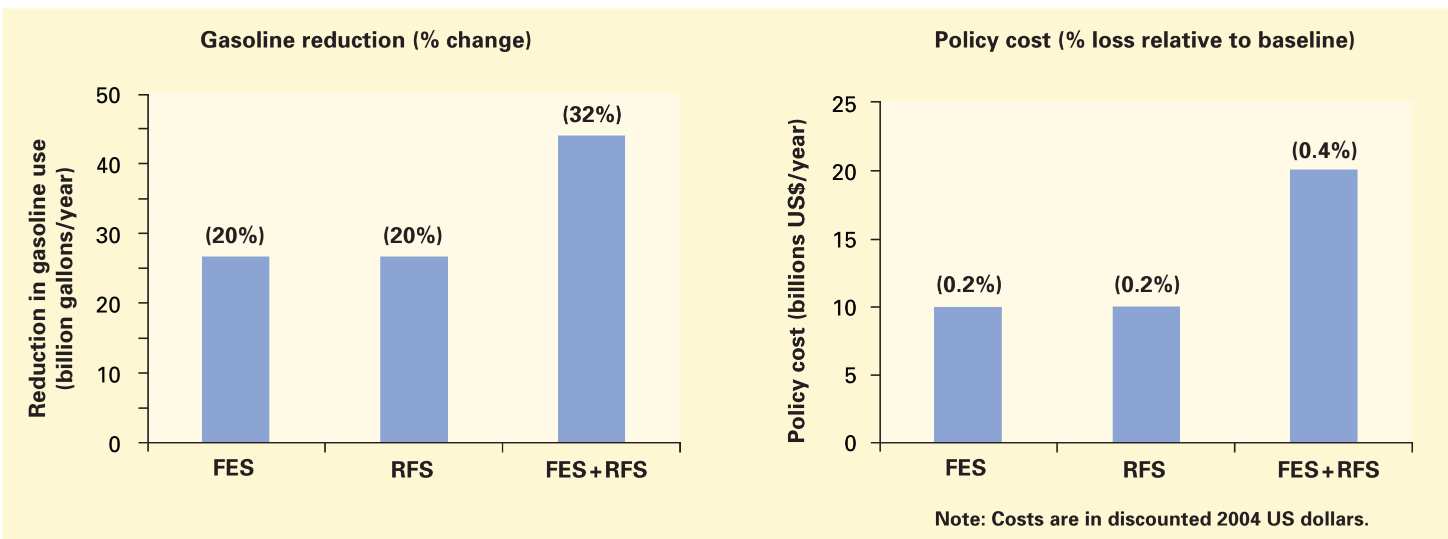
Karplus then looked at two representative policies for reducing gasoline use. The fuel economy standard (FES) policy regulates the sales-weighted average fuel economy of new vehicles (designed to be similar to the Corporate Average Fuel Economy, or CAFE, standards, which were enacted in 1978 and have been recently tightened). The renewable fuel standard (RFS) mandates that a portion of the fuel supply be composed of an alternative fuel, in this case advanced biofuels (similar to the RFS included in the US Energy Independence and Security Act of 2007, which gradually phases in biofuels over 15 years).

For comparison, she defined FES and RFS regulations that would achieve a 20% cumulative reduction in gasoline consumption between 2010 and 2050. She also designed a gasoline tax policy that would elicit the same cumulative reduction. (The tax was implemented as a constant percentage of the gasoline price, starting at $1.00 per gallon in 2010.) Consistent with other studies, her analysis of those three measures indicates that taxing gasoline is 6 to 14 times less costly than the alternative policies in achieving a 20% reduction in the use of that fuel between 2010 and 2050.

Understanding how the policies work helps clarify why their costs differ. The FES regulation affects only new vehicles, so its beneficial effect requires that those vehicles be bought and driven in significant number. The FES regulation is the most costly when fuel economy increases are phased in gradually. The timing of the required standards is critical. If the fuel economy standards ramp down gradually in the early years, achieving the cumulative 20% reduction requires introducing high levels of vehicle efficiency in the final compliance years—an increasingly expensive proposition.

Costs are lower with the RFS regulation. It immediately begins to displace some gasoline with biofuels in both new and used vehicles. In addition, biofuels cost

Impacts and costs of combining fuel economy and renewable fuel standards



These charts present the calculated impacts and costs of imposing a fuel economy standard (FES) and a renewable fuel standard (RFS) at the same time. Each standard is designed to reduce cumulative gasoline use by 20% between 2010 and 2050. (In this analysis, FES and RFS costs are roughly equal due to details of the assumed policies, notably the early timing of required changes.) As the charts show, the combined standards yield a 32% reduction in gasoline use—significantly less than the expected 40%. Yet the total cost roughly equals the costs of the two standards added together. These results demonstrate the need for integrated assessments of multiple policies to obtain an accurate forecast of their combined effects.

more than gasoline, so consumers have an incentive to drive less, thereby cutting their use of all fuels.

Finally, the gasoline tax incurs the least cost because it elicits responses on several fronts. It provides a strong incentive for consumers to buy fuel-efficient vehicles, adopt biofuels if they are cost-effective, and sharply curtail travel in both new and used vehicles.

Karplus also showed that combining the FES and RFS regulations led to roughly additive costs but less than additive benefits (see the figure on page 13). This result stresses the importance of performing integrated assessments of multiple policies that are enacted simultaneously. “When government agencies examine the cost-effectiveness of a proposed policy, they need to consider the action of other, complementary policies that might actually reduce cost-effectiveness,” says Karplus.

Impacts on GHG emissions

The other troubling feature of US passenger vehicles—their high contribution to GHG emissions—is not addressed by the three policies analyzed thus far. In Karplus’s results, the policies all produce comparable, relatively modest reductions in US GHG emissions (5% or less of total cumulative carbon dioxide emissions from fossil fuel use). She therefore added a measure that specifically targets GHG emissions, namely, an economy-wide cap-and-trade (CAT) policy, which has previously been considered in US legislative proposals to address climate change. She analyzed the impacts of a CAT policy alone and in combination with an FES regulation.

The analysis shows that the overall cost of the CAT and FES policies combined would be higher than the cost of the CAT policy alone—with no added reduction in GHG emissions. The CAT policy is designed to elicit the least-expensive GHG-reducing measures first. (If a firm needs to cut its emissions but its only options for doing so are expensive, it will buy less-expensive reductions from another firm.) An FES forces automakers to manufacture and sell more fuel-efficient cars—a step that is significantly more expensive than other available emissions-reducing options. The result: a higher cost to achieve the same emissions reduction.

Cost-effectiveness versus political feasibility

Karplus also investigated why, in the United States, choosing the most cost-effective energy and climate policy for passenger vehicles has proven so difficult. She identifies trade-offs between the features of policies that make them cost effective and those that make them politically feasible. For example, combining energy and climate goals may mean policies appeal to broader constituencies, but combining policies that achieve these goals separately may unintentionally reduce cost-effectiveness. She argues that these trade-offs are likely to mean that the most cost-effective policies will be out of reach in the near term. So, how do we move forward?

“We need to find ways to get past the age-old debate, starting with what is possible today but with an eye to what might be possible tomorrow as today’s policies change underlying incentives. Right now, economists push for the most cost-effective measures, and the policy community responds that such measures are politically impossible,” says Karplus. “Policies that are politically feasible now can be designed to maximize their cost-effectiveness, and every policy should include clear timelines for revisiting its impacts and for assessing the feasibility of moving to more cost-effective policies over time. That will help us achieve our critical energy security and climate goals.”

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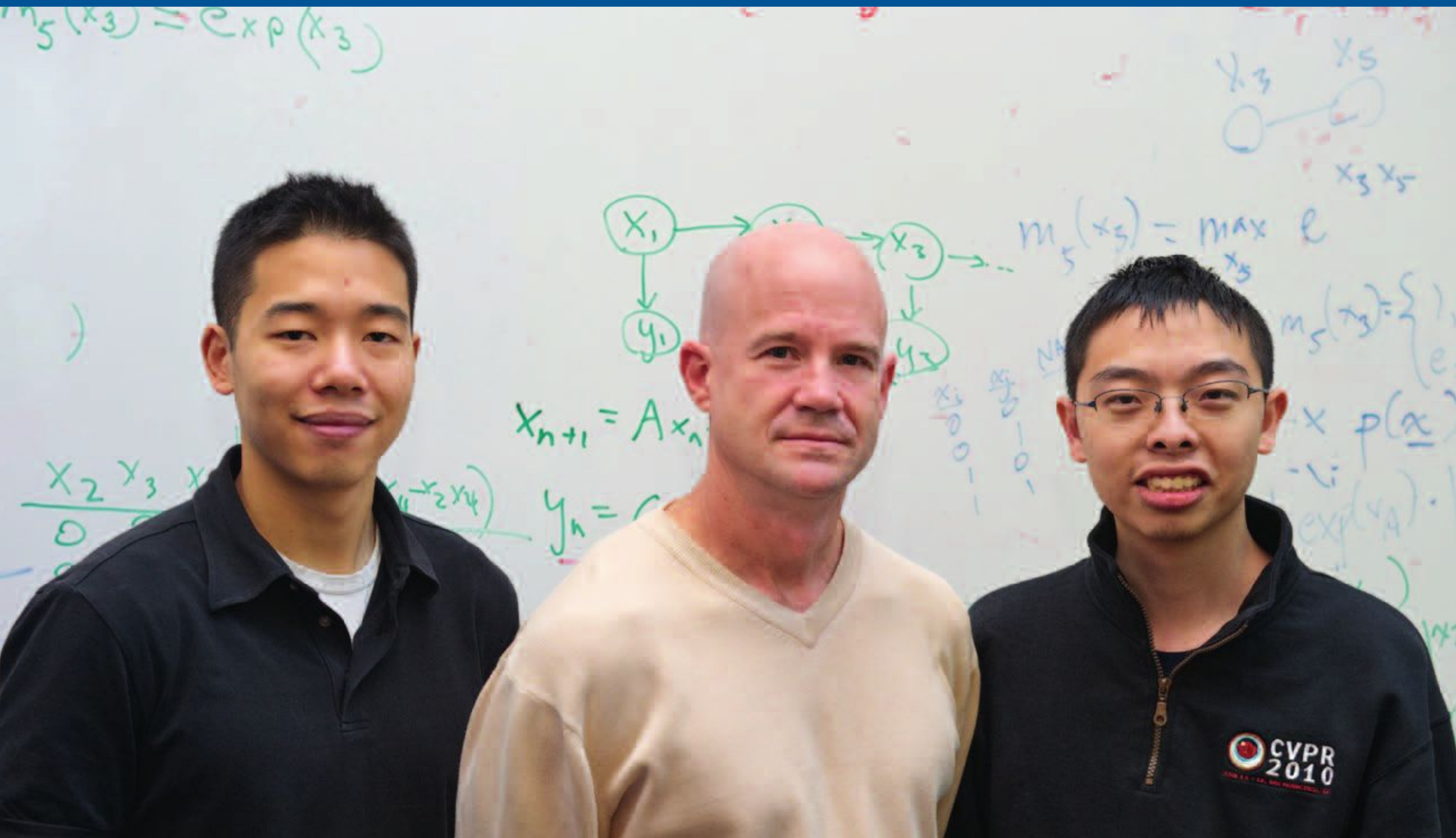
V. Karplus. *Climate and Energy Policy for US Passenger Vehicles: A Technology-Rich Economic Modeling and Policy Analysis.* PhD thesis, MIT Engineering Systems Division. February 2011.

V. Karplus, S. Paltsev, M. Babiker, J. Heywood, and J. Reilly. *Applying Engineering and Fleet Detail to Represent Passenger Vehicle Transport in a Computable General Equilibrium Model.* MIT Joint Program on the Science and Policy of Global Change, November 2011.

V. Karplus, S. Paltsev, M. Babiker, and J. Reilly. *Should a Vehicle Fuel Economy Standard Be Combined with an Economy-Wide Greenhouse Gas Emissions Constraint? Implications for Energy and Climate Policy in the United States.* MIT Joint Program on the Science and Policy of Global Change, November 2011.



Finding oil and natural gas deep underground

MIT statistical methods can help

Dr. John Fisher (center) and graduate students Jason Chang (left) and Dahua Lin are developing mathematical tools to help industry analysts find new oil and gas deposits located kilometers beneath the seafloor. Using the MIT tools, analysts can more quickly examine seismic images of the subsurface and identify geological formations where oil and gas may be located.
Photo: Justin Knight

In the search for new sources of oil and natural gas, energy companies are guided by evidence gleaned from huge arrays of data gathered by sending sound waves deep into the ground. At MIT's Computer Science and Artificial Intelligence Laboratory (CSAIL), experts in machine learning and computer vision are developing mathematical tools that can speed up the examination of such data sets and help human analysts "see" geological structures where oil and natural gas are likely to be trapped.

As the world's demand for oil and natural gas continues to grow, energy companies must search for deposits of those hydrocarbons in

Seismic image showing geological layers

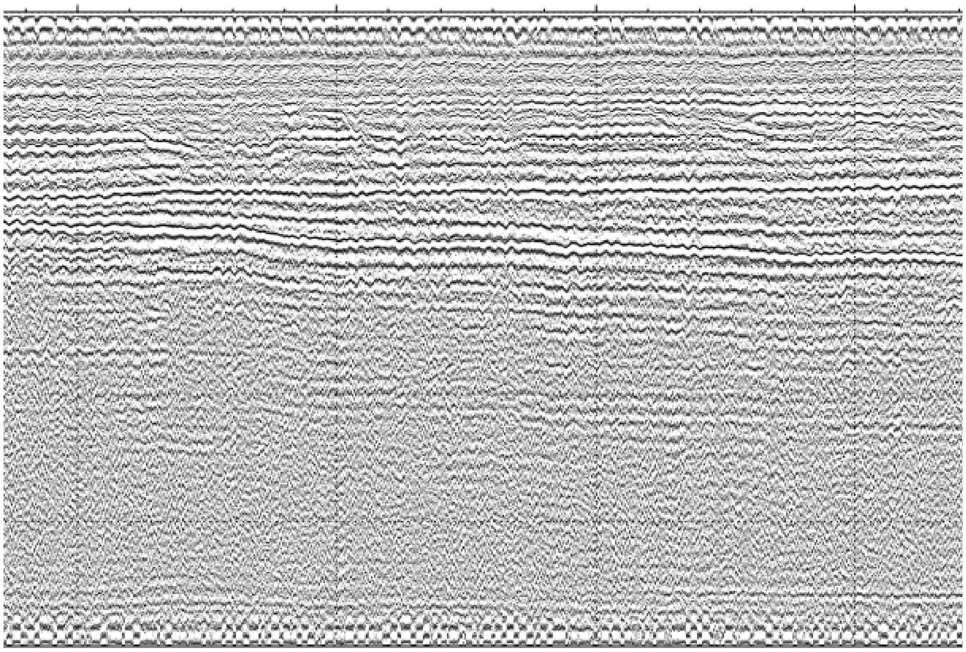


Image: US Geological Survey

When searching for new deposits of oil and natural gas, energy companies use seismic data to build up 3-dimensional representations of the subsurface in a given region. This image is one vertical slice through such a data set. To detect geological structures where oil and gas may be trapped, analysts must examine thousands of slices taken at different angles.

increasingly difficult locations, including complex geological structures buried many kilometers under the seafloor. The Earth's geological history suggests where to look. Over millions of years, layers of material were deposited on the seafloor, some of them rife with decomposing organisms that under high pressure became oil or natural gas. Those hydrocarbons would diffuse upward and escape unless either an impermeable layer were deposited on top or the layers were broken and tilted, creating a space where the hydrocarbons were trapped.

To identify such geological features deep underground, energy companies often perform seismic imaging. Using air guns or explosives, they send sound waves deep into the earth. How those waves are reflected by different underground layers provides information that sophisticated signal-processing techniques can turn into a 3-dimensional data set—a "seismic volume"—that represents the subsurface.

However, identifying geological structures within a seismic volume is difficult. The image on this page provides a sense of the challenge. This cross section is a single vertical slice from a volume based on acoustic information from a region below the seafloor. It provides a good side view of the geological layers that are present.

During an analysis, experienced company geologists or engineers would hand-mark this slice to note potentially interesting features. But then they would have to examine thousands of other slices oriented in various directions, building up an idea of the shapes of the layers and structures within the 3-dimensional space. After picking out likely trapping spots, they would generate more detailed images and examine them to see if their guesses held up. Although mathematical procedures, or "algorithms," help by generating the different views, the whole process can take months. That's a problem. Companies pay millions of dollars to lease time-limited drilling rights in certain areas, so it's important that analyses of the seismic data move forward quickly. And since drilling a single well can cost as much as $100 million, those analyses also must be as accurate as possible.

A new perspective

Performing such analyses is the focus of the Sensing, Learning, and Inference Group in CSAIL. "Our group focuses on statistical analysis of complex sensor data from sources such as high-resolution video cameras used for computer vision," says John W. Fisher III, senior research scientist at CSAIL and head of the group. "To extract higher level information from such data sets, we develop algorithms that can identify objects, shapes, patterns, edges—all the things that are important to human analysts." That capability is highly valuable to the analyst poring over seismic data to find geological structures where oil may hide.

"We aren't experts on seismic data, but we collaborate with those who are in order to leverage our expertise in mathematical algorithms, machine learning, and statistical inference for their applications," says Fisher. "We bring a different perspective to the data than the trained geologists and geoscientists do, and we are often able to adapt methods we've developed for processing other data types to their problems." The MIT team incorporates the experience and insights of the human experts into their algorithms, which then continue to learn on their own by using information gained in past analyses to perform subsequent ones more efficiently.

Evidence of salt domes in seismic videos

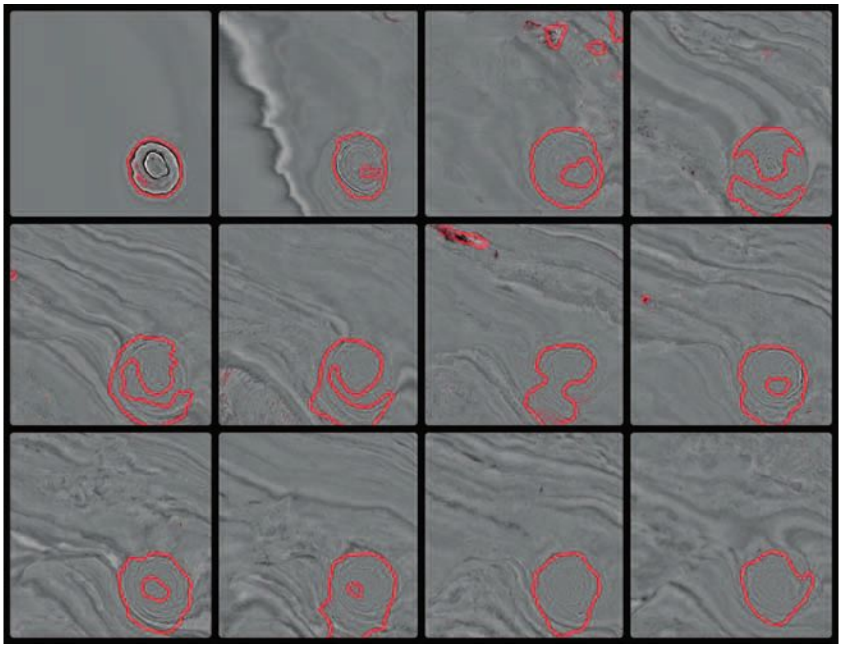


Image courtesy of Sensing, Learning, and Inference Group, CSAIL

Each square above shows a single frame from a seismic video moving downward through the subsurface. (Read from left to right, top to bottom.) In the first frame, the MIT tool marks in red a region that could be the boundary of a salt dome. In subsequent frames, the tool continues to mark regions of interest but soon stops tracking any that are not consistent with the shape of an emerging salt dome.

Finding shapes in seismic videos

"So how do we take this complex morass of data and pull out the structures that may hold hydrocarbons?" asks Fisher. One approach is to look for shapes—and an important shape is the salt dome. Salt domes form deep underground when salt beds from ancient oceans flow upward through heavier sedimentary layers above them. The salt extrudes upward (like globules rising inside a lava lamp, says Fisher) and in the process tilts and blocks off adjacent sedimentary layers, creating pockets where hydrocarbons can be trapped. To retrieve those hydrocarbons, an energy company must drill into the sedimentary rock but not into the salt dome itself because it will contain no oil. Knowing the shape of a given salt dome in some detail is therefore critical.

To see such a 3-dimensional shape, the MIT team studies videos made of sequences of slices from the seismic volume viewed in rapid succession—essentially a seismic video. (Think of "flip" books in which the line drawing on each page is slightly different from the ones before and after it. Flip the pages quickly and you see a movie.) In a video that moves downward through the seismic volume, a salt dome first appears as a small circle—its top—that stands out because of its fine-grained texture. As the video proceeds, the circle steadily grows larger as the slices cut through the dome's expanding girth and then shrinks again as the slices approach the bottom.

In computer vision, a standard approach to recognizing such a shape in a video is to impose a rule saying that no pixel can change significantly from one slice to the next. Any major change may indicate the edge, or boundary, of a shape. However, given the vast amount of seismic data, monitoring changes in all of the pixels would be a huge computational task.

Jason Chang, graduate student in electrical engineering and computer science (EECS) and a Shell-MIT Energy Fellow, has made the task more efficient by assigning those changes different probabilities of being a significant boundary. His first job was to establish a model based on common sense. If this emerging shape is a salt dome, what are we likely to see over time? "Knowing how salt domes grow, you'd think there'd be a gradual change from one slice to the next. You wouldn't think it'd spawn a new region," says Chang. "A boundary would probably grow or shrink in the same area as in the previous slice."

So his algorithm constantly compares current and previous observations. If a change occurs in the same region as a previous change did, those observations are assigned a high probability of being a boundary. A change occurring in a new region is assigned a low probability. But if subsequent changes occur in that new region, those changes are assigned a higher probability of being a boundary—possibly the emerging top of a different salt dome. If a given change is not followed by further changes in the same region, its assigned probability declines until the algorithm stops tracking it (see the image above). As a result, calculations are required only for changes that exhibit a growing probability of being the evolving edge of a salt dome—an approach that significantly reduces the computational load.

However, there's a further complication. As a salt dome pushes upward through the sedimentary layers, it can split into several branches. In a video that moves downward through the seismic volume, the first evidence of that salt dome may therefore be several distinct circular regions, which in subsequent images gradually coalesce into the main body of the structure. In the analysis, those circular regions must be handled together as one shape.

"This sounded pretty straightforward conceptually, but mathematically it was a challenge because we had to compute probabilities over shapes, and shapes turned out to be very complicated objects in this application," says Fisher. "For example, we couldn't assume a commonly used notion of simply connected shapes, meaning that each shape is confined to a single region with no branching." Chang's work allows for such variations while still maintaining computational efficiency—a critical aspect when processing such enormous quantities of data.

Tracking motion

In complementary work, graduate student Dahua Lin of EECS is developing a technique for analyzing seismic videos that involves tracking not shapes but motion itself. In general, a seismic video will progress smoothly because the sequential slices (the pages in our flip book) won't differ substantially. But occasionally there may be a discontinuity in the flow. Such an abrupt change could be caused by the presence of a fault, a feature created when sections of the earth shift relative to one another, sometimes trapping hydrocarbons in the process. Detecting such discontinuities required a way to estimate motion in the seismic video—the challenge taken on by Lin.

One method of estimating motion in video is called optical flow. It follows the trajectories of individual points or objects from one frame to the next and then combines all those trajectories to produce a so-called "motion field." Optical flow works well for, say, tracking the motion of a crowd of people walking on a New York City sidewalk, where individuals are likely to be walking in all different directions.

"But that approach wasn't really formulated as a way for estimating persistent motion, which is what we observe in our seismic video," says Fisher. To illustrate persistent motion, he points to the movement of cars on a highway. In that case, there's an overall pattern of motion that's pretty organized and consistent. "There's no single point or location that describes the motion," he says. "You can't look at a small section of the field—as if through a little window—and know what the overall motion is. Your perception of motion is the combined change of appearance across the entire scene."

Describing such motion therefore requires a method that can use all the data available in the entire video. It must aggregate concurrent observations over a long period of time and infer a common motion pattern. Drawing on a mathematical discipline called differential geometry, Lin is developing an algorithm that can perform that analysis, not only to estimate the persistent motion field but also to identify anomalies in the data that are not consistent with such motion and are thus possible indicators of geological faults.

The mathematics involved in these new techniques is highly sophisticated. "But there's no need for the seismic analysts to learn differential geometry," says Fisher. "That's what we do in our research group." He stresses that their job is not to replace the human experts but rather to provide statistical models that can help them do their work more quickly and easily. And he sees the relationship as "win-win." In working with the seismic analysts and data, he and his team have an opportunity to apply and extend their techniques to the important real-world task of finding hydrocarbon resources to meet near-term energy demand—and, says Fisher, "perhaps to help buy time for other researchers who are developing alternative energy sources so that we can reduce our reliance on oil and gas."

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This research was supported by Shell, a Founding Member of the MIT Energy Initiative. Further information can be found at groups.csail.mit.edu/vision/sli and in the following publications:

J. Chang and J. Fisher. *Analysis of Orientation and Scale in Smoothly Varying Textures.* 2009 IEEE International Conference on Computer Vision, Kyoto, Japan, September 27–October 4, 2009.

J. Chang and J. Fisher. *Efficient MCMC Sampling with Implicit Shape Representations.* 2011 IEEE Computer Vision and Pattern Recognition, Colorado Springs, Colorado, June 20–23, 2011.

D. Lin, E. Grimson, and J. Fisher. *Modeling and Estimating Persistent Motion with Geometric Flows.* 2010 IEEE Conference on Computer Vision and Pattern Recognition, San Francisco, California, June 13–18, 2010.

The microgrid

A small-scale, flexible, reliable source of electricity

Professor James Kirtley (left) and graduate students Michael Zieve (center) and Jared Monnin are building a laboratory-scale microgrid that they will use to verify and further investigate results from simulation studies performed by Masdar Institute collaborators. In their lab-scale microgrid, they are using off-the-shelf equipment plus computer controls to replicate the behavior of key electricity generating and consuming devices—for example, the "solar farm" shown in the photo. On the wall behind them are switches and controllers that connect and disconnect the power supplies and loads as well as circuit breakers that link and unlink the microgrid from the local power system.
Photo: Justin Knight

In the search for more reliable ways to provide electricity—and to incorporate renewable energy sources such as solar and wind—much attention is focusing on the microgrid, a small-scale power system that uses a combination of energy generation and storage devices to serve local customers. Research teams at MIT and the Masdar Institute are working to understand this option and how it can best be implemented.

In one project, researchers at Masdar have developed an analytical tool to help designers create the best possible microgrids for their needs, given the relative importance they place on minimizing emissions versus minimizing cost—two objectives that can't be fully realized at the same time. For a defined level of demand and reliability of service, this powerful tool can determine the mix of devices and the strategy for operating them that will best meet the needs and preferences of the designer.

Meanwhile, a team at MIT is building a laboratory-scale microgrid that they will use to investigate questions arising from computer simulation studies. Using off-the-shelf equipment and computer programming, they're making devices that behave like generators such as wind and solar energy systems, storage devices such as batteries, and customer loads such as fans and lights. When their microgrid is complete, they will see how well it operates, for example when it's disconnected and reconnected to the central power grid—a necessary transition that simulations suggest may lead to voltage instability.

The flexible microgrid

An appealing feature of the microgrid is its flexibility. It can act as a stand-alone source of electricity for remote communities, or it can be connected to a central power system, selling and buying electricity as needed. In the latter setup, it can increase the reliability of service to customers by continuing to operate even when the central system goes down. And it can be a good venue for incorporating fluctuating sources of energy such as solar or wind. When the sun doesn't shine or the wind doesn't blow, microgrid operators can get power from their batteries or diesel generators, they can buy it from their utility, or they can reduce demand by cutting service to self-selected customers.

For the past four years, James L. Kirtley, Jr., professor of electrical engineering at MIT, and Hatem H. Zeineldin, associate professor of electrical power engineering at the Masdar Institute, have been collaborating on studies focusing on the microgrid. Working with others at MIT and Masdar, they are performing analytical and experimental studies designed to help bring about a future of abundant microgrids, each one tailored to serve its particular customer base as smoothly, reliably, and cost-effectively as possible.

A powerful planning tool

In designing a new microgrid, a major challenge—and opportunity—is deciding what components to choose and then how best to operate them to meet demand. "To serve my customers, I have to make a certain number of kilowatts at times of peak load and a certain number of kilowatt-hours per year," says Kirtley. "Now the question is, How much generating capacity do I buy in solar PV panels and windmills? What do I need in diesel generators and batteries for backup? What mix will give me the performance I need at the least cost, or with the lowest possible emissions, or with some mix of the two?"

Unfortunately, those two objectives are inherently contradictory. In general, low costs mean high emissions, and vice versa. But system designers and operators may care more about achieving one objective than the other. Given those preferences, they need to decide how to configure and operate their microgrid.

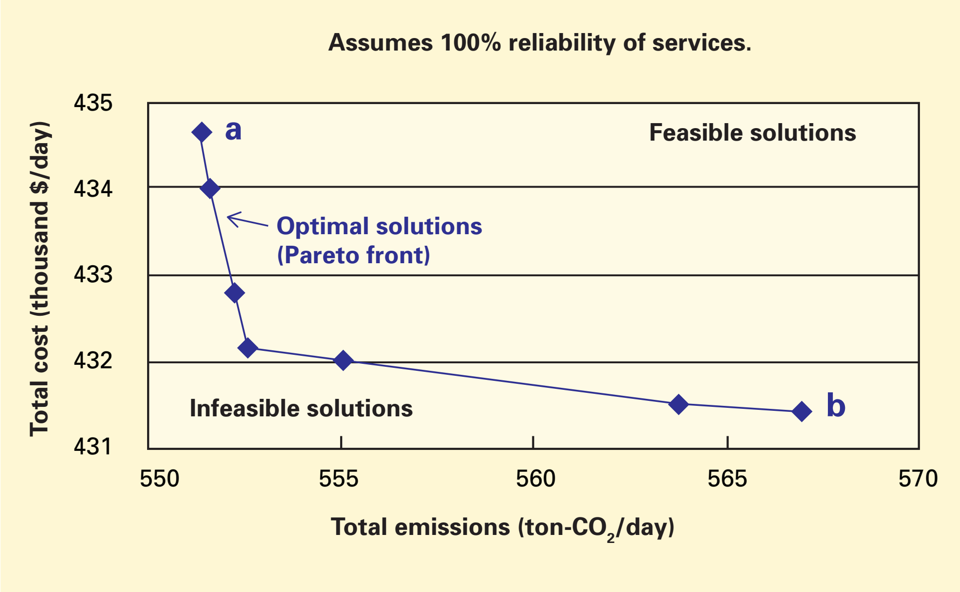
To help in that decisionmaking process, Ahmed Saif, graduate student at the Masdar Institute, developed an analytical method based on "multi-objective optimization" techniques. Because system configuration and operations planning are interdependent, his method analyzes those two factors simultaneously, determining the costs and emissions associated with all possible options. Based on the results, the method generates a set of optimal designs and operating strategies that will minimize costs and emissions, assuming different weighting on those two objectives.

To demonstrate his method, he performed a case study that involved planning a stand-alone microgrid for a city of 50,000 residents—a size similar to that of Masdar City, Abu Dhabi, the location of the Masdar Institute and a city designed to be the first zero-waste, "net zero"-carbon community relying entirely on renewable energy sources. Based on published data, he calculated a pattern of demand similar to that of Abu Dhabi but scaled down to his community of 50,000.

In the case study, the proposed microgrid could include PV panels, wind turbines, diesel electric generators, and sodium sulfur batteries. The system should run as much as possible on its renewable technologies, using the diesel generators or batteries when more power is needed. Finally, the system should provide perfect reliability—that is, it should never fail to meet total customer demand.

Saif used information from commercially available sources to determine the capital, operating, and maintenance costs associated with each component. Based on fuel consumption, he calculated the operational carbon dioxide emissions of diesel generators—the only component in the system that produces emissions when it runs. But for every device in the system, he included "embedded" emissions, that

Microgrid design and operation: Optimal choices for minimizing cost versus minimizing emissions



This figure shows results from a case study in which various component configurations and operating strategies were simultaneously evaluated for a microgrid being planned for a city of 50,000 people. Each point on the Pareto front is the optimal combination of design and operating choices for a given emphasis on minimizing cost versus emissions. At the extremes, point "a" minimizes emissions regardless of cost, and point "b" minimizes cost regardless of emissions.

is, emissions associated with making, installing, maintaining, and decommissioning the device. Including embedded emissions is critical to accurately represent the full environmental impacts of different generation options. Excluding them will yield a sub-optimal choice.

Results from his analysis appear in the figure on this page. The curve is the "Pareto front," where each point is the optimal combination of design and operating choices for a given emphasis on one objective over the other (say, minimizing cost more than emissions). At any point on the curve, it is impossible to make one objective better without making the other one worse.

The point marked "a" is the best choice if the only goal is to minimize emissions; point "b" is best to minimize cost, regardless of emissions. Interestingly, those two points differ by less than 1% in cost and 3% in emissions. The system configuration that minimizes cost also brings emissions close to the minimum attainable level, and vice versa. In both cases, the optimal system selected includes wind turbines, diesel generators, and batteries—but no PV panels.

Why is that? Because the wind turbine generators have the lowest cost and lowest emissions per kilowatt-hour of electricity delivered. When supplemented by large-scale storage, they can satisfy demand on the microgrid at most times. However, diesel generators are still needed when another generating unit fails and when storing wind-generated energy has not been feasible for long periods of time.

Relaxing the reliability

In another series of analyses, Saif assumed different levels of reliability and excluded the sodium sulfur battery option. (While that battery technology is promising, it has not yet been demonstrated at the scale needed here.) In these runs, he defined reliability in terms of "expected unserved energy" (EUE)—the expected amount of energy *not* supplied by the microgrid due to capacity deficiency.

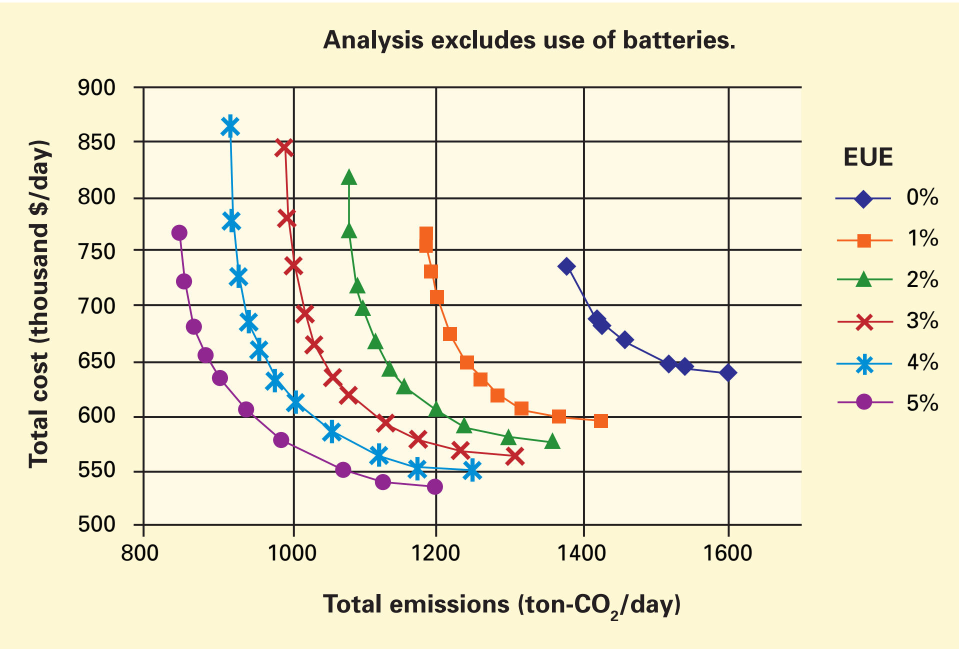
Results of those analyses appear in the figure on page 22. The Pareto front for 0% EUE—perfect reliability—shows the impact of excluding the battery option. Compared to the curve on this page, both costs and emissions are significantly higher at every point. That result demonstrates the importance of developing viable energy storage technology. But as the reliability constraint is relaxed—through accepting higher values of EUE—cost and emissions both decrease dramatically, largely because fewer system components are needed. Such results quantify the trade-offs available to the microgrid planner.

Testing microgrid behavior—at the laboratory scale

Simulation studies suggest that one of the biggest challenges for an operating microgrid may be disconnecting and then reconnecting with the central power system. When the power system shuts down, the microgrid may need to ramp up generation and possibly cut service to some customers; and when the power system comes back on, the microgrid must resynchronize with it for smooth operation. "Those changes should be made automatically, immediately, and seamlessly," says Kirtley. "I like to call it a bump-less transition."

Simulation studies by Ali H. Kasem Alaboudy, postdoctoral fellow at the Masdar Institute, and Zeineldin indicate one potential cause of problems during such transitions: the presence of inductive motors, the workhorses that run air conditioners, lathes, and other equipment common in industrial and commercial facilities. Simulation results

Microgrid design and operation: Impacts of varying reliability requirements



These results are from analyses that exclude the battery option and permit different levels of reliability, measured as "expected unserved energy" (EUE)—the expected amount of energy *not* supplied by the microgrid. Without batteries to store energy, both costs and emissions are higher. But permitting less reliable service (through higher EUEs) dramatically reduces costs and emissions. There is less need to buy and run expensive equipment to ensure continuous generation, for example, when the sun is down and there is no wind.

show that when those motors are suddenly cut off by the central power system and restarted by the microgrid, voltage on the microgrid can become unstable.

To verify and further investigate those and other simulation results, Kirtley and his students at MIT are building a lab-scale analog—a "micro-microgrid"—on which they hope to replicate such operating challenges. They are using standard, low-tech devices (DC motors and switches and capacitors) plus sophisticated computer modeling based on detailed understanding of how specific generating components and energy-consuming devices work. As Kirtley says, "We're phony-ing up a lot of things."

For example, graduate student Michael Zieve of electrical engineering and computer science (EECS) is simulating a diesel engine using a DC motor and some power electronics. Jared Monnin, also a graduate student in EECS, is using the same approach to simulate a solar farm. Several other students are contributing to a simulated wind turbine, including the dynamics of wind gusts that contribute to the variability of electric power generated by wind turbines.

On the other side, the system will include a variety of "customers." The team is incorporating inductive loads such as fans, and adjustable resistive loads such as light bulbs controlled by dimmers. The loads will be wired into the system through switches that can connect and disconnect them. All will be computer controlled.

Once the lab-scale microgrid is complete, the researchers will link it to the local power system through a standard utility circuit breaker box. They will then add one more critical component: a device that will protect the local power system from harmful effects as they create short circuits and other conditions intended to challenge their micro-microgrid. During those tests, the team will carefully monitor the behavior of every component as well as the overall system, gathering information that will provide guidance to designers who are planning microgrids with full-sized components and customers.

• • •

By Nancy W. Stauffer, MITEI

This research was supported by the Masdar Institute, a Founding Public Member of the MIT Energy Initiative. Further information can be found in:

A. Saif, K. Gad Elrab, H. Zeineldin, and S. Kennedy. *Multi-Objective Capacity Planning of a PV-Wind-Diesel-Battery Hybrid Power System*. IEEE International Energy Conference and Exhibition, Manama, Bahrain, December 18–22, 2010. DOI: 10.1109/ENERGYCON.2010.5771679.

A. Alaboudy and H. Zeineldin. *Critical Clearing Time for Isolating Microgrids with Inverter and Synchronous Based Distributed Generation*. IEEE Power and Engineering Society General Meeting 2010, Minneapolis, Minnesota, July 25–29, 2010. DOI: 10.1109/PES.2010.5590125.

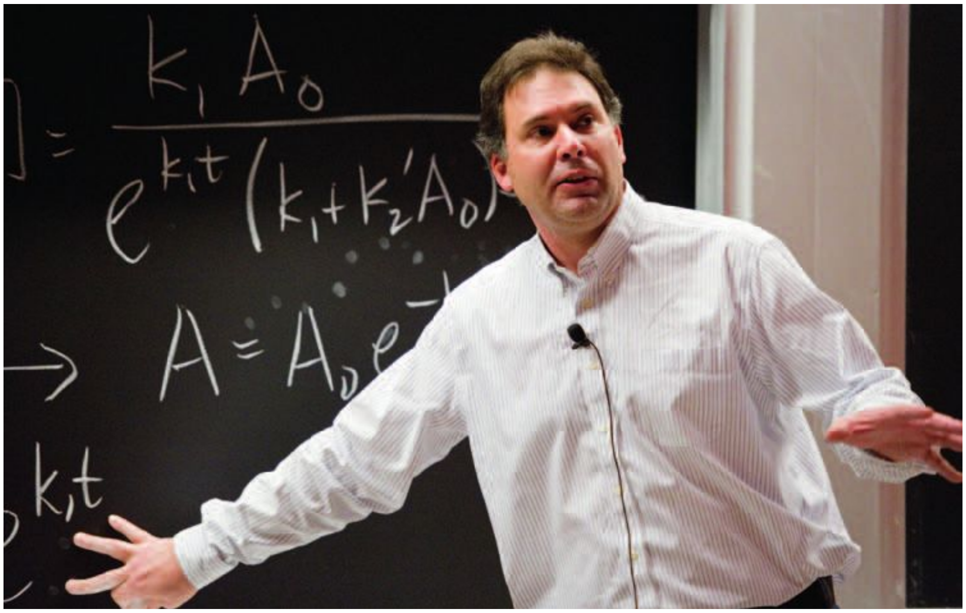
Energy Education Task Force marks five-year surge in energy-focused offerings

In just five years, the MIT Energy Initiative's (MITEI's) Energy Education Task Force has helped raise nearly $9 million for curriculum development, supported an explosion of energy-focused student research on campus, and—most significantly—launched the undergraduate Energy Studies Minor.

"I think we crystallized the essence of what energy education is at MIT. It had many different definitions before," says Vladimir Bulović, professor of electrical engineering and co-chair of the Energy Education Task Force (EETF). "With the collective knowledge of the participating faculty, we were able to pull together essential overlaps between different areas and distill the most important elements of what student energy education at MIT should be."

Established in 2009, the energy minor is a coherent but flexible curriculum that includes more than 40 classes—many of them new. Students from any major can pursue the minor to gain fluency in a balanced core of energy issues and to deepen knowledge in specific areas of energy interest. The core of the minor is interdisciplinary: students must take foundational classes in the science, engineering/technology, and social science of energy.

The minor spans all five schools, so another accomplishment was the creation of a unique governing structure to manage it—the Inter-School Educational Council. "That is revolutionary," says Donald Lessard, EPOCH Foundation Professor of International Management, who co-chaired the EETF during the development and launch of the minor. "There is no other five-school structure for an academic program at MIT."



Photos: Justin Knight

Andrei Tokmakoff, professor of chemistry, works through equations with students in Thermodynamics and Kinetics (5.60), which he co-teaches with Robert Silbey, also professor of chemistry. The Energy Education Task Force provided support for expanding energy-focused content in this class, which enrolls about 150 students each year.

"The validity of what we've done is shown through the output of the program," Bulović says, noting that more than 350 undergraduates—nearly 9% of the undergraduate student body—were enrolled in energy classes developed or adapted with EETF support during the 2010–11 academic year. Three students graduated with the energy minor in 2010 (the first year it was offered), and 13 in 2011. At press time, the 2012 cohort of energy minor applicants numbered 20 students.

New members of the Society of Energy Fellows at MIT are welcomed at the annual orientation reception in September 2011. The society numbers nearly 200 past and current graduate and postdoctoral fellows and spans 20 departments.

The task force has been successful in part because the MITEI vision was one that inspired donors, according to Robert Armstrong, Chevron Professor of Chemical Engineering and MITEI deputy director. When the task force was launched in 2006, the opportunities for energy-relevant education at MIT were diffuse and uncoordinated. "The charge for MITEI's Energy Education Task Force was to articulate a shared set of principles for undergraduate and graduate energy education at MIT, and to develop and implement a prioritized set of programs to deliver this education," he says.

The EETF includes faculty from 11 departments and all five schools at MIT, as well as undergraduate and graduate student representatives.

Photo: Justin Knight

From left to right: Francis Chen, Katherine Lee, and Priyanka Chatterjee, all incoming first-year students, participate in "Discover Energy: Learn, Think, Apply," MITEI's freshman pre-orientation program held during August 2011. In the activity shown here, the team works with a set of insulating and sealing materials and a lunchbox that has been retrofitted with an interior light bulb and thermometer. Each team constructed a custom lid for their box, sealed it shut, and then measured the temperature inside for a five-minute period. The highest resulting temperature measurement indicated the best insulation and sealing techniques—and the winners of the competition.

Amy Glasmeier, professor and head of the Department of Urban Studies and Planning, now co-chairs the task force with Bulović. MITEI's Education Office provides staff support for task force initiatives and other energy education activities across campus.

Since 2006, energy education efforts at MIT have attracted several major gifts, starting with $1 million in early funding from the Kabcenell Foundation and including a donation of $2.4 million from an anonymous alum and $5.4 million from the S.D. Bechtel, Jr. Foundation in 2009 to support the development of new classes, web resources, and the refurbishment of teaching space.

The task force has put that funding to use across campus, sponsoring curriculum development in all five schools with an emphasis on populating the interdisciplinary core of the minor, supporting textbook development, increasing opportunities for first-year students to be involved, and expanding offerings in project-based classes. "We've tried to embed energy learning opportunities throughout the curriculum," says Amanda Graham, director of MITEI's Education Office. The task force also collaborates with OpenCourseWare to publish energy classes for use beyond the Institute.

One of MITEI's most important educational activities is the Society of Energy Fellows at MIT, which has supported nearly 200 graduate and postdoctoral fellows to date, through the sponsorship of MITEI's Founding, Sustaining, and Associate Members. "That program has been a big boost to departments seeking to entice students into energy, to support energy research, and to foster the energy research community," Graham says.

At the undergraduate level, MITEI support for research via the Undergraduate Research Opportunities Program (UROP) has grown from 8 projects in the summer of 2008 to 29 in 2011, thanks to rapid growth in sponsorship by MITEI members as well as private donors. In addition, for the past three years, MITEI has offered an energy-focused pre-orientation program to freshmen, a hands-on introduction to all things energy at MIT that lasts four and a half days. This summer, 20 freshmen participated in "Discover Energy: Learn, Think, Apply," receiving an introduction to energy-focused students, faculty, research, and extracurricular activities at MIT.

Together, MITEI and the task force have big plans. Bulović says one project in the pipeline is a program that would help students attain meaningful energy-focused experiences in business and industry. "Our intent is very much to provide both theoretical and practical experience," he says.

The task force is also exploring a more focused offering for graduate energy education, such as a certificate or master's program. And it is working with the Campus Energy Task Force to find more significant ways to use the campus as a living laboratory for energy research.

"It's a very powerful educational motivator to be able to fix the place in which you live," Graham says. "Collaboration with the Department of Facilities and other key MIT units is increasingly paying both intellectual and practical dividends."

Fortunately, at five years old, the EETF is young and energetic. "We've done a lot, but we have many next steps to take," Bulović says.

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By Kathryn M. O'Neill, MITEI correspondent

Named Energy Fellows, 2011–2012


Photo: Justin Knight

The Society of Energy Fellows at MIT welcomed 52 new members in fall 2011. The Energy Fellows network now totals 191 graduate students and postdoctoral fellows and spans 20 MIT departments and divisions and all five MIT schools. This year's fellowships are made possible through the generous support of 20 MITEI member companies.

ABB
Edbert Sie Physics
Subramanian Sundaram Electrical Engineering and Computer Science

b_TEC
Vazrik Chiloyan Mechanical Engineering

Bosch
Gershon Dublon Media Arts and Sciences
Sang jin Lee Materials Science and Engineering

BP
Jane Chui Civil and Environmental Engineering
Timothy Kurcharski PhD Materials Science and Engineering
Christopher Lai Chemical Engineering
Wen Ma Nuclear Science and Engineering
Abhishek Nagaraj Management
Mark VanMiddlesworth Electrical Engineering and Computer Science/Woods Hole Oceanographic Institution
Guoqiang Xu Materials Science and Engineering
Robert Yi Earth, Atmospheric, and Planetary Sciences

Chevron
Dylan Erb Mechanical Engineering
Lucas (Bram) Willemsen Earth, Atmospheric, and Planetary Sciences

EDF
Jessica Hunter Nuclear Science and Engineering

Enel
Alessandra Vecchiarelli Civil and Environmental Engineering
Yi (Jenny) Wang Mechanical Engineering

Eni
Giulio Alighieri Chemical Engineering
Zachary Buras Chemical Engineering
Michael Chang Engineering Systems Division
Martina Coccia Earth, Atmospheric, and Planetary Sciences
Chen Gu Biological Engineering
Whitney Hess Chemistry
Jing Liu Earth, Atmospheric, and Planetary Sciences
Andrew Maher Chemistry
Ian Matts Materials Science and Engineering
Kanchana Nanduri Civil and Environmental Engineering

Entergy
Alice Chao Engineering Systems Division

Ferrovial
Jessica Debats Urban Studies and Planning
Noriko Endo Civil and Environmental Engineering

Hess
Leebong Lee Engineering Systems Division

ICF
Paul Kishimoto Engineering Systems Division

Lockheed Martin
Sumit Dutta Electrical Engineering and Computer Science
Sebastian Eastham Aeronautics and Astronautics

Saudi Aramco
Elizabeth Hocking Chemistry
Karthik Narsimhan Chemical Engineering

Schlumberger
Canay Ozden Science, Technology, and Society
Paul Rekemeyer Materials Science and Engineering

Shell
Jason Chang Electrical Engineering and Computer Science
Maxime Cohen Management
Roger Jia Materials Science and Engineering
Xuefeng Shang Earth, Atmospheric, and Planetary Sciences
Chunguan Yu Earth, Atmospheric, and Planetary Sciences

Siemens
Haofan Cheng Architecture
Joel Jean Electrical Engineering and Computer Science

Total
Jean-Philippe Peraud Mechanical Engineering
Yekaterina Tarasova Biology
Haoyue Wang Earth, Atmospheric, and Planetary Sciences

Vale
Renato Lima De Oliveira Political Science

Weatherford
Sunila Saqib Electrical Engineering and Computer Science
Jinshuo Zhang Materials Science and Engineering

The energy minor: A student perspective

This fall marks the MIT Energy Studies Minor's third year in action. Below, three students describe how the minor has affected their academic lives and career plans.

Meet the students

Paul Youchak '11 majored in nuclear engineering and minored in economics as well as energy studies. He is now at Stanford University in a one-year master's program in management science and engineering.

Lucy Fan '12 is a senior in chemical engineering and has already completed the Energy Studies Minor requirements. She interned this past summer with Exelon Corporation and hopes to secure an energy industry job after she graduates.

Kesavan Yogeswaran '11 is a master's student at MIT who majored in electrical engineering as an undergraduate. His current project in the MIT Laboratory for Electromagnetic and Electronic Systems involves an improved design for electric converters in solar panels.

What is your area of interest in energy?

Paul: I'm focused on the geopolitical and economic issues involved in the spread of nuclear technology worldwide. Many nations that find nuclear energy of potential interest have concerns that are proving to be a huge roadblock to achieving technological exchange and free trade.

Lucy: Right now, I like the idea of wind energy, given the great potential for

Lucy Fan '12

Kesavan Yogeswaran '11

Photos: Justin Knight

wind development in the United States. I can see myself working on better storage to incorporate wind and solar into the energy mix.

Kesavan: It will probably be some application of power electronics for energy systems. I'm also interested in learning more about developing and improving the electrical grid, ideally for alternative energy–related companies.

Why did you choose to pursue the energy minor?

Lucy: As soon as I heard about the minor, I had to do it. Because energy drives the modern way of life, and increased consumption will have a dramatic impact on the environment, I wanted to understand it better. The energy minor would provide a larger picture of which technologies could offer the most potential.

Paul: After watching *An Inconvenient Truth* in high school, I began to take global warming seriously, and I decided that in college I wanted to study something to do with the energy industry. At MIT, I majored in nuclear engineering. During my sophomore year, I learned the energy minor included opportunities to take economics and policy classes specifically related to energy, and I thought this was what I was looking for all along.

What was most memorable about your experience with energy at MIT (academic, research, extracurricular)?

Kesavan: The summer between my junior and senior year, I had an internship with Joby Energy, a startup working on an airborne wind turbine, a kind of wing with propellers tethered to the ground, flying like a kite. I thought the idea was really revolutionary. Everyone there was passionate about the project and so driven.

Paul: My favorite class, which I took the final semester of my senior year, was 15.031J, Energy Decisions, Markets, and Policies. It was interdisciplinary and offered topics I'd never covered in engineering or economics classes, like how you find ways to convince people to become more energy conscious, or why businesses fail to make investments to reduce energy consumption when it makes economic sense.

Undergraduate energy research: Fueled by team approach

How has the energy minor affected what you do now and what your plans are for the future?

Lucy: The energy minor opened my eyes to the complexity of the energy problem, that it is bigger than just one technology, and that there's not a single solution. The minor also shaped my plans, because it had me looking at energy from the economics and policy side. I am now thinking about getting into the business end of energy—perhaps promoting the competitiveness of renewable technologies. Without the minor, I would have been more technologically focused.

Kesavan: The minor convinced me that I would like to work in the energy sector. The classes also showed me how to put potential technological solutions for the energy problem in perspective. It gave me a well-rounded foundation for the work I hope to do in the power electronics field.

Paul: The minor got me interested in the politics and economics of the energy challenge. I want to be involved in decisionmaking on the policy and strategy side for the energy industry. I could work for a government organization such as the Environmental Protection Agency or the Department of Energy, or for the private sector. In 10 years, I hope to be in a position where I can help decide which avenues a company should explore or what kind of research the government should support.

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For information about the Energy Studies Minor, please go to web.mit.edu/energystudies.

Last spring, while in the thick of problem sets and finals, Nicholas Dou '12 began gearing up for a summer of challenging research in one of MIT's innovative energy laboratories. He was among 29 students whose work was sponsored by the MIT Energy Initiative (MITEI), which in 2011 marked its fourth year of supporting summer undergraduate research opportunities (UROPs). Dou's participation placed him among the 85% of MIT students who take advantage of UROPs—experiences that can dramatically enhance undergraduate education.

For Dou, whose project involved testing improvements for condensers used in solar collectors, the experience proved both immersive and rewarding. Whether sourcing equipment from vendors; modeling thermal resistance, pressures, and temperatures; or ensuring the accuracy of sensors, Dou felt "very involved and invested in the entire process." While he had previously undertaken research at MIT, Dou had never before helped design an experiment. "This time was different because I wasn't just hopping on and having someone tell me exactly what to do," he says. He found this taste of responsibility and independence "exciting and motivating."

The benefits of a UROP flow both ways. Dou's supervisors, Evelyn Wang, associate professor of mechanical engineering, and Ryan Enright, postdoctoral fellow in mechanical engineering, describe the typical MIT student as diligent, smart, and creative, with a terrific work ethic. "They often come up with ingenious solutions to problems a lot of us haven't thought about, and they contribute significantly to the larger project," says Wang. Dou proved no exception to the rule. According to

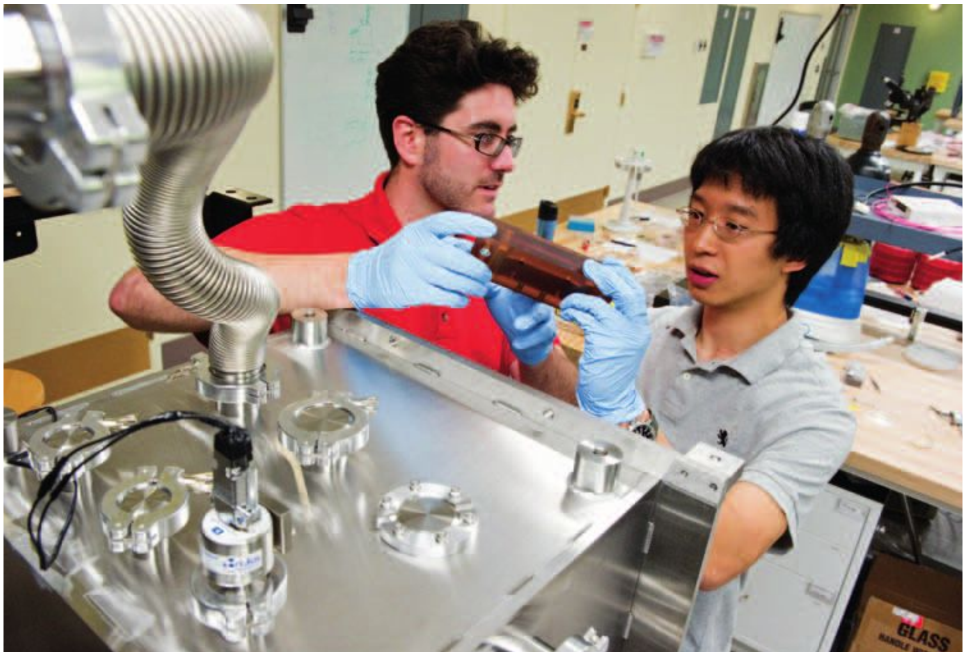
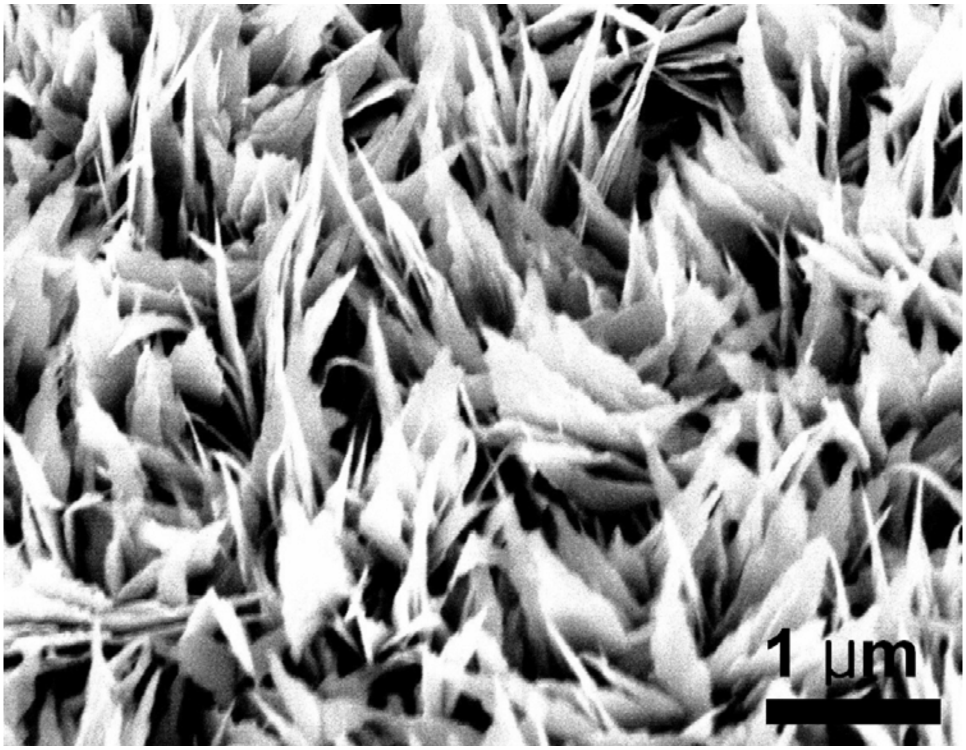


Photo: Justin Knight

Nicholas Dou '12 (right) and his advisor, postdoctoral fellow Ryan Enright, discuss improvements to a cold plate that Dou has created to test condensation behavior and heat transfer properties of nanostructured surfaces. Using such novel surfaces, Dou aims to improve the performance of condensers, thereby increasing the efficiency of solar collectors.

Image courtesy of Nicholas Dou '12



This scanning electron microscope image shows the nanoengineered structures on a copper oxide sample made by Nicholas Dou. A major selling point of this promising material is that it is easy to produce. Dou created this sample by simply immersing a copper sample in a hot alkaline solution for five minutes.

Enright, "You only have to give Nick the big picture and the resources to get it done, and he'll do it." Dou had initiated a relationship with the lab earlier in the school year, and as a result, says Enright, he "got in on ground level." During the summer, Dou swiftly transitioned from design-oriented tasks and modeling to "thinking in depth about what we're trying to achieve," and he acquired a significant degree of autonomy in the lab, says Enright.

Dou's study of novel, nano-sized structures to improve the performance of solar collector condensers may not yield immediate breakthroughs, but the research serves as a building block for scientists seeking to achieve greater energy efficiency in a variety of technologies. Andrew Cockerill, manager of university relations for BP, which financed Dou's summer UROP through MITEI, says, "Nick's research on nanostructured surfaces is much more broadly applicable to heat transfer questions that touch many industries.… If it yields new scientific insights about reducing energy loss, the research could have quite large impacts." Although BP, a Founding Member of MITEI, underwrites some very large projects at MIT, it also supports smaller research ventures in order to "keep an eye on what's happening in the entire MIT ecosystem," says Cockerill. "Companies like ours are interested in scanning for new thinking and ideas among faculty and graduate and undergraduate students. This is a way, with a relatively light touch, of meeting people and supporting a talent pipeline."

To Wang, the UROP can serve as an essential piece of this pipeline. "It exposes students to state-of-the-art research they don't get, even in lab classes," says Wang. "It opens their eyes to something unique. We excite them in that way, so they consider research as a profession."

Dou, a senior with a double major in mechanical engineering and electrical engineering and computer science, is currently pondering whether to pursue a PhD or join an energy startup. But his time in Wang's lab has only heightened his appetite for research. Dou hopes to extend the summer work into a senior thesis and believes that "this research experience will help me decide the right direction to take."

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By Leda Zimmerman, MITEI correspondent

Funding for MITEI UROPs in summer 2011 was provided by individual donors and by members of the MIT Energy Initiative. Founding Members BP and Shell each supported 10 UROPs. Others were supported by Affiliate Members with a particular interest in supporting undergraduate research (see web.mit.edu/mitei/about/members.html).

Scenes from undergraduate energy research

In 2011, the MIT Energy Initiative provided support to 29 undergraduate research projects, ranging from the physics of carbon dioxide migration and trapping to energy-harvesting textiles to maximizing the reversibility of lithium batteries. Several "UROP" projects are featured below. For a full list of projects, see web.mit.edu/mitei/docs/education/urop/project-descriptions.pdf.

Photos: Justin Knight

Rachel Dias Carlson '14, of mechanical engineering, attaches a charcoal agglomeration prototype to her pedal-power setup. Her UROP aimed to develop new machinery that can carbonize and briquette agricultural waste at the same rate at which the waste is produced in developing countries.

Charlotte Kirk '14, of chemical engineering, prepares to extract DNA under the supervision of chemical engineering graduate student Micah Sheppard. Kirk's research project involved the production of 6- and 7-carbon branched alcohols for use as a replacement for fossil fuels.

Martin Lozano '12, of mechanical engineering, solders components onto a circuit board to control an underwater robot. His summer UROP focused on creating a compact, submersible robot to inspect the underground pipes of nuclear power plants internally—a task that normally requires unearthing the pipes and risking exposure to potentially dangerous levels of radiation. Loranzo also programmed the robot's control code and designed a graphical user interface.

Aaron Fittery '13 and his graduate advisor Anirban Mazumdar, both of mechanical engineering, discuss changes that can be made to increase the efficiency of the small Coanda actuator, a component that will help propel the underwater robot as it navigates nuclear reactor piping systems (see caption to the left). Fittery modeled the device in Solid-Works and tested it using computational fluid dynamics (CFD).

Summer program informs, inspires students from Abu Dhabi

A showcase of pioneering MIT research in energy and sustainability proved a lively conclusion to a unique education program for 15 students from the United Arab Emirates, offered for the first time in June by the MIT Energy Initiative (MITEI). The showcase, a veritable innovation bazaar, featured MIT graduate students delivering 90-second "elevator pitches," in the words of master of ceremonies Vladimir Bulović, professor of electrical engineering and co-chair of the Energy Education Task Force. Subjects ranged from finding ways of improving coal gasification and exploiting the thermoelectric effect for better solar power conversion, to synthesizing new enzymes for biofuel production and deploying nanostructured materials for solar cells.

Photo: Justin Knight

Geoffrey Supran, doctoral candidate in materials science and engineering and an Eni-MIT Energy Fellow, explains quantum dot light-emitting device (LED) technology to Haleimah Zeyoudi, a student in the computing and information science master's program at Masdar Institute in Abu Dhabi.

Afterward, the visitors from Masdar Institute in Abu Dhabi—a Founding Public Member of MITEI—clustered around MIT speakers and their posters for deeper discussion, strengthening relationships initiated during the Masdar Institute Practical Experience at MIT. The 11-day program was an intensive introduction to integrated energy studies taught by MIT faculty in classes and labs, and supplemented by a field trip to a local energy firm with origins in MIT research. It was an experience the students found richly rewarding from start to finish.

"I had imagined studying at MIT," says Khaled Alobaidli, an electrical power engineering (EPE) student. "When I finally got here, it was something unbelievable." Another EPE student, Sultan Saeed Al Kaabi, says, "I can't believe how much we learned in our short program." The practicum, embodying MIT's approach to energy studies, provided courses in science, technology, policy, innovation, and entrepreneurship, and marked a new phase in the young collaboration between MIT and the Masdar Institute. And while the official focus may have been on education, the Practical Experience at MIT also delivered a large measure of inspiration, according to several Masdar Institute students.

Fatima Salem Bedwawi witnessed the creation of an artificial "leaf" in a class led by Daniel G. Nocera, Henry Dreyfus Professor of Energy and professor of chemistry, and declared the act "geniusistic." She found it astonishing that scientists could replicate the work of nature in photosynthesis, splitting water to create and store energy from the sun. In Nocera's class on solar fuels, Bedwawi says she discovered wondrous possibilities in the "simplest everyday things," like water.

Bedwawi, 25 years old and a student in Masdar Institute's program in computer and information systems, described the entire Practical Experience program as eye-opening. At MIT, she "learned for the first time about how to calculate carbon dioxide emissions and about solar technology, business, and policy." She is already thinking of ways to match her research interests in wireless networking and sensors to subjects she encountered at MIT. She says she imagines devising smart grids fed by solar photovoltaic energy sources, for instance. Bedwawi hopes such research will hasten the growth of solar power in the UAE and in the entire Middle

East, a region she believes sorely needs reliable energy to help people endure the brutal heat of summer.

Alobaidli says he experienced a "moment of insight" with nearly every professor he encountered. He made special note of Professors Steven Leeb and James Kirtley, Jr., of electrical engineering and computer science (EECS), who discussed electromechanical energy conversion, and Professor Marc Baldo of EECS and Bulović, who taught the students about organic thin films for use in optics. Alobaidli, who wants to help solve "the energy problem, which all scientists are chasing around the world," says he aims to connect his electrical engineering work to organic photovoltaic systems, which he found particularly intriguing.

Al Kaabi described gaining major new insights that will enable him to make headway on a research project in optimization and planning of power systems. A class on storage and batteries taught by Professor Gerbrand Ceder of materials science and engineering made a big impression. "This was the first time I learned about hydrogen energy storage," says Al Kaabi. "It will have a direct impact on my work." He also "asked professors many questions related to my thesis, and based on their answers and knowledge in these areas, I found that ideas I believed were invalid I could actually pursue." He intends to cultivate a direct research collaboration with newfound MIT partners as he finishes his master's degree and moves toward a PhD. While Al Kaabi remains on an academic track for the moment, he has a business plan in his pocket involving integrating plug-in hybrid vehicles into his nation's transportation system.

Photos: Amanda Graham, MITEI

Extracurricular sightseeing in Cambridge, Boston, and beyond left Masdar students with fond memories of verdant New England forests, bookstores, and streets crowded with students. But MIT may have made the biggest impression of all. Al Kaabi admired the intensity of scholarship among MIT students, as well as their openness and encouragement. Alobaidli noted the campus-wide emphasis on renewable energy and sustainability, and Bedwawi commented on the dedication of MIT peers to "serving the environment for the next generation." Before she arrived in the United States, Bedwawi knew only "that her mind would be expanded." She says that what she learned in a week and a half at MIT she plans "to tell all my friends, who will tell all their friends, so these ideas can get out to my whole community."

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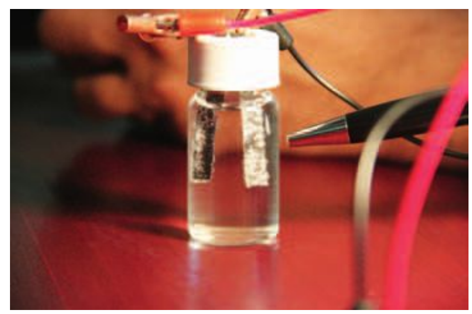
By Leda Zimmerman, MITEI correspondent



In a module led by Professor of Chemistry Daniel G. Nocera, Marwan Al Nuaimi (left) and Yaser Bin Zubaa from Abu Dhabi set up a demonstration to use energy from light to split water into hydrogen and oxygen. They use two electrodes, one coated with a cobalt catalyst discovered in Nocera's lab and the other with a nickel-based composition. When the electrodes are immersed in water and receive power from an illuminated photovoltaic, bubbles of hydrogen accumulate on the cobalt electrode, and bubbles of oxygen on the nickel-based one (see small photo above). This process holds potential for using solar energy to convert water into fuels that can be stored and later used to generate electricity.

Christopher R. Knittel named first energy faculty chair at MIT

Looking to expand MIT's institutional capacity in key areas of energy research and education, the MIT Energy Initiative has initiated a program to create several endowed faculty chairs across the Institute. The first new chair has been filled by Christopher R. Knittel, who was named the William Barton Rogers Professor of Energy Economics at the MIT Sloan School of Management in the spring.

Born in South Dakota, Christopher R. Knittel grew up in California and had hopes of one day becoming either a professional baseball player or a corporate lawyer. Both passions ultimately lost out when Knittel fell in love with economics as a freshman at California State University, Stanislaus. From there, he went on to the University of California at Davis for his master's degree and then to the University of California at Berkeley for his doctorate. After teaching for several years at Boston University's School of Management, he returned to UC Davis, joining the faculty there in 2002. He joined the MIT faculty in spring 2011.

Knittel now works mainly on the economics of transportation policy, but he originally focused on electricity during the deregulation push of the late 1990s. "Actually, when I think back, I'm surprised I didn't [go into transportation] early on. I've always been a car guy. In high school I built a '68 Mustang Fastback, took the engine out, doubled its horsepower…so I've always been into cars. My dad was an engineer for Peterbilt, so it's kind of in my blood," he says. "But on the economics side of things, I think [I'm motivated by] frustration. If you look at the policies in place, a lot of them are terrible. This is an area in which someone could have a sizeable impact, if they can show via their research what's actually going on."

Through various types of research—empirical, theoretical, and model-based—Knittel has done just that, showing the often-hidden costs and benefits of current and prospective policies. "A lot of policies that look really great from a high level and seem like a good thing to do can be quite inefficient. That's the frustration for economists working in this field: We sort of know what the right set of policies is, but they're politically unfathomable. Essentially, environmental economists want taxes to reverse the externalities associated with pollutants, whether they are nitrogen oxides or greenhouse gases, and policymakers are very reluctant to do that. A lot of my work seeks to make an influence in that arena by showing how inefficient these other policies are."

To that end, Knittel has investigated a wide range of areas. A working paper from August of this year, *Some Inconvenient Truths About Climate Change Policy*, finds that the most popular alternatives to a cap-and-trade program, such as ethanol subsidies, renewable fuel standards, and low carbon fuel standards, are as much as 2.5 to 4 times costlier. Another recent paper presents results from a study of the impact of traffic, weather conditions, and local pollutants on infant mortality rate; the analysis shows a clear relationship among those factors. And in 2009, he examined the very popular Cash for Clunkers program and found it to be a very expensive way of reducing greenhouse gases. (For copies of Knittel's working papers, go to web.mit.edu/ceepr/www/publications/workingpapers.html.)

Similar concerns regarding high cost and more widespread negative economic implications are often raised by carbon-tax and cap-and-trade opponents, but Knittel feels that there are ways to implement those programs that would avoid such outcomes and would make the measures more politically palatable. He uses his longtime home, California, as an example.

California will soon be implementing a cap-and-trade program for greenhouse gases that will eventually include transportation fuels. Knittel served on an advisory committee convened by the state to give recommendations on how to use the $12 billion that the government would raise each year by auctioning off emissions permits. "We basically said, you should use that revenue to lower taxes. The environmental taxes, as long as they're not too high, are good for the economy, but things like income taxes and sales taxes are bad for the economy. As long as you use the revenue generated from the [environmental] program—whether it be a carbon tax or a cap-and-trade system—to lower those other taxes, which are distortionary, you could actually create a boon to the economy," says Knittel. "We recommended that about 25% of the revenue be funneled back to low-income consumers, as we think this tax will be somewhat regressive. So it can be done; it just has to be implemented."

With his work spanning so many fields—from engineering to public health to climate science, often in fine, technical detail—the strength of MIT across disciplines was a big draw for Knittel, as was its institutional commitment to tackling the energy challenge. "The work I do draws heavily on a broad set of sciences…so even at Davis, I was tapped into the engineering

Photo: Justin Knight

Christopher R. Knittel, the William Barton Rogers Professor of Energy Economics, discusses policy options for addressing climate change during an MIT Earth Week colloquium in April 2011. Knittel holds the first endowed chair enabled by MITEI in order to recruit faculty in key disciplines for MIT energy research and education.

faculty as well as the science faculty a lot. And Davis is great, but on the science side and the economics side, there's nothing like MIT. For instance, I was in a research group discussion with [Professor Emeritus and Sloan Automotive Laboratory stalwart] John Heywood just this week....The people who are here and the resources are just mind-boggling."

Knittel's first foray into the classroom at MIT will come in spring 2012, when he teaches Energy Economics and Policy (15.037J), a new class that will focus on energy taxes, price regulation, deregulation, energy efficiency, and policies for controlling pollution and carbon dioxide emissions. "There are a lot of markets in the economy that we don't worry about because there's nothing wrong with them. A market economy is a great way to organize things," Knittel says. "But sometimes markets fail. The big thing about energy economics is understanding those failures as well as the optimal policies to correct them."

The class will examine various energy markets and how their structures differ and can be differently impacted by policy. "We think of the oil market as a world market, and there's very little the US can do to influence oil prices. But US policymakers can have a big influence on gasoline prices," Knittel explains. "Just understanding the structure of the markets is important for understanding which policies are optimal or can have an influence." Students will get a bit of "real-world experience" as well through an in-class simulation of the oil market in which they will play firms and make decisions on output and pricing under changing market conditions.

Knittel hopes that the students will also benefit from each other. "Maybe because my research draws on different disciplines, my ideal class is to have students from various fields in the classroom talking about the economics behind all [aspects of energy]," he says. "Inevitably you have to bring in the science, and with [a mix of] students around, everyone's teaching everyone. That's the hope, at least."

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By Jameson Twomey, MITEI

Five-year effort by Campus Energy Task Force saves MIT millions of dollars, kilowatt-hours

MIT will save $3.5 million on energy this year and broadly advance sustainability across campus thanks to five years of work by the MIT Campus Energy Task Force—and the effort continues to build momentum, according to Theresa M. Stone, who chaired the task force up until she retired as executive vice president (EVP) and treasurer earlier this fall.

What began with an energy audit and a small seed fund has grown to engage the whole MIT community—from individual "Green Ambassadors" who spread sustainable practices through the workplace, to the Institute itself, which recently teamed up with NSTAR to create a new model of corporate energy efficiency.

"You see a lot more awareness of energy issues on campus today," Stone says.

In 2006, when the Campus Energy Task Force was founded as a pillar of the MIT Energy Initiative (MITEI), a new era began at MIT—one in which faculty, staff, and students would coordinate their efforts to help MIT "walk the talk" on energy efficiency and sustainability while offering new learning opportunities using the campus as a living energy laboratory.

"We really have got all the different parts of the MIT community together in 'Walk the Talk,'" says Leon R. Glicksman, professor of building technology and mechanical engineering and task force co-chair.

Charged with leveraging the expertise of MIT's diverse community and tapping into MIT's research resources to minimize the Institute's energy footprint, the task force includes faculty members from all five schools; the directors of Facilities, Student Life, and Environment, Health, and Safety; other key administrative and support staff members; and both undergraduate and graduate students. Glicksman now co-chairs the task force with EVP Israel Ruiz, who took over the position after Stone retired this fall.

"The task force has helped build a base of allies across campus that's been very helpful in supporting our energy efficiency goals," says Walter E. Henry, director of the Systems Engineering Group for the Department of Facilities.

"In addition to the tremendous success in breaking the logjam for energy efficiency on campus, one of the biggest accomplishments has been the collaboration with the academic community," says Steven M. Lanou, deputy director of the Sustainability Program in the Environment, Health, and Safety Headquarters Office. "The Energy Initiative has been terrific in helping to prioritize and enhance projects on campus." The task force has successfully integrated many campus energy and sustainability challenges into project-based classes, undergraduate research opportunities, theses, and a variety of voluntary service projects.

Indeed, one of the task force's first success stories was identifying a portfolio of energy efficiency and conservation measures for MIT to undertake. In spring 2007, students in the MIT Sloan School's Laboratory for Sustainable Business (S-Lab) class examined potential campus projects for both their financial and environmental benefits. Working in collaboration with staff from the Department of Facilities and several other administrative departments, the student and staff team outlined $14 million worth of projects that would recoup all costs through energy savings within three years or less.

With this blueprint in hand, further refinement by the Department of Facilities, and $500,000 in seed money from the EVP's Office, the task force proceeded to pilot projects ranging from monitoring building control systems in real time to retrofitting inefficient light fixtures—steadily making improvements across the campus.

"Monitoring changes and verifying returns has been a key part [of the task force's mission]," Glicksman says. "Typically, others do projected savings and that's it. We try to be unique and do it the MIT way—propose an experiment, do the experiment, and on that basis, maybe enlarge."

For example, MIT replaced all the radiator steam traps in one East Campus dorm and then left its twin dorm unrepaired to test the impact of better heat regulation. "What they showed was that the repair saved 50% of the energy used to heat the dorm," Glicksman says. "The savings paid off the cost of the work in less than a year."

Students have also been enlisted through the Student Campus Energy Project Fund, which MITEI established in 2008. Student teams compete for $1,000 awards from the fund, which has provided 38 grants in the past three years—supporting such projects as a dorm competition to reduce electricity use and development of a campus energy use map.

"It was a good way to engage students," Lanou says. "The benefits have been mutual: we have gained new insights into our own campus, and students have deployed emerging technical and leadership skills."

Photo: Donna Coveney, MIT

Leon R. Glicksman (left), professor of architecture and mechanical engineering, and Theresa M. Stone, executive vice president (EVP) and treasurer, co-chaired the Campus Energy Task Force until fall 2011, when Stone retired and her role was assumed by the new EVP, Israel Ruiz (see page 36).

Photo: Stuart Darsch

The Campus Energy Task Force meets monthly throughout the academic year. At its September 2011 meeting, the group reviewed achievements from its first five years and began discussing new goals in the areas of energy efficiency, measurement and verification of energy improvements, increased community engagement, educational activities, and more.

Photo: Stuart Darsch

Alix de Monts '13 (center), chair of the Undergraduate Association (UA) Sustainability Committee and undergraduate representative on the Campus Energy Task Force, provides an update on the UA's spring 2011 exchange of 1,000 compact-fluorescent light bulbs for incandescent bulbs in student dorms.

Inspired by the task force's early successes, Jeff Silverman '68 donated $1 million and David desJardins '83 gave $500,000 in 2009 to seed further campus projects. "They liked that MIT had a plan and a robust measurement and verification process that would increase the impact of their support for MIT," Lanou says.

Silverman's and desJardins' donations launched the creation of an energy-efficiency investment fund and inspired other alumni gifts. MIT replenishes the revolving fund with the savings gained through energy efficiencies, allowing early projects to fund later endeavors—a smart way to make meaningful and sustained progress, Stone says.

MIT's impressive track record also led to a long-term partnership between MIT and its utility company, NSTAR. The partnership was unveiled in May 2010 and is designed to support the Commonwealth of Massachusetts' aggressive energy-efficiency goals. "NSTAR asked MIT to create a new model for delivering large-scale energy efficiency programs," Lanou says. The result, a program called Efficiency Forward, centers on a long-term agreement between the Institute and the utility and aims to save MIT $50 million over the lifetime of the energy-efficiency projects undertaken through the program.

With MIT serving as the pilot, the objective is to inspire other businesses to enter into similar agreements. MIT's commitment is to save 34 million kilowatt-hours within three years—15% of the Institute's total electricity use. NSTAR will provide incentive financing, energy-efficiency tools, and expertise to help MIT reach its target. In the program's first year, MIT surpassed its savings goal for the year by 30%.

In addition to working to improve the efficiency of existing buildings, MIT has also made a concerted effort to ensure that its new buildings are as energy efficient as possible—aiming for Leadership in Energy and Environmental Design (LEED) Gold certification for both the new Sloan School of Management and the Koch Institute for Integrative Cancer Research buildings. Designed to use 30% less energy than a typical new lab building, "the new Koch building is much more efficient—and performing even better than we anticipated," Henry says. "We also set very aggressive goals for the Sloan building, and it is meeting or exceeding those goals."

"Could we do more? Yes, we could always do more," Glicksman says. But MIT's efforts have already earned recognition. Just this year, the City of Cambridge gave MIT its GoGreen Award; the Northeast Energy Efficiency Partnership named MIT a "Business Leader for Energy Efficiency"; and Massachusetts Interfaith Power and Light honored the Institute for "Leading by Example."

Looking forward, Glicksman says he is working with members of MITEI's Energy Education Task Force to put more resources into using the campus as a living laboratory for energy innovation. "In the next phase, I hope we can raise money for full-time grad students to do more energy research on campus and continue to build on our strong foundation of engaging the entire community," he says.

"So far, our energy cost reduction efforts have focused on relatively straightforward work and measures that use tested technology," Henry says. "In the next few years we will have exhausted that pool and will move toward more complicated measures. Collaboration among faculty, staff, administration, and students will become even more important in those efforts."

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By Kathryn M. O'Neill, MITEI correspondent

EVP Israel Ruiz to co-chair Campus Energy Task Force

Photo: Patrick Gillooly, MIT

New Executive Vice President and Treasurer Israel Ruiz has been named co-chair of the MIT Energy Initiative's Campus Energy Task Force (CETF). He succeeds Theresa M. Stone, who retired this fall after serving five years on the task force.

"The CETF started with the vision of engaging the broad MIT community, building awareness, and making an impact on sustainability practices," Ruiz says. "A lot has been accomplished in the past five years, and it is exciting to be a part of its future."

Ruiz is looking forward to working with Co-Chair Leon R. Glicksman, professor of building technology and mechanical engineering, as well as with others at MIT to analyze and document the challenges of running energy-intensive labs and other facilities and to disseminate best practices.

"At MIT, magic happens when faculty, students, and staff collaborate to tackle complex problems," he says. "CETF projects and collaborations have shown the results of this powerful combination. I would like us to keep increasing our engagement, amplifying the impact on campus."

By Kathryn M. O'Neill, MITEI correspondent

MIT to test energy-saving building projects for DOE

MIT is one of just 24 building owners and projects nationwide selected to participate in a $21 million US Department of Energy (DOE) initiative to accelerate the adoption of cost-effective energy-saving measures in commercial buildings.

The Commercial Building Partnership initiative teams corporate entities with researchers at DOE's national laboratories and building experts in the private sector. The teams will design, construct, measure, and test low-energy building plans in an effort to improve energy efficiency.

"DOE's selection of MIT is a reflection of the maturity of campus energy activities," says Steven M. Lanou, deputy director of the Sustainability Program in the Environment, Health, and Safety Headquarters Office. "The DOE is interested in partnering with organizations that have strong and proven energy efficiency programs, and our Department of Facilities has established a leading position."

MIT qualified for the program through a competitive process that evaluated potential participants based on five criteria: likelihood of achieving significant energy savings; probability of success; potential for widespread deployment of energy-saving tools and strategies; contribution to the Commercial Building Partnership portfolio of energy-saving solutions; and commitment of resources to improving energy efficiency.

The DOE hopes to achieve 30% measured energy savings in existing buildings and 50% energy savings in new construction projects through the Commercial Building Partnership, according to US Energy Secretary Steven Chu, who announced the program in November 2010. The partnership is funded via the American Recovery and Reinvestment Act.

"These Recovery Act projects are bringing together experts from our national laboratories and the private sector to help businesses and organizations reduce the energy they use in their facilities, saving them money on their energy bills and making them more competitive economically," Chu said in a press release. "This initiative will also demonstrate to other commercial building operators that cost-effective, energy-efficient technologies exist today that will help lower the operating and energy costs of their buildings."

MIT has been partnered with Lawrence Berkeley National Laboratory and its team of consulting firms, which are providing technical assistance to help identify worthwhile projects for two buildings on campus: the Stata Center (32) and W91, which houses the data center for Information Services and Technology.

A host of approaches and technologies are being weighed for these buildings as part of the program. Lighting is the primary focus at the Stata Center, and heating, ventilation, and air conditioning (HVAC) at W91.

In the Stata Center, MIT is considering a suite of approaches, including replacing incandescent bulbs with long-life LED sources in lecture halls for both energy and maintenance benefits; daytime dimming controls to harvest the abundant natural light the Stata Center affords; and wireless controls to enable the new systems.

HVAC measures under consideration for W91 include air distribution improve-

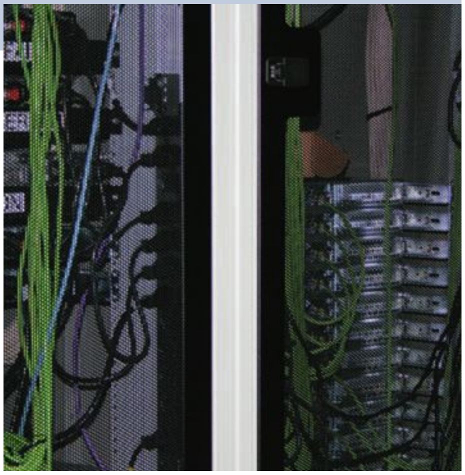

Photo: Mike Mullett, MIT

One proposed target for energy-saving measures under the DOE program is the energy-intensive MIT Data Center in building W91. Installation of advanced controls and use of outside air could improve air distribution at the computer racks (shown above), reducing energy use while ensuring protection of temperature-sensitive equipment.

ments at the computer racks, including temperature monitoring that will allow operators to confidently reduce the use of computer room air handlers when possible. The team is also evaluating ways to use outside air to cool the computer room when temperatures are favorable by employing water-side or air-side economizers.

"The relationship developed [between MIT and the DOE] through this project has been mutually beneficial," says Julia Ledewitz, sustainability coordinator for the Department of Facilities and a member of the System Engineering Energy Team that is overseeing the collaboration. "MIT has received new ideas about energy solutions, and we've also shared our own best practices and energy solutions for both common and unique energy problems in laboratory and academic buildings."

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By Kathryn M. O'Neill, MITEI correspondent

A study in green building on campus

Like any ambitious construction project, the new MIT Sloan School of Management building has a story to tell—one that does not primarily revolve around architecture or technology, in spite of a striking façade and state-of-the-art classrooms. Instead, the story of E62, featuring the Joan and William A. Porter 1967 Center for Management Education, involves a decade-plus effort to design a building with the highest energy performance standards possible.

Integrated, not decorated

"We tried hard, and I think succeeded, to get a building where the sustainability is baked in," says Walter E. Henry, director of the Systems Engineering Group in the Department of Facilities. "It isn't the frosting but a fundamental part of how we designed the building."

John Sterman, Jay W. Forrester Professor of Management, recalls an old Sloan building where rusted windows admitted frigid gusts in winter and keenly appreciates "a very pleasant new place to work and teach." He proudly notes E62's tight building envelope with its triple-insulated windows, carbon-dioxide sensors triggering fresh air flow, and secure underground bike parking to encourage cycling to school. Cindy Hill, MIT Sloan School director of Sloan Capital Projects, particularly likes the first-floor gallery of the Porter Center with its terrazzo floor, which uses green and brown crushed glass from recycled beer bottles.

The new building does not sport the conspicuous "whiz-bang" technology that some MIT visitors seem to expect. Sterman notes, "Our first priority was

Photo: Andy Ryan

MIT's new Sloan School of Management building is a showcase of high-performance, integrated design. During its first months of operation, the building consumed about half as much energy for lighting, heating, and cooling as would a comparable office building of standard design.

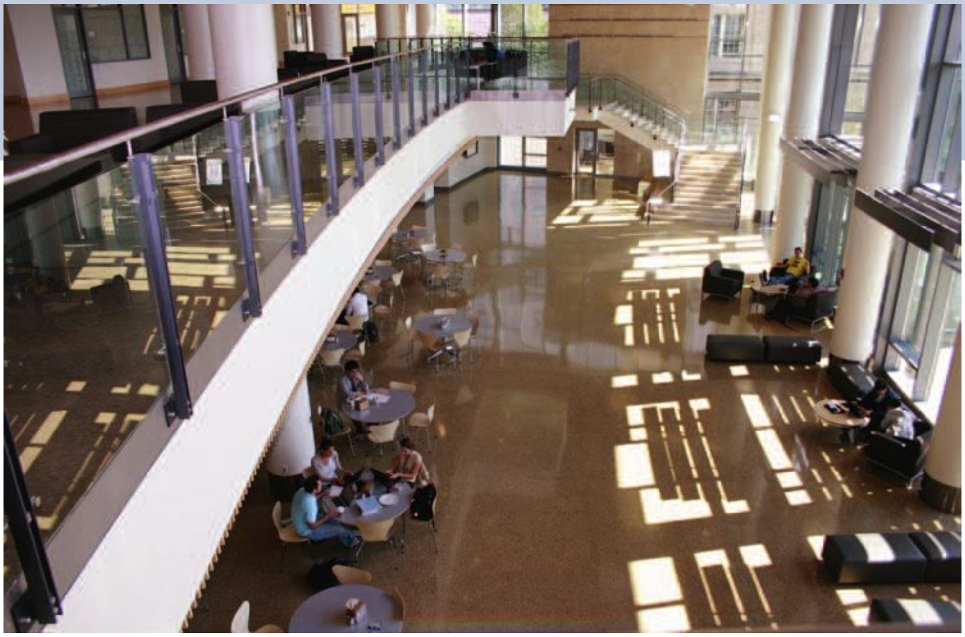
Photo: Melody Craven, MIT

The new building offers inviting public spaces where people can meet and work. Use of advanced lighting and shade controls maximizes natural daylight and controls heating from the sun—measures that serve to increase both comfort and energy efficiency.

the highest building insulation you can achieve." Henry adds that the building's sustainable elements were designed "to be more felt than seen." That does not mean innovation was lacking. In fact, in 1997, when MIT Sloan first took up the idea of creating a central home for its far-flung faculty, recalls Sterman, "we pushed to make the building as green as it could possibly be." These green advocates were able to demonstrate that sustainable features were both best for the building and its occupants—and a sound investment.

Passion, persuasion, and process

Meeting this challenge required years of collaboration, persistence, and "passion," according to Hill, an effort sustained through tough fiscal times that hindered fundraising, and through two MIT administrations. There were countless meetings and, not surprisingly, continual reviews of facts and numbers.

One strategic decision made early in the evolution of the new building proved critical to this long and successful effort: the adoption of an integrated design process (IDP). In this approach to construction, all the stakeholders must coordinate their ideas from the very beginning, agreeing on a set of goals and establishing a production scheme for achieving them. The IDP means a slower startup for a building project, but because the give-and-take among players occurs at the earliest stages, costly mistakes can be avoided later in construction. Guided by Marc Rosenbaum of Energysmiths, an MIT group including Sterman, Hill, and Henry, and the architects, lighting designers, and engineers began meeting early on to map out aggressive energy performance goals for E62.

Rosenbaum says that together they "looked at what was possible" for E62 and figured out ways to achieve what were for MIT unprecedented efficiency targets in cooling, heating, lighting, and ventilation—always utilizing the most precise performance metrics. MIT had selected architecture firms (Moore Ruble Yudell and Bruner/Cott) and engineers (van Zelm Engineers) with demonstrated interest and experience in energy performance, so there was an unusual degree of cooperation during the IDP, according to Henry.

Hill, who admits "I didn't know much about green then," shuttled back and forth between the IDP team and school officials, describing such innovative technology as chilled beams for heating and cooling, a heat wheel for energy recovery, and automated window shades. She had to "research, get information, make presentations," and even then, sometimes, "everybody made a leap of faith." Says Sterman, "We had to persuade people that building green was something important, that it would benefit people working in the building and Institute, not just save energy and reduce greenhouse gas emissions."

But does it cost more?

From the outset, there was concern that integrating green performance into Sloan's new home might add substantially to the project expense. "Are we getting the right thing for this kind of money?" Hill recalls sensing from administrators. Sterman gives former Sloan Dean Richard Schmalensee, the Howard W. Johnson Professor of Economics and Management, credit for "stepping up and saying, 'We're going to do it anyway.'" In the end, in large part because of the thorough design process, the team found that high energy performance features would not mean additional expense and might in fact save MIT money. When you do the detailed analysis and thinking up front, says Rosenbaum, "there will be fewer mistakes and costly changes later in the process." The IDP actually "let us find better and cheaper solutions," Sterman says. "A lot of people were skeptical," he says, but "our building came in on time and on budget."

Photo: Melody Craven, MIT

This "enthalpy wheel"—located in building E62—preconditions incoming air so as to reduce the need for heating and air conditioning. The wheel salvages useful energy from used building air and transfers it to incoming fresh air, warming and humidifying it in the winter and cooling and drying it in the summer.

"These things take a long time, and we're the beneficiaries of the fact that they were out there, working together to identify ways to have the highest energy performing building," says Theresa M. Stone, who served as executive vice president and treasurer during the project. Although Stone arrived after the planning process, she firmly grasped the "level of focus, conviction, and insistence of all the interested parties—the people executing and those who would be consumers. It was an impressive collaborative process."

Green dividends

After a partial year of occupancy, ongoing studies are validating predictions that going green also makes good business sense. "The numbers so far show great energy savings," says Henry. Building energy modeling studies compared the as-designed building to the same building designed to meet only current construction codes. The E62 design came out consuming 43% less energy. In operation, the building has met or exceeded the goals MIT set for the architect and engineers for peak loads: for every square foot of floor area, it uses 0.75 watts for lighting and 10 Btu per hour for heating, and for every 1,000 square feet, 1 ton of cooling. Those numbers are all about half of typical building design values.

E62 "embodies all the things MIT wants in a building," sums up Stone. It demonstrates "the kind of thinking and research MIT stands for" around energy issues, and that it is possible to design "beautiful and functional" facilities that save on energy costs and contribute to the long-term financial stability of the institution. The building is expected to be recognized with a strong Gold rating by the US Green Building Council's Leadership in Energy and Environmental Design (LEED) program.

Sloan's new building has already begun to make its mark on current and upcoming campus construction. A sister Sloan building is under renovation, applying some of the same energy efficiency measures used in E62, and the recently completed Koch Institute for Integrative Cancer Research incorporates key laboratory energy conservation ideas. Beyond specific building techniques, E62 has important lessons for MIT. The Institute is now committed to using the integrated design process in its new projects, and emphasizing energy performance. Stone says, "This building demonstrates that it is not a good idea to design a beautiful building and then think about energy features, but that the thinking has to be integral from the outset." Sterman adds even more forcefully, "There is no reason to build a building in a traditional way. It's a sign of haste or laziness." Concludes Henry, "If we can show that the building works well and that the incremental cost was small or none, then we will have more support to follow the process for future buildings....We will never do better and make advances if we do what everyone has done before."

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By Leda Zimmerman, MITEI correspondent

Senate energy committee holds hearing on MIT's Future of Natural Gas study

The MIT Future of Natural Gas study was the subject of a July 19 hearing of the US Senate Committee on Energy and Natural Resources. Professor Ernest J. Moniz, director of the MIT Energy Initiative, testified at the hearing, highlighting the results of the three-year study, released in early June of this year.

The Future of Natural Gas study is the fourth in a series of energy studies aimed at elucidating the steps needed to provide marketplace options for a clean energy future. The study presents the results of an integrated, technically grounded analysis, carried out by a large multidisciplinary group of MIT faculty, senior researchers, and students. An interim report released last year focused largely on assessing US natural gas supplies and modeling the role of natural gas under various carbon constraint scenarios. Results of the interim report were summarized in an article in the autumn 2010 issue of *Energy Futures.*

In addition to more in-depth analyses in these areas, the final study examines in greater detail gas end use and gas power generation, including its role in the event of large-scale penetration of intermittent renewables. The following are excerpts or study conclusions in these new areas summarized in Moniz's written testimony.

Overall conclusion

In broad terms, the study concludes that, given the large amounts of natural gas available in the United States at moderate cost (enabled to a large degree by the shale gas resource), natural gas can indeed play an important role over the next couple of decades (together with demand management) in economically advancing a clean energy system. However, natural gas power generation would eventually become too carbon intensive to meet stringent carbon dioxide (CO_2) emissions reduction targets by mid-century, which highlights the importance of a robust innovation program for zero-carbon options.

Fuel substitution options

The US natural gas supply situation has created new opportunities for expanding natural gas use, enhancing the substitution possibilities for natural gas in the electricity, industry, buildings, and transportation sectors.

Natural gas substitution for coal in the power sector. Natural gas combined cycle (NGCC) turbines can operate up to about 85% of nameplate capacity. Currently the US NGCC fleet averages 42%, so there is significant unused gas generation capacity. Because natural gas has been a higher cost fuel than coal or nuclear, it tends to get used last in the electricity dispatch order, which is determined largely by the marginal cost of generation. The analysis concludes that, if existing NGCC plants were dispatched ahead of coal generation, then:

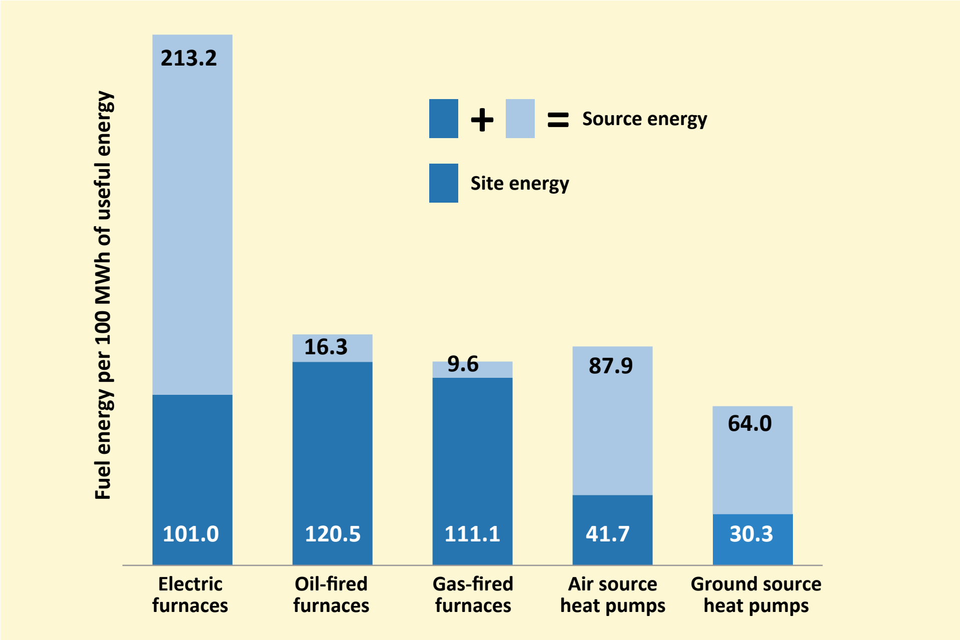
- Nationwide, CO_2 emissions from power generation would be reduced by 20%.
- The cost of CO_2 emissions avoidance would be around $16 per ton, implying that a very modest emissions charge could effect this change of dispatch order.
- Mercury and nitrogen oxides emissions would be reduced by a third.
- This change would require an additional 4 trillion cubic feet (Tcf) of natural gas, or a little less than 20% of annual US gas consumption.

The study recommends that the United States pursue substitution of NGCC power generation for coal generation as the only large-scale, near-term practical option for achieving CO_2 emissions reductions from power generation.

Natural gas substitution for coal in the industrial sector. US industry consumes about a third of all natural gas used in this country, and most of it is used to provide heat for manufacturing. Industrial boilers alone provide over a third of manufacturing demand for gas.

Around two-thirds of large industrial boilers are coal-fired boilers, and these are likely to require significant additional controls to meet new pollution regulations. These coal boilers are relatively inefficient compared to natural gas super-boilers, which can achieve efficiencies of 94%–95% and meet lower pollutant emission requirements. The study examined the energy, economic, and carbon impacts of an alternative compliance pathway: substitution of large industrial coal boilers with natural gas super-boilers. The analysis showed that a complete switch-out would consume slightly less than 1 Tcf of incremental gas per year, would have a short payback time, and would reduce CO_2 emissions by 52,000 to 57,000 tons per year per boiler. Thus, replacing coal boilers with super-efficient gas boilers could be a cost-effective alternative for complying with the anticipated Environmental Protection Agency Maximum Achievable Control Technology standards. Interestingly, because the savings are so significant, there is a negative per ton CO_2 emission avoidance price of about $5.

Site versus source energy efficiency of residential heating systems



This figure depicts energy consumed by furnaces comparing site and source methods for calculating consumption. The dark blue portion of the bars is the amount of fuel energy required per 100 MWh of useful energy when energy consumption is measured at the point of use (site energy). The light portion plus the dark portion of the bar is the amount of fuel energy required per 100 MWh of useful energy when energy consumption is measured from its source, including production, distribution, and point of use (source energy).

Gas substitution for electricity in the buildings sector. The methodology for establishing appliance and space conditioning efficiency standards is an important issue for natural gas because a third of US natural gas demand is for commercial and residential buildings. (This does not include natural gas used for electricity generation.) The US Department of Energy (DOE) has historically set appliance and space efficiency standards based only on "site efficiency," or energy consumed at the point of use. This standard-setting method tends to mask overall energy consumption because only about one-third of the energy consumed in generating power becomes electricity sold to the customer. In contrast, in gas heating and dual-fueled appliances, about 94% of the energy actually reaches the consumer.

In 2009, the National Research Council (NRC) recommended that DOE move to "source efficiency" standards, which take the full fuel cycle into account, including the energy lost in power generation and transmission. The analysis in the study validates the NRC recommendation. Using a site calculation, a gas furnace consumes 10% more energy than an electric furnace. When source energy is considered, an electric furnace consumes 194% more energy than a gas furnace. (For more details, see the figure on this page.) These numbers are compelling, but such standards are complicated to establish because of regional climates and electricity generation mixes. The study recommends incorporating efficiency metrics to provide full fuel cycle comparisons, but it also finds that there is a need to inform consumers, developers, and state and local regulators about the cost-effectiveness and suitability of various technologies relative to local conditions.

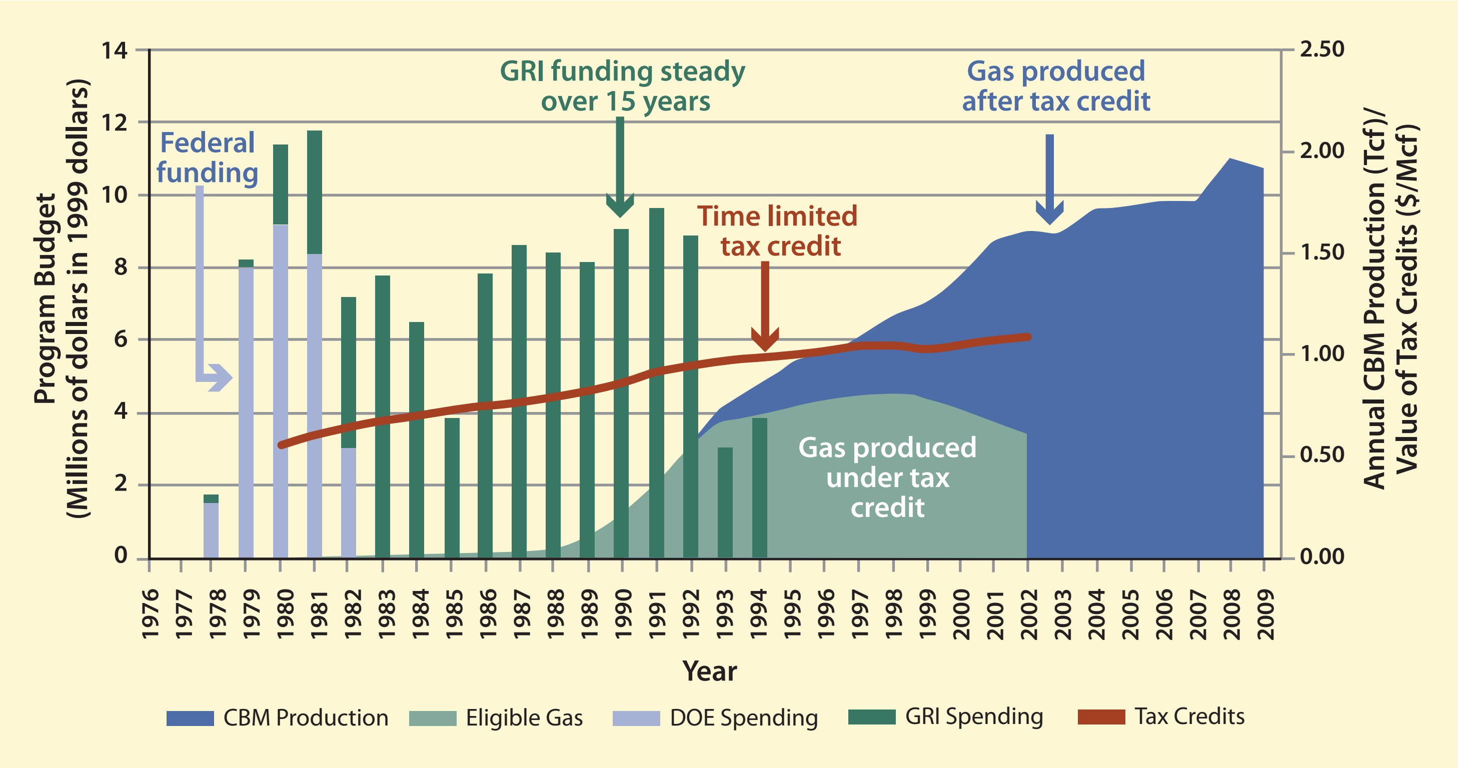
Gas substitution for oil in the transportation sector. The study examines options for direct uses of natural gas for transportation as well as for conversion of natural gas to liquid fuels.

- Compressed natural gas (CNG), a direct use of natural gas in transportation, offers a significant opportunity in US heavy-duty vehicles used for short-range operation (buses, garbage trucks, delivery trucks), where payback times are about three years or less and infrastructure issues do not impede development. However, significant penetration of CNG into the passenger fleet is unlikely in the short term.
- As a result of operational and infrastructure considerations, high incremental costs, and an adverse impact on resale value, liquefied natural gas (LNG) does not appear to be an attractive option for general use in long-haul heavy trucks. There may be an opportunity for LNG in the rapidly expanding segment of hub-to-hub trucking operations.
- Methanol is a widely produced commodity and, in the United States today, is substantially cheaper than gasoline. Because of its corrosive nature, its use would require engine modifications and an appropriate distribution infrastructure. Introducing methanol, in addition to ethanol, and flexible fuel vehicles has the energy security benefit of providing consumer fuel options derived from petroleum, biomass, and natural gas feedstocks.

Natural gas power generation and intermittent renewables

Natural gas-fired power generation provides the major source of backup to intermittent renewable supplies in most US markets. Modeling of the ERCOT

Natural gas RD&D spending: A successful public-private partnership for coalbed methane



This figure depicts the research funding history for coalbed methane (CBM) development. The US Department of Energy initially funded research to develop natural gas from coal seams—gas that poses a hazard during coal mining. This funding was largely aimed at resource characterization. The Gas Research Institute (GRI), a research organization funded by a surcharge placed on gas volumes and administered by the Federal Energy Regulatory Commission, assumed research funding for CBM. At the same time, Congress passed a time-limited tax credit for development of unconventional resources, including CBM. The tax credit ended in 1992, but wells that were producing when the credit was eliminated were grandfathered so that gas volumes from those wells were still eligible for the credit. CBM produced after the tax credit eligibility expired were as much as 10% of domestic gas production, demonstrating the long-term impact of the public-private research funding on unconventional gas development.

system (Texas), for example, provides a more detailed understanding of the generation impacts of doubling wind generation in the short term. This modeling demonstrates that:

- Wind generation primarily displaces generation from NGCC plants.
- Baseload coal or nuclear plants could be required to ramp up and down, raising environmental and economic questions about system optimization.
- Natural gas peaking plants, from which generation is relatively expensive, are used more.

If policy support continues to increase the supply of intermittent power, then—in the absence of affordable utility-scale storage options—additional natural gas *capacity* will be needed to provide system reliability, even if it is used infrequently. Regulatory changes will be required in many markets to incentivize the building of this capacity. The key issue is that more technical and regulatory planning is needed at the system level to handle a major increase in intermittent generation.

Natural gas research and development

Given the importance of natural gas in a carbon-constrained world and these opportunities for improved utilization of the resource, an increase in the level of public and public-private RD&D funding is warranted. (The figure on this page demonstrates the effectiveness of that approach.) The study recommends that the Administration and Congress support a broad natural gas RD&D program both through a renewed DOE effort, weighted towards basic research, and a complementary industry-led public-private program, weighted towards applied RD&D.

The complete report, *The Future of Natural Gas: An Interdisciplinary MIT Study*, can be found at web.mit.edu/mitei/research/studies/natural-gas-2011.shtml.

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By Ernest J. Moniz, MITEI, with contributions by Melanie A. Kenderdine, MITEI

MIT, France team up on energy research

With assistance from the MIT Energy Initiative (MITEI), MIT and the government of France have agreed to work together on several efforts to boost collaborative energy research.

Notably, MIT has entered into an agreement with the Centre National de la Recherche Scientifique (CNRS), France's national scientific research center, to launch a joint international laboratory that will focus on multiscale materials science for energy and the environment. Located at MIT, the lab will house four to six CNRS researchers, who will serve as co-principal investigators with MIT researchers.

MIT President Susan Hockfield announced the lab—and several other agreements—at the France-MIT Forum on Energy held in Paris in June. MITEI organized the forum with the MIT-France Program and the French Ministry of Higher Education and Research (MESR).

"French energy research is first-rate, and for MIT faculty and students to collaborate with labs in France is a great opportunity," says Suzanne Berger, the Raphael Dorman-Helen Starbuck Professor of Political Science and director of the MIT-France Program, which helped launch the initiative. "In puzzling over how to solve big problems, having different approaches, different methodologies, and being able to work together can really lead to important breakthroughs."

The joint lab, founded as a *unité mixte internationale*, or UMI, is co-sponsored by CNRS and co-directed by Franz-Josef Ulm, the George Macomber Professor of Civil and Environmental Engineering (CEE), and Roland Pellenq, a CNRS scientist who is also a senior research scientist in CEE. In addition to its MIT and CNRS sponsorship, the UMI will seek funding for specific research projects from industrial and government sources. The initial agreement will last two to four years, after which it may be renewed.

Photo courtesy of MESR

MIT President Susan Hockfield (right) and Alain Fuchs (center), president of the Centre National de la Recherche Scientifique, sign an agreement to launch a joint laboratory in materials research. Looking on is Ronan Stephan, general director for research and development at the French Ministry for Higher Education and Research.

Summer short courses for energy professionals

MIT Professional Education Short Programs are designed by MIT experts to connect busy professionals in industry to late-breaking knowledge at MIT. Short Programs give participants unparalleled access to top experts in a variety of fields. This highly focused learning experience allows them to learn about topics of vital interest to their companies and to engage with faculty while creating an international network of talented colleagues. The following courses in energy and transportation are offered for summer 2012:

- Carbon capture and storage: science, technology, and policy (R. Juanes, H. Herzog)
- Design of motors, generators, and drive systems (J. Kirtley, S. Leeb)
- Energy in the context of climate policy: strategic challenges and opportunities (M. Webster)
- Energy, sustainability, and life cycle assessment (T. Gutowski, B. Bakshi, D. Sekulic)
- Innovations in sustainable urban mobility (K. Larson, R. Chin)
- Modeling and simulation of transportation networks (M. Ben-Akiva)
- Nuclear plant safety (M. Kazimi, N. Todreas)
- Solar energy: capturing the sun (D. Nocera)
- Sustainability: principles and practice (N. Selin)
- The future of vehicular transportation: propulsion, fuels, and emissions (J. Heywood, W. Cheng)

Additional courses are offered on data modeling and analysis, innovation, leadership, systems engineering, technology and organizations, and other topics of importance to scientists, engineers, and technical professionals.

To learn more, visit shortprograms.mit.edu or e-mail shortprograms@mit.edu.

Closing the gender gap in energy policy: MITEI and the C3E Initiative

Energy ministers from 21 countries met in Abu Dhabi at the 2nd Clean Energy Ministerial in April 2011 to discuss a range of initiatives to accelerate a global transition to clean energy, with a goal of eliminating the need for 500 midsize power plants worldwide in the next 20 years. Governments participating in the Clean Energy Ministerial included Australia, Brazil, Canada, China, Denmark, the European Commission, Finland, France, Germany, India, Indonesia, Italy, Japan, Korea, Mexico, Norway, Russia, South Africa, Spain, Sweden, the United Arab Emirates, the United Kingdom, and the United States.

Photo courtesy of Clean Energy Ministerial Secretariat

Participants in the half-day C3E forum at the ministerial, among them Dr. Sultan Ahmed Al Jaber (center front), chief executive officer of the Abu Dhabi Future Energy Company and a member of the MIT Energy Initiative (MITEI) External Advisory Board; Fred Moavenzadeh (back row, second from left), James Mason Crafts Professor of Systems Engineering and Civil and Environmental Engineering and president of Masdar Institute; and Melanie Kenderdine (back row, second from right), executive director of MITEI.

An important new focus of the Ministerial was the Clean Energy Education and Empowerment Women's Initiative—C3E—which was highlighted in a half-day forum at the Ministerial. Melanie Kenderdine, executive director of the MIT Energy Initiative (MITEI), joined other high-profile women from industry, government, and academia to discuss ways to enhance the role of women in energy fields. The forum was hosted by Abu Dhabi's Masdar Institute.

Women continue to fill a minority of positions in energy science, engineering, and policy. Kenderdine's panel at the forum, "The Policy Gap—Recommendations for Action," also included Nawal Al Hasany, associate director of sustainability from the Masdar Institute (a MITEI Founding Public Member); Joan McNaugton, senior vice president at Alstom Power; and Mary O'Kane, the chair of the Australian Center for Renewable Energy.

In her remarks, Kenderdine, who previously headed the US Department of Energy Policy Office, highlighted progress at MIT, citing a report released by the Institute this year, *A Report on the Status of Women Faculty in the Schools of Science and Engineering at MIT.* This report highlighted, for example, dramatic increases in the number of women faculty in positions of academic and administrative leadership at MIT, including the president of the Institute, two of five academic deans, and two of six department heads in the School of Science, as well as the growth of women faculty in the School of Engineering from 10% in 2001 to 17% today.

Kenderdine also noted that "mentoring is important. Established women in energy should mentor young women getting started in their careers...and undertake outreach activities at middle schools and high schools in their communities, with the goal of connecting to and inspiring the next generation of clean energy leaders." She also praised the Masdar Institute, which has made female representation in its graduate research programs a high priority.

Keynote speakers at the forum included Dipuo Peters, minister of energy of South Africa; Maud Oloofsson, the Swedish minister of energy and enterprise; and Lykke Friis, minister of energy and climate change and gender equality of Denmark. Each minister highlighted the critical need for more women in energy. In describing the barriers women have to overcome in energy fields, Friis said, "After climbing one hill, one finds that there are more hills to climb."

Kenderdine also highlighted the women leaders in energy who have inspired her in her career. "The first US energy secretary I worked for was Hazel O'Leary, and she led the way in new investment in wind, solar, and high-efficiency automobiles. Deputy Secretary Betsy Moler was a leader in modernizing regulation of the electric grid. Now, I am honored to work with MIT President Susan Hockfield, who has harnessed the substantial resources of MIT to advance energy research and education. C3E creates an opportunity to translate the vision of such leaders into more opportunities for women in energy."

Kenderdine's comments about the forum and more information about C3E can be found at energy.gov/articles/closing-gender-gap-energy-policy.

Symposium honors David H. Marks


Photo: Justin Knight

David H. Marks, professor of civil and environmental engineering and engineering systems.

In autumn 2010, the MIT Energy Initiative (MITEI) and the Department of Civil and Environmental Engineering (CEE) sponsored a symposium to honor David H. Marks, professor of civil and environmental engineering and engineering systems, who has retired after 41 years at MIT. The meeting—titled Complexity and Sustainability: Perspectives on Environmental Technologies and Global Systems—drew Marks's colleagues old and new, including current and former students, along with many members of the MIT community interested in those topics.

During his years at MIT, Marks served as head of CEE, MIT faculty coordinator of the international Alliance for Global Sustainability (AGS), and director of the Laboratory for Energy and the Environment (LFEE), which combined the 30-year-old MIT Energy Laboratory and the Center for Environmental Initiatives, which was also founded and directed by Marks. In 2006, LFEE and its affiliated programs became part of the newly formed MITEI.

Keynote speakers at the symposium included two of Marks's students who became university presidents: Jared Cohon, president of Carnegie Mellon University, and former MIT Provost Lawrence S. Bacow, president of Tufts University, whose remarks were relayed via video from London. Remembering three decades of collaboration and friendship, Bacow described Marks as an "extraordinary citizen of the Institute, fabulous teacher, terrific scholar, an entrepreneur among the MIT faculty, and wonderful friend and mentor to so many at MIT." Cohon noted Marks's capacity to work with integrity across disciplines and to "derive theory from real problems."

The meeting, held in the Wong Auditorium, was moderated by Joseph Sussman, JR East Professor of Civil and Environmental Engineering and Engineering Systems, and included 14 other speakers. Among them were Roberto Lenton, chair of the Inspection Panel at the World Bank, and Peter Edwards, professor of plant ecology and coordinator of the AGS at ETH Zürich.

The first session of the symposium, opened by Andrew Whittle, professor and department head of CEE, focused on the planning and design of civil engineering systems, particularly water systems. Marks was involved in operational and management studies of the Aswan High Dam. Fred Moavenzadeh, professor of civil engineering and currently president of the Masdar Institute, recalled—via video—asking Marks to come to Egypt to work on the project. Within a year, he said, Marks had "developed a model that transformed the regime of the water release from agriculture to energy and saved millions of dollars" for the people of Egypt.

The second session focused on education. As head of Course 1, Marks emphasized the systems nature of civil engineering, particularly in relation to environmental processes—it was during his tenure as head that "environment" was added to the department's name. Gregory J. McRae, MIT professor emeritus in chemical engineering, and Kenneth A. Oye, associate professor of political science and engineering systems, discussed the challenges of interdisciplinary approaches in an institution composed of individuals with powerful, discipline-focused accomplishments and perspectives. Edwards outlined the evolving world of global academic and educational collaboration in environmental studies.

The concluding speaker was Ernest J. Moniz, the Cecil and Ida Green Professor of Physics and Engineering Systems and director of MITEI, who outlined the status of the Initiative and the central role that Marks played in laying the foundation for MITEI—not just putting together LFEE but in numerous other ways. As an example, he detailed Marks's role in the core team that established the Engineering System Division, which provides an academic home for research and analysis at the intersection of technology and policy—a key for MITEI's outreach mission. Most importantly, Moniz reminded the audience of Marks's irrepressible humor!

The symposium was followed by a reception and dinner at the Faculty Club. Further tributes, some in a decidedly humorous vein, were offered along with commemorative gifts from CEE and MITEI. Marks welcomed all with his usual aplomb. He said, "The celebration was amazing. In a 40-year-plus career one does a lot of things, but it is often hard to see them in context. It was heart-warming to see it all pulled together. In my many years at MIT there have been times when I went home happy and times when I was sad, but I never went home bored. MIT is usually a no-praise zone so I thank all my friends who broke the rule this one time, and thank MIT for a great ride."

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By Teresa L. Hill, MITEI

Welcoming the Martin Fellows, 2011–2012

The Martin Family Society of Fellows for Sustainability was established at MIT in 1996 by Lee ’42 and Geraldine Martin through The Martin Foundation, Inc., to foster graduate-level research, education, and collaboration on issues related to sustainability. At a dinner held on September 14, 2011, 23 graduate students from across the Institute were welcomed into the society for the academic year 2011–2012. Two weeks later, Martin Fellows spent a weekend retreat at Harvard Forest in Petersham, Massachusetts. Managed by Harvard University, this 3,500-acre research forest is one of the oldest and most intensively studied forests in North America.

Photos: Justin Knight

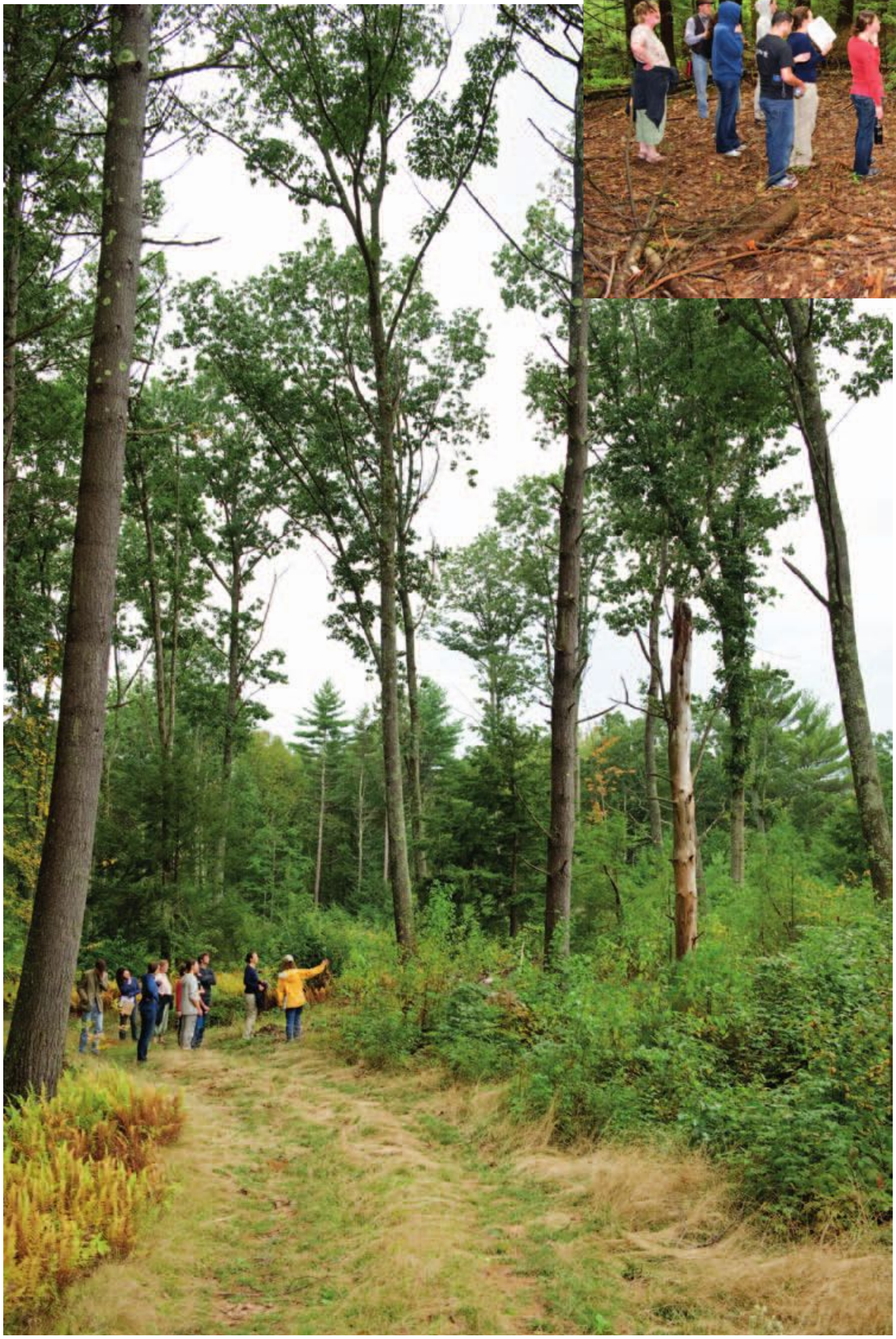
Hallie Martin (far left) and her father, Casper Martin (far right), a director of the Martin Foundation, Inc., join members of the 2011–2012 group of Martin Fellows at the annual induction reception and dinner in September.

MIT Chancellor W. Eric Grimson, the Bernard M. Gordon Professor of Medical Engineering and professor of computer science and engineering, stresses the importance of interdisciplinary training and urges Martin Fellows to take full advantage of the opportunity for cross-disciplinary collegiality offered by the Martin Society.

Benjamin Scandella G of civil and environmental engineering receives a certificate marking his entry into the Martin Family Society of Fellows for Sustainability from Heidi Nepf, professor of civil and environmental engineering and a member of the Martin Fellowship selection committee.

Audrey Barker-Plotkin, licensed forester and Harvard Forest research site coordinator, leads Martin Fellows on a tour around Harvard Pond. This picturesque pond, ringed by dense hemlock forest and pockets of open-land habitat, supports a diversity of aquatic and terrestrial plant and animal life and is also rich in cultural remnants from the Colonial era.

Audrey Barker-Plotkin explains a new experimental treatment in an eastern hemlock stand. The fenced "exclosure" prevents moose—but not deer—from grazing within the 20-meter-square plot. The experiment, which also includes plots that exclude both moose and deer, will demonstrate the potential impacts on plant species diversity of a continued increase in moose and deer populations in the region.



Martin Fellows and Harvard Forest staff discuss the effects of the recent harvesting of a red pine plantation, where hardwoods—such as the red oak trees pictured here—were left standing.

Frequent sightings of wildlife, particularly the Eastern newt (shown here in the terrestrial juvenile, or "red eft," stage), were a highlight of the retreat.

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 89 seed grant projects across the campus as well as fellowships for nearly 200 graduate students in 20 MIT departments and divisions.

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Portuguese Science and Technology Foundation

Members as of November 1, 2011

MITEI Associate and Affiliate Members

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

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Photo: Andy Ryan

MIT Sloan building: A model for future campus construction

The new MIT Sloan School of Management building (E62) is a showcase of high-performance, integrated design—the product of a decade-plus process of collaboration among MIT leaders, future occupants, architects, engineers, and others. Key features of E62 include a tight building envelope with triple-insulated windows; carbon-dioxide sensors that trigger fresh airflow; and advanced lighting and shade controls that maximize the use of natural daylight while ensuring comfortable temperatures. The end result: a 43% reduction in energy use compared to that of a standard office building. See page 37 for more details.