Energy Futures

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Making electricity with photovoltaics: No sunshine required

IN THIS ISSUE

Energy Futures

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Update on the MIT Energy Initiative

Dear Friends,

MIT is celebrating its sesquicentennial—honoring the innovators, leaders, educators, alumni, and students who have shaped the Institute, consistently contributed to solutions of major national and global challenges, and often invented unexpected technology-driven futures. This history has in turn shaped the MIT Energy Initiative (MITEI), as our faculty, staff, students, and partners work to help transform how we produce, distribute, and consume energy.

The April 1861 Commonwealth of Massachusetts "Act to Incorporate the Massachusetts Institute of Technology and to Grant Aid to Said Institute" deserves some reflection. William Barton Rogers and 20 other citizens were "hereby made a body corporate… for aiding generally, by suitable means, the advancement, development, and practical application of science in connection with arts, agriculture, manufactures, and commerce." This represented a significant departure from the historic focus of higher education on classical studies, taken in response to the Industrial Revolution. The emphasis on collaboration with industry has been a distinguishing feature of MIT among institutions of higher education and is central to MITEI's construct. Our Founding and Sustaining members support a broad spectrum of innovative and transformative energy research.

The 1861 Act has a second part that is less often referenced—"…to Grant Aid to Said Institute." This was an early recognition of the importance of public support for higher education as an enabler of economic growth. In 1861, it took the form of a land grant. Eighty-four years later, Vannevar Bush—another prominent MIT contributor to the development of the US research and educational enterprise—extended the rationale for public support to encompass national security and public health as well with his seminal report *Science: The Endless Frontier.* Today, MITEI has built upon the foundation of industry collaboration by facilitating a strong engagement with government, and specifically with the Department of Energy (DOE). As detailed in previous issues of *Energy Futures,* the DOE has established important peer-reviewed programs that span basic energy research to energy technology commercialization and that have engaged the innovation capacity at MIT and other research universities for multiyear research efforts.

The energy system is facing tremendous uncertainty in light of recent events. Coal use faces the uncertainty both of carbon dioxide emission mitigation policies and, in the United States, of Environmental Protection Agency regulation to limit emissions of criteria pollutants, mercury, and perhaps carbon dioxide.

Oil supply has the challenge of the Deepwater Horizon spill and the geopolitical uncertainty of the "Arab Spring" in the world's leading oil-producing region. Exploration in the deepwater of the Gulf of Mexico has been slowed, and oil prices have again reached levels that pose challenges to economic recovery in the major oil-consuming economies.

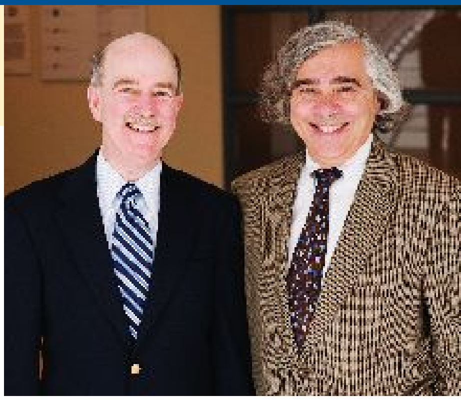
Shale natural gas supply, which has greatly increased domestic supply, is experiencing significant opposition because of concerns about environmental impacts, both in producing regions and in exploration regions, such as France.

The nuclear power "renaissance" has been cast into confusion by the events at Fukushima. While the cause and final impact of the Japanese nuclear crisis are unknown at present, reexaminations of both life extension of current plants and the pace of new plant construction are on the table.

Renewables are also raising complex issues. For example, the intermittency of wind, and to a lesser extent solar, has created electricity system challenges as these sources have increased market share, elevating concerns about the unintended consequences of deployment mandates in the absence of cost-effective storage or other system approaches to matching supply and demand.

Sorting out all of this will take some time, reinforcing the importance and timeliness of the MITEI mission. Yet, it is clear that some combination of these and other energy supplies must be employed to meet growing energy demand, especially in the developing world. This brings us back to the efforts of the faculty, staff, and students engaged with MITEI.

This edition of *Energy Futures* highlights some of the multitude of research and education programs that aim to innovate energy technologies, policies, and business models and to train a new generation with the knowledge and skills to make a difference in the MIT tradition. MITEI was fortunate to host Todd Stern, the chief US climate change negotiator, for our Earth Week colloquium. Mr. Stern noted that the lack of commitment to the Kyoto Protocol in Cancun—including that of the United States and China—should not be "cause for despair" and suggested that we could still make substantial progress in reducing greenhouse gas emissions



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

through investments in emissions-reducing technologies and support for a range of policies and standards that have multiple benefits—climate, security, economy. Increasingly, it appears that lower-cost low-carbon technology will be the "pull" on carbon policy, rather than the other way around.

The MITEI seed fund program is one of our key initiatives for facilitating such research and, as described in this edition, generous support from our alumni is allowing us to materially increase the scale and scope of the program. This amplifies the core support of our MITEI Founding and Sustaining members. We are very grateful for this targeted support and for the enthusiasm of the alumni to help seed new research directions. This round of seed funds had a particular emphasis on efficiency, a prime example of technology and policy advances with multiple benefits.

MITEI continues to drive a number of studies and symposia that aim to bring analysis that is firmly grounded in technology reality to the policy debate. A number of reports have been issued since the last edition of *Energy Futures*. Options for large-scale reductions in carbon dioxide emissions are examined in detail in two major MITEI-led energy studies—*The Future of the Nuclear Fuel Cycle* and *The Future of Natural Gas*—completed this year. These studies are designed to provide policymakers and industry leaders with unbiased, in-depth research and analysis to inform their decision-making on critical no- and low-carbon fuel options.

The results of two symposia held last year have also been published: *Electrification of the Transportation System* and *The Role of Enhanced Oil Recovery in Accelerating the Deployment of Carbon Capture and Sequestration.* This symposium series is proving to be an effective form of outreach to the policy community on timely issues, and we are evaluating options to expand the activity and its impact. All of these reports can be accessed through the MITEI website (web.mit.edu/mitei).

This edition also chronicles the considerable progress that is being made on campus energy management. We have an unusually productive alliance between our faculty, students, and MITEI staff, and those responsible for managing the campus, resulting in both novel educational activities and real results in energy efficiency and operational cost savings. Alumni support was crucial for launching these important programs.

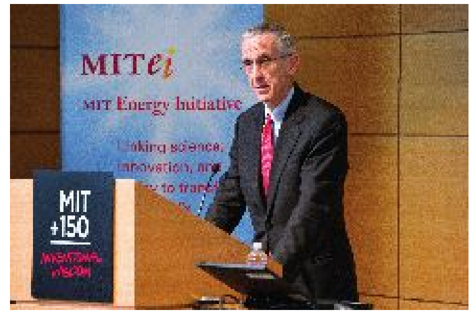
We are gratified by your enthusiasm and support, and aspire to take an appropriate place in the next chapter of MIT's history as an initiative that made a difference!

Sincerely,

Professor Ernest J. Moniz
MITEI Director

Professor Robert C. Armstrong
MITEI Deputy Director

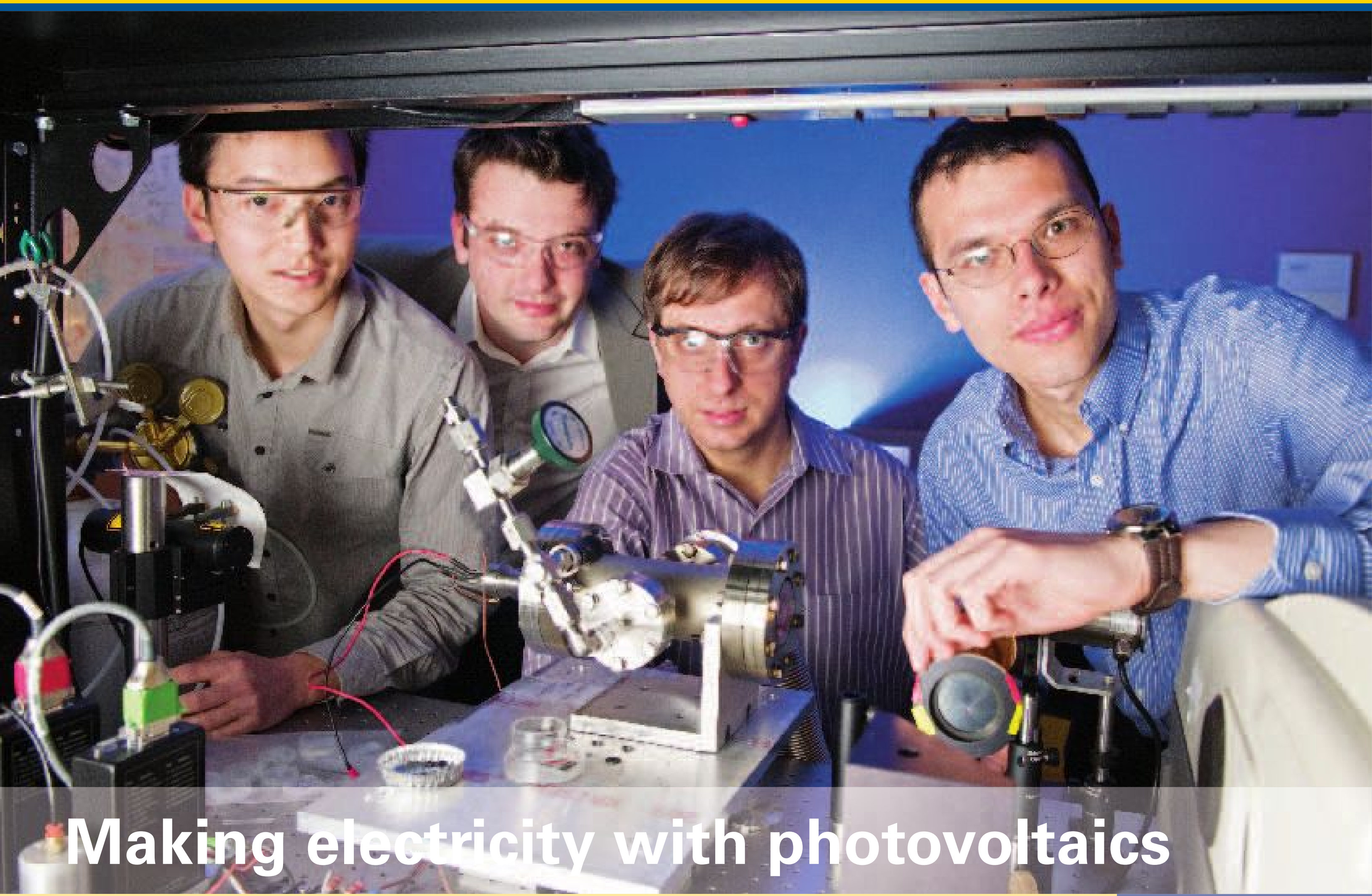
June 2011



Photos: Justin Knight

In an address hosted by the MIT Energy Initiative (MITEI) on April 21, Todd Stern, Special Envoy for Climate Change, US State Department, stressed that the United States should continue to move forward in addressing climate change issues, despite the absence of a global climate treaty. Stern's address was part of an Earth Week colloquium co-sponsored by MITEI and the Joint Program on the Science and Policy of Global Change in coordination with MIT150 celebrations.

Following Stern's talk, an MIT panel discussed scientific developments in climate change over the past 150 years and made projections for the next 100 years, based on climate models and on-the-ground action to address global warming effects. Panel members included (left to right) Kerry Emanuel, the Breene M. Kerr Professor of Atmospheric Science; Ronald Prinn, the TEPCO Professor of Atmospheric Science; MITEI Director Ernest Moniz, the Cecil and Ida Green Professor of Physics and Engineering Systems; Christopher Knittel, the William Barton Rogers Professor of Energy Economics; and Sarah Slaughter, MITEI's associate director for buildings and infrastructure. Moderating was John Reilly (not shown), co-director of the MIT Joint Program on the Science and Policy of Global Change. Videos of Stern's address and the panel discussion are archived at web.mit.edu/mitei/news/video.html.



Making electricity with photovoltaics

No sunshine required

Photo: Justin Knight

A novel MIT technology is now making possible remarkably efficient photovoltaic (PV) systems that can be powered by the sun, a hydrocarbon fuel, a decaying radioisotope, or any other source of heat. The key to the efficient operation: a specially engineered material that absorbs the heat and then—because of billions of nanoscale pits on its surface—selectively radiates to the PV cell only those wavelengths that the cell can convert into electricity.

Based on that technology, the MIT researchers have fabricated a button-sized power generator that's fueled by butane, can run

Above (from left): YiXiang Yeng, graduate student in electrical engineering and computer science (EECS); Ivan Celanovic ScD '06, research engineer in the Institute for Soldier Nanotechnologies (ISN); Marin Soljačić, associate professor of physics and ISN researcher; and Walker Chan, graduate student in EECS.

three times longer than a lithium-ion battery of the same weight, and can be recharged instantly by snapping in a tiny cartridge of fresh fuel. Another device, powered by a radioisotope, should generate electricity for 30 years without refueling or servicing—an ideal source of electricity for spacecraft that head out of our solar system.

According to the US Energy Information Administration, 92% of all the energy we use involves converting heat into mechanical energy and then often into electricity. But today's mechanical systems have drawbacks: their reliability is poor (moving parts can break); their efficiency is relatively low; and they can't be successfully scaled down to the small sizes needed to match so many of today's power-consuming devices, from sensors to smart phones to medical monitors.

"Being able to convert heat from various sources into electricity without moving parts would bring huge benefits," says Ivan Celanovic ScD '06, research engineer in the Institute for Soldier Nanotechnologies (ISN), "especially if we could do it efficiently, relatively inexpensively, and on a small scale—a few millimeters, centimeters, or meters."

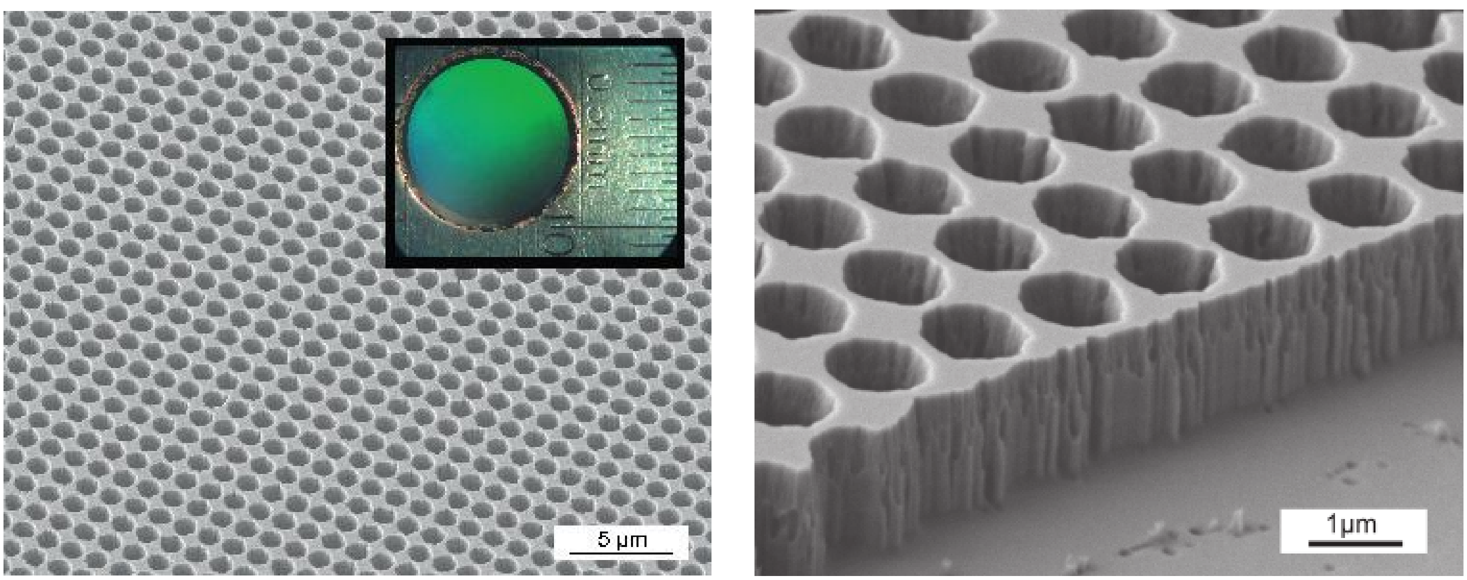
PV cells are solid-state electricity generators—and they needn't always run on sunlight. Half a century ago, researchers developed thermophotovoltaics (TPV), an approach that couples a PV diode (the active part of a solar cell) with any source of heat. In a TPV system, a burning hydrocarbon, for example, heats up a solid piece of material called the thermal emitter; the thermal emitter radiates heat and light onto the PV diode; and the PV diode generates electricity.

Because the thermal emitter is not as hot as the sun is, its radiation includes far more infrared wavelengths than occur in the solar spectrum. "Low band-gap" PV materials invented less than a decade ago can absorb more of that infrared radiation than standard silicon PVs can; but much of the heat is still wasted, so efficiencies remain relatively low.

An ideal match

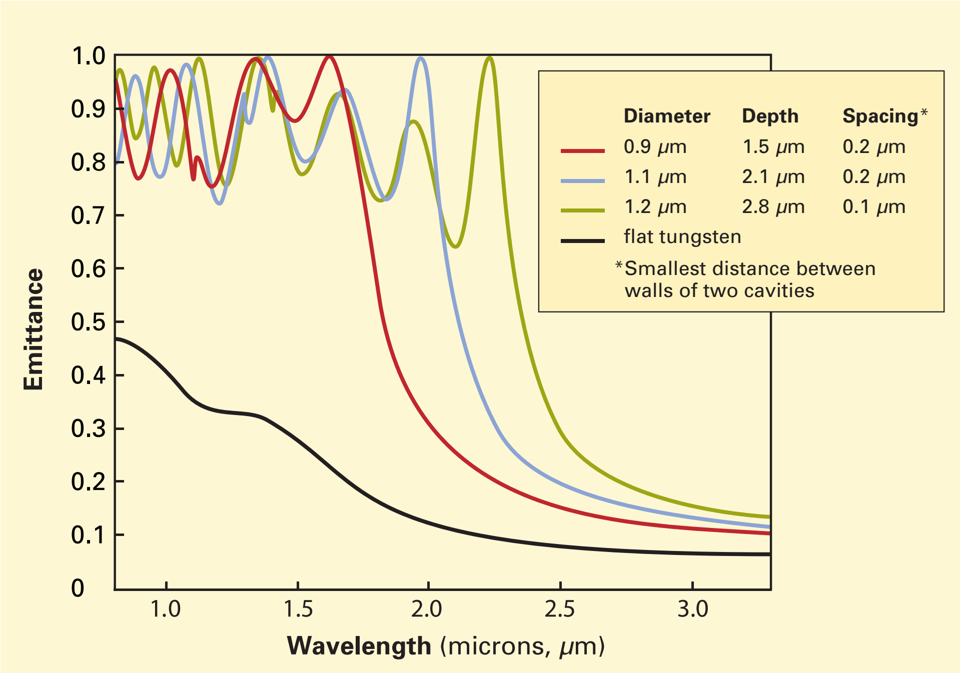
The solution, says Celanovic, is to design a thermal emitter that radiates only the wavelengths that the PV diode can absorb and convert into electricity—and suppresses emission of all other wavelengths. "If you have perfect spectral matching between your heat source and your PV diode, you'll get optimal efficiency for the overall system," he says.

Tungsten photonic crystals for thermophotovoltaic (TPV) system



Using new nanofabrication techniques, MIT researchers made these samples of tungsten with billions of regularly spaced, uniform nanoscale holes on their surfaces. In their TPV system, this type of photonic crystal serves as a thermal emitter, absorbing heat and then—because of its surface structure—radiating to the PV diode only those wavelengths that the diode can convert into electricity. The inset shows a digital photo of the full 1 cm-diameter sample, illuminated by white light. The color suggests the diffraction of white light into green as a result of the surface pattern.

Tailoring the emission spectrum by tailoring the nanostructure



This diagram demonstrates how manipulating the nanostructure of the tungsten photonic crystal can affect the spectrum of the light it emits. (Emittance is an indicator of radiation efficiency.) In this example, the three colored spectra come from heated tungsten samples that contain nanoscale holes of differing diameters, depths, and spacing. Those differing geometries dramatically change the dominant wavelengths in the emitted light. The spectrum drawn in black is from a sample of tungsten with a smooth surface.

"But how do we find a material that has this magical property of emitting only at the wavelengths that we want?" asks Marin Soljačić, associate professor of physics and ISN researcher. The answer: make a photonic crystal. Take a sample of material and on its surface create some nanoscale features—say, a regularly repeating pattern of holes or ridges. Light will now propagate through the sample in a dramatically different way than it did when the material was in its natural form.

"By choosing how we design the nanostructure, we can create materials that have novel optical properties," says Soljačić. "This gives us the ability to control and manipulate the behavior of light."

This powerful approach—co-developed by John D. Joannopoulos, the Francis Wright Davis Professor of Physics and ISN director, and others—has been widely used to improve lasers, light-emitting diodes, and even optical fibers. But to the MIT team, this new type of material was exactly what they needed to engineer the spectrum of their thermal radiation to what their PV diode could use.

Designing the photonic crystal

To start, they needed a material that could be heated to extremely high temperatures and then glow with an intensely bright light. The obvious choice was tungsten, which for 100 years has served as the filament in incandescent light bulbs. To make a slab of tungsten into a photonic crystal, they created an array of tiny pits—cylindrical cavities—on the surface. When the slab heats up, it generates a bright light but now with an altered emission spectrum.

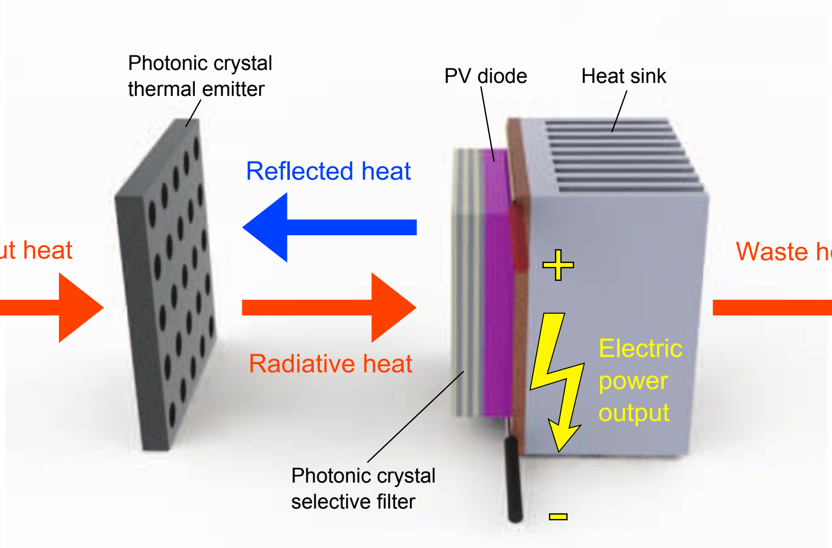
Why? Each pit acts as a resonator, capable of giving off radiative heat at only certain wavelengths. It thus provides wavelength selectivity. Celanovic offers as an analogy an acoustic resonator. "It's kind of like when you put a seashell next to your ear and you hear a humming noise. You hear the noise amplified at the resonant frequencies of the seashell cavity. It's the same principle, the same physics, but rather than acoustic resonance, this is electromagnetic resonance," he says.

To implement their "designer material," the researchers needed to find a practical means of fabricating a nanoscale structure in tungsten. After much work, they developed a method based on lithography and reactive ion etching, processing techniques used to make small features, for example, on microprocessors. In their case, interference between two overlapping laser beams creates an etch mask with identical tiny holes, which are then transferred to a tungsten substrate by reactive ion etching. Using that approach, the MIT team has fabricated tungsten photonic crystals that are 1 cm in diameter with surfaces that contain billions of tiny holes, equally spaced from one another and nearly uniform in diameter and depth (see the photos on page 5).

The diagram above demonstrates how manipulating the surface geometry changes the spectral emittance of a photonic crystal. The curves show thermal emittance at various wavelengths. The spectrum drawn in black is from a heated tungsten sample that has a smooth surface. The three colored spectra are from tungsten samples that contain holes of differing diameters, depths, and spacing. As a result, their emission spectra are distinctly different. "So by changing the geometrical parameters of a photonic crystal for a given material, you can tune the cutoff between where it radiates and where it doesn't radiate," says Celanovic.

The diagram to the right shows the basic setup of their photonic crystal-enabled TPV system. Heat from a source at the left raises the temperature of the tungsten photonic crystal—the thermal emitter—which radiates heat at selected wavelengths toward the PV diode, and the diode converts it into electric power. Despite careful tailoring, the tungsten emitter delivers some heat at wavelengths that the PV diode cannot convert into electricity. To prevent that waste, the researchers mount on the face of the diode another photonic crystal, this one fabricated with a series of alternating layers of silicon and silicon dioxide—a nanostructure that can be tailored to transmit certain wavelengths and reflect others. Here, it reflects any radiation at unacceptable wavelengths back to the tungsten emitter, where it is reabsorbed and subsequently reemitted to provide more heat at wavelengths that the PV diode can use.

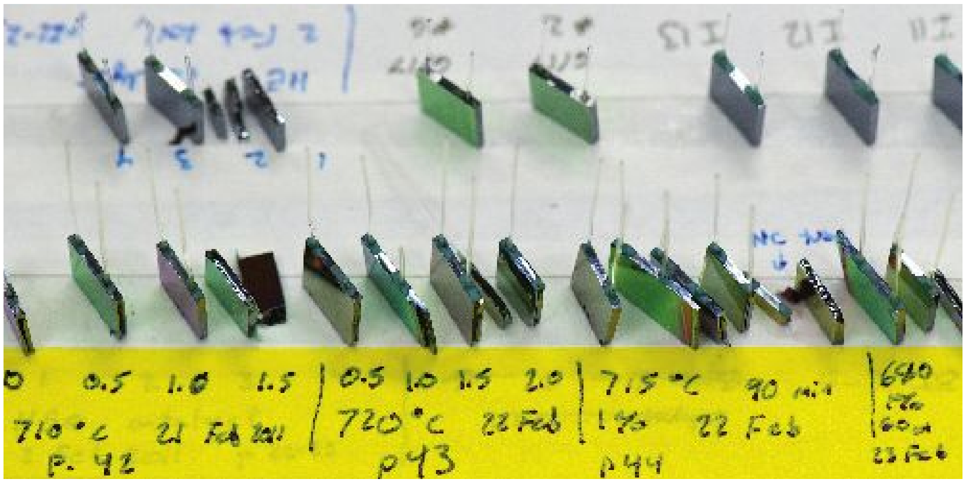
The efficient TPV system

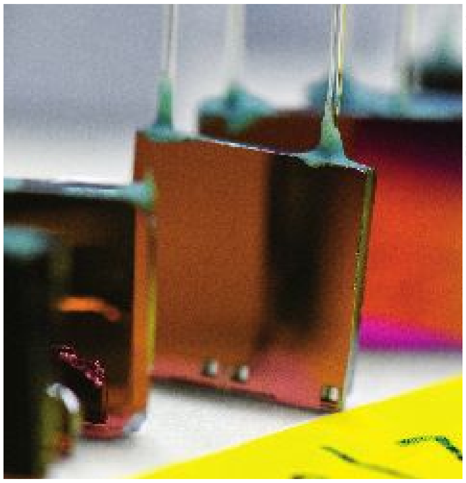


In this novel MIT design, input heat from an energy source raises the temperature of the tungsten photonic crystal, which transmits radiative heat at selected wavelengths to the PV diode. A second photonic crystal—mounted on the face of the PV diode—lets through heat at wavelengths that the diode can convert into electricity and reflects the rest back to the tungsten photonic crystal, where it is reabsorbed and reemitted. Electricity from the PV diode passes to an electronic circuit that adjusts its voltage to match the external device being powered.

Deploying their novel TPV system

Using this TPV system, the MIT team is working with collaborators at MIT and elsewhere to create several novel electricity-generating devices. One example is the micro-TPV power generator, a button-sized solid-state device that uses as its heat source hydrocarbon fuels such as butane or propane. At the heart of the device is a "micro-reactor" designed by Klavs Jensen, the Warren K. Lewis Professor of Chemical Engineering, and fabricated in the Microsystems Technology Laboratories. This tiny reactor is a silicon chip with an interior channel where injected fuel undergoes catalytic reaction, generating heat. Photonic crystals are deposited on the top and bottom surfaces of the micro-reactor, and low band-gap PV diodes are placed above and below the reactor separated by tiny gaps. Heated by the





Photos: Justin Knight

Each of these silicon chips is a micro-reactor with photonic crystals on both faces and external tubes for injecting fuel and air and ejecting waste products. Inside an interior channel, the fuel and air react, heating up the photonic crystals. In a complete system, that heat would pass to electricity-generating PV diodes that would be mounted just above and below each face, separated by a tiny gap.

micro-reactor, the TPV system generates electricity, which passes to an electronic circuit that was specially designed by Robert Pilawa, graduate student, and David Perreault, associate professor, both of electrical engineering and computer science. The circuit dynamically adjusts the voltages and currents to suit a smart phone, sensor, or other device while extracting the maximum amount of power from the TPV system.

Prototypes of their micro-TPV power generator are "pretty exciting," says Celanovic. The devices achieve a fuel-to-electricity conversion efficiency of about 3%—a ratio that may not sound impressive, but at that efficiency their energy output is three times greater than that of a lithium ion battery of the same size and weight. The TPV power generator can thus run three times longer without recharging, and then recharging is instantaneous: just snap in a new cartridge of butane. With further work on packaging and system design, Celanovic is confident that they can triple their current energy density. "At that point, our TPV generator could power your smart phone for a whole week without being recharged," he says.

Other work focuses on using radioisotopes—materials that undergo radioactive decay, giving off heat in the process. Their energy density can be orders of magnitude higher than that of chemical fuels, and radioisotopes need not be dangerous. (Indeed, some are used in pacemakers that are implanted for 10 years.) A TPV power generator fueled by a radioisotope could run for three or more decades and could be ideal for certain high-level applications that need electricity for years but are difficult or impossible to access for recharging. In one project, for example, the MIT team is working with collaborators at NASA and Creare, Inc. (Hanover, NH) to develop a radioisotope-based TPV generator for deep space probes—a setting where even the best rechargeable batteries and solar panels are not an option.

Finally, the researchers are looking at ways to use their photonic crystal to improve the conversion of solar energy into electricity. For example, optical concentrators such as parabolic mirrors could focus solar radiation onto a photonic crystal absorber and emitter, which would reshape the solar spectrum to better match the properties of a PV cell. Collaborators are members of the Solid State Solar Thermal Energy Conversion Center, which is directed by Gang Chen, the Carl Richard Soderberg Professor of Power Engineering.

Celanovic and Soljačić stress that building practical systems requires integrating many technologies and fields of expertise. "It's a really multidisciplinary effort," says Celanovic. "And it's a neat example of how fundamental research in materials can result in new performance that enables a whole spectrum of applications for efficient energy conversion."

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By Nancy W. Stauffer, MITEI

This research was supported in part by a seed grant from the MIT Energy Initiative. Research on the micro-TPV system was supported in part by the US Army Research Office through the Institute for Soldier Nanotechnologies. The radioisotope-TPV work was supported in part by the NASA Glenn Research Center under the Small Business Technology Transfer Program. The Solid State Solar Thermal Energy Conversion Center is supported by the US Department of Energy. Further information can be found in:

P. Bermel, M. Ghebrebrhan, W. Chan, Y. Yeng, M. Araghchini, R. Hamam, C. Marton, K. Jensen, M. Soljačić, J. Joannopoulos, S. Johnson, and I. Celanovic. "Design and global optimization of high-efficiency thermophotovoltaic systems." *Optics Express 18*, pp. A314-A334, 2010.

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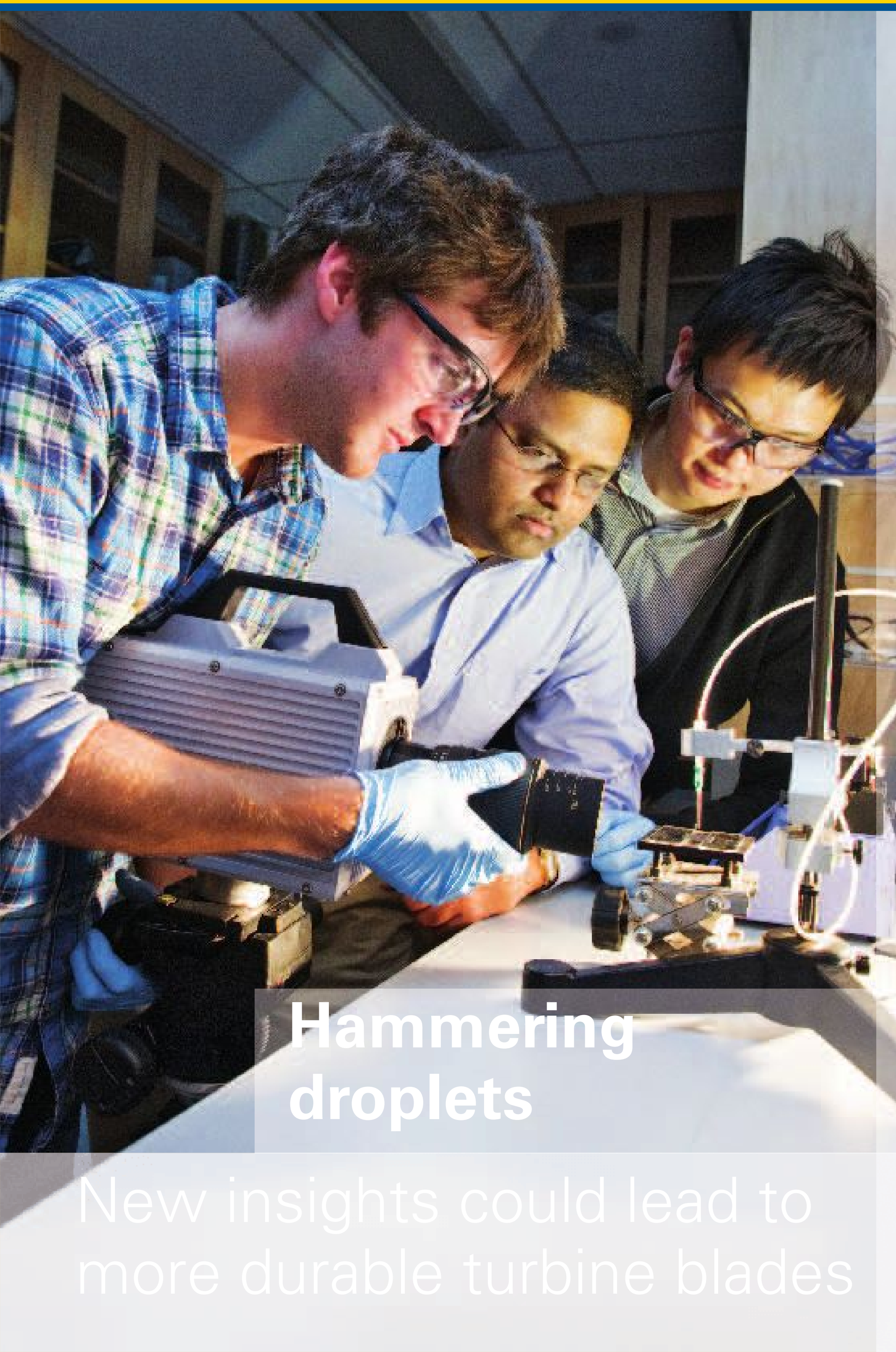
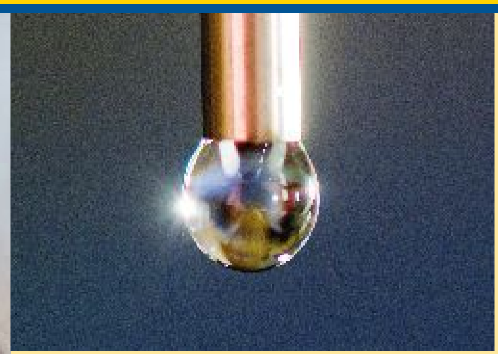




Hammering droplets

New insights could lead to more durable turbine blades

Photos: Justin Knight

Above: Professor Kripa Varanasi (center) with graduate students Adam Paxson (left) and Hyuk-Min Kwon, all of mechanical engineering.

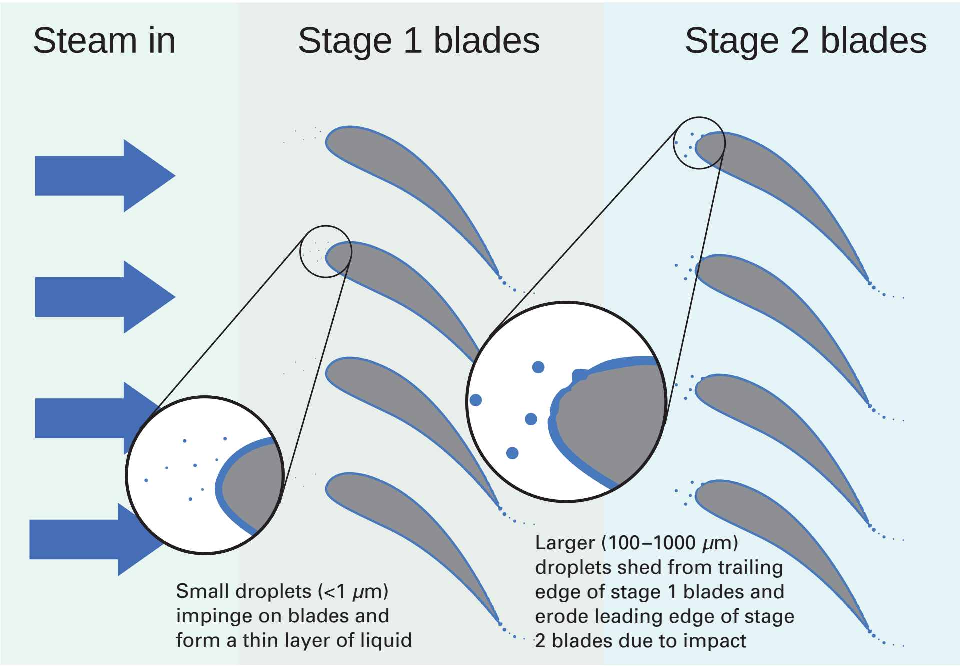
People living in older buildings often hear pounding noises in their plumbing or radiator pipes. It's a well-known effect called a water hammer, which can occur when a valve is suddenly opened or closed in a pipe carrying water or steam, causing a pressure wave to travel down the pipe with enough force that it can sometimes cause the pipe to burst. Now, new research shows that a similar effect takes place on a tiny scale whenever a droplet of water strikes a surface.

Kripa Varanasi, the d'Arbeloff Assistant Professor of Mechanical Engineering, says that awareness of the phenomenon could help engineers design more durable condensing surfaces, which are used in steam-based power plants and desalination plants.

Varanasi says the effect explains why blades used in power plant

Effect of droplet formation on steam turbine blade erosion and efficiency

Image: Adam Paxson G, MIT



As steam expands inside a turbine, small water droplets (submicron in diameter) spontaneously form. When these droplets hit a turbine blade, they adhere, creating a film of liquid that is propelled along the blade by the high-velocity steam. As this flow reaches the trailing edge of the blade, it sheds to form much larger drops (100s of microns). Because of the droplets' large size and velocity, the turbine has to do work on them to accelerate them through the turbine. In addition, the impact of the drops onto subsequent turbine blades results in massive water hammer pressures causing severe erosion. Hence, moisture formation leads to significant mechanical, aerodynamic, and thermodynamic losses, resulting in a substantial decrease in overall turbine efficiency.

turbines tend to degrade so rapidly and need to be replaced frequently, and could lead to the design of more durable turbines. Since about half of all electricity generated in the world is produced using steam turbines—whether driven by coal, nuclear fuel, natural gas, or petroleum—improving their longevity and efficiency could reduce the downtime and increase the overall output for these plants.

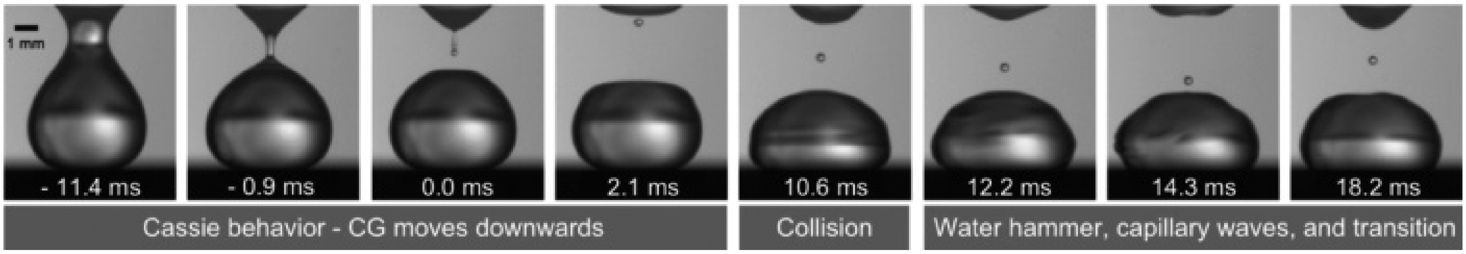
There has been widespread interest in the development of superhydrophobic (water-repelling) surfaces, Varanasi says, which in some cases mimic textured surfaces found in nature, such as lotus leaves and the skin of geckos. But most research conducted so far on how such surfaces behave have been static tests. To see the way droplets of different sizes spread out on such surfaces (called wetting) or how they bead up to form larger droplets, the typical method is to add or subtract water slowly in a stationary droplet. But this is not a realistic simulation of how droplets react on surfaces, Varanasi says.

"In any real application, things are dynamic," he says. And the research performed by Varanasi and his collaborators—graduate students Hyuk-Min Kwon and Adam Paxson of mechanical engineering and Associate Professor Neelesh Patankar of Northwestern University—shows that the dynamics of moving droplets hitting a surface are quite different from droplets formed in place.

Specifically, such droplets undergo a rapid internal deceleration that produces strong pressures—a small-scale version of the water hammer effect. It is this tiny but intense burst of pressure that accounts for the pitting and erosion found on power plant turbine blades, he says, which limit their useful lifetime.

"This is one of the biggest unsolved problems" in power plant design, he says. In addition to damaging the blades, the formation and growth of water droplets mixed with the flow of steam saps much of the power, accounting for up to 30% of the system losses in such plants. (See the figure to the left.) Since some steam-based power plants, such as natural gas combined-cycle plants, can already have overall plant efficiencies of up to 60% in converting the fuel's energy to electricity, eliminating these droplet losses could provide a significant boost in power.

Small-scale texturing of surfaces can prevent the droplets from wetting the surfaces of turbine blades or other devices, but the spacing and sizes of the surface patterns need to be studied dynamically, using techniques such as those developed by Varanasi and his team. Regularly spaced bumps or pillars on the surface can produce a water-shedding effect, but only if the size and spacing of these features are just right. This research shows that there seems to be a critical scale of texturing that is effective, while sizes either larger or smaller than that fail to produce the water-repelling effect. The new analysis



should make it possible to determine the most effective sizes and shapes of patterning for producing superhydrophobic surfaces on turbine blades and other devices.

This work is related to Varanasi's research on how to prevent ice formation on airplane wings, also using nano-texturing of surfaces. (For more details on that study, go to web.mit.edu/newsoffice/2010/frost-formation-1222.html.) But the potential applications of this latest research are much broader. In addition to power plant turbines, the findings could also affect the design of condensers in desalination plants and even the design of inkjet printers, whose operation is based on depositing droplets of ink on a surface.

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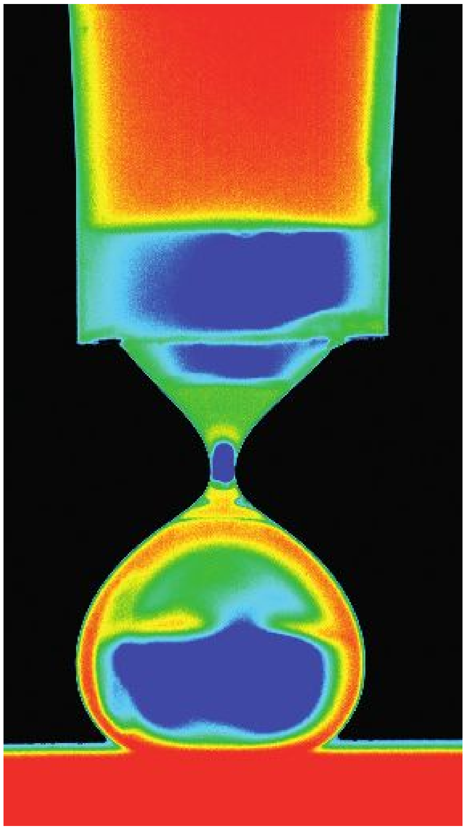
By David L. Chandler, MIT News Office

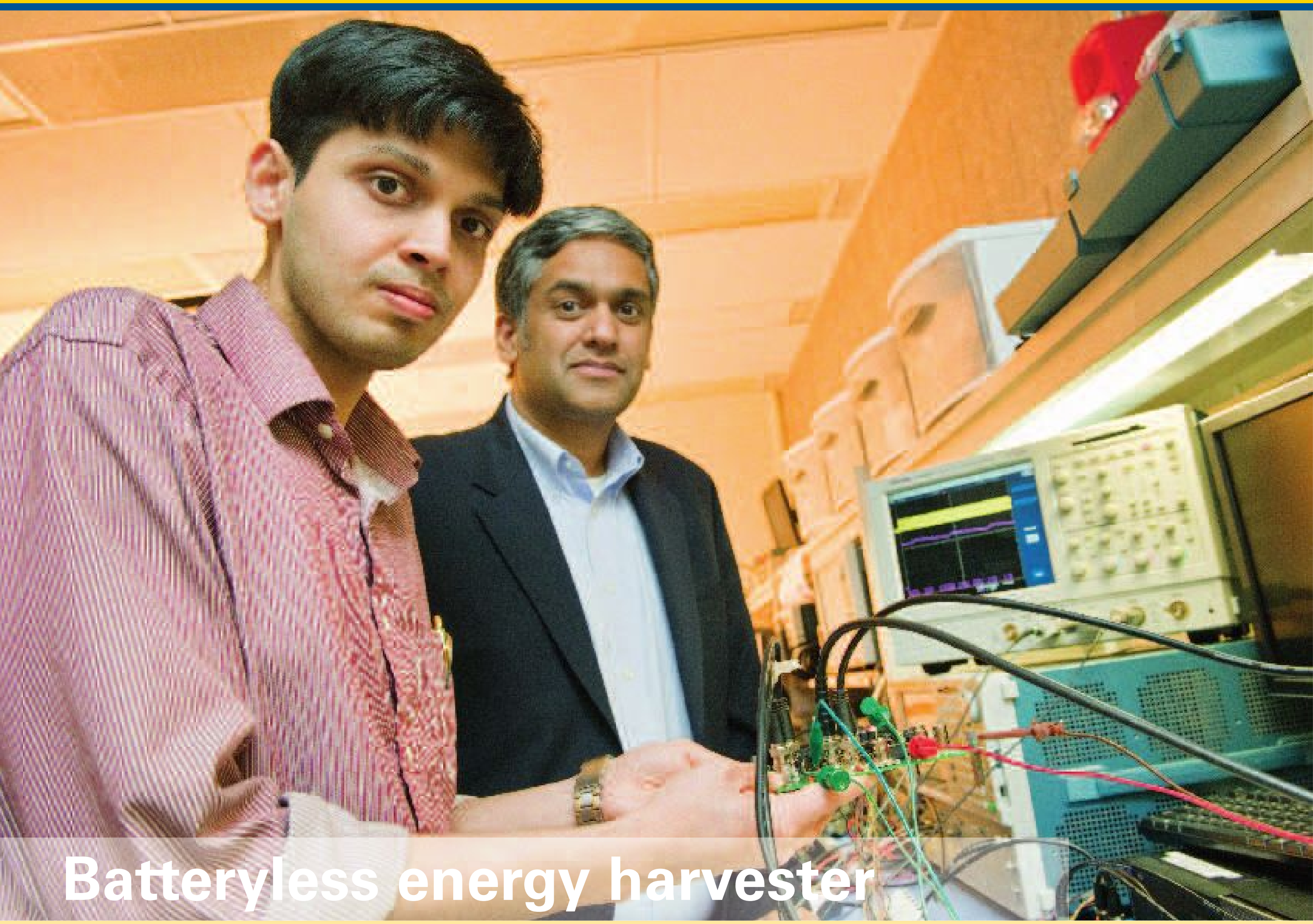
This research was funded by a seed grant from the MIT Energy Initiative, the National Science Foundation, the DuPont-MIT Alliance, and the Initiative for Sustainability and Energy at Northwestern University. MIT's Edgerton Center also provided high-speed video equipment. Further information can be found in:

H.-M. Kwon, A. Paxson, K. Varanasi, and N. Patankar. "Rapid deceleration-driven wetting transition during pendant drop deposition on superhydrophobic surfaces." *Physical Review Letters*, 20 January 2011.



Images: courtesy of Kripa Varanasi, MIT

This color-enhanced image shows a droplet of water being deposited on a superhydrophobic surface, just before it separates from the dropper used to deposit it. At the moment of separation from the dropper, ripples move down through the droplet, revealing the sudden deceleration caused by impact with the surface, which causes a brief burst of high pressure. For a video of the process, go to www.youtube.com/watch?v=YIsGXk7jxDE.



Batteryless energy harvester

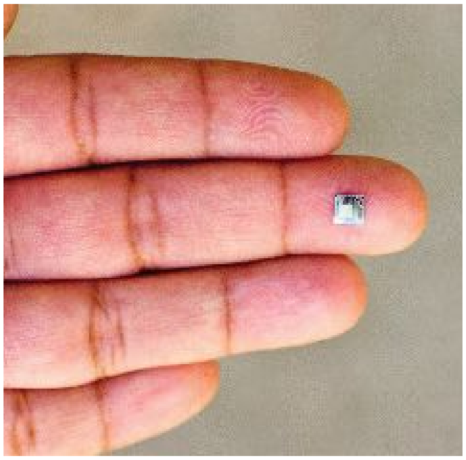
Running electronics on body heat

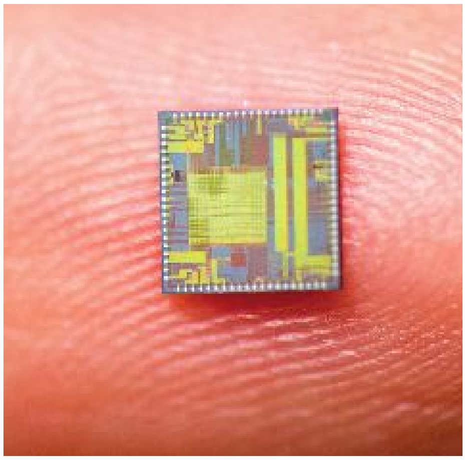
Photo: Justin Knight

MIT researchers have demonstrated a wearable power generator that uses the difference in temperature between your skin and the surrounding air—even just a couple of degrees—to produce a small, steady flow of power to run your medical monitor or your Bluetooth® headset. No need for a battery.

In the wearable power generator, a commercially available "thermal harvester" turns the temperature difference into electricity, but the

Above: Professor Anantha Chandrakasan (right) and graduate student Saurav Bandyopadhyay of electrical engineering and computer science.





Photos: Justin Knight

In a wearable power generator, a thermal harvester uses temperature differences to generate electricity, but the generated voltage and power are too small and variable to run an electronic device. The tiny chip shown above contains the MIT team's "interface circuit" that efficiently takes the harvester's output and delivers it to the electronic device in a form it can use—the key to a practical wearable system.

generated voltage and current are tiny. The MIT solution: a novel "interface circuit" that boosts that tiny voltage to a useful level, keeps it constant despite temperature changes, and delivers the highest-ever fraction of the power from the harvester to the device.

"Energy harvesting, in which energy is gathered wirelessly from temperature differences, vibrations, or other ambient sources, is an emerging technology that offers the promise of wireless powering of electronics indefinitely," says Anantha P. Chandrakasan, the Joseph F. and Nancy P. Keithley Professor of Electrical Engineering and director of the MIT Microsystems Technology Laboratories. "This technology directly addresses today's energy challenge by generating clean energy in a highly distributed manner."

Chandrakasan, Yogesh Ramadass SM '06, PhD '09, now an electrical design engineer at Texas Instruments (Dallas), and their colleagues have been working with a harvester that uses a thermoelectric material—a type of semiconductor in which a temperature difference between one side of a sample and the other produces electricity. Most work to exploit this effect focuses on generating power from temperature differences of tens to hundreds of degrees, for example, to run industrial monitors and sensors.

In general, there is a temperature difference between the surface of a person's skin and the ambient air (unless the air is exactly 98.6° F). A thermoelectric device worn on an arm or leg could use that difference to run wearable devices such as medical monitors, toxic gas sensors, and portable communications and video gadgets.

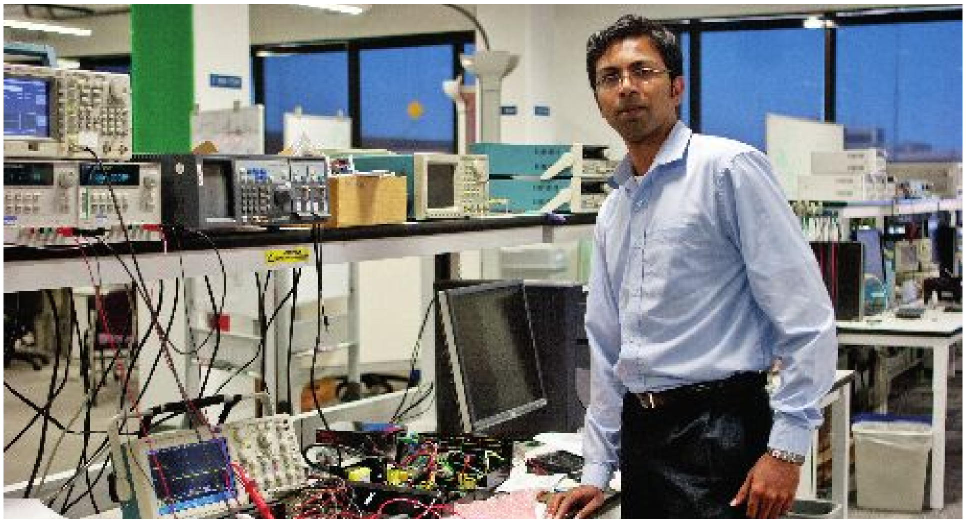


Photo: Gangadhar Burra, Texas Instruments (Dallas)

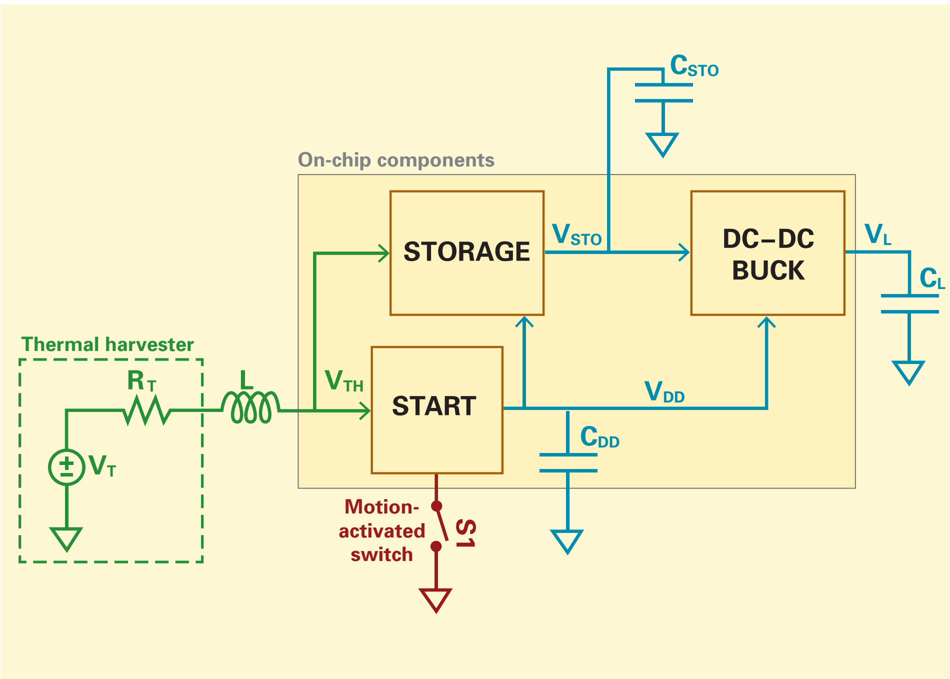
With support from the MIT Energy Initiative, Yogesh Ramadass SM '06, PhD '09 developed the first-generation MIT interface circuit for a wearable power generator. Ramadass is now an electrical design engineer at Texas Instruments (Dallas).

Until recently, that scenario was just a dream because such devices needed far more power than a wearable thermal harvester could produce. But over the past decade, the power consumption of such electronic devices has been reduced by a factor of 10 or even 100. "That's low enough that one can envision using an energy-harvesting system and eliminating the battery entirely," says Chandrakasan.

Even so, the output from a harvester can't be sent directly into an electronic device. The temperature difference in a body-worn harvester is generally only a few degrees, so it will generate just 25–50 millivolts (0.025–0.050 volts). Despite recent advances, electronic devices still typically require one or two volts to function properly. The amount of power such a harvester can generate is likewise tiny. And changes in external temperatures will cause the voltage and power generated by the harvester to vary, potentially damaging the device it's running.

Increasing the harvester's energy output is not feasible: its voltage is directly proportional to the temperature difference, and that relationship can't be changed. "So, to create a practical harvester system, we needed to add an interface circuit that could continuously deliver as much of the harvester's

Architecture of the MIT interface circuit



This circuit—shown above in a simplified overview—adapts the electrical output of a wearable power generator so that it can run an electronic device in place of a battery. The commercial thermal harvester at the left produces a tiny flow of power from the temperature difference between the surface of the skin and the ambient air. The power passes to the STORAGE block until its voltage is sufficiently high. It is then released to the DC-DC BUCK, which lowers the voltage and maintains it at the level required by the electronic device at the end (not shown). Key electronic components will not start up at the low initial voltage, so the circuit includes a motion-activated switch (shown in red) that turns on just long enough to raise the voltage to the critical level, thereby jump-starting the electronic circuit without need for a battery.

output as possible to the electronic device in a form that it could use," says Ramadass.

Conventional approaches to designing an interface circuit wouldn't do the trick. For one thing, a conventional system for voltage conversion would burn up all the available power, even when it's sitting idle. In addition, transistors used as switches in electronic circuits won't start operating below 1 V. Several groups designing body-worn harvesters use a battery to provide that startup voltage, but that approach would defeat the main goal of the MIT team—to go batteryless. An interface circuit suited to this application required some serious innovation.

Creative problem solving, effective design

The figure above shows a model of the basic architecture of the MIT interface circuit. In this overview, the harvester (drawn in green) and the three major blocks (in brown) contain many components and connections. Shown separately are the capacitors (C), which are used to store and accumulate electric charge as needed to control the flow of power through the circuit.

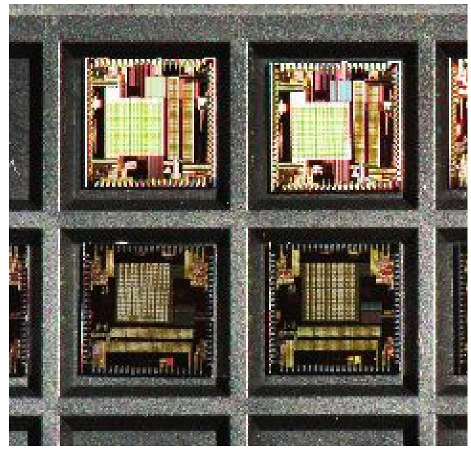


Photo: Justin Knight

Each of these chips contains all of the components within the gray outline in the diagram to the left.

During continuous operation, the 25–50 mV generated by the thermal harvester flows to the STORAGE block, which is designed to extract as much energy as possible and store it on the large capacitor called C_{STO}. Whenever the charge on C_{STO} exceeds 2.4 V, a switch opens and allows the energy to move onto the DC-DC BUCK, a converter that brings the voltage down to the level required by the electronic device—here 1.8 V—and keeps it steady as it is being used.

When the circuit is first starting up, the charge from the harvester is not sent to the STORAGE block but rather is stored temporarily on an external inductor (L), another type of storage component. To generate the voltage needed to "cold-start" the electronics, the design includes a special START block controlled by a switch run not by electricity but by vibrations. Inevitably, a person wearing a harvester will move a bit (swing an arm, shift a leg, look around). The resulting vibrations cause the motion-activated switch (a mechanical spring) to open and close—and just once is enough. During that time, current that has accumulated on the

"This technology directly addresses today's energy challenge by generating clean energy in a highly distributed manner."
— Professor Anantha P. Chandrakasan

external inductor while the switch was closed is released and charges up capacitor C_{DD}. When that charge exceeds 1 V, the transistors and other electronics begin to operate. The START block turns off, and power begins to flow directly from the harvester to the STORAGE block.

Cutting waste, maximizing efficiency

With so little power available, another concern is "end-to-end efficiency," a measure of how much of the extracted energy makes it from the harvester to the electronic device. Conventional controls for transferring energy from the harvester to the device consume a lot of power, so the MIT group instead uses a simple technique that compares voltages at the various capacitors on the circuit and then switches blocks on and off as needed to minimize power consumption. Ramadass stresses the importance of using digital controls. "The traditional analog approach to control works well at high power levels, but at low power levels you don't get good enough efficiency," he says.

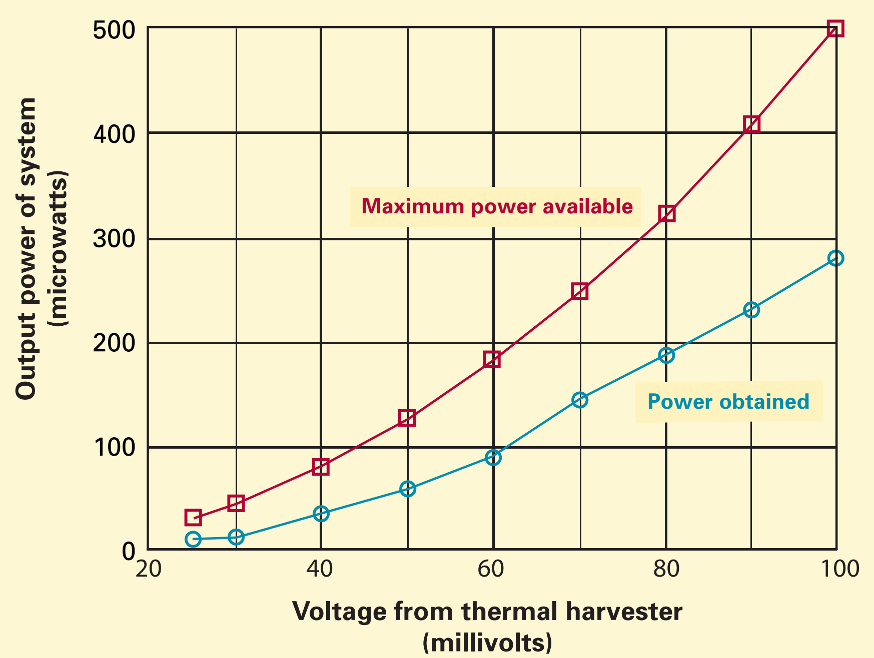
Another key to maximizing power transfer involves resistance, that is, the opposition to flow of an electric current through a material. Here, the goal is to match the resistance in the overall interface circuit to the resistance in the harvester (indicated in the diagram on page 14 as R_T). If there's a mismatch, some of the power from the harvester won't move onto the interface circuit. To ensure smooth power transfer, designers often use sophisticated algorithms to run the converter so it always matches the resistance of the energy source. But running such algorithms burns up power.

To avoid that loss, the MIT team uses a different approach. In their interface circuit, charge is sent to the big storage capacitor in discrete packets until the voltage builds up to the target level. The rate of transfer is controlled by a clock that turns transmission of the charge packets on and off. During the design process, the frequency of that on-off switching is set to a single value that can be calculated based on the resistance in the harvester and certain characteristics of the storage components. The result is that the resistances match, and they track together as temperatures change.

Demonstrations, features, and plans

Tests of their interface circuit with a commercially available thermal harvester produced encouraging results. The diagram below shows the output power of the system as a function of the voltage coming from the harvester (which changes with the temperature difference). The red curve shows the theoretical maximum power available from the system, while the blue curve shows the measured power at the end of the interface circuit.

End-to-end efficiency of MIT system



This diagram shows output power at the end of an experimental generator (a commercial harvester plus the MIT interface circuit) as a function of voltage coming from the harvester. The red curve shows the theoretical maximum power available from that system; the blue curve shows the power measured in tests with the actual device. The maximum end-to-end efficiency is 58% of the theoretical maximum, and the minimum voltage required to run the system (once it is operating) is just 25 millivolts.

"That curve captures the essence of the system," says Ramadass. "The system starts up at 35 mV input, but once it's started up, it operates all the way down to 25 mV, and the peak overall end-to-end efficiency is 58%." That efficiency is higher than in any other state-of-the-art system that includes the whole process—harvester to end use—and unlike the other contenders, the MIT system both delivers a regulated voltage and continues to produce maximum power as the temperature differential changes.

Chandrakasan likes to point out another feature of their interface. "The main storage capacitor could be viewed as a battery, but it is really more like an energy buffer," he says. "You can trickle charge it; and when you need to use it, you can burst out the energy." He notes that devices like sensors and medical monitors often have a "peaky" type of demand. "A sensor may wake up, transmit a lot of information, and then go back to sleep," he says. "While the sensor is sleeping, the system stores energy onto the buffer so that it's ready to deliver another burst when the sensor next wakes up."

The researchers are continuing to improve the performance of their interface circuit and are working to further miniaturize the whole harvesting system. In the longer term, they may increase storage capacity by incorporating new technologies such as the carbon nanotube-based ultracapacitors now being developed by MIT colleagues. They are also exploring the feasibility of having a single interface circuit that incorporates both heat- and vibration-harvesting devices and perhaps even a solar cell. Such a combined system could produce more power and would work well in situations where the energy sources vary and one or another might not always be available.

Meanwhile, the MIT team is continuing to reduce the power consumption of a range of electronic devices. "So we're working from both ends," says Chandrakasan. "By increasing the amount of energy generated by harvesters and decreasing the power consumption of electronic devices, we hope to make possible many new applications of these systems so we can increasingly rely on ambient sources of energy that are endlessly available everywhere."

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By Nancy W. Stauffer, MITEI

This research was supported by a seed grant from the MIT Energy Initiative and by the MIT Center for Circuits and Systems. Further information can be found in:

Y. Ramadass and A. Chandrakasan. "A batteryless thermoelectric energy-harvesting interface circuit with 35 mV startup voltage." *IEEE International Solid-State Circuits Conference, Digest of Technical Papers,* pp. 486–488, February 2010.

Deepsea oil and gas recovery: Designing robots that can help

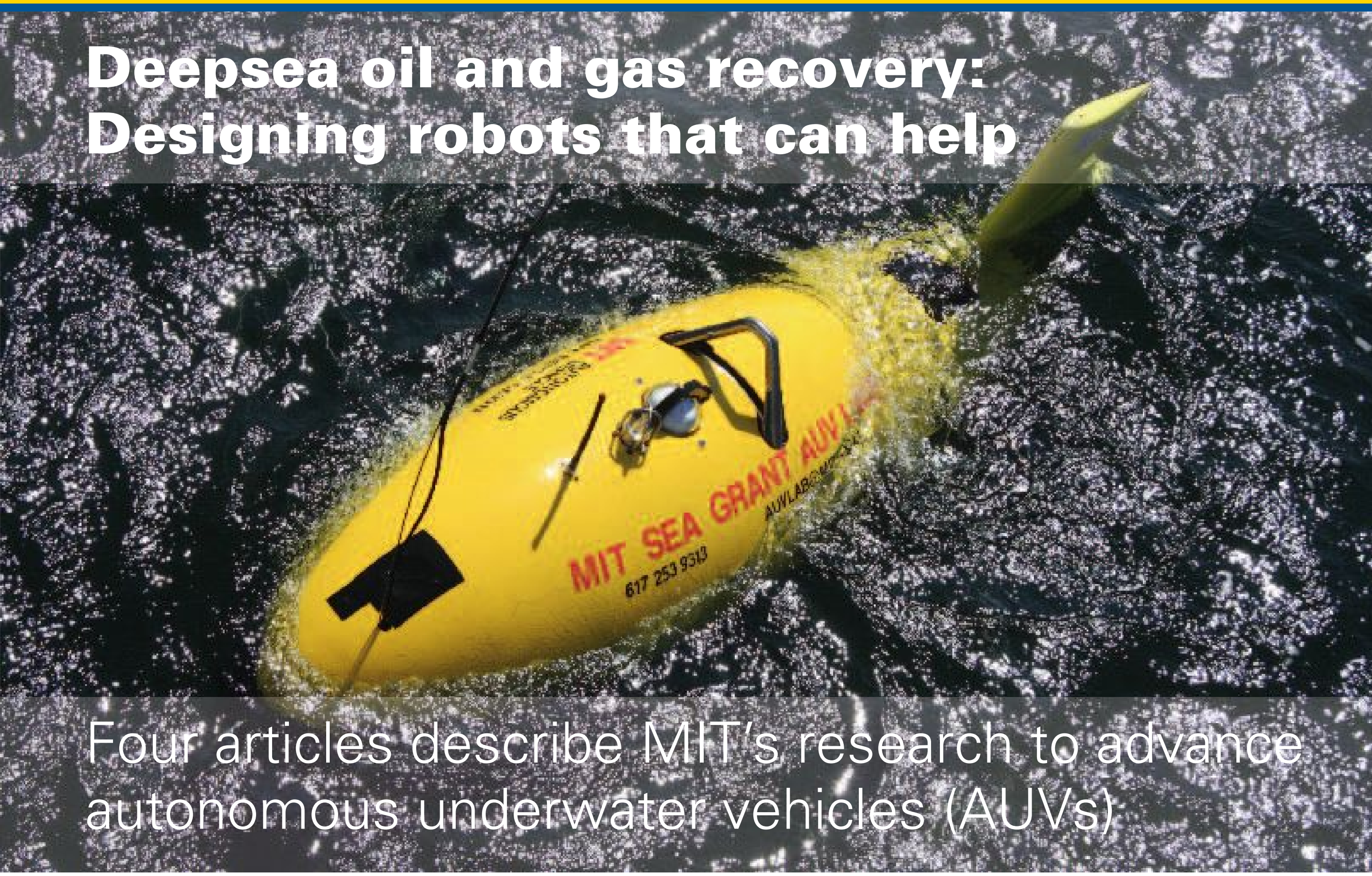

Photo: courtesy of MIT Sea Grant College Program

Four articles describe MIT's research to advance autonomous underwater vehicles (AUVs)

A critical challenge for energy companies running deepwater oil and gas operations is inspecting, maintaining, and repairing complex equipment at unprecedented ocean depths. Today, remotely operated underwater vehicles (ROVs) are invaluable in inspecting subsea structures and sending real-time videos and environmental data to human operators who supervise the task at hand. But those vehicles are connected by a data and power tether—a heavy cable that can be miles long and can easily get tangled and damage subsea structures.

About 20 years ago, MIT researchers started working on a solution: a small underwater vehicle that could do all those tasks without tethers, cables, or direct human intervention. Since then, MIT and others have developed so-called autonomous underwater vehicles (AUVs), which now work alongside the ROVs. Without the tether, the AUVs can be lighter, smaller, more maneuverable, and far less expensive than their tethered counterparts. But with no cable to transmit signals, communication with a human operator is difficult—and today's AUVs aren't quite ready to do the necessary tasks without instruction. As a result, they are generally limited to collecting data and delivering it to the surface.

MIT teams are now working to make AUVs that can perform more complex functions, thereby combining the attractive features of the tethered and the untethered vehicles. Already they have developed an AUV that can cruise efficiently in the deep ocean and then stop to hover near a site of interest or concern. Other research activities focus on extending the vehicle's capabilities. If all goes as planned, future AUVs will wirelessly send videos of what they're seeing to onshore operators. They will navigate with no human guidance, simultaneously making a map of their surroundings and pinpointing their own locations on the map. They will monitor nearby ocean currents and eddies, and will respond with maneuvers that keep their travels efficient and precise. And they will anchor firmly onto pipes or other surfaces while they turn a valve or repair a leak.

The articles that follow provide a closer look at that work and its motivations.

AUVs
From idea to implementation

As the search for oil and natural gas resources moves into deeper and deeper water, companies are facing increasing costs. Building and installing a single offshore drilling platform now costs more than a billion dollars, so companies are using their platforms as efficiently as possible. Advances in technology have enabled them to service several oil fields from a single platform, and much of the infrastructure for well operations has moved to the seafloor, which may be as much as 4,000 meters (almost 2.5 miles) below the surface. As a result, inspecting, servicing, and repairing underwater equipment has become an ever-greater challenge.

Many companies accomplish those tasks using remotely operated vehicles (ROVs)—robots that are operated by a person aboard a surface vessel. Because radio signals do not propagate through seawater, the ROVs are connected to the vessel by cables that carry data as well as power. But as the distance between a platform and its wells has increased, the cables, or "tethers," have become longer and heavier. To support that weight, the vessels needed to launch and recover them have become larger and more expensive. Running an ROV and its ship now costs a quarter of a million dollars per day.

For the past two decades, MIT researchers have been working on a different approach motivated by the notion that "small is good"—the operating premise of Chryssostomos Chryssostomidis, director of the MIT Sea Grant College Program, the Doherty Professor of Ocean Science and Engineering, and professor of mechanical and ocean engineering. "In the late 1980s, I suggested a revolutionary concept: an underwater vehicle that has no tether and travels in the deep ocean without input from an operator," says Chryssostomidis. The AUV would be fully functional and operational but always small so that deploying it wouldn't require a huge ship. Getting rid of the tether would make it far more maneuverable and flexible. It could get into small spaces—for example, after an accident—without worrying about the tether dragging along and getting tangled.

Photo: courtesy of MIT Sea Grant College Program

MIT researchers launch Odyssey IV for sea trials off Woods Hole, Massachusetts. The vehicle weighs 450 kg (1,000 lb). Once in the water, it can cruise at speeds of up to 1.4 meters per second or can hover in place.

The goal, therefore, was to make an AUV that the offshore industry could use to service its deepwater operations—and that researchers could use to explore and monitor the deep ocean. To that end, in 1989 Chryssostomidis founded the Autonomous Underwater Vehicles Laboratory within the MIT Sea Grant College Program, and he and his colleagues began developing a series of AUVs.

A first challenge was how to navigate without knowing details of the deepsea landscape. Early efforts were helped by insights from roboticist Rodney Brooks, now the Panasonic Professor of Robotics (emeritus). Brooks' idea was that the AUV—like other robots—didn't need to know anything about its environment. It only needed to know when it was approaching an obstacle and should go right, left, up, or down to avoid a collision. "So he enabled me to start developing AUVs without having to address that problem," says Chryssostomidis.

Since then, the lab has developed and demonstrated a series of AUVs, all of them small, relatively inexpensive, and artificially intelligent. Of particular note was the early "Odyssey" series of vehicles, which had a torpedo shape with a streamlined horizontal axis specially designed for efficient cruising. For a decade, Odyssey II vehicles have run successful surveying missions, demonstrating rapid long-distance travel and good battery life due to their hydrodynamic efficiency.

But while surveys are important, they are not enough. "The next frontier is going to be intervention," says Chryssostomidis. An AUV will examine, say, the footing of an oil platform or another piece of subsea equipment and then perform a task. An Odyssey II vehicle isn't suited to such close study. Like a shark, it must keep swimming forward in order to maintain its maneuvering capability. As a result, it can prepare a detailed image of an object only by repeatedly circling over it, taking a photo at each pass.

Performing close-up inspections, service, and repairs would be better accomplished by an AUV that could stop and hover in one place. Members of the AUV Lab and their collaborators therefore designed a hovering AUV, which has a full six degrees of freedom while standing still and is extremely maneuverable. However, its lack of a streamlined axis doesn't allow for efficient cruising, and its small thrusters and battery don't provide enough force to withstand any but the smallest of currents.

Enter the Odyssey IV, a hybrid cruising/hovering vehicle that gains advantages from both vehicle designs. This two-meter-long craft has a smooth, teardrop profile derived from the streamlined body of the Odyssey II, and it has four commercial off-the-shelf thrusters—one in the bow, one in the stern, and two mounted on arms that protrude out the sides of the vehicle and can be rotated about its lateral axis. A custom-designed battery consisting of 648 lithium ion cells provides the vehicle with the power necessary to fight currents and the longevity to dive to full ocean depth. The vehicle's conservative size and weight make it deployable from small, less-expensive boats, but it still has room inside for a substantial payload.

In sea trials, the Odyssey IV has demonstrated that it can both move quickly and hover in place. It can travel through the deep ocean—6,000 meters below the surface—at a rate of 1.4 meters per second when going straight ahead. Having located its objective, the Odyssey IV can precisely hold its position to within centimeters of the desired location. If a current pushes it in one direction, its controller activates the appropriate thruster and brings it back into position. It can thus hover like a helicopter, making detailed inspections of particular subsea structures or the natural landscape. It can also pick up samples and other cargo from the deep sea and bring them back to the surface for inspection and analysis.

Remaining challenges include developing better power-storage and communications capabilities so that the vehicles can stay underwater longer and send back more information to operators on shore. Chryssostomidis notes that his team has made great strides in both areas. The Odyssey IV has enough power that it can operate for a day or more without refueling, and an onshore operator can receive still frames of what the AUV is "seeing" with only a few-second delay (due to the time it takes for sound to travel through water). The researchers continue to improve the efficiency with which video is transmitted under water, largely due to new techniques of data compression developed by Milica Stojanovic, a visiting scientist at MIT Sea Grant and associate professor at Northeastern University.

What's the future? To illustrate, Chryssostomidis refers to the blowout preventer—the device that's at the heart of underwater operations and that dominated news reports about the BP accident. For now, he is sure he will be allowed to send an AUV within five meters of a blowout preventer and observe. If all goes well, he predicts that in a few years he'll be allowed to have an AUV touch that critical piece of equipment. In a few decades, the AUV may perform a real repair. And one day, Chryssostomidis says, an AUV will be able to do tasks without a human in the loop. It will head underwater, locate a problem, make a judgment, formulate a plan, and perform a repair—all on its own.

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By Nancy W. Stauffer, MITEI

This research was supported by Chevron, DeepStar, the Office of Naval Research, and National Sea Grant—National Oceanic and Atmospheric Administration. For more information on the MIT Sea Grant College Program's Autonomous Underwater Vehicles Laboratory and its activities, see the following publications and visit auvlab.mit.edu/.

J. Eskesen, D. Owens, M. Soroka, J. Morash, F. Hover, and C. Chryssostomidis. *Design and Performance of Odyssey IV: A Deep Ocean Hover-Capable AUV*. 16th International Symposium on Unmanned Untethered Submersible Technology, 2009.

J. Morash, R. Damus, S. Desset, V. Polidoro, and C. Chryssostomidis. *Adapting a Survey-Class AUV for High Resolution Seafloor Imaging*. 14th International Symposium on Unmanned Untethered Submersible Technology, August 2005.

M. Rentschler, F. Hover, and C. Chryssostomidis. "System identification of open loop maneuvers leads to improved AUV flight performance." *IEEE Journal of Oceanic Engineering*, April 2005.

Navigating blindfolded

Where am I—and where have I been?

Imagine dropping an underwater vehicle into the ocean and having it survey the ocean floor for debris from an accident or examine a ship's hull for signs of damage. Without any outside guidance or prior knowledge, the vehicle would traverse the target area in a methodical fashion, never repeating itself or going astray and all the while generating a map that shows the surface of interest.

An MIT team has developed advanced mathematical techniques that enable such a scenario to occur—even when the area being examined is large, complex, and cluttered, and the information coming from the vehicle's sensors is not always clear and accurate.

"A big problem for an autonomous underwater vehicle (AUV) is knowing where it's been, where it is now, and where it should go next—without any outside help," says John J. Leonard, professor of mechanical and ocean engineering and a member of the MIT Computer Science and Artificial Intelligence Laboratory. Navigating underwater is tricky. Radio waves don't propagate through seawater, so an AUV can't use GPS as a guide. Optical methods don't work well. Computer vision is difficult, even for terrestrial robots; water reflects and refracts light in complex ways; and visibility may be poor due to murkiness and turbidity.

What's left? Sound waves, which can be monitored by acoustic sensors. To help an underwater vehicle navigate, a deepwater energy company may drop a network of acoustic transponders onto the seafloor. The vehicle exchanges acoustic "pings" with the transponders, generating data with which it can calculate its position. But sometimes the signal bounces off extraneous objects, producing inaccurate data. Sometimes several robots share multiple transponders, leading to confusion. And sometimes deploying enough transponders to cover a sufficiently large area is prohibitively expensive.

"So here's the challenge. You want to place the AUV at an unknown location in an unknown environment and—using only data from its acoustic sensors—let it incrementally build a map while at the same time determining its location on the map," says Leonard. Robot designers have studied the so-called mapping problem for decades, but it's still not solved. As Leonard notes, it's a chicken and egg problem: You need to know where you are to build the map, but you need the map to know where you are.

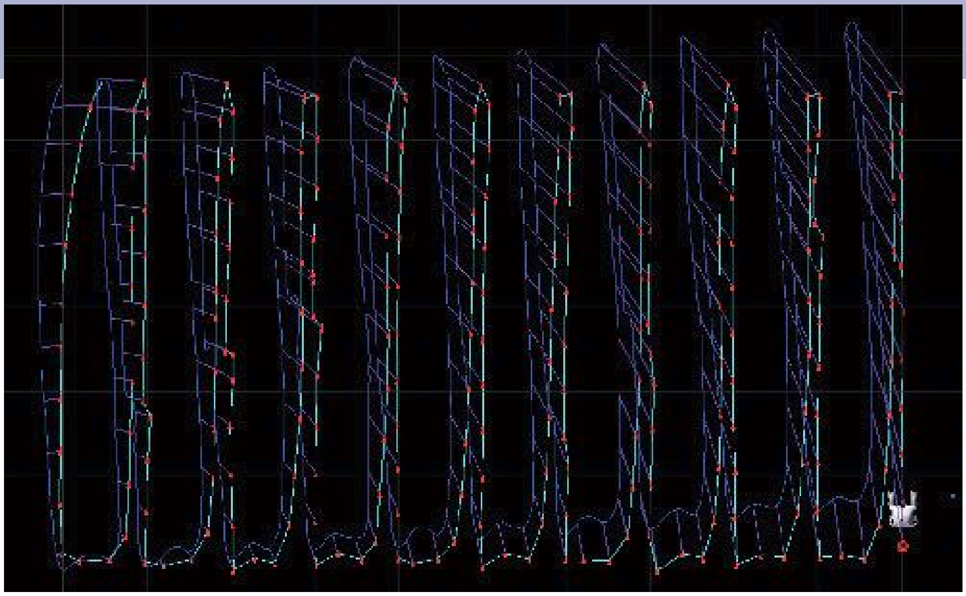
To illustrate how robotic mapping works—and doesn't work—Leonard considers the aftermath of a hypothetical accident. The seabed is covered with debris, and we need to figure out where it all is. We'd like to send down our AUV and have it cruise back and forth in a lawn-mower-type pattern, recording information about where it is and what it sees.

One conventional way of accomplishing that task is using dead reckoning. The AUV starts out at a given position and simply keeps track of how fast and in what direction it's going. Based on that information, it should know where it is located at any point in time. But the calculations to determine its position quickly become wrong, and over time, the error grows "without bounds." Leonard likens it to mowing the lawn blindfolded. "If you just use dead reckoning, you're going to get lost," he says. Using expensive accelerometers, gyroscopes, and other equipment will make the error grow more slowly but not eliminate it entirely.

So how can an AUV use poor data from relatively inexpensive sensors to build a map? To tackle that problem, Leonard and his team have been using a technique called Simultaneous Localization and Mapping, or SLAM. With this approach, the AUV records information, builds a map, and concurrently uses that map to navigate. To do so, it keeps track of objects that it observes—in the accident example, say, a particular piece of debris on the seafloor. When the AUV detects the same object a second time—perhaps from a different vantage point—that new information creates a "constraint" on the current map. The computer program generating the map now adds that object and at the same time optimizes the map to make its layout consistent with this new constraint. The map adjusts, becoming more accurate.

"So you can use that information to take out the error—or at least some of the error—that has accrued between the first time you saw that object and the next time you saw it," says Leonard. Over time, the program continues to optimize the map, finding the version that best fits the growing set of observations of the vehicle's environment.

In some cases, the AUV may see the same object again just a few minutes later. Identifying it as the same object is easy. But sometimes—especially when surveying a large area—the AUV may see the same object early on and then again much later, possibly even at the end of its travels. The result is a "loop closing" constraint. "That's a very powerful constraint because it lets us dramatically reduce the error," says Leonard. "That helps us get the best estimate of the trajectory of the vehicle and the structure of the map."



This figure shows results from using MIT's SLAM technique in an experiment performed in collaboration with Franz Hover, Finmeccanica Career Development Professor in the Department of Mechanical Engineering. In the experiment, a hovering autonomous underwater vehicle must examine a 20 meter by 12 meter area of the seafloor in a back-and-forth lawn-mower pattern. The blue line shows the pathway resulting from calculations based on dead reckoning. The green line shows the pathway corrected using the SLAM algorithms. The red dots and purple lines link uncorrected and corrected readings at specific locations. Without the constant correction, the dead reckoning pathway would soon go wrong and the vehicle would be lost. To see a movie of the run, go to groups.csail.mit.edu/marine/hauv/videos/2009-11-30-Sailing.avi.

While SLAM has been studied for several decades, the Leonard group has made significant advances. For example, they've come up with new computational algorithms that can calculate the most likely map given a set of observations—and can do it at high speed and with unprecedented accuracy, even as new sensor information continues to arrive (see the figure above). Another algorithm can help determine whether a feature that the robot sees now is in fact the same one it saw in the past. Thus, even with ambiguous data, the algorithm can reject incorrect "feature matching" that would have made the map less rather than more accurate.

Finally, their methods ensure that uncertainty is explicitly addressed. Leonard emphasizes that SLAM may not produce a perfect map. "It's easy for a vehicle to get fooled by errors in the acoustic information," he says. "So we don't want to be overconfident. There's a certain inherent uncertainty to the sensor data, and it's important to get that uncertainty right. So we're not only building the map but also including the right error bounds on it."

A problem of particular interest to Leonard is using AUVs to enable rapid response to accidents and other unforeseen events. For example, one challenge during the BP oil spill was determining whether there was a spreading plume of oil and, if so, tracking where it was going. A network of AUVs working together could play a critical role in carrying out such tasks.

To that end, Leonard and his team are developing techniques that will enable AUVs to communicate with one another so that they can navigate and collect information cooperatively. "If they can share information, they can accumulate data far more quickly than if they work alone," he says. "Together, they'll be able to sweep a large area and quickly produce the best possible map so that people can understand what's going on and develop and implement an effective response."

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By Nancy W. Stauffer, MITEI

This research was supported by the Office of Naval Research and by the MIT Sea Grant College Program. Further information can be found in:

A. Bahr, M. Fallon, and J. Leonard. "Cooperative localization for autonomous underwater vehicles." *International Journal of Robotics Research*, v. 28, pp. 714–728, June 2009.

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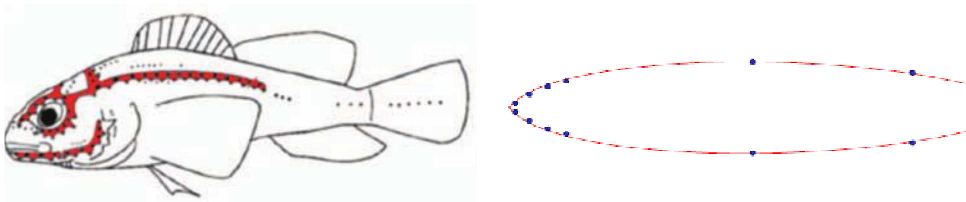
Going with the flow

Pressure sensors help guide ocean-going vessels

Anyone who has steered a boat has experienced the effort needed to keep the boat on course when currents are pushing it in a different direction. Now, MIT researchers have developed sensors that can measure the pressure of flows around an ocean-going vessel so that it can utilize rather than fight those flows, saving energy and improving maneuverability. Other work aims to go a step further: to change flows from patterns that impede progress to patterns that will help.

Sensing flows



"Lateral lines" in fish contain hundreds of tiny pressure and velocity sensors that enable them to navigate through currents and eddies as efficiently as possible. To mimic that ability, MIT researchers have developed inexpensive, sensitive MEMS-based pressure sensors and mounted them on a small experimental vessel in a pattern that replicates the distribution of the lateral lines.

Flows around autonomous underwater vehicles (AUVs) and other vessels—from ships to submarines—can significantly affect their performance. For example, when a vessel going 20 mph turns sharply, it pushes into the current on one side and creates swirling eddies on the other; as a result, its speed can suddenly drop to 7 mph. The behavior of control surfaces such as rudders and propellers can also be affected. A propeller operating in waves, for instance, can experience cavitation, a phenomenon in which vapor layers form around the blades, impeding performance. Preventing such phenomena could mean smoother, more energy-efficient operation. Indeed, ocean-going vessels are now responsible for 8.6% of the world's total annual oil consumption, so even a small increase in efficiency could mean significant energy savings.

Natural sea creatures do not experience such problems because they have special organs that enable them to sense their environment. In many fish, dark-colored "lateral lines" running down their sides and around their heads contain hundreds of tiny pressure and velocity sensors that perceive every minute change in the water flowing by, enabling the fish to turn or take other appropriate action. The effect can be astonishing. The Mexican cavefish, for example, lives in absolute darkness. As a result, it has no eyes and must navigate using only its lateral lines. In an experimental setting, a cavefish can dart among obstacles, moving quickly along their edges and ducking through openings between them.

"We want to design sensors for our vessels that can do exactly what the lateral lines do for fish," says Michael Triantafyllou, the William I. Koch Professor of Marine Technology and professor of mechanical and ocean engineering. "But while we get ideas from fish, we needn't use exactly the same design that they do." In fish, the lateral lines are made up of systems of fluid-filled canals containing tiny hairs that monitor flows and send messages directly to the fish's brain.

"This is an organ we don't have, so we have no idea of how it really works; but it's good because it's simple and doesn't require the intense computation that vision requires, for example," says Triantafyllou. The engineered version should likewise generate "simple signals so that—without using a huge computer—we know immediately what's going on and can take action."

To design and fabricate his pressure sensors, Triantafyllou turned to the MIT Microsystems Technology Laboratories (MTL). There, experts make various types of inexpensive, high-performance sensors based on microelectromechanical systems (MEMS)—the technology of small mechanical devices driven by electricity. Led by Jeffrey Lang, professor of electrical engineering, an MTL team designed arrays of pressure sensors, each of which is a 2-mm-wide cavity covered by a 20-micron-thick silicon membrane that bends in response to pressure. A metal strain gauge on the surface of each membrane senses that deflection and generates a signal that indicates pressure. Electronic systems amplify and integrate the signals from all the sensors, producing pressure information that can be continuously displayed online.

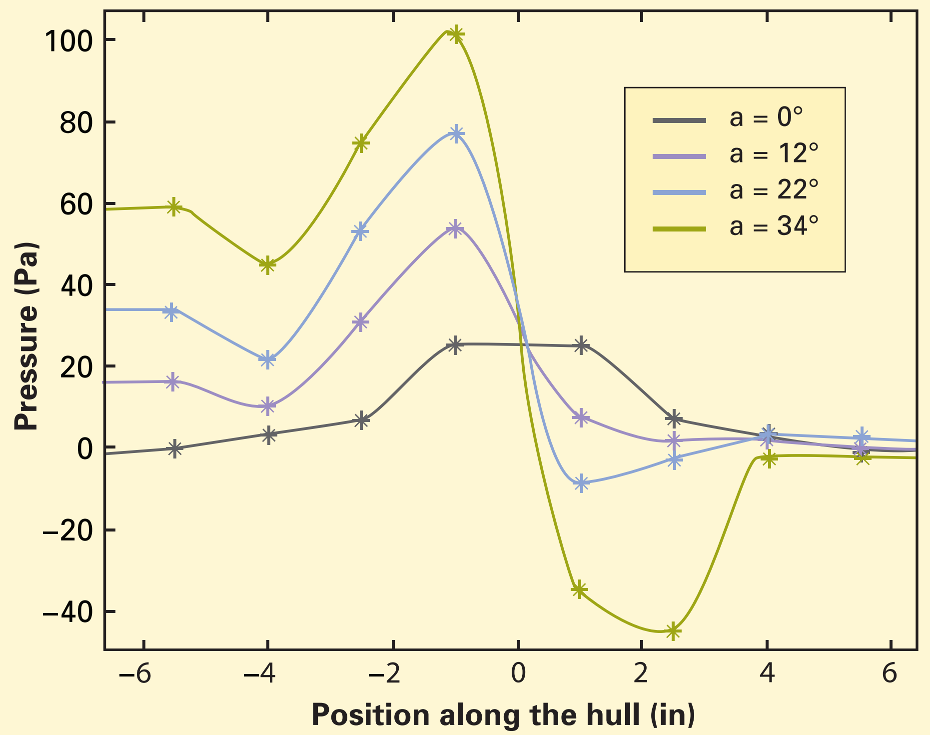
In tests on small vessels and propellers, the sensor arrays proved robust and even more sensitive than expected. In one set of experiments, Triantafyllou and his colleagues in the Center for Ocean Engineering equipped a small vessel with sensors in locations that mimic where they are on fish (see the schematics above). They also installed commercially available sensors that would generate reliable measurements for comparison and guidance. Then they performed experiments in the 108-foot-long MIT Towing Tank, a test facility equipped with a wave generator.

In those experiments, they simulated a commonly occurring situation: A vessel is traveling straight ahead, but the oncoming current is approaching at an angle, so the vessel must exert energy to offset that force. A more energy-efficient approach would be to head straight into the current as long as possible and then turn, much as a sailboat tacks in the wind. Pressure measurements could guide the execution of such an energy-saving maneuver.

To replicate that situation, the researchers propelled their vessel directly into oncoming flows from the wave generator and then at a gradually increasing angle. The graph to the right shows pressure measurements from the sensor at the nose of the boat (the zero point) and from the sensors down each side. The black curve displays results when the vessel is heading straight into the current. Pressure is highest at the nose and lower at the sides, with the side readings symmetrical left and right. The purple line shows results when the boat is 12 degrees off the center, and therefore subject to the force of a side current. The pressure at the nose is the same, but readings on the left and right sides are no longer symmetrical. As the angle increases, that asymmetry increases dramatically. The low pressure on one side and high on the other creates a drag force that must be overcome—a significant waste of energy.

"The effect is very detectable," says Triantafyllou. "These sharp pressure signals can guide us as we develop techniques to navigate and maneuver more efficiently."

Effects of side currents on magnitude and distribution of pressure



These curves show measurements at pressure sensors located at the nose and down the sides of an experimental vessel as it is towed straight into an oncoming current and then at increasing angles to that flow. As the angle of attack increases, so does the difference between the pressure readings on the two sides of the boat. Overcoming the drag force created by that situation means that significantly more energy is required to stay on course. Such results can help researchers develop navigating techniques that will reduce energy consumption and improve maneuverability.

Other work aims to detect eddies, swirling fluid structures that can also profoundly affect navigation. Again, fish use their lateral lines to identify eddies—and then take advantage of them. In one video, a trout swims in a tank as eddies come toward it from first one side and then the other. The trout senses the eddies and then uses their suction force to stay in one place without swimming, thereby expending little energy.

To test their ability to identify eddies, the researchers again used the MIT Towing Tank. For these tests, they seeded the water with small particles and shone a laser beam from below so as to observe the patterns of flow without disturbing them. Four sensors measured pressure as hand-generated eddies swirled through the tank. Based on the pressure signals, a flow model estimated the position and strength of the eddies. The model accurately tracked the behavior of the eddies within the tank.

Triantafyllou and his team are now developing methods of controlling flows that interfere with propulsion and maneuverability. In one project, they designed a torpedo-shaped submersible vehicle that has pressure sensors plus two small rotating cylinders running down its sides. When the submersible heads at an angle into the oncoming flow, the pressure sensors detect the formation of eddies and start the small cylinders spinning. The cylinders spin in opposite directions, creating suction that immediately prevents eddies from forming.

The team is also looking at another possible animal model: the whisker of a seal. This organ has a remarkable ability to sense the velocities of flows. In experiments, a blindfolded harbor seal can detect the passage of a fish by using its whiskers to sense changes in flow velocity—even 30 seconds after its prey has passed by.

The researchers recently acquired whiskers shed by seals at the New England Aquarium. They have now developed large-scale models of these elaborate, undulating structures and are developing computer simulations of how they behave. "We're trying to understand why these whiskers work so well," says Triantafyllou. "Once again, we hope to emulate the ability of sea-going creatures to sense flows around them—a prerequisite to developing ways to make our vessels more energy efficient and maneuverable."

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By Nancy W. Stauffer, MITEI

This research was supported by the Center for Environmental Sensing and Modeling of the Singapore-MIT Alliance for Research and Technology and by the National Oceanic and Atmospheric Administration's Sea Grant Program. More information can be found in:

H. Choi, C. Tan, S. Yang, V. Fernandez, J. Miao, M. Triantafyllou, and G. Barbastathis. *Pressure and Velocity MEMS Sensor Arrays in Autonomous Underwater Vehicle for Optimized Navigation Path*. International Conference on Intelligent Unmanned Systems (ICIUS-2010), Bali, Indonesia, November 4–5, 2010.

V. Fernandez, S. Hou, F. Hover, J. Lang, and M. Triantafyllou. "Development and application of distributed MEMS pressure sensor array for AUV object avoidance." *Proceedings*, Unmanned Untethered Submersible Technology Symposium, Durham, NH, August 23–26, 2009.

V. Fernandez, S. Hou, F. Hover, J. Lang, and M. Triantafyllou. "Lateral-line inspired MEMS-array pressure sensing for passive underwater navigation." *Proceedings*, Unmanned Untethered Submersible Technology Symposium, Durham, NH, August 19–22, 2007.

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Making underwater repairs

Helping robots hold on

If an underwater robot is to open a valve or repair a damaged pipe, it needs to anchor itself to a solid surface so it can apply force to carry out its task without pushing itself away. It then needs to detach and move on to its next assignment.

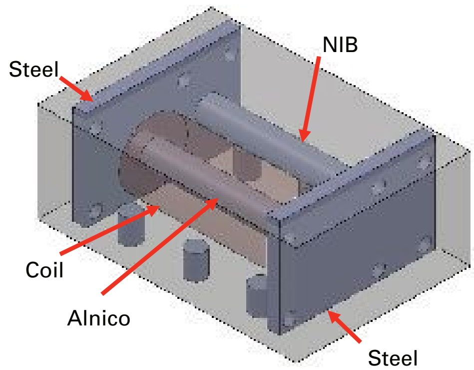
A group of MIT researchers has designed a "controllable adhesion system" for underwater robots that offers the needed features: a high holding force on various geometries and textures, low energy consumption, chemical resistance to seawater, and low maintenance.

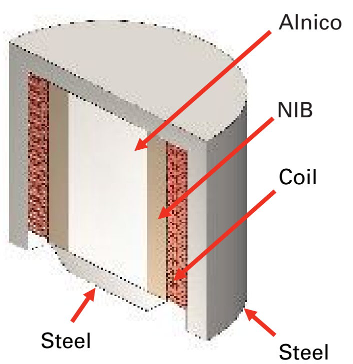
Underwater vehicles have become good at using propellers and thrusters to stay in one place, even in strong currents (see article on page 18). But holding onto a surface while exerting force to do a job is quite another challenge—one that Sangbae Kim, the Edgerton Career Development Assistant Professor in mechanical engineering, and his collaborators have been tackling for the past year. They are working on several approaches, but their best success to date has come using a magnet, or to be more specific, an electromagnet. Take a bar of iron, wrap a coil of wire around it, send an electrical current through it—and you have a magnet. Switch off the current, and the magnetic field disappears.

But there's a drawback to this approach: you need to send electrical current to the robot all the while it's completing its task. Stop the current and the magnet goes neutral, and the robot can float away.

So Kim's group turned to "controllable electromagnets"—magnetic devices that can easily be turned on and off using little energy. The concept has been around for 30 years and has been used for various applications. However, there is little published information on how these devices are designed, what they're made of, and how they work, so the researchers had to develop an understanding of the fundamentals involved.

Controllable adhesion systems for underwater robots





Schematics of two switchable magnets designed to anchor a robot onto a deepsea structure while making repairs and then release it afterward. The module in the upper drawing consists of two bar magnets, one strong (NIB) and the other weak (alnico). The module is neutral when the north and south poles of the two magnets are at opposite ends. Sending a pulse of current through the coil switches the polarity of the alnico magnet, and the module becomes a strong electromagnet. Another pulse switches the polarity back, neutralizing the module. With this device, energy is required only when the robot is latching on and letting go, not while it is performing its task. The lower drawing shows an improved design with higher efficiency, in part due to the outside steel shell, which minimizes leakage by confining the magnetic field to the open end.

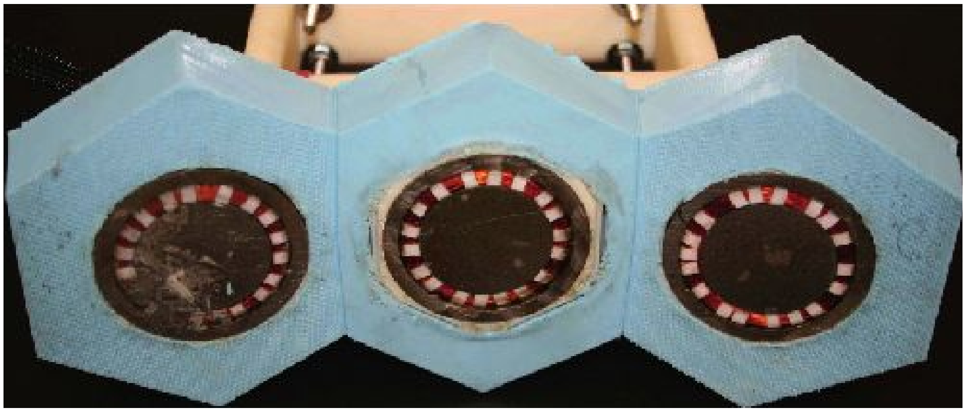
Guided by that understanding, they designed a module consisting of two parallel bar magnets next to each other (see the top figure to the left). One is a very strong magnet made of neodymium, iron, and boron (NIB). The other is a weak magnet made of aluminum, nickel, and cobalt (alnico). Around the alnico magnet is a coil through which an electrical current can flow.

To start out, the two magnets have their north and south magnetic poles at opposite ends—a configuration in which the magnetic fields cancel each other out. The combination is neutral; the module is not magnetic. But send a pulse of current through the coil, and the polarity of the alnico magnet changes, that is, its north and south poles swap places. Now the module is a strong electromagnet—perfect for anchoring a robot on a pipe or a ship's hull. Send another pulse of current, and the polarity of the alnico magnet changes back. The module is neutralized, the robot released.

The best feature is that no energy is required to keep the module in either state—as a magnet or a not-magnet. "Instead of having to spend energy continuously while the robot is working, with our system, you need to spend a pulse of energy only when you switch the state," says Kim.

Based on results from experiments and simulations, the researchers created a novel design with improved performance. In the new design—shown

Multiple modules



Based on simulations, the researchers have developed a manufacturing technique that can combine multiple modules as shown above. Here, three modules are mounted on a base of silicon rubber. The overall unit bends freely, so it can conform and adhere tightly to a curved surface such as the outside of a pipe. Despite their proximity, the three modules operate independently with no interference.

in the bottom figure on page 25—the two magnets are concentric rather than parallel bars. At the center is a cylinder-shaped alnico magnet, and surrounding it is an NIB magnet shaped like a hollow tube. A coil around the outside can carry current to switch the polarity of the alnico magnet. (The NIB magnet is too strong to be affected.) In this configuration, the module can still be switched on and off. But now the whole structure can be covered by a steel cup—an outside shell that confines the magnetic field to the open side and minimizes its leakage when the module is clamped onto a surface.

To determine the strength of their prototypes, they used a materials-testing machine that measures the force exerted by a magnet at gradually increasing distances from an iron plate. The tests revealed certain behaviors about their different designs. For example, they confirmed that the cylinder type is stronger than the bar type. But the results also showed that the cylinder type performs best when the alnico magnet is tall—specifically, five times taller than it is wide. The initial prototypes were fairly short and wide, and those modules quickly demagnetized a short distance from the iron plate. New prototypes with the taller profile performed markedly better.

In other work, the researchers created an electric circuit that pulses just enough energy at the right voltage to cause the alnico magnet to change orientation. Tests confirmed that little energy is needed to achieve almost all the theoretically possible "latching force" and even less energy is needed to deactivate the module.

The team also developed a manufacturing technique that combines multiple modules, as shown in the diagram above. Here, three modules are mounted on a base of silicon rubber. This three-module unit is flexible enough to conform to a curved surface—for example, wrapping around a pipe—and the individual modules don't interfere with one another.

Much work remains. In particular, the researchers need to test their adhesion system on samples of actual pipes and other equipment used by industry. One concern is that their module may not be able to attach directly to metal surfaces because of protective plastic coatings or deposits of biological organisms on structures. They need to establish the impact of such interfering layers on performance and adapt their designs to take them into account.

Kim is pleased with their progress to date. "We've developed a good fundamental understanding and have made some promising prototypes," he says. "Now we want to implement our magnetic adhesion system by collaborating with other researchers who are designing robots to perform underwater maintenance and repairs."

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By Nancy W. Stauffer, MITEI

This research was supported by a seed grant from the MIT Energy Initiative and by Chevron. Publications are forthcoming.

MIT Energy Initiative announces new seed grant awards

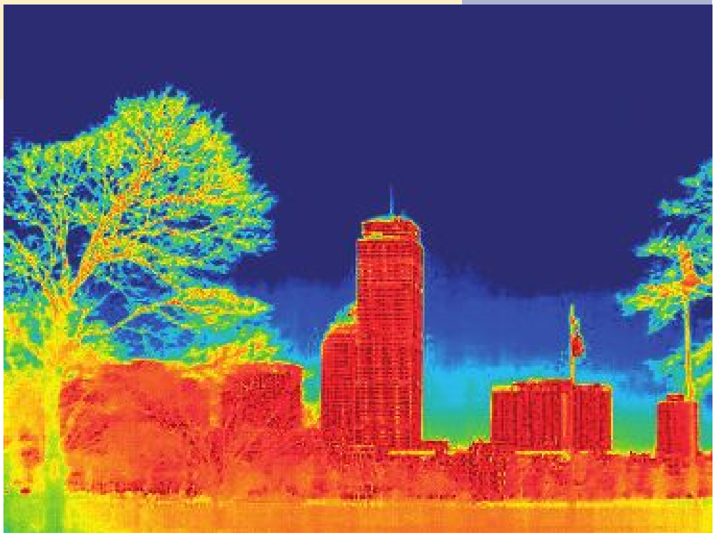

Image: Long Phan G, MIT

In one new project, MIT researchers will further develop their high-resolution scanning thermal imaging system for detecting energy leaks in buildings. At right: A thermal image of the Boston skyline.

The MIT Energy Initiative's latest round of seed grants will support early-stage, innovative projects on a wide range of topics including energy efficiency, new materials, thermal imaging, rock fracturing, efficient irrigation, and integration of renewables into the smart grid.

Over $2 million was awarded to 14 projects, each lasting up to two years. The funded projects span 14 departments, laboratories, and centers and all five of MIT's schools.

As in the past, the call for proposals welcomed submissions on any energy-related topic, but this time MITEI's industry sponsors particularly encouraged projects focusing on end-use efficiency. In response to the call, MITEI received a total of 44 proposals, 17 of which focused on diverse approaches to reduced energy use in buildings and industrial processes.

Six of the efficiency-related proposals were funded. Professors Nicolas Hadjiconstantinou and Rohit Karnik of mechanical engineering are, for example, designing and developing novel nanoporous graphene membranes for gas separation. The use of graphene opens a new frontier in the field of separation because it forms a flat sheet just one atom thick. Graphene membranes are expected to have very high permeability, which translates directly into high energy efficiency, as well as a high degree of selectivity through size exclusion. The researchers will focus initially on separating methane from hydrogen, which is important for natural gas processing. Their approach can be extended to other applications relating to carbon dioxide sequestration, oxycombustion, and syngas production.

In another project, Professor Mircea Dinčа of chemistry is developing a new class of crystalline microporous heterogeneous catalysts that are expected to affect industrially relevant catalytic transformations. The proposed materials—called metal-organic metallosilicates (MOMs)—display highly regular pores whose surfaces can be engineered at an atomic level, providing the size, shape, and chemical selectivity required for energy-efficient and environmentally responsible catalytic transformations. The synthesis of new materials that are tunable in the nanoporous regime is essential for improving the energy efficiency of producing bulk and fine chemicals.

Professor Sanjay Sarma of mechanical engineering and his colleagues in MIT's Field Intelligence Laboratory will further develop their high-resolution scanning thermal imaging system for detecting energy leaks in buildings. Energy consumption for heating and cooling buildings constitutes more than 10% of total US energy demand. Identifying energy leaks so that proper sealing and insulation can be installed could thus yield significant energy savings. The researchers' novel approach to scanning buildings while driving through neighborhoods overcomes significant challenges in long-wave infrared (IR) thermography ranging from the cost of the cameras to poor resolution and from the effective use of IR optics to scanning while in motion. (See sample image above.)

Other funded projects address various energy-related issues outside the efficiency category. For example, the increasing demand for electricity coupled with environmental concerns has motivated the need for smart power grids that can integrate vast amounts of electricity from renewable sources. But renewable sources are intermittent and uncertain, leading to a greater need for backup reserves and rapid ramping ability to ensure grid stability. Professor Munther Dahleh of electrical engineering and computer science is examining the interplay between storage and renewables, specifically, defining and analyzing market mechanisms involving storage, quantifying the benefits of investment in storage capacities, and designing and implementing energy management algorithms that can be used to maximize the value from renewable generation using storage.

Another project is examining rock fracture processes, with a focus on induced seismicity in enhanced (engineered) geothermal systems (EGS). Hydraulic fracturing is well established as a technique for stimulating oil and gas extraction, but its use with

EGS raises new concerns, including the possibility of induced seismicity. Professor Herbert Einstein and Dr. John Germaine of civil and environmental engineering are attempting to determine whether EGS conditions produce fracturing processes that differ from those that occur during oil and gas production. The researchers will investigate fracturing processes in the laboratory and will use their results as the basis for scaling up analytical models, thereby producing tools that can better predict the impacts of EGS stimulation.

In her project, Professor Jing Kong of electrical engineering and computer science plans to develop a variety of novel aerogels—porous solid materials with ultra high surface areas, low bulk densities, and low thermal conductivities. Aerogels have potential uses in catalysis, sensing, energy storage, solar cells, fuel cells, thermal insulation, ultra light structural media, and other energy-related applications. Despite the considerable need, at present there are only limited types of materials that can be made in the aerogel structure. Kong and her research team have recently developed a new method of making gels that they will use to fabricate novel aerogel materials, with a special focus on materials tailored for use in supercapacitors.

Another funded project will focus on linkages between water-use efficiency and energy intensity in large-scale irrigation systems. The agricultural sector is responsible for 70% of global freshwater use, and that sector is likewise dependent on electric power for pumping. Professor James Wescoat of architecture and Dr. Afreen Siddiqi of MIT's Engineering Systems Division will produce a scalable analytical framework to take into account uncertainties associated with the effects of climate change, fluctuating demand, and rates of technology adoption. This understanding is particularly important in semi-arid regions, where population growth and urbanization have created deficiencies in energy supply, in some cases leading to water supply disruptions. The framework and its application will be a valuable tool to guide water and energy policy, planning, and analysis in both developing and developed countries.

Funding for the new seed grants comes chiefly from MITEI's Founding and Sustaining members, supplemented by funds from the Chesonis Family Foundation, David desJardins '83, and gifts from other generous alumni. The availability of funds from the alumni gifts enabled MITEI to match industry funds for five of the 14 projects. The alumni contributions were essential to expanding the scope of the seed grant research program and enabling the participation of faculty across the Institute.

To date, MITEI's seed grant program has supported 89 early-stage research proposals, with total funding of over $10 million.

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By Karen L. Gibson, MITEI

Best poster awards

Photo: Samantha Farrell, MITEI

Posing with MITEI Director Ernest Moniz (left) and MITEI Deputy Director Robert Armstrong (far right) are the recipients of the MITEI awards for best poster (left to right): Carla Thomas, Toby Anna Klein, and Georgina Amy Campbell.

In conjunction with this year's seed grant review meeting, MITEI organized a day of oral and poster presentations on completed or nearly completed seed grant research projects. Three students were given awards for best poster.

Georgina Amy Campbell, Engineering Systems Division: "Innovation Policy, Innovation Prizes, and the Energy Economy: Analyzing the Role of Prizes as a Policy Mechanism for Energy Innovation"

Toby Anna Klein, Mechanical Engineering: "Solar Energy Conversion Using the Phenomenon of Thermal Transpiration"

Carla Thomas, Chemical Engineering: "Self-Assembled Polymer-Enzyme Nanostructures for Low Temperature CO_2 Reduction"

Awards were given for especially noteworthy poster presentations, judged on the basis of content and quality of presentation. Awards for best poster will be offered twice a year in conjunction with special events for the MITEI members that sponsor the seed grant program.

Recipients of MITEI seed grants, Spring 2011

High-temperature salts for solar thermal electricity production and high-temperature nuclear heat storage
Jacopo Buongiorno, Charles Forsberg, Thomas McKrell
Nuclear Science and Engineering

Towards efficient integration of renewables using energy storage: Optimal sizing and management
Munther Dahleh
Electrical Engineering and Computer Science and Laboratory for Information and Decision Systems

Metal-organic metallosilicates (MOMs) with large crystalline pores: New materials for energy efficient catalytic transformations
Mircea Dincă
Chemistry

An experimental evaluation of industrial energy audits in India
Esther Duflo
Economics

Rock fracture processes with emphasis on induced seismicity in EGS (Engineering Geothermal Systems)
Herbert Einstein, John Germaine
Civil and Environmental Engineering

Computational design of all-carbon solar photovoltaics
Jeffrey Grossman
Materials Science and Engineering

Graphene membranes for energy efficient, highly selective gas separation
Nicolas Hadjiconstantinou, Rohit Karnik
Mechanical Engineering

A method to produce ultrahigh surface area functional materials for energy applications
Jing Kong
Electrical Engineering and Computer Science and Research Laboratory of Electronics, Microsystems Technology Laboratories

Designing subsidies for solar technology adoption
Georgia Perakis
Management

Building envelope assessment using street-scanning super-resolution infrared thermal imaging
Sanjay Sarma
Mechanical Engineering and Laboratory for Manufacturing and Productivity

Magnetic bearings for high-speed machines
David Trumper
Mechanical Engineering

Scale inhibition technologies: From nanoengineering to microbe engineering
Kripa K. Varanasi
Mechanical Engineering and Laboratory for Manufacturing and Productivity
Anthony Sinskey
Biology

Coupling water use efficiency and energy intensity under uncertainty in large-scale irrigation systems
James Wescoat
Architecture
Afreen Siddiqi
Engineering Systems Division

Bioengineered algae for bio-hydrogen production
Shuguang Zhang
Center for Biomedical Engineering

Stephanopoulos receives 2011 Eni prize

Photo: Webb Chappell

Gregory Stephanopoulos, MIT's Dow Professor of Chemical Engineering and Biotechnology, has received the "Renewable and Non-Conventional Energy" prize from the Italian oil company Eni S.p.A.

The announcement, made April 19, cites his "pioneering research in the rising field of metabolic engineering, aimed at modifying the gene structure of particular bacteria so as to make them more efficient in the conversion of renewable raw materials into hydrocarbons. This is a research topic of great interest as it is oriented toward the production of second-generation biofuels, not in competition with the food sector."

At MIT, Stephanopoulos directs the Bioinformatics and Metabolic Engineering Laboratory. Among his activities are projects aimed at improving the rate and efficiency of biofuel production, supported in part by seed grants from the MIT Energy Initiative (MITEI).

The Eni Award was established in 2007 to encourage better use of energy sources and to develop new generations of researchers. The 2011 prizes in four categories will be delivered on June 8 at the Palazzo del Quirinale in the presence of the President of the Republic Giorgio Napolitano. Eni is a founding member of MITEI.

Tsinghua/Cambridge/MIT alliance awards second round of seed grants

The Low Carbon Energy University Alliance (LCEUA)—a collaboration among Tsinghua University in China, the University of Cambridge in England, and MIT in the United States—has announced its second round of seed grant awards.

For this round, the alliance invited proposals in four categories: IT and the energy delivery infrastructure; novel uses of nuclear energy; clean coal technology; and low-carbon cities—policies for efficient urban design. Each proposal had to involve researchers at Tsinghua in collaboration with those at Cambridge or MIT or both. In response, the alliance received 13 proposals, nine for three-way collaborations and four for Tsinghua-MIT collaborations.

On March 1, 2011, the LCEUA steering committee met to review the proposals and agreed to fund the following four, one in each of the areas listed above.

Superconducting DC power distribution for datacenters and microgrids
(Zeng Rong, Tsinghua; Bartek Glowacki, Cambridge; John Brisson II, MIT). The large-scale use of superconducting DC power distribution lines combined with cryogenic technology could minimize energy losses; increase grid efficiency, capacity, and reliability; and support the efficient implementation of renewable sources. In this project, the research teams will design, build, and test the components needed for a helium-gas-cooled superconducting DC power line. The work will culminate in the installation and operation of such a power line to and within data and telecommunications centers at Tsinghua.

Flexible nuclear power for clean fuels and peak electricity production by co-electrolysis of CO_2 and H_2O
(Bo Yu, Tsinghua; Paul Bristowe, Cambridge; Bilge Yildiz, Charles Forsberg, and Mujid Kazimi, MIT). This project aims to develop an advanced technology—using heat and electricity from a nuclear power plant to drive the electrolysis of steam and CO_2 captured from coal power plants or other sources—to produce clean liquid fuels for the existing transportation infrastructure. This technology will enable nuclear plants to produce useful fuels when electricity demand is low. Overall plant economics will improve, and nuclear power will become an economic means of meeting peak demand, facilitating the integration of variable renewable energy sources into the electric grid. The research project will focus on materials behavior and process design, using advanced experimental and computational methods to optimize the longevity and cost-effectiveness of this technology starting from the atomic level.

Electrochemical conversion of de-ashed coal in solid oxide direct carbon fuel cells (Ningsheng Cai, Tsinghua; Bartek Glowacki, Cambridge; Ahmed Ghoniem, MIT). Direct carbon fuel cells (DCFCs) could one day be a far more efficient, less polluting source of electricity than conventional coal-fired power plants. DCFCs are fueled by solid carbon—a clean, high-energy-density fuel readily produced from coal and other sources. This project will examine the mechanisms of electrochemical oxidation of carbon in solid oxide DCFCs. The research teams will develop a multiscale mathematical modeling framework and will explore two approaches to improve and optimize performance, namely, adding an ionic conductor-catalyst to extend and improve reaction activity on the anode and adopting a fluidized-bed anode design to enhance mass and heat transfer.

Low-carbon urban design: From options assessment to policy implementation
(Mao Qizhi, Tsinghua; Koen Steemers, Cambridge; Dennis Frenchman and Christopher Zegras, MIT). This project aims to identify low-carbon planning and design patterns at both the system and neighborhood level and to find quick and effective ways to implement them in fast-growing Chinese cities. Building on their extensive experience in urban design and urban policy analysis, the researchers will establish an assessment tool kit and use it to appraise the energy and carbon performance of existing and innovative urban development typologies. Working with policymakers and developers, they will use their findings to develop practical policy and design guidelines and to test them in case studies.

Each project receives US$600,000 and will last between two and three years.

The LCEUA was formed in October 2009 as a cooperative relationship under which the three world-class institutions will conduct collaborative scientific research on low-carbon energy technologies and carry out policy research and analysis on low-carbon energy solutions, with a particular focus on China. The alliance was initiated with an investment of about US$10 million from the Chinese government to fund core operations plus collaborative seed projects. Thus far, the LCEUA has awarded a total of US$4.4 million for eight seed projects.

Photo: courtesy of Tsinghua University

Officials and dignitaries from MIT, Cambridge University, and Tsinghua University attended the first International Conference on Low Carbon Energy and Climate Change, held in Beijing on March 24, 2011. Speakers at the conference included Ernest Moniz, director of the MIT Energy Initiative (MITEI), and Umberto Vergine, senior executive vice president, Studies and Researches, at Eni, a MITEI Founding member. The conference took place as part of Tsinghua's 100th anniversary celebrations.

New project: Extending MIT analytical tools for studies of China

In parallel with the technology and policy program, researchers at Tsinghua and MIT's Joint Program on the Science and Policy of Global Change are collaborating on a special project to analyze China's national economy and its energy system in the context of climate change.

During the past decade, Joint Program researchers have used their analytical tools and expertise to investigate special challenges faced by China. They have examined energy use in China through 2025, characteristics of the nation's energy demand, interaction of climate policy and air-pollution-related health effects, and more. Key to those studies has been MIT's Emissions Prediction and Policy Analysis (EPPA) model, which was designed for studying global economies, energy use, and greenhouse gas emissions (GHGs) and for assessing the potential impacts of GHG control policies and the potential commercial success of low-carbon energy alternatives. Further, the EPPA model is a component of the MIT Integrated Global System Model, which provides a broader capability to analyze global economic activity and climate processes, including potential feedbacks of climate change and its interaction with regional pollution on national economies.

In the new work, MIT and Tsinghua researchers will collaborate to expand and improve those analytical tools for studies of the Chinese energy economy and emissions. Detailed economic and technical data provided by the Chinese participants will permit the team to incorporate into the EPPA model a multisector, multiregion representation of China. Special attention will be given to key components of the energy supply system unique to China—from potential application of coal-to-liquids technology and carbon capture to the evolution of the demand system, notably personal transportation. The team will also incorporate engineering process models developed by Chinese analysts, thereby enhancing studies of particular technical issues.

Using the enhanced models, the researchers will work together on studies of alternative future pathways of energy and economic development in China, including important interactions through international trade as well as the environmental impacts of pursuing different technology strategies.

This five-year, $2.5 million project will involve regular joint meetings plus the exchange of faculty, research staff, and graduate students. Funding is provided in part by MIT Energy Initiative Founding Members Eni S.p.A. and Shell and by the global services firm ICF International.

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By Nancy W. Stauffer, MITEI

MIT energy students carry on the MacVicar legacy

Perched on a plastic seat, Vladimir Bulović yanked a red joystick that propelled the three-wheeled go-cart down a Stata Center corridor at a good clip while needles spiked in response to the electric motor. The go-cart—created by first-year students in a seminar led by Bulović's fellow professor of electrical engineering and computer science Steven B. Leeb—was one of the hands-on student projects showcased March 9 as part of MacVicar Day 2011.

This year marked the 20th anniversary of honoring Margaret MacVicar '64, ScD '67 (1943–1991), MIT's first dean for undergraduate education, for her creation of the Undergraduate Research Opportunities Program (UROP). This year's events focused on new offerings in energy education and the explosion of energy-related real-world projects students have undertaken recently, many of which were presented to MacVicar Day attendees after a faculty panel.

Photo: Justin Knight

During MacVicar Day, a panel of MIT faculty who teach subjects within the Energy Studies Minor shared their insights into the benefits and challenges of interdisciplinary teaching and the goals and pedagogies of their specific subjects. Panel members included (left to right) Leon Glicksman, professor of building technology and mechanical engineering; Donald R. Lessard, Epoch Foundation Professor of International Management at the MIT Sloan School of Management; Robert L. Jaffe, the Jane and Otto Morningstar Professor of Physics; and Vladimir Bulović, professor of electrical engineering and MacVicar Faculty Fellow.

Junior mechanical engineering student Angela R. Hojnacki told participants about the 150 gallons of fuel Biodiesel@MIT has generated from waste vegetable oil to help run MIT-owned vehicles; electrical engineering and computer science graduate student Sam Nicaise described how an MIT solar car decked out with 403 solar cells traveled at 30 mph for 200 miles, after students redesigned the "too-heavy" nine-ounce carbon fiber steering wheel; and senior chemical engineering major Bob Chen held up a baggie filled with powdery, light brown sorghum while he explained why it might be a better source of ethanol fuel than corn. Mechanical engineering graduate student and D-Lab: Energy instructor Amy Banzaert showed off a simple solar-powered distiller that could generate clean water for turbines and solar systems and a stove fashioned from a single piece of sheet metal that allows the use of charcoal, a cleaner cooking fuel than wood.

Other presenters included the MIT Energy Club and some of the 23 students who conducted energy-specific UROPs during summer 2010—recent incarnations of the MIT signature program MacVicar launched four decades ago.

Major accomplishments on energy minor

In addition to the poster session in the Stata lobby, the MacVicar Day event included a faculty panel discussion in which Bulović and Daniel Hastings, dean for undergraduate education, spoke about the far-reaching impact of UROPs and described classes that support the new Institute-wide, multidisciplinary Energy Studies Minor launched in 2009.

The panel included Donald R. Lessard, Epoch Foundation Professor of International Management at the MIT Sloan School of Management and co-chair with Bulović of the Energy Education Task Force; Robert L. Jaffe, the Jane and Otto Morningstar Professor of Physics; and Leon Glicksman, professor of building technology and mechanical engineering and co-chair of the Campus Energy Task Force. "The students like to be motivated by real human need," said Jaffe, who co-designed and co-teaches "Physics of Energy" with Professor of Physics Washington Taylor.

Jaffe says energy solutions are particularly thorny because they involve policy, economics, and politics—and on top of that, must conform to the laws of physics. "There's no denying the rules of the game in this domain," he said, comparing "the energy game" to chess, which also involves unbendable rules and strategic thinking. "The laws of thermodynamics and basic physics draw lines around what you can and can't do" in terms of harnessing various sources of energy, he said.

His subject is taught with a real-world perspective so that "every MIT undergraduate can learn enough physics to know the basics and not have to rely on experts." He hopes that students leave with the ability to conduct back-of-the-envelope calculations on whether a proposed energy solution would actually pan out in the real world. "We cover everything from the way energy is produced in stars to savings from double-glazed storm windows," he said.

Lessard, who helped design and co-teaches "Energy Decisions, Markets, and Policies," describes himself as "a finance and corporate strategy guy" who focuses on "how markets work and how we form and influence policies that govern global energy systems. To effect change, we need to understand prices, markets, the physical management of energy, cultures, regimes, values, how firms make decisions. We need to understand the behavior of individuals, firms, and other organizations and how these are influenced not only by prices but also by social norms and prior decisions," Lessard said. This subject, which fulfills the social science requirement of the Energy Studies Minor, is a remarkable endeavor for the three social science faculty who have created it: "None of us have ever taught anything like this before," he said.

Glicksman described his fall 2010 project-based class, "Fundamentals of Energy in Buildings," which focused on energy efficiency on the MIT campus. "We touched on issues of economics, behavior, and the environment to design projects where students design solutions for energy problems. We ask them to go out on campus and make measurements before and after to see how well their solutions work," he said. Last semester, students diffused skylight glare in an architecture design studio, plastic-wrapped heat-leaking windows in the student center, and analyzed why people used swing-open doors instead of more efficient revolving doors, among other projects.

"Students find hands-on experience most valuable," Bulović agreed. "That's the best part of what we supply here at MIT."

Hastings announced the recipients of the four MacVicar fellowships awarded this year for outstanding teaching: Bish Sanyal of the Department of Urban Studies and Planning; Christopher Schuh of the Department of Materials Science and Engineering; and George Verghese and Patrick Winston, both of the Department of Electrical Engineering and Computer Science. The Teaching and Learning Laboratory organized the daylong celebration with assistance from the MIT Energy Initiative.

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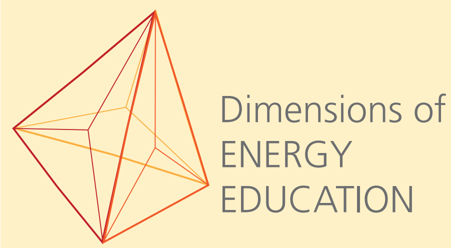
By Deborah Halber, MITEI correspondent

Major updates to Minor website

The Energy Studies Minor recently unveiled freshly redesigned web pages to highlight student experiences and make it easier to find key information about the minor. The new pages feature stories about recent graduates from the minor as well as profiles of faculty teaching in energy, and will host articles spotlighting energy minor classes and projects. The site also debuts a conceptual model, Dimensions of Energy Education, which illustrates the integrated content and approach of the Energy Studies Minor curriculum. Visit us at web.mit.edu/energystudies.



"Fundamentals of Photovoltaics" sheds light on new technologies

Sprinting up three flights of stairs from the photovoltaics (PVs) laboratory in the basement of Building 35 to his office, Tonio Buonassisi, assistant professor of mechanical engineering, gives the impression of someone with little time to waste and a lot of ground to cover. This hard-charging approach is evident in Buonassisi's class, "Fundamentals of Photovoltaics" (2.626/7). In a single semester, Buonassisi asks students to absorb the basics of photoelectric conversion, grasp current commercial and emerging PV technologies, and grapple with the implications of this renewable energy in a real-world context. Students find the class both exhilarating and challenging.

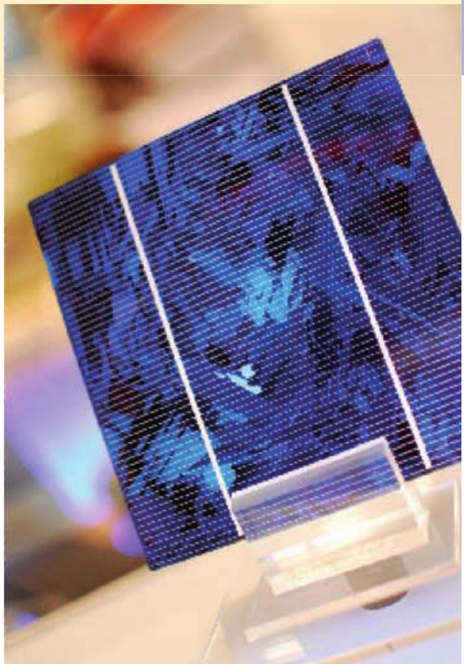
While Buonassisi "moves at a very fast pace," says first-year mechanical engineering graduate student Sin Cheng Siah, he is both "engaging and insightful, passing on his excitement about the field to the class." Chemical engineering senior Desiree Amadeo, who leapt at the opportunity to study PVs, calls 2.626/7 "informative, thought-provoking, and exciting." Robert Clarke '81, who returned to MIT looking for a career change, credits 2.626/7 not only for its "technical depth and breadth in terms of different political and economic aspects," but for giving him "a very good background to get involved in the industry."

Although Buonassisi finds it gratifying when his course inspires students to dedicate their careers to solar, his mission does not explicitly involve advocacy but rather a deep education in the science, engineering, policy, and economic issues surrounding PVs. By term's end, he says, "I want them to be able to take a cold, hard, facts-based approach" to a new technology and "really make heads or tails out of it."

To achieve this ambitious goal, Buonassisi structures the class around three learning objectives. The first involves the fundamentals of capturing light with a solar cell and converting that energy into electricity. "It might sound really straightforward, really simple…but we could easily spend three or even four semesters teaching in detail the physics" behind each of the components involved, says Buonassisi. "We adopt an engineering approach and try to focus on what the students need to know."

Collaborating with graduate instructor Joseph Sullivan of mechanical engineering, Buonassisi designs the lectures "with different audiences in mind." Enrollees typically include both graduate and undergraduate students, concentrating in such areas as mechanical, electrical, and chemical engineering; materials science; physics; and business. By "utilizing analogies to a great extent and relating phenomena students observe to things they have already seen," the course gets the basics across to a diverse group, says Buonassisi.

Another objective involves analyzing current commercial and emerging PV technologies and applying cost models, so students come to understand "the use-inspired nature of this research." To wean the world from fossil fuels, solar power must become much more cost-effective and achieve "grid parity," says Buonassisi. 2.626/7 walks students through the details of pricing and discusses barriers to reducing solar power to a competitive $1 per watt. The class illustrates how the manufacturing and installation of PV technology affect system efficiency and cost. "Ultimately, we're challenging them to 'do the difficult,' which is to take science and engineering and bridge across the disciplines to economics, to understand what the tradeoffs are in our system," says Buonassisi.



Photos: Alexandria Fecych, MIT

A multicrystalline silicon solar cell, which is a key component in 40% of the photovoltaic modules manufactured worldwide today. This technology, as well as thin-film and next-generation devices, are discussed in the class 2.626/7, Fundamentals of Photovoltaics.

The third component of the class focuses on hurdles in scaling PV technology to the terawatt level, where "it makes a real dent in our total electricity needs." To bring home the challenges facing PVs, Buonassisi dips into his collection of news clippings and selects issues for students to debate, such as the use of potentially dangerous materials for PV cells or China's subsidization of its solar industry. Students visit Buonassisi's research lab and nearby solar firms, hear from guest lecturers with direct experience in building and marketing PV technology, and develop group projects that explore questions with actual implications for the implementation of solar energy (see the article on page 35).

There is a larger theme uniting his learning objectives, suggests Buonassisi.

Student project identifies improvements for campus PVs

During lab sections of the class, the students are divided into small groups to maximize student-instructor interaction. Here (left to right), Alison Greenlee and Jacob Miller of mechanical engineering, Juan Porras of physics, and others receive instructions before commencing measurements on PV devices.

Photo: Steven Lanou, MIT

These solar panels on the roof of the Student Center were among the MIT installations examined by students in Fundamentals of Photovoltaics. By analyzing years of energy output data, the student team detected unexpected losses of efficiency, thereby identifying steps that MIT can take to improve PV performance.

The Photovoltaic Research Laboratory in Building 35 is not the only venue on campus for hands-on investigation of solar technology. Last fall, students from Tonio Buonassisi's class, "Fundamentals of Photovoltaics" (2.626/7), discovered unexpectedly rich learning opportunities high atop the Alumni Pool building, Hayden Library, and the Student Center, the sites of three photovoltaic (PV) installations. With the assistance of the MIT Department of Facilities, students explored the performance of these solar modules, resulting in what Buonassisi calls "a stellar class project with real-world implications for on-campus solar installations."

Robert Clarke '81, who took 2.626/7 while enrolled in MIT's professional education program, says his group hoped to determine the efficiencies of PV modules under actual operating conditions: "We wanted to look at real modules in the field, not theoretical ones." Peter Cooper, manager of sustainability engineering and utility planning at MIT Facilities, helped the team extract years of performance data from the solar installations' computer monitoring system, which in Cooper's words, was "not user-friendly."

After long hours of analysis and late-night meetings, says Clarke, the students were able to characterize the energy output of these installations for a six-year period, which they then compared to the systems' peak energy ratings. The team detected greater losses of efficiency than expected, and tracked down the causes, which included orientation of the panels on the roofs, dirt, snow, and shading. To the surprise of utility managers, the students also discovered that the systems intermittently failed altogether. These shutdowns at times went unnoticed because the PV installations lacked real-time operational alerts to managers.

The team's final report is "the first comprehensive look at our installations," says Cooper, and one that is "terrifically informative." While Cooper notes that PV-generated electricity makes up less than 1% of MIT's overall energy capacity—the largest system, on the Alumni Pool, was installed in part to offset electricity used to relight the Great Dome—the PV arrays "advance learning and education around renewable energy on campus." The students' project, he says, fits right in with MIT's goal of "trying and learning new things about energy," as well as "developing expertise about what our systems can and can't do."

In practical terms, the study also helps MIT prioritize ways of improving PV performance, whether by cleaning and reorienting panels or launching a real-time alert system to flag PV failures. And when the time comes for the next installation of solar panels, Cooper says, "we will be looking at this report to optimize all of the components they studied."

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By Leda Zimmerman, MITEI correspondent

"The Trojan horse is PVs: People think they're learning about PVs, which is really the case. But more than that, they're learning an approach to tackling interdisciplinary problems." The capacity to "think about complex questions in terms you weren't necessarily trained to do, and look across disciplines for solutions" is increasingly essential in the modern workplace, he believes. This point is not lost on his 2.626/7 students.

Desiree Amadeo intends to head straight into the solar energy industry after MIT, well equipped, she says, "to ask the right kind of questions and to judge what would be a good, reliable energy source." Sin Cheng Siah, whose MIT education is funded by a Singapore clean energy scholarship, described 2.626/7 as "unique" in his college studies. He learned from the class that "to go far in the research, you must understand not only the relevant fundamentals, but also the economic aspects of the technology, and the social impact—the good things this technology will bring to make a better world."

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By Leda Zimmerman, MITEI correspondent

MIT signs international charter, deepening commitment to campus sustainability

In January 2011, MIT submitted its first annual report to the secretariat of the Sustainable Campus Charter, an agreement signed by MIT President Susan Hockfield and leaders of 25 other internationally known universities during the 2010 World Economic Forum in Davos, Switzerland.

By signing the inaugural charter, Hockfield pledged to deepen the Institute's long-standing commitment to improve sustainability, foster energy efficiency, and reduce waste in all campus activities. She further pledged to cooperate with her fellow charter members in sharing new information and experiences that emerge through their local sustainability efforts.

To those ends, the first annual report presents an overview of MIT and then highlights programs that demonstrate the Institute's commitment to the principles of the charter, including setting goals, taking action, and reporting progress each year.

Hockfield noted that signing the charter reaffirms MIT's commitment to sustainable development and to guiding campus operations toward a more sustainable, energy-efficient future. "The charter provides a platform for sharing ideas and experiences with many international peer institutions," she said. "We all want to harness the intellectual power of our faculty, capitalize on the enthusiasm of our campus community, and seek innovative ways to speed our campuses towards true sustainability."

The Sustainable Campus Charter was initiated by the Global University Leaders Forum (GULF), a community of leading university presidents—including Hockfield—that was convened in 2006 by the World Economic Forum to help address the world's pressing problems, among them, sustainability. The International Sustainable Campus Network, a nonprofit organization, partnered with GULF to develop, implement, and manage the new charter.

Universities that signed the charter also include Carnegie Mellon University, Yale University, Oxford University, Cambridge University, Harvard University, and others in the Americas, Europe, and Asia.

As members of the charter, the university presidents pledge to continue their sustainability efforts locally and to share information globally, with an emphasis on three core sustainability goals:

- Improve the design and functioning of campus facilities, especially buildings.
- Integrate the issue of sustainability into institution-wide planning.
- Work toward developing the university as a living laboratory, with students and faculty using their home institutions as research platforms to explore energy conservation, efficient materials use, improved transportation, and related issues.

"For MIT, this commitment will serve as a guiding feature in many aspects of our campus development, and we look forward to engaging the broad MIT community in shaping our progress," said Steven M. Lanou, deputy director for sustainability in the MIT Environment, Health, and Safety Headquarters Office, who took the lead in preparing MIT's report to the secretariat.

The report provides an overview of MIT's mission, history, and organization. It then addresses all three of the charter's goals, citing specific commitments, achievements, and investments in energy and resource conservation and efficiency, both during the past two decades and within the last few years. Included are examples of methods used to involve the campus community as well as to integrate energy and sustainability into classwork and other learning opportunities, including testing innovative ideas on the campus itself.

A key component of the charter is energy-efficient buildings. Buildings account for major expenditures of energy, so how they are designed and operated is critical. At MIT, two new buildings have been designed to minimize energy use without compromising livability, convenience, and quality. Those buildings—the Koch Institute for Integrative Cancer Research and the MIT Sloan School of Management—use 30% and 43% less energy, respectively, than typical buildings of comparable size and use. Members of the charter will work together to learn from their experiences as they build and operate major facilities on their campuses.

According to Lanou, the coming year's focus will be on additional goal setting and progress measurements to support the charter as well as MIT's own sustainability objectives.

This expanding effort to enhance sustainability at MIT is being supported in part by generous grants from alumni, including a gift of $1 million from Jeffrey Silverman '68, which created the Jeffrey Silverman Evergreen Energy Fund, and a $500,000 donation from David desJardins '83. Both donors are deeply committed to enhancing energy efficiency on the MIT campus.

For a copy of the annual report, go to ehs.mit.edu/site/sustainability.

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By Robert Cooke, MITEI correspondent

A shared success story points to a hopeful energy future for Massachusetts

When it came to saving energy, MIT outdid itself in 2010. MIT surpassed by 30% its institutional goal of saving 10 million kilowatt hours as part of a first-of-its-kind collaboration with gas and electric utility NSTAR.

At a daylong forum in January, MIT shared the details of its success with more than 100 administrative, financial, and facilities leaders from local institutional energy customers. MIT faculty and staff led "how-to" workshops for business, community, and university leaders who would like to develop organizational and financial models to build large-scale, innovative energy efficiency programs such as the one created by MIT and NSTAR.

"Efficiency Forward: Partnering for Success" was held, fittingly, in E62, the new MIT Sloan School of Management building, which was designed with the ambitious goal of achieving a high-level LEED® Gold rating by the US Green Building Council. The building is now being reviewed for final LEED certification.

"The forum was designed not only to recognize the first year's success of Efficiency Forward, but also to convene influential organizational decision-makers to facilitate the adoption of similarly focused, large-scale energy efficiency programs at their institutions," said Steven M. Lanou, deputy director for sustainability in the MIT Environment, Health, and Safety Headquarters Office.

Aggressively efficient

In May 2010, MIT and NSTAR established a multimillion-dollar collaboration that, according to MIT President Susan Hockfield, set as its goal saving 34 million kilowatt hours (kWh) over three years through upgrades to heating, ventilation, and air conditioning (HVAC), electrical systems, lighting, and other high energy-use areas, as well as sustainable design and construction.

The lifetime savings of the initiative is estimated at potentially more than $50 million, saving a total of 20,000 metric tons of greenhouse gas emissions annually. MIT's goal over the next three years is to conserve the equivalent electrical use of 4,500 Massachusetts homes in a year.

Photo: courtesy of NSTAR

To promote large-scale energy-efficiency programs such as the MIT-NSTAR collaboration, MIT shared details of its energy-efficiency strategy during a daylong forum with 100 leaders of the largest utility customers in Massachusetts. After a series of opening remarks, MIT faculty and staff led "how-to" workshops for business, community, and university leaders seeking to develop their own energy-efficiency programs.

With average electricity consumption around 18 million kWh per month, MIT aimed to save 10 million kWh in year one and 12 million kWh in each of years two and three. In 2010, MIT surpassed its first benchmark by saving a total of 13 million kWh, thanks to lighting retrofits, a chiller plant expansion, and savings accrued from the two newest, most energy-efficient buildings on campus—the MIT Sloan School of Management and the Koch Institute for Integrative Cancer Research.

NSTAR has dubbed the venture with MIT as its largest and most aggressive efficiency project to date. In part, it involves:

- A long-term commitment from MIT to save energy matched with enhanced financial incentives from NSTAR.
- Implementing innovative combinations of technologies and approaches.
- Access to NSTAR's preferred procurement rates for equipment and service.
- Reinvesting money saved in additional energy projects.
- Engaging students through a student advisory group and study projects.

Hockfield credited NSTAR CEO Tom May with leadership and farsighted efforts on clean energy. "I believe regional partnerships are key to our successes, and I hope this summit will trigger a continuing dialogue," she said.

"This is a prototype for the future," May said of Efficiency Forward. "This partnership is unique. It's the first time a large institution actually signed a memorandum of understanding for a three-year commitment with specific plans, goals, and budgets. It makes tremendous business sense."

Also presenting opening remarks were Cambridge Mayor David Maher and Philip Giudice, undersecretary for energy in the Executive Office of Energy and Environmental Affairs. Energy efficiency programs "aren't all sexy and aren't all exciting, but they all make a difference," Giudice said.

Maher cited potential energy-saving ventures in Cambridge such as installing solar panels on the water treatment center, LED streetlights, retrofitted lighting in official buildings, and wind turbines on buildings. "What the universities are doing has helped us set the bar with private developers in this city, and that's a good thing," he said. "It's helped citizens and politicians come together around this issue." Giudice noted that by "simply focusing on ways to stop wasting energy, we will live more comfortable lives; we will save ourselves money and have a better future for us all."

Low risk, big payback

Afternoon sessions at the one-day forum included an overview of how Efficiency Forward led to a success story for MIT as well as sessions on financial, organizational, and motivational strategies for developing energy efficiency programs.

The conventional wisdom is that efficiency is expensive; that green buildings are good for the environment but bad for your budget, said John Sterman, MIT professor of management. "In fact, energy efficiency is just about the best investment around."

Photo: courtesy of NSTAR

Left to right: Philip Giudice, undersecretary for energy, Massachusetts Executive Office of Energy and Environmental Affairs; MIT President Susan Hockfield; Tom May, president and CEO of NSTAR; David Maher, mayor of the City of Cambridge; David Schmittlein, dean of the MIT Sloan School of Management; and Theresa Stone, executive vice president and treasurer of MIT.

"The workshops at the Efficiency Forward event showed that investments in energy efficiency often yield returns on investment of 30% a year or more, with very low risk," said Sterman, who moderated a workshop on organizational and mobilization strategies.

Green buildings aren't much more costly to build than conventional buildings, he pointed out. Money spent on high-quality energy-efficient windows and creating a tight building envelope, for instance, can be offset by savings achieved through a smaller HVAC system.

The workshops showcased a number of energy-saving examples at MIT, including the new home of the MIT Sloan School of Management, now the greenest building on the campus, and retrofits to many other MIT buildings. Participants toured the new MIT Sloan building, which is over 40% more energy efficient than typical buildings of its size and function, noted MIT Sloan Dean David Schmittlein in his opening remarks. It has high-efficiency windows, a reflective white roof, demand-sensitive heating and cooling systems, and other innovations. "This is a technology-enabled green building that allows us to showcase what is possible in these structures," Schmittlein said.

The participants shared their own experiences, highlighting successes in a wide range of organizations, public and private, and discussed the challenges they faced and the opportunities for further progress.

"In addition to our green building design efforts, we look to reduce energy use in existing buildings," said panelist Rick Mattila, environmental affairs director at Genzyme Corporation. "Events such as Efficiency Forward that increase awareness of potential customer-utility partnerships are valuable to us and in educating all utility customers about the opportunities available through the energy conservation programs." Mattila is a voting councilor on the Massachusetts Energy Efficiency Advisory Council.

The event helped celebrate and illuminate the opportunities of partnership-based, large-scale energy conservation and efficiency programs, Lanou said. "These types of programs are exactly what's needed to achieve aggressive local and regional energy efficiency goals."

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By Deborah Halber, MITEI correspondent

MIT study of nuclear fuel cycles: Reassessing the options

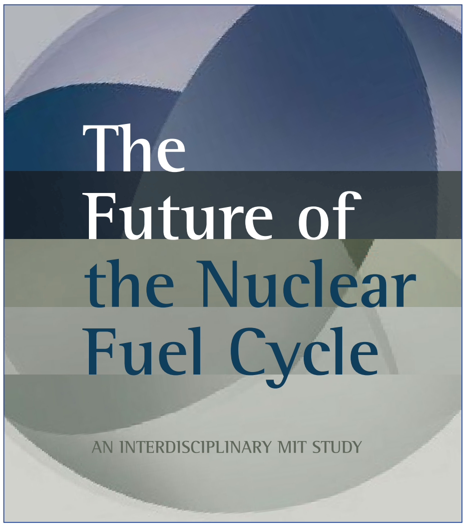
The availability of uranium supplies will not limit the expansion of the nuclear power industry in the United States or around the world for the foreseeable future, according to a major new interdisciplinary study produced under the auspices of the MIT Energy Initiative (MITEI).

That conclusion runs contrary to the view that had prevailed for decades—one that guided decisions about which technologies were viable. "The failure to understand the extent of the uranium resource was a very big deal" for determining which nuclear fuel cycles were developed and the schedule of their development, says Ernest J. Moniz, director of MITEI and co-chair of the new study.

The nuclear fuel cycle is a concept that encompasses both the kind of fuel used to power a reactor (currently, most of the world's reactors run on mined uranium that has been enriched, while a few run on mixtures of plutonium and uranium) and what happens to the fuel after it has been used (either stored on-site or disposed of underground—the "once-through" cycle—or reprocessed to yield new reactor fuel as part of a "closed" fuel cycle system).

The study challenges old assumptions about the timing, need, and nature of a closed fuel cycle with reprocessing to advance nuclear energy. It suggests instead that nuclear power using today's reactor technology with a once-through fuel cycle can play a significant role for many decades in displacing the world's carbon-emitting fossil-fuel plants, and thus help to reduce the potential for global climate change.

And determining the best fuel cycle for the next generation of nuclear power



plants will require more research, the report concludes.

For several decades, fuel cycle research primarily aimed to develop fast reactors that breed plutonium. Nuclear reactors convert non-fissile forms of uranium—that is, uranium isotopes that are not capable of sustaining a nuclear reaction—into different fissile elements as they produce electricity. The elements produced include plutonium, which could be used to fuel other reactors. By maximizing the conversion of isotopes into plutonium, fast breeder reactors actually produce more fuel than they consume. But it would take a conventional light-water reactor (LWR) 30 years just to provide the plutonium for the initial startup of one such breeder reactor, and so far, that approach has not been found to be economically viable.

Another fast reactor option emphasized in the report is a self-sustaining system that produces roughly the same amount of fissile material that it consumes. Self-sustaining fast reactors offer several benefits over breeders. A self-sustaining reactor fleet allows for more efficient utilization of existing uranium resources, minimizes the throughput of fuel recycling plants, and opens the field for a wider array of reactor designs.

The new study suggests an especially promising self-sustaining system—one that can be started on enriched uranium and will thereafter continuously recycle just enough fissile material to be self-sustaining. This is a relatively simple fuel cycle with several benefits: It does not require reprocessing LWR spent fuel (as do the plutonium-initiated fuel cycles described above), and it allows for more rapid deployment of a large fast reactor fleet—if such reactors can be built economically.

One of the report's major conclusions is that the selection of reactors and fuel cycles must be informed by a better understanding of the technologies and how they perform, clarity on the trajectory of nuclear power deployment, and a narrowing of the options for waste disposal. More research is needed in all of these areas, and there is ample time to make choices.

Looking at whole systems

One reason the study came to such different conclusions from previous research is because it looked at the various components—from mining to reactor operation to waste disposal—holistically, explains Mujid Kazimi, the TEPCO Professor of Nuclear Engineering at MIT and co-chair of the study. "When you look at the whole thing together, you start seeing things that were not obvious before," he says.

The report—the latest in a series of broad-based MITEI studies of different aspects of energy—was produced by 10 faculty members, three contributing authors, and eight student research assistants, with guidance from a 13-member expert advisory panel from

Photo: © Rick Friedman

Ernest Moniz (right), the Cecil and Ida Green Professor of Physics and Engineering Systems and director of the MIT Energy Initiative, responds to a question during a press conference on April 26, 2011, at which the 253-page report, *The Future of the Nuclear Fuel Cycle*, was released. Moniz co-chaired the interdisciplinary study with TEPCO Professor of Nuclear Engineering Mujid Kazimi (left), who also is director of the MIT Center for Advanced Nuclear Energy Systems.

industry, academia, and nonprofit organizations.

"There has been relatively little research on the fuel cycle for about 30 years," says Charles Forsberg, MIT research scientist in nuclear engineering and executive director of the study. "People hadn't gone back and looked at the underlying assumptions."

In this study, Kazimi says, "what we found was that, at any reasonable expected growth of nuclear power over this century, the availability of uranium will not be a constraint."

The report also concludes that in the United States, significant changes are needed in the planning and implementation of spent-fuel storage and disposal options, including the creation of a new quasi-governmental body to oversee the process. Planning for how to deal with the spent fuel should be closely integrated with studies of the optimal fuel cycle, the authors suggest.

The report strongly recommends that interim storage of spent nuclear fuel for a century or so, preferably in regionally consolidated sites, is the best option. This allows the fuel to cool, and most importantly preserves future fuel cycle choices to eventually send the fuel to a geological repository or reprocess it for energy resource and/or waste management benefits. The optimal choice will reflect future conditions, such as the scale of nuclear power deployment and the state of technology and its costs.

Ultimately, how to treat the spent fuel depends on the outcome of research, Moniz says. "Today, we would argue that we do not know whether spent fuel is a waste product or a resource," he says. If the world continues to build once-through LWRs, it can be treated as waste and simply disposed of in a geological repository, but if the industry in the US and worldwide switches to a plutonium-based fast reactor system, then spent fuel will become an important resource, providing the raw material for producing new fuel.

The report also strongly supports the present US government policy of providing financial assistance for the first several new nuclear plants to be built under newly revised licensing rules. Positive experience with "first-mover" plants—the first of these new US plants built after the current long hiatus—could reduce or eliminate financing premiums for nuclear plant construction. Once those premiums are eliminated, Forsberg says, "we think nuclear power is economically competitive" with coal power, currently the cheapest option for utilities.

The potential for using nuclear power to reduce greenhouse gas emissions is significant, the study suggests. In the US, nuclear power now represents 70% of all zero-carbon electricity production. While no new US plants have been ordered in 30 years, 27 new license applications have been submitted since new regulations were instituted to streamline the process. Meanwhile, China, India, and other nations have accelerated construction of new plants.

One key message of the report is that it's time to really study the underlying basis of nuclear fuel cycle technology—what kind of fuel goes in, what comes out, what happens to it, and what waste streams are created—before focusing too much money and effort on the engineering details of specific power plant designs. "You want to start with the things that drive all your choices," Forsberg says. "People had not looked at these options enough."

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By David L. Chandler, MIT News Office, and Lara Pierpoint, PhD candidate, MIT Engineering Systems Division

The tragic 9.0-magnitude earthquake and resulting tsunami that struck Japan on March 11, 2011, occurred as *The Future of the Nuclear Fuel Cycle* report was in the final stages of production. As a result, the consequences of events at the Fukushima Dai-ichi nuclear complex have not been factored into the study. While the situation in Japan has not changed any of the basic report conclusions, it likely will have several impacts, among them increasing the urgency of dealing with radioactive spent fuel and possibly raising the cost of new and operating plants. The Japanese crisis underscores the study's conclusion that preserving options in spent fuel management and fuel cycle choices is critical.

This study was funded by the Electric Power Research Institute, the Idaho National Laboratory, the Nuclear Energy Institute, Areva, GE-Hitachi, Westinghouse, Energy Solutions, and Nuclear Assurance Corporation. To download a copy of the report, go to web.mit.edu/mitei/docs/spotlights/nuclear-fuel-cycle.pdf.

MIT symposium: Combining enhanced oil recovery, carbon sequestration

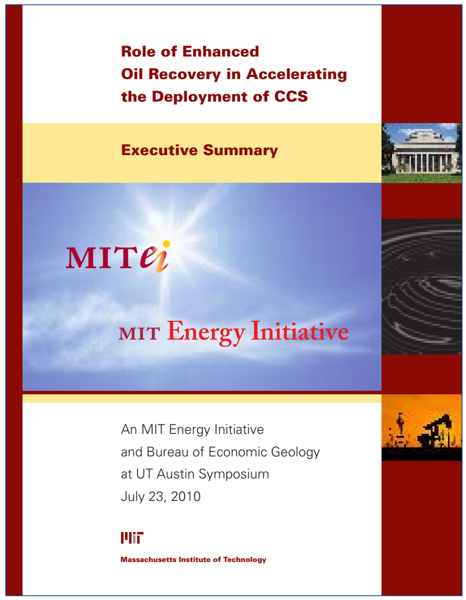
On July 23, 2010, a group of about 60 experts participated in a symposium to consider the viability of a combined response to two national energy priorities, namely, enhancing domestic oil production through increased tertiary recovery, and establishing large-scale carbon capture and sequestration (CCS) as an enabler for continued coal use in a future carbon-constrained world.

Those security and environmental goals could both be advanced by taking carbon dioxide (CO_2) captured from combustion of coal (and natural gas) and injecting it into oil wells to achieve enhanced oil recovery (EOR).

Many questions remain about the efficacy and implementation of such a program at large scale. The symposium—co-hosted by the MIT Energy Initiative (MITEI) and the Bureau of Economic Geology at the University of Texas (UT-BEG)—laid out the issues on EOR-CCS, explored the business case for this option, and discussed what might be an appropriate government role in facilitating this opportunity.

Chairing the symposium were Ernest J. Moniz, the Cecil and Ida Green Professor of Physics and Engineering Systems and director of MITEI, and Scott W. Tinker, the Allday Endowed Chair in the Jackson School of Geosciences at the University of Texas at Austin and director of UT-BEG. Moniz and Tinker wrote a summary for policymakers that is included in the full report, but it states that the observations presented "are those of the authors and are not offered as a consensus view of the participants."

The summary concludes that anthropogenic CO_2 capture, transportation, and use for EOR has the potential to be a



significant contributor to domestic oil production and, if increased several fold from today's injected volumes, to accommodate anticipated CO_2 sequestration needs for at least a couple of decades, quite possibly more.

The potential benefits of enhanced domestic oil production and the opportunity to sequester CO_2—along with the high costs involved for first movers—suggest that a government-supported program to scale up EOR-CCS warrants serious consideration.

Status of EOR and CCS

Currently, about 65 million tons of new CO_2 is used each year for EOR in the United States, along with another 50 million tons of recycled CO_2. Most of the CO_2 comes from natural sources and is delivered to EOR sites through a few thousand miles of commercial CO_2 pipeline. This EOR yields just over 100 million barrels of oil a year, or about 5% of domestic crude production. But estimates of economically recoverable oil from CO_2-EOR range from 35 to 50 *billion* barrels, suggesting that larger volumes of CO_2 could be employed to enable the recovery of this oil.

The 65 million new tons of CO_2 is equivalent to only about 3% of current emissions from US coal plants. Over time, that fraction could increase. However, a previous MIT symposium concluded that a limited percentage of the current coal fleet are candidates for post-combustion capture of CO_2 with today's technology (see report at web.mit.edu/mitei/research/energy-studies.html).

In anticipation of the need to dramatically reduce CO_2 emissions from coal combustion, the federal government continues to invest significantly in research and development on CCS. Sequestration programs have focused largely on deep saline aquifers because of their enormous CO_2 storage potential. However, discussion at the symposium brought into sharper focus a key outcome: An organized CO_2-EOR program using anthropogenic CO_2 could, with the appropriate CO_2 transportation infrastructure, kick-start larger-scale sequestration in the United States and meet sequestration needs associated with power generation and other stationary sources for a significant period, while simultaneously enhancing domestic oil production.

In fact, EOR has attractive features for CO_2 storage relative to deep saline aquifers, including the likelihood of a much smaller footprint for the underground CO_2 plume, the availability of abundant reservoir data and production history, and the already-existing infrastructure at the site.

However, the symposium summary stresses that the cost of CO_2 capture—

even with evolutionary technology advances and engineering experience—will remain high for first-mover power plants. With no regulation or price on CO_2 emissions, government support likely will be required to help motivate the first-mover demonstrations.

A key issue in gauging the appropriateness of government support of a major EOR-CCS effort is verifiable permanence of CO_2 storage over centuries. There is a clear need to establish well integrity standards and an adequate and affordable monitoring system and verification protocol. In addition, a substantial fraction of the injected CO_2 comes out with the produced oil, then is separated and reinjected. Therefore, careful and continuous CO_2 "accounting" will be required.

Implementation challenges

One key issue in scaling up CO_2-EOR with government support is infrastructure development. Federal CCS programs have paid relatively little attention to the CO_2 transportation infrastructure, yet a major CO_2-EOR program in the future could require tens of thousands of miles of CO_2 pipeline. Careful long-term planning is required to build and regulate such a large infrastructure.

Balancing CO_2 supply and demand will also be a challenge. The CO_2 from a large baseload coal plant will not always match the needs of individual EOR operators. Approaches to balancing supply and demand include linking CO_2 sources with multiple EOR projects and/or temporarily storing "excess" CO_2 in pore spaces in depleted natural sources of CO_2 or in deep saline aquifers.

Finally, many regulatory issues will arise. For example, who should assume long-term liability for CO_2 storage? A combination of state and federal governments could take on liability for first-mover projects while the regulatory regime is developed. Another question concerns ownership of pore space. Unitization—legal agreements that enable oil reservoirs to be operated as a single system even if different landowners are affected—must be extended to CO_2 storage in order to facilitate the monitoring and verification needed for establishing the monetary value of stored CO_2.

Recommended actions

The symposium summary strongly urges that the US Department of Energy develop and implement a comprehensive RD&D program on EOR-CCS that

- provides data on permanence of CO_2 storage in EOR;
- develops the tools for end-to-end systems analysis of CO_2 capture, transportation, and storage;
- provides an analytical framework for the value proposition for power plant, pipeline, and EOR operators and for the government;
- puts forward principles for resolving critical regulatory issues;
- explores the potential for EOR in unconventional geological zones; and
- maps out a phased implementation program for CO_2-EOR, including the build-out of transportation infrastructure.

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By Nancy W. Stauffer, MITEI

This symposium was sponsored by Denbury Resources, Inc., an Associate member of the MIT Energy Initiative. To download a copy of the report from the symposium as well as commissioned white papers and other reports submitted by attendees, go to web.mit.edu/mitei/research/reports/EOR-CCS.html.

MIT symposium: Electrifying the transportation system

The technologies needed to begin seriously weaning the US transportation system away from petroleum and toward alternatives such as hybrid and pure electric vehicles have made great progress. But harnessing them on a scale that would significantly lower greenhouse gas emissions or oil imports is complicated by issues of choosing the right policies and of implementing needed infrastructure improvements.

This was a clear message from a high-level panel of experts who met last year at MIT to discuss the issues in a one-day symposium, whose conclusions were released as a report, *Electrification of the Transportation System,* on January 13, 2011, by the MIT Energy Initiative (MITEI).

The impetus for moving transportation systems away from petroleum is twofold, as MITEI Director Ernest Moniz explained in introducing the report: to reduce the nation's dependence on oil imports and to reduce the greenhouse gas emissions that contribute to global climate change.

MIT Institute Professor John Deutch, who with Moniz was co-chair of the symposium, said there were some clear areas of agreement among members of the panel, who represented a diversity of fields and areas of expertise. "The predominant view was that if you had a strong carbon policy, many of the steps that would have to be taken" to reduce petroleum dependence would happen naturally. But given the present political realities in the US, he said, "we're not going to have that, so the most desirable policy option is not in front of us."

Another area of agreement, he said, was the need for a strong government policy in support of research and development in this area. While panelists disagreed on the extent to which this should extend into manufacturing, he said, there was a strong endorsement of continued government support for the development of petroleum-free transportation technologies. But much more than that is needed, he said. While it would be technically feasible to reduce US greenhouse gas emissions by 50% by mid-century, he said, the likelihood of the government enacting and maintaining the necessary policies over that period of time is "quite dim" due to political forces.

One key enabling technology involves modernization of the nation's electric grid, permitting more real-time monitoring and dynamic control down to the level of individual buildings, because patterns of usage could change significantly if the recharging of electric vehicles grows at a rapid pace. At the same time, the batteries in electric or plug-in hybrid vehicles could be used as an extra short-term backup system, storing energy from the grid when there is an excess and delivering it back when needed, in order to flatten peaks in electricity use. This could eliminate the need for construction of some new power plants, but only if changes are made to the grid infrastructure to enable such uses, said Marija Ilić, a visiting professor in the MIT Engineering Systems Division.

John Heywood, the Sun Jae Professor Emeritus of Mechanical Engineering and former director of the Sloan Automotive Laboratory, said the report does a good job of summing up the complexities of the decisions facing this country and the world. In terms of figuring out which technologies—plug-in hybrids, fuel cells, biofuels, or something else—would make the biggest dent in petroleum use, "the technology hasn't developed enough to have clear answers," he said. "We don't know yet where we're going to end up."

All of the transportation technologies, both the conventional ones and the newer ones, are improving all the time, Heywood said, and the newer ones are getting better faster. But for now, those in the industry tend to see electrification—whether through plug-in hybrids or pure electric vehicles—as just a niche market, primarily because such vehicles are too expensive in their current form, and petroleum currently is not expensive enough.

Heywood said that recent developments in automotive technologies have improved fuel efficiency on average by about 1% per year, whereas projections of economic and population growth suggest worldwide fuel usage is increasing by about 2% per year—a disparity that is clearly not sustainable.

Yet-Ming Chiang, the Kyocera Professor of Ceramics at MIT and co-founder of battery company A123 Systems, said that battery technology has been improving faster than expected, as shown by the fact that projections of future battery costs have been dropping steadily. In addition, he said that automotive use is far more demanding than other applications. So even when batteries are no longer suitable for use in a car, they could still have value for other applications such as backup power supplies for homes—potentially easing the cost further by providing a secondary market. "There will still be value after it's ended its automotive life," he said.

Moniz said he came away from the symposium more optimistic about battery technology and the prospects for significant reductions in battery costs, but more aware of the complexities involved in policy issues and in questions about how to develop the infrastructure changes needed for a significant shift away from petroleum.

On the policy front, the speakers agreed that the present situation consists of a hodgepodge of specific legislative incentives such as tax breaks, national standards such as vehicle-efficiency levels, and a wide variety of state regulations. "There really isn't a defined national policy" with regard to curbing petroleum use or fostering an electrified future, Heywood said, "and we desperately need one." He added, "If you really want change, it's got to be pulled and pushed by broader policies with bite."

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By David L. Chandler, MIT News Office

This symposium was sponsored by the MIT Energy Initiative (MITEI) together with MITEI members Ormat, Hess, Cummins, and Entergy. To download a copy of the report, go to web.mit.edu/mitei/docs/reports/electrification-transportation-system.pdf.

Alumni energy ambassadors promote energy interest

Under the leadership of energy ambassador Doug Spreng '65, a member of the MIT Alumni Association's Energy, Environment, and Sustainability Working Group, five other alumni energy ambassadors have been named to carry out energy, environment, and sustainability events and programs focusing on a range of compelling energy topics. Spreng, a veteran of the high-tech industry who is bringing entrepreneurial spirit to his volunteer activities to advance MIT's energy research, is heading up the group of ambassadors helping to connect the MIT Energy Initiative (MITEI) to the alumni population. When Spreng retired in Northern California in 2006, he wondered what he could do that would have a significant impact on the world. "I thought about energy," he says. And so began his new avocation. "Now I'm a professional volunteer."

The other five alumni were selected in key regions where alumni interest in energy is high and total alumni populations are large. The alumni volunteers include Matt Albrecht MBA '08 (MIT Club of Boston, Massachusetts); Bo Bai PhD '06 (MIT Club of New York City, New York); Murli Nathan SM '86, PhD '89 (MIT Club of Southern California); Hari Reddy SM '01 (MIT Club of Washington, DC); and Jimmy Jia '02, SM '04 (MIT Club of Puget Sound, Seattle, Washington).

The group meets regularly to discuss the activities and speakers they have recruited locally, and to discuss best practices for generating local interest. The events they have coordinated range from faculty speakers, such as recent "MITEI on the Road" talks given by Donald Sadoway, the John F. Elliott Professor of Materials Chemistry, in both Northern California and Seattle, to energy-focused networking events in Washington, DC, that have drawn large

Photo: Liv Gold, MIT Alumni Association

At the 2010 Alumni Leadership Conference, Natalie Givans '84 (left) and Doug Spreng '65 offer a workshop on developing energy programming in alumni clubs.

crowds of alumni looking to find others with similar interests.

The energy ambassadors also reach out to the nearly 800 MIT alumni who have identified their energy interests and expertise by registering as part of the Energy, Environment, and Sustainability (EES) Network, part of the MIT Alumni Association's Infinite Connection online community.

If you would like more information about energy ambassadors or the EES network, please contact us at alumnienergy@mit.edu. To read more about Spreng and see a video describing his experiences, visit alum.mit.edu/volunteering/profiles/spreng.

Many generous alumni have also made financial contributions to MITEI, and those gifts have enabled MITEI to significantly expand its program of seed grants for early-stage research projects at MIT. To find out more about the seed grant program, please see page 27.

In addition, Natalie Givans '84, another member of the alumni Energy, Environment, and Sustainability Working Group, showed her support of MITEI by joining as an Affiliate member and by organizing alumni events.

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By Christine L. Tempesta, MIT Alumni Association

Martin Fellows, 2011–2012

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

Timothy Cronin
Earth, Atmospheric and Planetary Sciences
Impact of elevated concentrations of CO_2 on plants

Pearl Donohoo
Engineering Systems Division
Robust electric transmission expansion planning

Deepak Dugar
Chemical Engineering
Pathways for synthesis of advanced biofuels

David Fenning
Mechanical Engineering
Reducing the negative impact of metal impurities in silicon solar cells

Jessica Fitzsimmons
Earth, Atmospheric and Planetary Sciences
Geochemistry of iron in the ocean

Betar Gallant
Mechanical Engineering
Developing nano-structured materials for high-power lithium storage applications

David Keith
Engineering Systems Division
Understanding barriers to adoption of hybrid and electric vehicles

Sean Kessler
Chemical Engineering
Formation mechanisms of organic particulate matter in the atmosphere

Alyssa Larson
Chemistry
Use of non-leaching antimicrobial surfaces to purify drinking water

Andrej Lenert
Mechanical Engineering
Control of nanoscale phenomena for efficient solar thermal energy conversion

Ankur Mani
Media Arts and Sciences
Mechanisms for promoting cooperative behavior in networked societies for sustainable living

Nicholas Martin
Political Science
Environmental policy and China's large state-owned energy companies

David Quinn
Architecture
Analytic tools to assess resource efficiency at the neighborhood scale

Laura Ralston
Economics
Influence of environmental conditions on conflict between individuals and communities in developing countries

Stephen Ray
Mechanical Engineering
Natural ventilation to decrease energy consumption in buildings

Philip Reusswig
Electrical Engineering and Computer Science
Capturing infrared solar radiation for use in solar cells

Vivek Sakhrani
Engineering Systems Division
Sustainable delivery of large energy projects in the developing world

Nidhi Santen
Engineering Systems Division
Methods for simulating decision making under uncertainty: US electricity sector

Benjamin Scandella
Civil and Environmental Engineering
How lakes vent methane to the atmosphere

Christopher Schantz
Mechanical Engineering
Nonintrusive diagnostic techniques to detect fault conditions in HVAC and refrigeration plants

Alexis Schulman
Urban Studies and Planning
Making adaptive management work

Teresa Yamana
Civil and Environmental Engineering
Malaria transmission—developing and testing new physical biological models

Tea Zakula
Architecture
Optimizing HVAC systems to minimize energy consumption

MIT and Cyprus Institute

Expanding joint research, education

In late 2007, MIT and the Cyprus Institute (CyI) launched a research and educational collaboration between energy, environment, and water programs at the two institutions.

Since then, the initial joint research projects have made substantial progress, new ones have begun, and five postdocs funded by CyI have come to MIT to participate in the research.

"This is a unique interaction between MIT and this recently formed research institute in Cyprus," says David H. Marks, the Morton and Claire Goulder Family Professor of Civil and Environmental Engineering and Engineering Systems. "And the bonds between MIT and CyI are growing."

MIT is collaborating on projects through its Cyprus Institute Program for Energy, Environment, and Water Resources (CEEW), which is directed by Marks and housed within MIT's Laboratory for Energy and the Environment (LFEE).

The LFEE cooperated in the development of CyI's Energy, Environment, and Water Research Center (EEWRC). Since its formal inauguration in December 2007, MIT and CyI researchers have been working together on initiatives of importance to the Mediterranean island nation and the region.

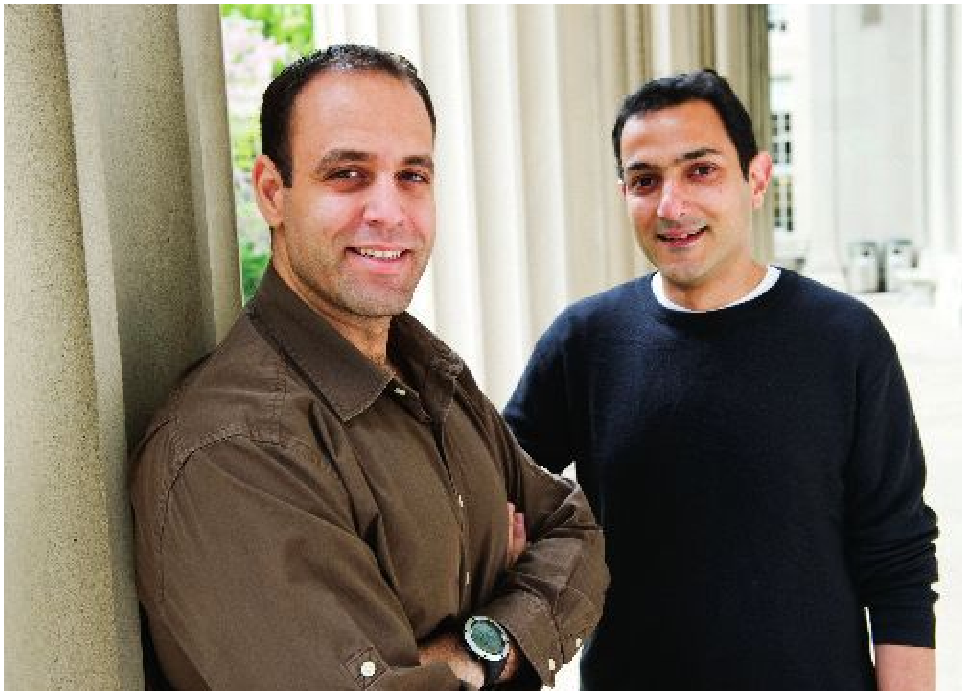

Photo: Justin Knight

Anastassios Mavrokefalos (left) and Panagiotis Parpas are spending two years as postdoctoral Cyprus Fellows participating in research at MIT. Mavrokefalos is focusing on the use of solar and thermal energy for power generation systems, while Parpas is developing control algorithms for integrated multiscale models of complex energy systems. The fellows will subsequently return to Cyprus to continue their research at the Cyprus Institute.

Issues of water, energy, climate change

Cyprus faces serious shortages of both drinking water and energy—and the nation uses fossil fuels to power water desalination, so the two problems are intertwined. A major joint research project has therefore been investigating the use of concentrated solar power to produce both electricity and desalinated seawater. Analysis has shown that this novel cogeneration concept is technologically viable and economically sustainable in Cyprus. Among the concepts coming out of this work are an innovative storage system, installation of heliostats on hillsides, and an advanced-design desalination system. The government of Cyprus has endorsed this project and will provide funds for the construction of a prototype desalination unit that will be driven by solar-thermal power.

Meanwhile, the major climate change study launched at the EEWRC inauguration continues to make progress and gain attention. Changes in climate conditions are expected to be particularly severe in the Eastern Mediterranean and North Africa, with increased temperatures and temperature extremes, decreased precipitation, and shifts in vegetation. Coordinated by CyI, an international group of scientists is clarifying potential changes and exploring political and economic implications and possible new adaptation strategies. A key contribution from MIT is expertise in the integrated assessment of economic and environmental change, as implemented by the Integrated Global System Modeling framework, a comprehensive mathematical tool for analyzing global climate change and its social, economic, and environmental consequences.

Cyprus Fellows at MIT

A vital element in the CyI and MIT collaboration is having postdocs from Cyprus spend two years as postdoctoral associates at the MIT Energy Initiative (MITEI). The most recent "Cyprus Fellows" arrived on campus in fall 2010.

Anastassios Mavrokefalos, who holds a PhD from the University of Texas, is working with Gang Chen, the Carl Richard Soderberg Professor of Power Engineering. Much of his research focuses on creating nanoscale pyramid structures on the surfaces of crystalline silicon photovoltaic (PV) devices to increase solar optical absorption. He has developed a procedure to fabricate such structures on crystalline silicon thin films based on cleanroom microfabrication techniques. Optical measurements show that his novel thin films that are only a few microns thick can absorb as much solar energy as can traditional cells that are 100–300 microns thick. Half the cost of current crystalline silicon PV modules comes from the silicon material used, so reducing the silicon required will bring a corresponding reduction in the cost of PV modules.

Panagiotis Parpas, who earned his PhD from Imperial College, London, is collaborating with Mort Webster, assistant professor in MIT's Engineering Systems Division. Today's engineered energy systems—for example, electric power grids and transportation systems—are extremely complex, in part due to recent advances in science and technology (distributed power generation, vehicle-to-grid systems, smart metering systems, and so on) as well as societal changes such as electric power deregulation and expanded use of renewable energy sources. Energy models must include a mix of economics, technology, and engineering, and as a result they are composed of many heterogeneous subsystems that have dynamics that evolve on different temporal and spatial scales. Parpas is developing simulation and control algorithms for such integrated multiscale models so as to make possible the computation of optimal system designs, which will inform engineering and policymaking at different scales.

Previous Cyprus Fellows have worked on computational problems relating to carbon sequestration, the impacts of climate change on water management in the Mediterranean Basin, and concentrated solar energy technologies for simultaneously generating electricity and powering seawater desalination.

According to Marks, the program is designed "not just to increase [the fellows'] research abilities, but also to bring them into the world network, give them visibility, and get them started on projects that'll extend beyond the two years that they're fellows here." After their time at MIT, the fellows are expected to continue their research at CyI.

The MIT-CyI program was initiated by Ernest J. Moniz, the Cecil and Ida Green Professor of Physics and Engineering Systems at MIT and director of MITEI, and his friend and former MIT physics PhD student Costas Papanicolas, who is now president of CyI.

CyI was formally established in 2005 as a major research-based science and technology educational and research institution that would play an important regional role. Its research focuses on three areas: science and technology of archaeology; high-performance computation; and energy, environment, and water resources. CyI researchers are now working on about a dozen projects in each of those areas with colleagues from world-class international research, academic, and governmental institutions.

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By Nancy W. Stauffer, MITEI

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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Members as of June 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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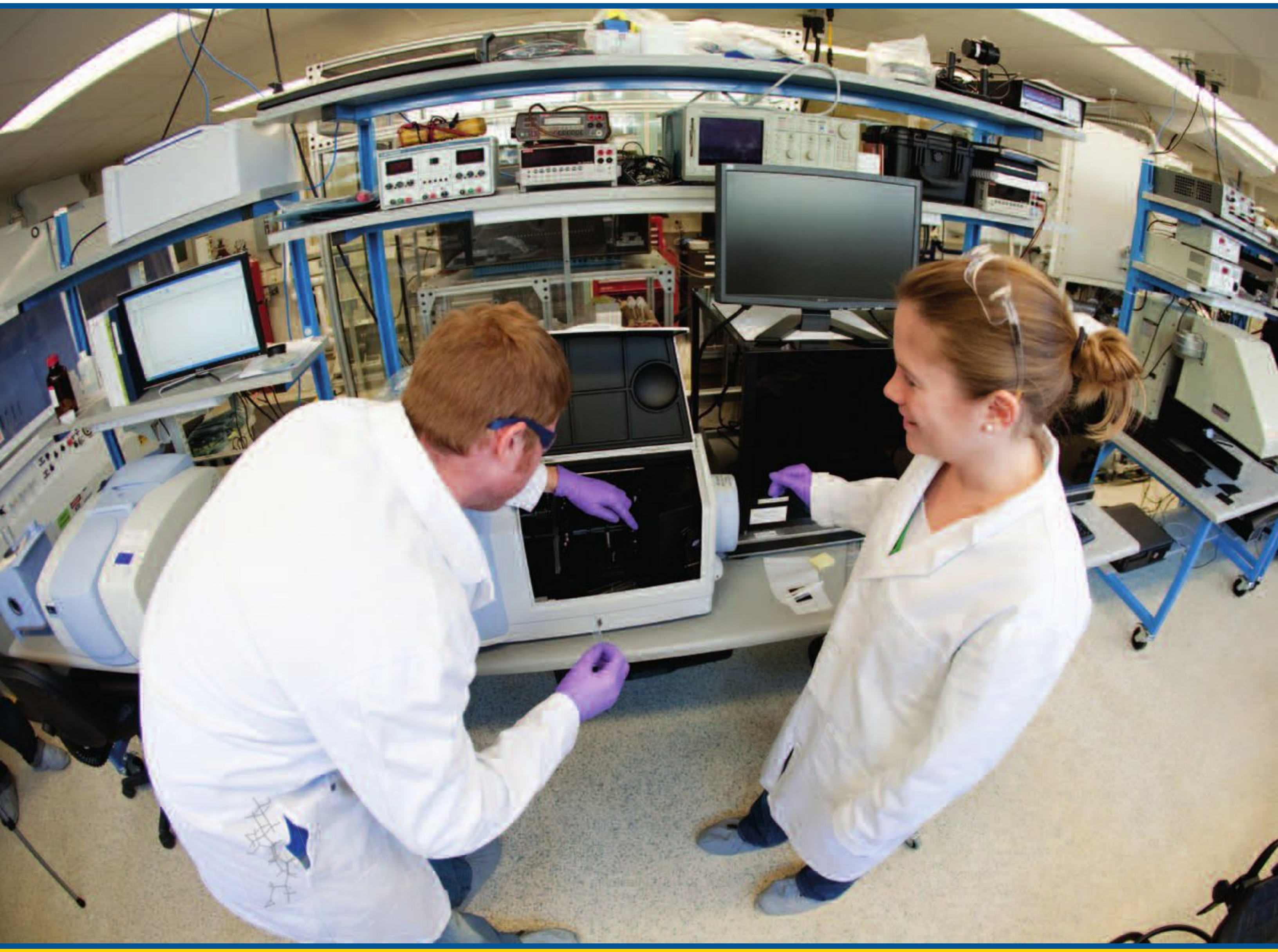

Advanced photovoltaics lab provides hands-on learning opportunities

Joseph Sullivan (left), 2008–2009 Bosch-MIT Energy Fellow, current NSF fellow in mechanical engineering, and a teaching assistant for the MIT class "Fundamentals of Photovoltaics," mounts a sample into a spectrophotometer, an apparatus that measures the optical properties of PV device layers. During lab sections of the class, students use this tool and others in the Photovoltaic Research Laboratory, which is headed by Professor Tonio Buonassisi, also the instructor for the "Fundamentals" class. Looking on is Dr. Bonna Newman PhD '08, a former Clare Boothe Luce Postdoctoral Fellow in Energy and now at Twin Creeks Technologies (San Jose, CA), where she continues to work on developing low-cost, high-performance solar cells. See page 34 for more about the class.

Photo: Sandra Mallalieu, MIT Alumni Association