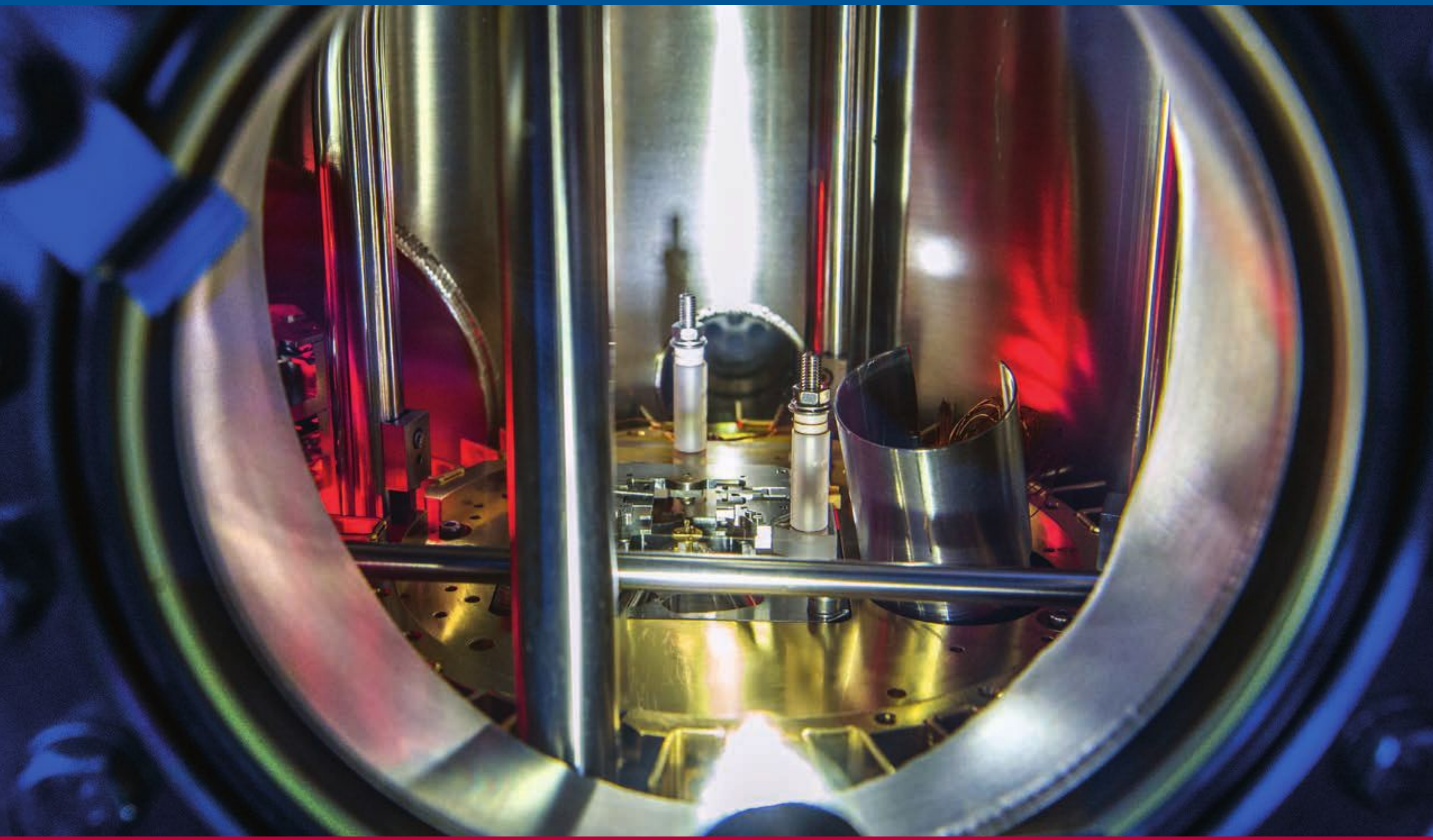
Energy Futures

MIT ENERGY INITIATIVE MIT AUTUMN 2012



Stress corrosion cracking: New experiments, new insights

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Energy Futures

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Update on the MIT Energy Initiative

Dear Friends,

Uncertainty continues to be the watchword for global and national energy challenges. There are alarming indicators that the impacts of climate change are accelerating faster than expected, including the record disappearance of Arctic sea ice, the acidification of the oceans, regional stresses on water supply, and extreme weather events. Yet there has been very little collective action to alter the trajectory of greenhouse gas emissions and few indicators of major actions to come in the near future. Economic pressures both in the United States and in other key economies around the world threaten to diminish support for incentives for a range of renewable energy options. Unrest in the Middle East continues to unnerve the oil markets, and post-Fukushima concerns are clearly affecting the nuclear power industry in some countries.

In the US, the appropriate role of government in shaping the energy marketplace remains contentious, and federal support for energy research is threatened by substantial cuts in funding and changing priorities. In this environment, even the evident benefits of plentiful, low-carbon natural gas create unease that the drive for zero-carbon options may stall.

Despite all of this, one certainty is that the world will continue to seek energy supply ample for growing economies. Core MIT Energy Initiative (MITEI) organizing principles—the focus on industry partnerships, and a research portfolio balanced between technology and policy innovation for today's energy demand, delivery, and supply systems and transformational technology development for a low-carbon future—remain resilient. At the same time, we continue to advance our technically grounded, policy-relevant analyses of key energy issues in the interest of providing some degree of rationality in the ongoing political discussion. We are also partnering with Stanford University, through the good offices of Secretary George Shultz (chairman of the MITEI External Advisory Board), to carry to Washington, early in the next administration, a message about the importance of robust and sustained support for energy research.

Our public outreach efforts also led to two very special events this autumn, both of which are described in this issue. The first was the Women in Clean Energy Symposium (see page 45), a component of the Clean Energy, Education, and Empowerment (C3E) program of the US Department of Energy (DOE). C3E is a nine-country initiative of the international Clean Energy Ministerial group focused on supporting women in clean energy disciplines. The symposium included awards for mid-career women and engaged C3E ambassadors committed to encouraging young women to join clean energy fields. The "energy level" was extraordinary and inspirational. The second event was an energy debate by senior surrogates for the presidential candidates (page 48). It was held at Kresge Auditorium with almost 800 students, faculty, and other guests in attendance and a national audience reached through E&E TV. The discussions were spirited and laid out priorities for the new administration. With both events, MIT's convening power on energy issues was brought to bear on issues of both near- and long-term significance.

Turning to the coming year for MITEI, we will continue to rely principally on our industry partnerships. Our program was designed with these partnerships as the core element of MITEI, and we remain convinced that this is the pathway to maximum impact for advancing MIT's research and educational mission, for meeting the companies' science, technology, and human-capacity strategic objectives, and for influencing the energy future. The Founding and Sustaining Members listed with their logos on the last page of this magazine made initial five-year commitments between 2007 and 2012. More than half of them became MITEI members during a one-year period between autumn 2007 and autumn 2008, providing tremendous early impetus. Given this timing, MITEI is now at an important time for renewal.

We are very pleased that our inaugural Founding and Sustaining Members, BP and Chevron, respectively, have both recommitted and that discussions are well along with several other members. The best part of these discussions is the opportunity to work with each company on new directions in their research portfolios, with a growing circle of faculty investigators, and on new avenues for engaging our graduate and undergraduate students. The result is both a shared sense of accomplishment over the last five years and an excitement about new directions in the coming years.

Of course, our industry-supported research programs are complemented by government, foundation, and philanthropic programs. Starting in 2009, DOE launched energy research programs with longer time horizons and more university participation than had been the case. The Energy Frontier Research Centers aim at sustained efforts addressing key basic science enablers for clean energy technologies, and two were awarded to MIT in 2009. The Solid-State Solar-Thermal Energy Conversion Center and the Center for Excitonics are highlighted in this

Photo: Justin Knight

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

issue (pages 7 and 24, respectively). In addition, the first DOE Innovation Hub, the Consortium for Advanced Simulation of Light Water Reactors awarded in 2010, has strong MIT involvement and is also highlighted (page 12).

Philanthropic support continues to play a crucial role in seeding early-stage projects and supporting new junior faculty members, laying the foundation for continuing high-impact research and education into the future. A number of seed and ignition grant projects, supported both by our industry partners and by our generous alumni and friends, are also featured in this issue.

The Society of Energy Fellows—graduate students in energy supported by MITEI Founding, Sustaining, and Associate Members—has surpassed the 250 mark. Many of these students have now graduated. In this issue, we introduce a new feature—"Energy alumni: Where are they now?"—with profiles and updates on a few (pages 35–37). We hold great hope for the contributions that our energy graduates will make to society. Undergraduates continue to be engaged as well. Our members, alumni, and friends have supported more than 100 MITEI Undergraduate Research Opportunity Program (UROP) projects, and by the end of this academic year, MIT will have graduated more than 50 students with the Energy Studies Minor. After only three years, the minor is the fifth largest at the Institute, with all five schools and 14 departments represented among graduates and currently enrolled students.

In the last six months, MITEI held four community town hall meetings with faculty and senior researchers to solicit input on some important research directions that are positioned for greater emphasis and impact. The research domains of these forums included: the energy-water nexus; the built environment; smart infrastructure and grids; and energy and life sciences. Initial steps have been taken based on the forum discussions, and we hope to have a lot to report on these initiatives in future issues.

The energy world, and energy research and education, show no signs of becoming boring! At MITEI, we expect another eventful and productive year in 2013, and we hope you enjoy this tenth edition of *Energy Futures*.

Sincerely,

Professor Ernest J. Moniz
MITEI Director

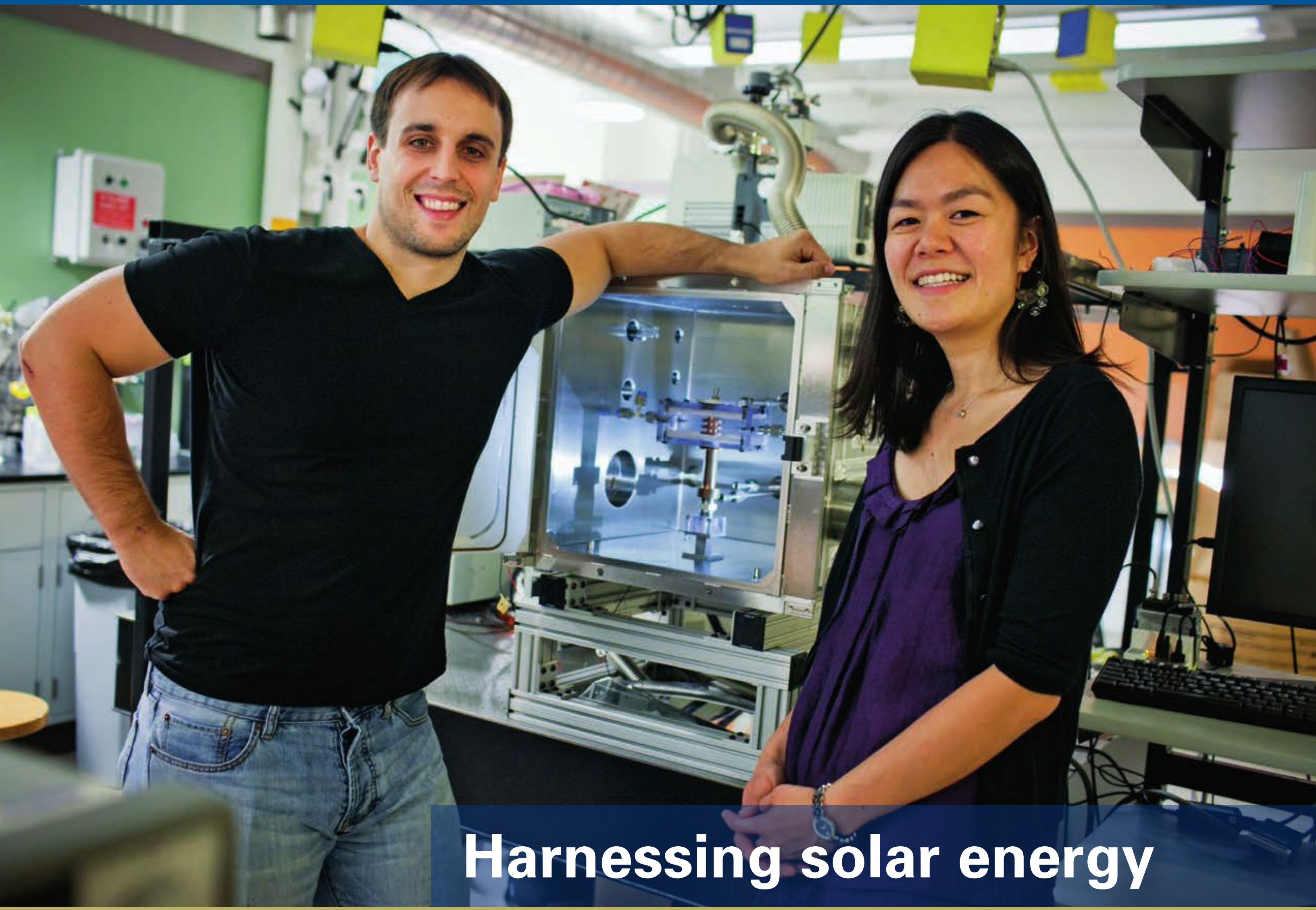
Professor Robert C. Armstrong
MITEI Deputy Director

November 2012

Photos: Justin Knight

On October 26, 2012, BP announced that it was renewing its commitment to the MIT Energy Initiative (MITEI) through an agreement to provide another $25 million for continued energy research over the next five years. Shown at the signing ceremony are (left to right) Andrew Cockerill, director, university relations, group technology at BP; MIT President L. Rafael Reif; Ellen Williams, BP chief scientist; and MITEI Director Ernest J. Moniz. For more information, go to mitei.mit.edu/news/bp-renews-commitment-mit-second-25-million-pledge.

Chevron and the MIT Energy Initiative (MITEI) celebrated their continuing partnership at an October 1, 2012, reception. The $2 million "check" represents Chevron's total contribution to MIT over the last year, including sponsored research, gifts, grants, consortia membership, and more. Above, left to right: Paul Seigele, president, Chevron Energy Technology Company; Ernest J. Moniz, director, MITEI; John McDonald, vice president and chief technology officer, Chevron Corporation; Robert C. Armstrong, deputy director, MITEI; and Cynthia Murphy, Chevron University Affairs.



Harnessing solar energy

Novel approach yields both electricity and heat

Nenad Miljkovic (left) and Evelyn Wang of mechanical engineering are designing a specially adapted solar energy collector that will simultaneously produce electricity and steam or hot water at wide-ranging temperatures suited for home or industrial use.

This research was supported in part by the MIT Solid-State Solar-Thermal Energy Conversion Center, an Energy Frontier Research Center funded by the US Department of Energy. For a complete list of sponsors, see page 7.

Photo: Dominick Reuter

MIT researchers have designed an efficient, potentially low-cost system that will use the sun's energy to produce electricity and hot water or steam simultaneously. Their design is based on a conventional solar thermal system but incorporates special features that make it more efficient and flexible. For example, it uses evaporation, condensation, and gravity to move the captured heat to the point of consumption—no need for an energy-consuming pump. It generates electricity using a solid-state technology that converts the captured solar energy directly to electricity with no moving parts. And depending on the materials used, the heat output can range from low-temperature water for household use to high-temperature process heat for industrial applications such as aluminum smelting. The researchers are now building a prototype of their system.

As the world looks for new ways to fulfill its appetite for energy, there are many technologies that can produce either heat or electricity using the energy of the sun. For example, in many parts of the world, people get warm water for their homes from systems in which sunshine heats up water inside a glass tube or black tank. Such systems are simple and inexpensive, but in that configuration they provide only warm water, no electricity. For electricity production, much interest is focusing on thermoelectric (TE) devices. When a TE device is hotter on one side than the other, it generates electricity—no combustion and no moving parts involved. But until recently, solar-driven electricity-generating systems using TE materials have not proved very efficient.

Now Evelyn Wang, associate professor of mechanical engineering and director of the MIT Device Research Laboratory, and Nenad Miljkovic, graduate student in mechanical engineering, have designed a novel hybrid system that brings those two approaches together to produce electricity and hot water or steam at the same time, pushing up both the temperature of the water and the efficiency of the overall system.

Their system is based on a standard solar energy collector called a parabolic trough. In this type of device, a long parabolic mirror reflects sunlight onto a fluid-filled tube that runs its length at its focal point. A mechanical pump moves the heated working fluid through the tube to the point of consumption. There, it can be used directly for space heating or for running industrial processes, or it can be used to produce steam to drive an electricity-generating turbine.

In their version of the parabolic trough—shown on page 6—Wang and Miljkovic use three concentric tubes. To maximize solar energy capture, they coat the outside surface of the middle tube with a selective absorber. Then, to keep the captured heat from escaping, they place that tube inside an outer glass tube, with a vacuum between them. The system thus absorbs as much sunlight and emits as little heat as possible.

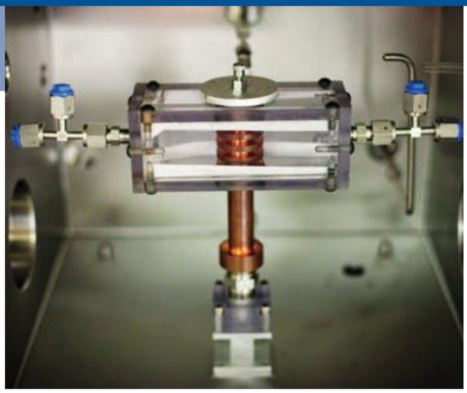


Photo: Dominick Reuter

The MIT researchers used this laboratory setup to test the principles behind their concept for a novel hybrid system that can deliver electricity as well as heat.

They then incorporate two technologies that increase efficiency and decrease cost and complexity. To get rid of the energy-consuming mechanical pump, they move the captured heat to the point of consumption using a "thermosyphon"—the central tube in the diagram. In this arrangement, the tube is only partially filled with a specially selected working fluid that evaporates when heated by the sun. The vapor that forms rises and flows naturally through the tube until it reaches a cool surface, where it condenses, releasing its heat. Because the system is designed with an upward tilt, gravity then forces the condensed fluid to flow back down to the area of the hot solar absorber, where it undergoes the heat-gathering, heat-releasing cycle again.

The thermosyphon not only transfers the heat without mechanical assistance but also does it extremely efficiently. "In a thermosyphon, you utilize the phase change of a liquid—the vaporization and subsequent condensation—to move the heat to where you want it," says Wang. "It's as if it were a very, very good thermal conductor—much better than, say, diamond, which is one of the best solid conductors."

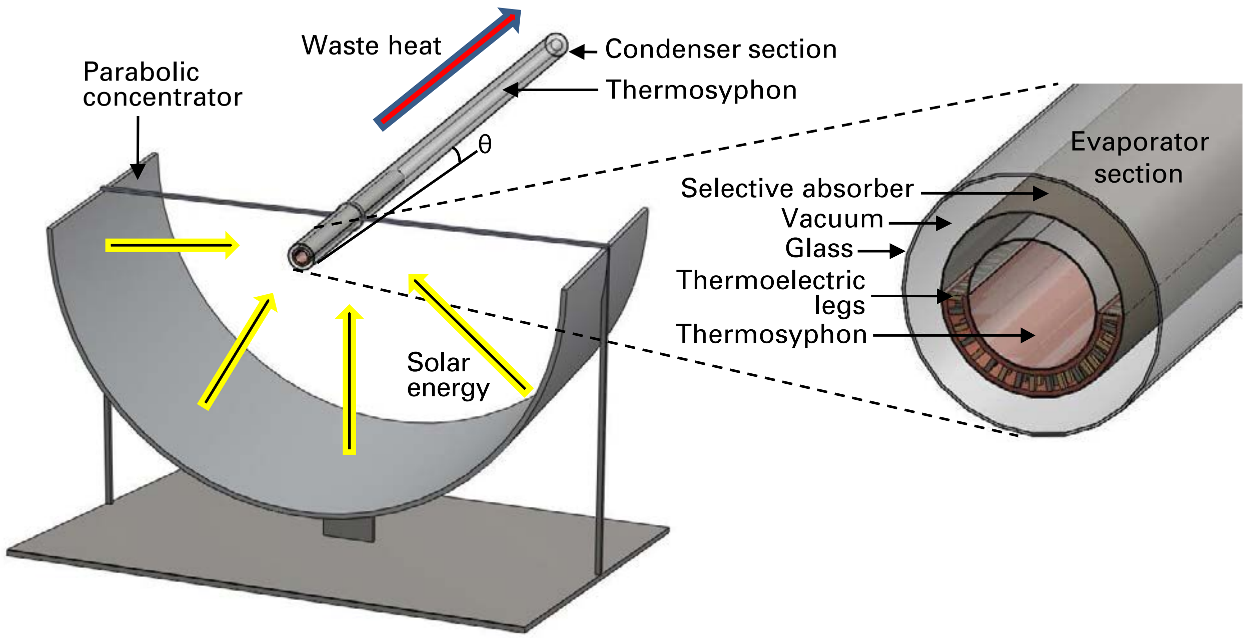
The second technology they incorporate provides a simpler means of generating electricity than that used in a conventional parabolic-trough system. Instead of raising steam to run a generator, they use a TE material, strategically located to maintain the temperature difference that causes electricity to flow. As shown in the diagram, the TE material is incorporated in the form of "legs" that run between the absorber wall and the exterior surface of the thermosyphon, spaced at regular intervals with a vacuum in the gaps between them. In this configuration, heat from the absorber surface travels through the TE legs to the thermosyphon, where it is removed by the vaporization of the working fluid. As a result, each leg has one end attached to the hot absorber wall and the other attached to the constantly cooled exterior of the thermosyphon. The temperature difference is maintained, and current flows.

The thermoelectric advantage

TE devices are an attractive electricity-generating choice for several reasons. An obvious advantage is that they involve no moving parts, so they are simple, durable, and robust. Photovoltaic (PV) cells are likewise a solid-state system, and they are far more efficient at turning solar energy into electricity than TE materials are. But to work properly, PVs must be extremely pure and perfect, so making them involves carefully controlled and costly processes. In contrast, TEs actually work better when they are flawed; so even if rare materials are used, they can be fabricated using bulk manufacturing techniques.

Perhaps more important, while conventional PV cells do not operate well at

Novel MIT hybrid solar-thermoelectric system



In this design, the parabolic concentrator focuses solar energy onto the surface of the absorber. The outermost glass tube keeps the captured heat from escaping by conduction or convection. The heat is transported by "legs" of a thermoelectric material to the central tube in the system—a thermosyphon partially filled with a working fluid. The fluid evaporates, and the hot vapor moves passively along the tube to a cool section, where it condenses, releasing its heat for use in various applications. The condensed fluid then flows naturally through the downward sloping tube back to the absorber section, where it vaporizes once again. Because the thermoelectric legs are constantly heated at one end and cooled at the other, they continuously generate electric current.

high temperatures, TE materials thrive in the heat. "That's an important advantage," says Miljkovic. "We can use our system at high temperatures. And in mechanical engineering, high temperatures are generally good. Systems—especially any electric power generation cycle—are a lot more efficient when operating at higher temperatures."

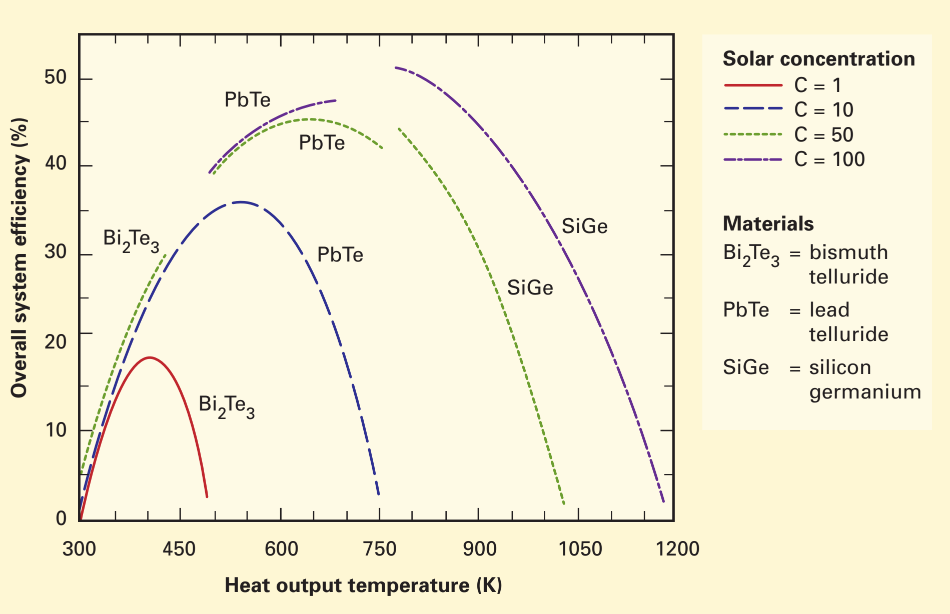
Moreover, using a specially formulated computer model, the researchers found that by carefully choosing their TE material, they could tailor their system to operate efficiently while delivering waste heat at a wide range of pre-specified temperatures. The figure on page 7 shows heat-output temperature at the end of the thermosyphon versus the overall efficiency of the system (heat and electricity combined). Solar concentration measures the degree to which the solar energy is concentrated by the parabolic trough. Concentrations of 50 to 100 are typical of today's technology, and higher concentrations bring higher operating efficiencies.

The curves show results for three TE materials, each of which has a distinct operating range where efficiency is maximized. Bismuth telluride works well at low temperatures, lead telluride at medium temperatures, and silicon germanium at high temperatures. "So each of these TEs has a distinct operating range where you maximize efficiency," says Miljkovic. "And then, for each one correspondingly, there is a thermosyphon system that can operate in that range."

Using their model, the researchers identified a thermosyphon working fluid and tubing material that can operate in the same temperature range as each of the TE materials. For example, conventional water inside a copper tube works well with bismuth telluride. That system's output heat is 300–500 K—appropriate for residential heating or for low-temperature industrial processes. Mercury contained inside a stainless steel tube combines with lead telluride to produce heat appropriate for low-temperature industrial processes such as chemical drying. And liquid potassium inside a nickel tube works with silicon germanium to generate high enough temperatures for processes such as aluminum smelting. In each case, rising temperature brings an increase in efficiency, but eventually radiant heat losses—which increase more dramatically with temperature than efficiency does—dominate and efficiency drops back down.

The example of aluminum smelting demonstrates a major benefit of this new system. Generally, the extreme heat required for the aluminum smelting process is produced using electricity. "But this technology can help minimize electricity consumption. Instead of using electricity to generate the heat, our system can provide the heat by solar concentration from the sun during daylight hours," says Miljkovic. "So you'll use the heat to do the heating, and still have the electricity for other uses." At the other extreme,

Efficiency and heat output of various system designs



Using different thermoelectric materials in the hybrid system yields differing output temperatures. Bismuth telluride, for example, produces low-temperature water suitable for residential use. For each material, increasing the solar concentration increases energy input and therefore thermal efficiency. For a given solar concentration, each design has an optimal efficiency beyond which thermal gains from increasing temperatures begin to be outweighed by growing radiant heat losses.

a system designed for a single house could provide abundant heat along with enough electricity to meet the homeowner's needs. The natural gas or oil now consumed for home heating could be used elsewhere for other applications.

Guided by their simulations and a series of optimization studies, Wang and Miljkovic are now building a prototype to demonstrate how their hybrid system could work. Practical implementation of their approach may be several years away, but they are optimistic about the ultimate outcome, in part because of related research activities under way in Wang's Device Research Laboratory. "All of our projects focus on efficiently transferring heat and mass in various types of systems," Wang says. And what is unusual, notes Miljkovic, is that they incorporate surface science into their work. For example, one project looks at how to structure surfaces to make the phase change process itself—the vaporization and condensation—more efficient.

"So within the design of our thermosyphon, we can actually introduce structuring of the surfaces to further enhance efficiency," says Wang. By drawing on results from that and other projects, they will be able to continue improving the performance of their novel hybrid solar-thermoelectric system.

• • •

By Nancy W. Stauffer, MITEI

This research was supported by the MIT Solid-State Solar-Thermal Energy Conversion (S^3TEC) Center (see sidebar), an Energy Frontier Research Center funded by the US Department of Energy, Office of Science, Office of Basic Energy Sciences, and by the Natural Sciences and Engineering Research Council of Canada. Further information can be found in:

N. Miljkovic and E.N. Wang. "Modeling and optimization of hybrid solar thermoelectric systems with thermosyphons." *Solar Energy,* vol. 85, pp. 2843–2855, 2011.

Center focuses on converting heat to electricity

In 2009, the Solid-State Solar-Thermal Energy Conversion (S^3TEC) Center began to pursue its mission: to create novel solid-state materials and devices that can convert sunlight and heat into electricity—efficiently, at low cost, and with no moving parts. S^3TEC was established as an Energy Frontier Research Center by the US Department of Energy, with funding of $17.5 million over five years. It is directed by Gang Chen, MIT's Carl Richard Soderberg Professor of Power Engineering and director of the Pappalardo Micro and Nano Engineering Laboratories. The work involves a diverse group of experts at MIT, Boston College, Oak Ridge National Laboratory, and Rensselaer Polytechnic Institute. At MIT, participants include 11 faculty members from five departments in the Schools of Engineering and Science.

Key to the research are two solid-state technologies that can convert heat from the sun and other sources into electricity. "Solar thermoelectric energy conversion" uses solar radiation to create a temperature difference across a solid-state material, which then generates electricity. In "solar thermophotovoltaic" devices, solar radiation first raises the temperature of an object; that object then emits photons optimized to the bandgap of a photovoltaic cell, and the cell generates electricity. Both technologies can also operate on heat from other sources, including geothermal heat and waste heat from industrial processes, transportation, and buildings.

The S^3TEC researchers have already achieved fundamental advances that are, for example, enabling them to fabricate thermoelectric devices with significantly increased efficiency and to create spectrally selective surfaces critical to high-performance thermophotovoltaic systems.

Stress corrosion cracking

New experiments, new insights

F. William Herbert of materials science and engineering (left) and Bilge Yildiz of nuclear science and engineering are examining how nanoscale disruptions in the crystalline structure of metals affect those materials' vulnerability to stress corrosion cracking.

This research was supported in part by an ignition grant from the MIT Energy Initiative (MITEI); by BP, a Founding Member of MITEI; and by the Consortium for Advanced Simulation of Light Water Reactors, a multi-institution Innovation Hub funded by the US Department of Energy. See page 12 for a complete list of sponsors.

Photo: Justin Knight

High stresses combined with a corrosive environment can cause critical components inside power plants and other systems to crack and fail, sometimes with little warning. MIT researchers now have new insights into how such "stress corrosion cracking" may be affected by nanoscale disruptions in the crystalline structure of metallic materials. Using novel experimental methods, they showed that mismatches between adjacent crystals can create regions with altered mechanical properties, including hardness. In addition, those defects can change the electronic properties of the surface in the region, making reaction with oxygen more likely and accelerating the pace of corrosion. Ultimately, the MIT researchers hope to define nanostructures that can help prevent this pervasive, insidious form of material degradation and failure.

Nuclear power plants are designed for decades of operation. But finding materials that age well in the extreme environment inside an operating plant is difficult. A major problem is stress corrosion cracking, which combines chemical attack in the form of corrosion with stress from mechanical loads. "Corrosion causes a material to age in a particular manner and speed, and stress causes it to fracture after a certain period of time," says Bilge Yildiz, associate professor of nuclear science and engineering. "But when you have those two processes together, they interact, and both processes are accelerated." Worse still, the damage often is not obvious, so failure can be both unexpected and catastrophic. Stress corrosion cracking has been blamed for failing power plants, exploding natural gas pipelines, collapsing bridges, crashing airplanes, and more.

One challenge is that local structures in a material can make it more vulnerable to both fracture and chemical attack. Many of the most advanced materials for power plant components are polycrystalline, that is, made up of many tiny crystals, or "grains." The atoms inside each grain are lined up in a regular pattern. But neighboring grains within a solid may be oriented in different directions, so rows of atoms can be misaligned where two or more grains meet. According to one hypothesis, misalignments at those grain-to-grain interfaces—the "grain boundaries"—can affect the material's local response to stress and can create dislocations in the crystalline structure nearby that are more chemically reactive with oxygen and are thus more likely to corrode.

Yildiz, head of MIT's Laboratory for Electrochemical Interfaces, notes that carefully controlled processing conditions can produce materials with grains of pre-defined sizes and orientations. "So if we had a better understanding of the relationship between grain-boundary structure, response to mechanical stress, and resistance to corrosion, we might be able to create a surface structure or texture that would help inhibit stress corrosion cracking," she says.

But even after decades of corrosion research, there is still no conclusive picture of the processes going on at the grain boundaries. Part of the problem is that the effect is extremely local. "A grain boundary extends over only one or a few nanometers, so it's a confined medium," says Yildiz. "And it's a coupled chemical-mechanical degradation mode. So we needed new, high-resolution tools to reach the mechanical as well as chemical properties of these localized structures."

Looking for weakness

Yildiz's first task was to determine whether—and how—well-defined grain boundaries affect the mechanical properties of a material. She used a technique called nanoindentation, which involves pushing a hard tip into a solid sample while carefully controlling and monitoring the downward pressure of the tip. The relationship between the applied load and the volume of deformed material beneath the indenter serves as a measure of the material's hardness.

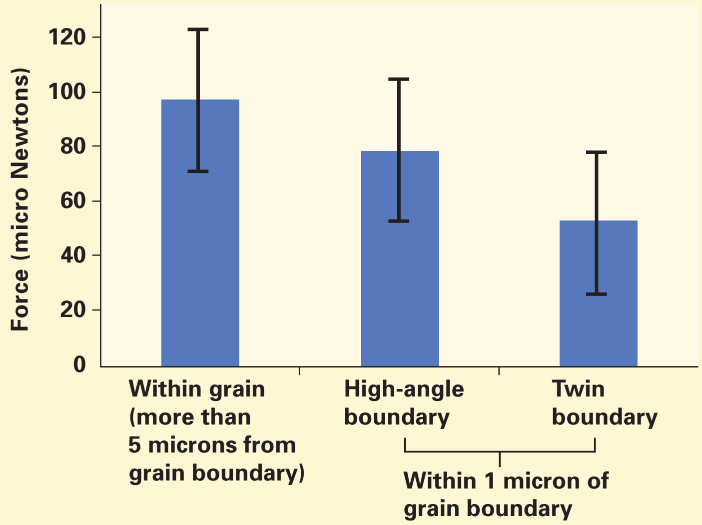
To perform the experiments, Yildiz and graduate student F. William Herbert of materials science and engineering worked with Krystyn Van Vliet, the Paul M. Cook Career Development Associate Professor of Materials Science and Engineering, director of MIT's Laboratory for Chemomechanics, and an expert in nanoindentation.

As their test material, they used Inconel 690, a nickel-based, corrosion-resistant superalloy especially suited for nuclear applications. They fabricated a sample with a variety of grain orientations and then made 200 nm-deep nanoindentations, spaced 2 microns apart and running in diagonal lines across the grain boundaries. These nanoindentations measured increasing force (or load) while monitoring the changing displacement as the diamond probe pressed into the metal surface.

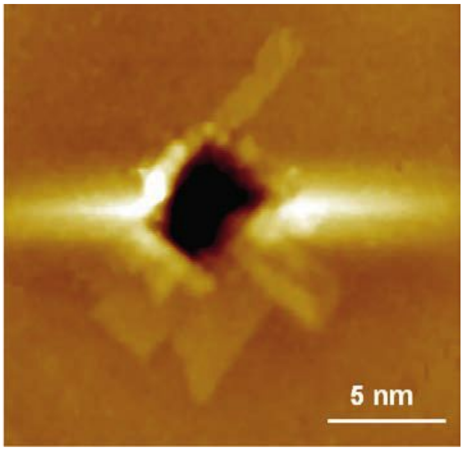
Photos: Justin Knight

The view inside the customized scanning tunneling microscope that the researchers are using in the photo to the left. With this device, they create carefully controlled indentations on a surface and then determine atom-by-atom changes in the physical structure as well as local alterations in chemical reactivity that result.

Pop-in loads on the surface of a nickel-based superalloy sample



These bars show the force (or load) at which the indenter first elicits a sudden displacement of 5 nm in the surface of a sample of Inconel 690, a nickel-based superalloy. The left bar shows results from a test within a single crystal, or "grain." The center and right bars show results from tests within 1 micron of an interface between two adjacent grains. Two types of grain-to-grain misalignments were tested (see text below).



Using a customized scanning tunneling microscope, the researchers made controlled indentations in the carefully prepared, pristine surface of a single crystal of pure nickel. With the same device, they then took micrographs that showed the resulting surface damage nearby (example above). In addition, they probed the energy levels of electrons at locations near and far from the damage to determine the chemical reactivity with oxygen.

One measure of interest is the "pop-in" load. In general, the gradually increasing force of the probe will elicit uniformly increasing penetration into the metal surface, with growing displacement of material. But at certain loads there are sudden bursts in displacement called pop-ins. The team defined the pop-in load as the first load that caused a displacement of more than 5 nm.

The figure above shows pop-in loads for indentations made more than 5 microns from any grain boundary (left bar)—so that deformation occurred "far" from a boundary, within a single grain—and those made within 1 micron of two types of grain boundaries. In a high-angle boundary (center bar), rows of atoms in the adjacent grains are oriented at a high relative angle. In a twin boundary (right bar), the atoms in the two grains are aligned at an angle that minimizes the interfacial energy at the boundary.

The series of tests shows that pop-in loads are significantly lower near both types of grain boundaries than away from the boundaries. In addition, the pop-in load is lower near the twin boundary than near the high-angle boundary, suggesting that the specific structure of the boundary may have an impact on how much resistance a given grain boundary has to permanent deformation.

Thus far, the researchers cannot conclude unequivocally that the observed difference in pop-in load is related only to the grain-boundary structures. More work is needed to understand other factors that may affect the outcome, for example, possible differences in the local chemical makeup or in the direction of the indenter during the test. Their novel tests to date do, however, confirm that resistance to stress is lower near grain boundaries than within grains, an outcome with implications for local vulnerability to stress corrosion cracking.

Creating defects, testing corrosion susceptibility

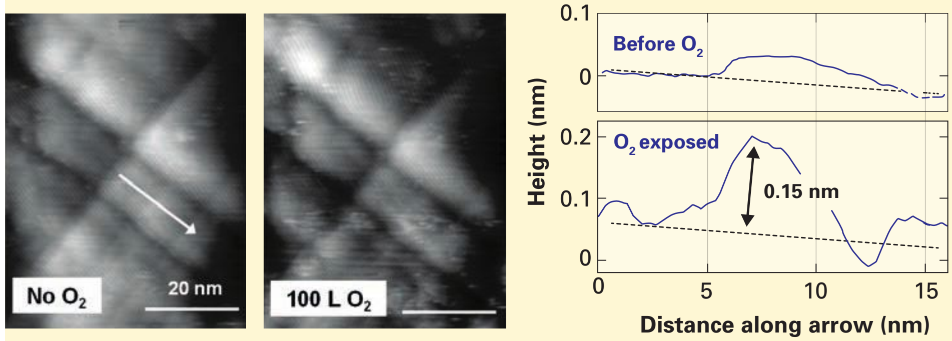
The next question is: Do dislocations associated with grain boundaries increase chemical reactivity, accelerating corrosion susceptibility even without changes in chemical composition? To find out, the researchers created their own well-defined dislocations on a pure surface and then tested for differences in chemical reactivity with oxygen near and away from the damaged regions.

A scanning tunneling microscope (STM) can map the atom-by-atom topography across a surface and also determine the electronic structure, that is, the energy levels of electrons at a single location—a good indicator of how chemically reactive or passive a material is. So a single instrument can determine both the physical structure and the chemical reactivity on a surface within an extremely localized region.

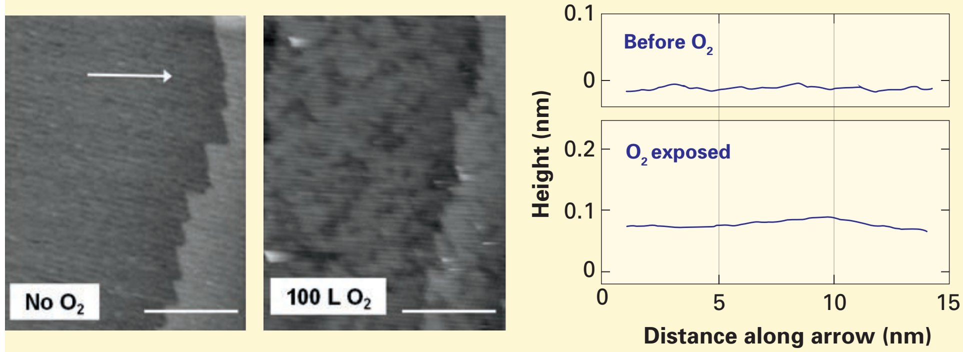
By adapting an STM in Yildiz's lab, the team added one more capability: the ability to create well-defined dislocations by indenting the surface with the STM tip. In normal operation, the tip of the STM must continually hover very close to the surface but never touch it. "Usually if you crash the tip into the sample, you do it by mistake,"

Damaged and undamaged nickel surfaces, before and after exposure to oxygen

Damaged surface



Undamaged surface



Scanning tunneling microscope (STM) images of a pure nickel surface, taken near and far away from indentations created by the STM probe. The top images show contours of dislocations near the indentation before (left) and after (right) exposure to oxygen. The bottom images show the flat, undamaged surface away from the indentation, before and after oxygen exposure. The curves at the right show changes in height at locations indicated by the white arrows in the left-hand images. As the curves show, after exposure to oxygen, the undamaged surface is unchanged, whereas the damaged surface now has an added protrusion of 0.15 nm—precisely the height of newly formed nickel oxide deposits reported by others.

says Yildiz. "But with our customized STM tip, we can do it in a controlled manner, and it works as a very local, shallow indenter."

To begin the experiments, the researchers fabricated a single grain of pure nickel and polished it until it had an absolutely smooth, pristine surface. Using their customized STM, they then made indentations of varying depths between 0.5 and 20 nm. With the same instrument, they took images of the surface topography (see example on page 10) and probed the energy levels of the electrons in the material both near and away from the damaged zones created by the indentations.

Their measurements showed that it is easier to transfer electrons from the surface to oxygen in the region of the dislocations than it is in the damage-free, flat regions. "So from an electronic structure perspective, the dislocations are likely to provide preferential nucleation sites for oxidative chemical reactions," says Yildiz. That finding supports the hypothesis that surfaces with dislocations will experience enhanced oxygen adsorption and subsequent formation of nickel oxide—the first steps in corrosion.

Visual evidence

The next step was to look for physical signs of corrosion. The researchers exposed their nickel surface to ultra-pure oxygen and then used the STM to take atomic-level images of various regions of the surface.

Sample results are shown above. The top two images show the surface near the indentation, first in ultra-high vacuum (left) and then after exposure to oxygen (right). The left image shows smooth contours—the result of dislocations created by the indentation. In the right image, an added protrusion is evident. The bottom pair of images shows the undamaged surface. No noticeable bumps are present either before (left) or after (right) oxygen exposure.

The curves at the right show the height of the surface measured along the white arrows in the images at the far left. In the bottom figure—the pristine surface—there is essentially no change in level, either before (top curve) or after (bottom curve) oxygen exposure. In the top figure, the oxygen-free surface shows a small swelling indicating surface damage. When oxygen is present, the trace of the sample surface shows an added protrusion about 0.15 nm tall.

Work by other researchers has shown that nickel oxide initially forms in protrusions that are 0.15–0.2 nm tall. The new MIT images showed protrusions of precisely that height, consistent with early-stage nickel oxide formation. "And the protrusions formed preferentially on and along dislocations," says Yildiz. "So while theory has suggested that dislocations should be sites of faster corrosion, our images provide direct proof of it."

Computational studies

While continuing their experimental work, Yildiz and her colleagues are also developing new computational tools that can shed additional light on the corrosion process as well as on radiation damage. That work is part of the Consortium for Advanced Simulation of Light Water Reactors (CASL), a multi-institution Innovation Hub led by the Oak Ridge National Laboratory and funded by the US Department of Energy (see sidebar at right).

Yildiz's work focuses on zirconium alloys used as nuclear fuel cladding, an outer tube that surrounds the ceramic fuel pellets inside today's reactors. Since thinning of the cladding raises safety concerns, power plant operators use computer models to predict how fast damage from corrosion will progress.

In those models, certain critical parameters are based on experimental results and empirical observations. But Yildiz believes that many of them could instead be obtained through calculations based on first principles, that is, on fundamental laws of physics. Accordingly, she and her team have developed a new computational approach that can model corrosion-related deformation at the atomic scale over far longer time scales than achievable with traditional atomic-level methods—times compatible with the slowly progressing corrosion process.

According to Yildiz, models incorporating these new computational methods should help operators more accurately predict the impact of corrosion and radiation damage on the aging and performance of the fuel used in today's power plants. And for the longer term, her team's novel experimental techniques may yield materials with surface textures and nanostructures tailored to resist the mechanical stresses and corrosive environments that prevail in power plants, pipelines, and other critical components of today's infrastructure.

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By Nancy W. Stauffer, MITEI

The experimental research was supported by the Nuclear Regulatory Commission Young Faculty Grant Program and by BP's Inherently Reliable Facilities Program. Early work was funded by an ignition grant from the MIT Energy Initiative. The computational research on corrosion of nuclear materials is being supported by CASL (see sidebar). Experimental and computational research on corrosion of oil and gas exploration field materials is being supported by the BP-MIT Advanced Materials and Corrosion Program. Further information can be found in:

F.W. Herbert, B. Yildiz, and K.J. Van Vliet. "Nanoindentation induced deformation near grain boundaries of corrosion resistant nickel alloys." *Materials Research Society Symposium Proceedings*, vol. 1297, pp. 187–192, 2011.

F.W. Herbert, K.J. Van Vliet, and B. Yildiz. "Plasticity-induced oxidation reactivity on Ni(100) studied by scanning tunneling spectroscopy." *MRS Communications,* vol. 2, issue 1, pp. 23–27, 2012.

Institutions collaborate on critical tools for nuclear industry

For more than two years, MIT and nine partner organizations have been developing computer simulation tools to enable the nuclear energy industry to tackle two challenges: extending the lifetime and increasing the output of existing reactors, and improving nuclear plant designs of the future.

Led by Oak Ridge National Laboratory, researchers in the Consortium for Advanced Simulation of Light Water Reactors (CASL) are drawing on the world's most powerful computers to create a simulation—with unprecedented spatial resolution—of an operating light water reactor. Using that "virtual model," they will be able to improve reactor reliability, safety, and performance. Future refinements will permit analyses of next-generation designs.

Work at MIT focuses on modeling the behavior of key materials such as fuel and fuel cladding together with energy generation and transport processes to provide better estimates of how those materials will perform in the extreme environment of a nuclear reactor. The MIT team is led by principal investigator Professor Mujid Kazimi, director of the MIT Center for Advanced Nuclear Energy Studies, and co-principal investigators Professors Sidney Yip and Jacopo Buongiorno. Participants include faculty and research staff from nuclear science and engineering, materials science and engineering, and mechanical engineering.

CASL was the first of three Energy Innovation Hubs announced in 2010 by the US Department of Energy. It was awarded up to $122 million of funding over five years and involves collaborators from universities, industry, and national labs. MITEI Director Ernest Moniz served as the inaugural chairman of the CASL Board of Directors.

Water desalination

A novel, energy-saving approach

The availability of fresh water is dwindling in many parts of the world, a problem that is expected to grow as populations increase. One promising source of potable water is the world's virtually limitless supply of seawater, but so far desalination technology has been too expensive for widespread use. Now, MIT researchers have come up with a new approach using a different kind of filtration material: sheets of graphene, a 1 atom-thick form of the element carbon, which they say can be far more efficient and possibly less expensive than existing desalination systems.

Jeffrey Grossman (left) and David Cohen-Tanugi of materials science and engineering have designed graphene sheets with precisely controlled pores that have the potential to desalinate water more efficiently than existing methods can.

This research was partially funded by a seed grant from the MIT Energy Initiative and by a Schlumberger-MIT Energy Fellowship. See page 15 for more information on sponsors.

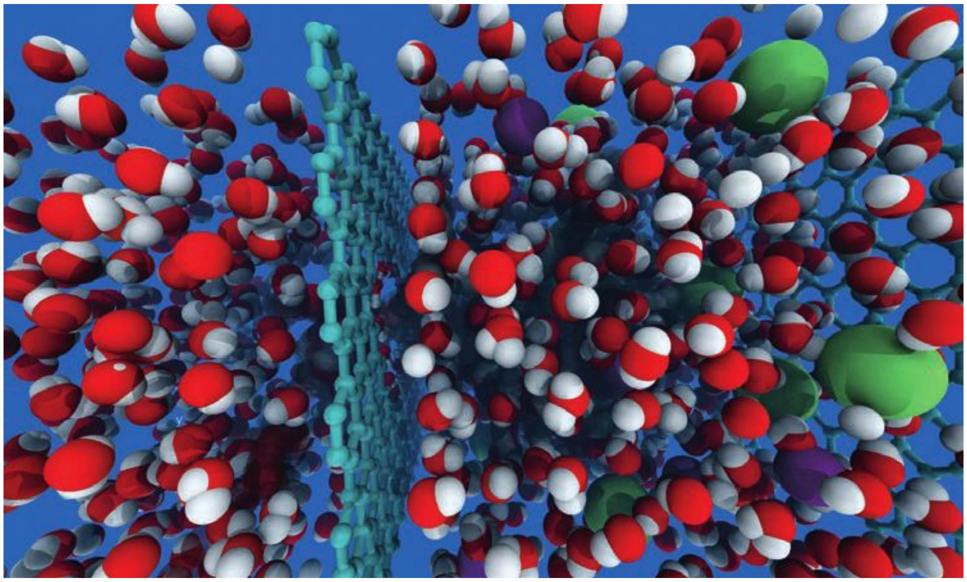
Photo: Justin Knight

"There are not that many people working on desalination from a materials point of view," says Jeffrey Grossman, the Carl Richard Soderberg Associate Professor of Power Engineering in MIT's Department of Materials Science and Engineering. He and David Cohen-Tanugi, a graduate student in the same department and a 2010–11 Schlumberger-MIT Energy Fellow, aimed to "control the properties of the material down to the atomic level," producing a graphene sheet perforated with precisely sized holes. They also added other elements to the material, causing the edges of these minuscule openings to interact chemically with water molecules—either repelling or attracting them (see images at right).

"We were very pleasantly surprised" by how well graphene performed compared to existing systems in computer simulations, Grossman says.

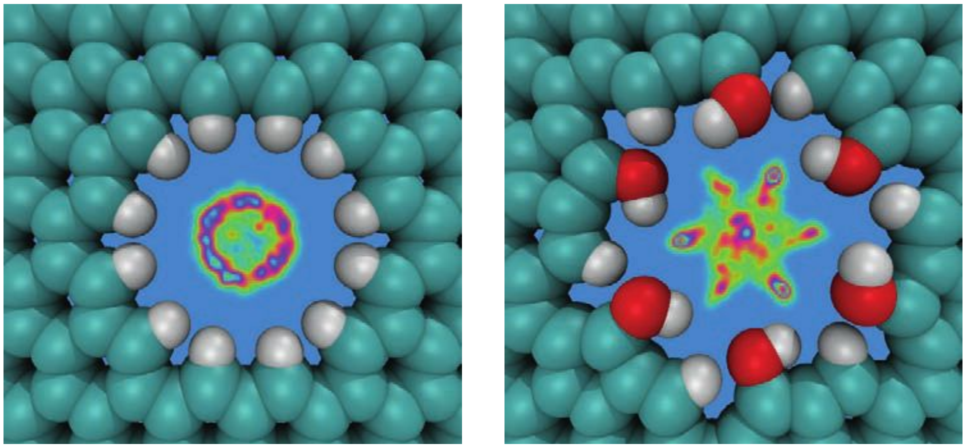
One common method of desalination, called reverse osmosis, uses membranes to filter the salt from the water. But these systems require extremely high pressure—and hence, energy use—to force water through the thick membranes, which are about a thousand times thicker than graphene. The new graphene system operates at much lower pressure and thus could purify water at far lower cost, the researchers say.

While reverse osmosis has been used for decades, "really basic mechanisms of separating salt from water are not well understood, and they are very complex," Cohen-Tanugi says, adding that it's very difficult to do experiments at the scale of individual molecules and ions. But the new graphene-based system, he says, works "hundreds



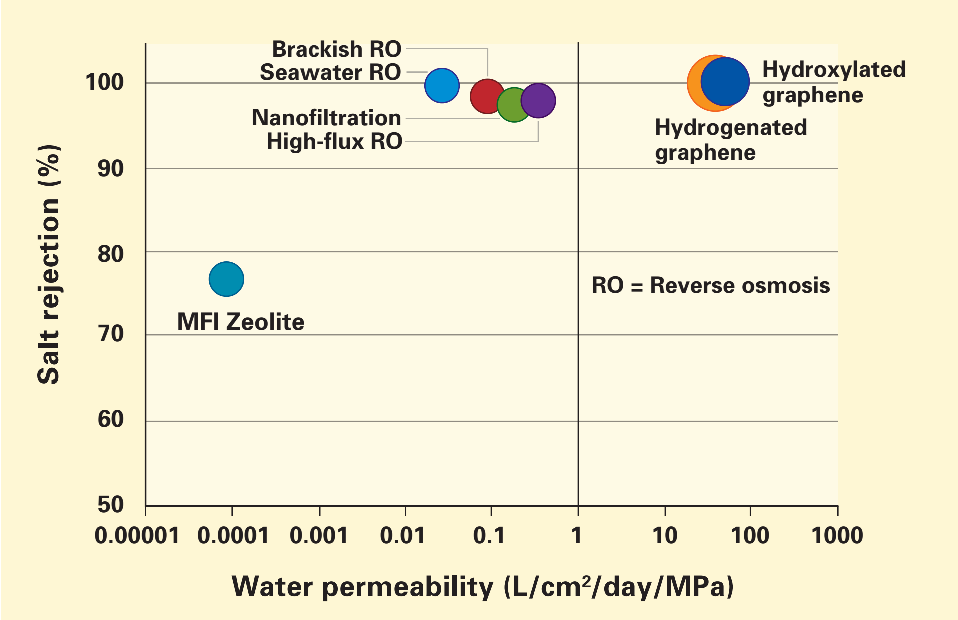
Graphics: David Cohen-Tanugi G, MIT

When water molecules (red and white) and sodium and chlorine ions (green and purple) in saltwater, on the right, encounter a sheet of graphene (pale blue, center) perforated by holes of the right size, the water passes through (left side), but the sodium and chlorine of the salt are blocked.



The investigators ran simulations to determine the effect on flow of adding materials that would line the holes in their graphene layers with "hydrophobic" (water-repelling) or "hydrophilic" (water-attracting) elements. They found that, in a given time period, roughly twice as much water flows through the membranes with the hydrophilic pores. To understand why, they examined the behavior of the water molecules as they pass through the pores. The images above show representative pores lined with hydrophobic hydrogen (left) and with a hydrophilic hydroxyl group (right). The central colored plots represent the water stream, with warmer hues indicating where water molecules are most likely to go. Light blue areas are devoid of water. Since water molecules interact more favorably with the hydrophilic pore edges, they are able to get closer to them. As a result, the overall water stream is wider, and more water passes through. In addition, analysis of the structure of the water molecules near the pores revealed that the hydrophobic edges permit molecules only in certain orientations to pass by—a phenomenon that further slows the flow.

Salt rejection and water permeability for various desalination technologies



This chart shows the performance of the simulated nanoporous graphene membranes compared with a variety of conventional technologies. For each technology, it shows the percentage of salt rejected and water permeability, measured in liters per square centimeter per day at a constant flow pressure. The graphene membranes examined here could reject the salt while achieving water permeability 100–1,000 times higher than that of commercial reverse osmosis membranes.

of times faster than current techniques, with the same pressure" (see chart above)—or, alternatively, the system could run at similar rates to present systems but with lower pressure.

The key to the new process is very precise control over the size of the holes in the graphene sheet. "There's a sweet spot, but it's very small," Grossman says—between pores so large that salt could pass through and ones so small that water molecules would be blocked. The ideal size is just about 1 nm, or one billionth of a meter, he says. If the holes are just a bit smaller—0.7 nm—the water won't flow through at all.

Other research groups have worked to create pores in graphene, Cohen-Tanugi says, but at very different sizes and for very different purposes—for example, making much bigger holes to filter large molecules such as DNA or to separate different kinds of gases. The methods used for those processes were not precise enough to make the tiny holes needed for desalination, he says, but more advanced techniques to make precise holes in graphene—such as helium-ion bombardment, chemical etching, and self-assembling systems—might be suitable.

Until recently, Grossman and Cohen-Tanugi have been doing computer simulations of the process to determine its optimal characteristics. "We began working on prototypes this fall," Grossman says.

Because graphene is the subject of research into many different applications, there has been a great deal of work on finding ways to make it inexpensively and in large quantities. And for desalination, because graphene is such a strong material—pound for pound, it's the strongest material known—the membranes should be more durable than those presently used for reverse osmosis, says Grossman.

In addition, the material needed for desalination does not need to be nearly as pure as for electronic or optical uses, he says: "A few defects don't matter, as long as they don't open it up" and allow salt to pass through.

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By David L. Chandler, MIT News Office

This research was partially funded by a seed grant from the MIT Energy Initiative. David Cohen-Tanugi was supported by a Schlumberger-MIT Energy Fellowship and a John S. Hennessy Fellowship. Calculations were performed using computer resources at the National Energy Research Scientific Computing Center. Further information can be found in:

D. Cohen-Tanugi and J.C. Grossman. "Water desalination across nanoporous graphene." *Nano Letters,* vol. 12, no. 7, pp. 3602–3608, 2012.

Innovation prizes

Understanding how they work

A systematic MIT analysis of how a multi-million-dollar automotive design prize competition actually works has produced insights that don't always match accepted understanding. For example, theorists would argue that prizes intended to stimulate innovation should be designed to maximize efficiency and avoid duplicating effort. But typically they aren't. Instead, they are designed simply to focus as much attention as possible on the targeted problem and to attract as many people as possible. But running an effective prize is not simple or cheap. The MIT findings suggest that a competition must be carefully designed and managed to provide a variety of incentives—from money to fame to fun. Done right, a prize can spur innovations that provide critical but financially undervalued social benefits such as reducing carbon dioxide emissions.

By analyzing a recent major automotive design competition, Fiona Murray of the MIT Sloan School of Management produced some concrete guidelines on how such Grand Innovation Prizes should be designed to maximize their effectiveness in spurring innovation.

This research was supported in part by a seed grant from the MIT Energy Initiative. For more information on funding, see page 19.

Photo: David Sella, courtesy of MIT Industrial Liaison Program

Prizes have long been used to induce solutions to national challenges. Between the 16th and 19th centuries, prizes yielded the vaccine inoculation, the lifeboat, a method of calculating longitude at sea, new food-preservation techniques, and more. But by the late 19th century, prizes had largely been replaced by two other mechanisms: patents and grants. However, those tools have limitations. Patents lead to innovation only in areas where inventions have commercial potential; and given the structure of government funding, grants are awarded to a narrow range of eligible recipients.

As a result, prizes have been making a comeback. "Prizes are an incentive mechanism that is particularly interesting when you want to specify the kinds of innovations you're looking for and when you want to diversify the base of potential innovators," says Fiona Murray, the David Sarnoff Professor of Technological Innovation, Entrepreneurship, and Strategic Management in the MIT Sloan School of Management. Accordingly, in early 2011, the Obama administration adopted regulations explicitly designed to accelerate the adoption of "ambitious prizes in areas of national priority."

For Murray, the growing emphasis on prizes as a policy tool raises questions: What sorts of prizes work and for what; and how should they be structured to elicit innovation relating to the particular problems we care about? Current literature on the topic includes extensive anecdotal evidence and a "fairly significant body of economic theory that creates models of how prizes should work," she says. But there is little formal analysis of empirical evidence from actual prizes—especially big prizes—and how they function "on the ground."

To fill that gap, she set out to perform a systematic study of an ongoing "Grand Innovation Prize." Her goals were to get insights into how a prize works in practice and then compare that empirical evidence to the ideas of both the economists who study prizes and the advocates and policymakers who design them. Seeing how those perceptions differ could help lead to the more effective use of prizes to stimulate innovation in areas where patents and grants may fail.

The energy focus

One area of national concern where prizes are particularly relevant is energy. "Energy is an area where we've got lots of core underlying skills and expertise. But are they being focused on the right kinds of problems and on technology that fulfills the right sorts of technical criteria?" asks Murray. It's also an area where patents and grants have limited effectiveness. In energy, she says "it's especially hard because the kinds of things that you might want—like a super-efficient vehicle—aren't really valued by customers and because lots of externalities—like carbon dioxide emissions—aren't really being priced." With technological advances undervalued, profit-seeking inventors have little interest. In that situation, a prize is a good mechanism to focus attention and elicit new ideas and solutions.

Among the many energy-related prizes recently offered, one of the biggest and most publicized is the Progressive Insurance Automotive X-Prize (PIAXP). In late 2009, the PIAXP offered a $10 million cash prize to teams that produced clean vehicles that exceeded 100 miles per gallon equivalent and could be manufactured on a commercial scale. In addition to being a model Grand Innovation Prize, the PIAXP was supported by the X-Prize Foundation, which has had a presence on the MIT campus since 2007 through the X-Prize Lab@MIT. Murray decided that the PIAXP would make an ideal case study.

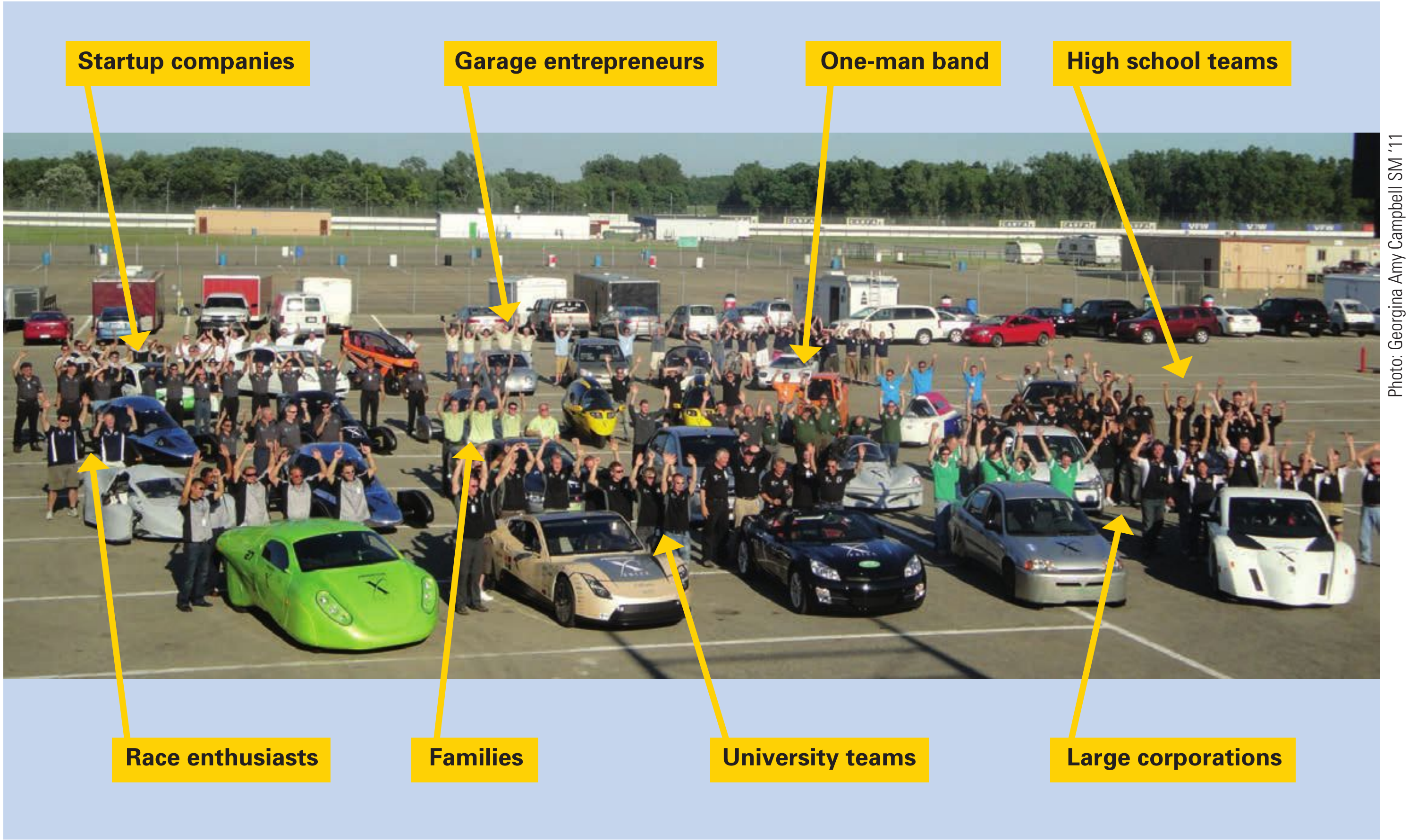
Her first task was to develop a formal analytical methodology that was comprehensive, generalizable, and could capture the essence of any prize being evaluated. Her approach uses both qualitative and quantitative methods to evaluate three dimensions of a prize: its objectives; its design, including initial specifications and incentives, qualification rules, and award governance; and its performance, that is, its success in engendering innovation.

With permission from the X-Prize Foundation, Murray, graduate student Georgina Amy Campbell SM '11 of the Engineering Systems Division, and their collaborators began gathering information. They interviewed participating teams as well as the PIAXP organizers and sponsors; they observed key events; and they performed periodic surveys to understand the incentives, organizational efforts, and technical outcomes involved. They then compared specific aspects of the PIAXP with findings from theoretical analyses and with views put forth by policymakers and other prize advocates.

Some surprising observations

One striking feature of the PIAXP is the sheer number of participants. At the start of the competition, 111 teams entered 136 vehicles. The teams were largely supported by private money, generally provided by team members and their friends and family. Collectively, the teams spent far more on the task than the winners would get in the prize purse. Indeed, three individual

Diverse participants in the PIAXP competition



teams spent more than they could have won in prize money.

Those observations demonstrate a central feature of today's prizes: They are intended to maximize effort, not efficiency. Theory assumes that prizes should be designed to elicit an efficient level of effort, that is, the maximum amount of innovation in the most productive and efficient way. "If you tell an economist that a hundred people showed up with new ideas, they're horrified because they say that's incredibly inefficient. All that duplication of effort!" says Murray. "But if you're not quite sure what the solution should look like and you want to focus attention on something, then you actually don't mind the fact that lots of people are turning up and coming with novel ideas."

The PIAXP participants brought to their mission a wide variety of backgrounds and perspectives. The entrants included garage entrepreneurs, race enthusiasts, families, university teams, high school teams, and startup companies (see above). Individuals of all ages participated, many with undergraduate and some with graduate degrees. And they represented a surprising range of expertise, including mechanical and electrical engineering but also finance, computer science, and some life sciences. While theoretical analyses do not stress the benefits of focusing diverse perspectives on a problem, that approach provides a clear advantage when the range of possible solutions is hard to predict.

Why did the PIAXP attract such a diverse group? While most discussions of innovation focus on monetary rewards, in fact prizes offer multiple incentives that appeal to different kinds of people. In responding to surveys, PIAXP entrants said that they were inspired by the opportunity to get publicity, to develop new markets, to have fun, and more (see the chart on page 19). Indeed, for many respondents, winning wasn't a significant motivator. So the fact that they spent more than the prize purse is not necessarily an indicator of inefficiency. They were getting other benefits from participating.

That finding has several practical implications for prize design. To attract a large and diverse group of competitors, an effective prize must offer activities and events that provide a wide range of incentives. Prize design is thus an unexpectedly challenging task. "You can't just put up the money, walk away, and come back a year later and give people a prize," says

Murray. "You have to create events around it." The PIAXP, for example, included a highly publicized series of races specifically intended to draw attention to the competition and to make "heroes" out of the winners.

As a further complication, the rules and procedures must be defined before the competition starts—and they may not prove up to the task. In the PIAXP, for example, there was originally one class of competitors and a single race. Along the way, the organizers found it necessary to split the competition into two divisions and add two more races. Murray notes that such modifications and adaptations of the rules are almost inevitable, but they must be handled in a way that respects the rights and opinions of participants already committed to the effort.

The need for multiple events has one more implication: Executing a well-run prize turns out to be unexpectedly costly. In general, people assume that the only investment required is the prize purse; the cost of running the competition is disregarded. "The government recognizes that running a grant-making system is expensive; they have entire agencies to do it. But they think that prizes come for free," says Murray. "Running a prize effectively is actually quite a costly business. The infrastructure required is not zero cost."

Murray and her colleagues are now using the new analytical framework to evaluate additional Grand Innovation Prizes, and she hopes others will do the same. As the PIAXP study demonstrated, careful planning is critical to having a prize that meets the goals and objectives of the organizers. "At the moment, I think, there's just not enough thought given to all the design considerations," says Murray. "This is a relatively new kind of design activity that people haven't got experience doing." Systematic analysis of a variety of prizes will help ensure that this traditional incentive mechanism will spur much-needed innovative solutions to today's critical social problems.

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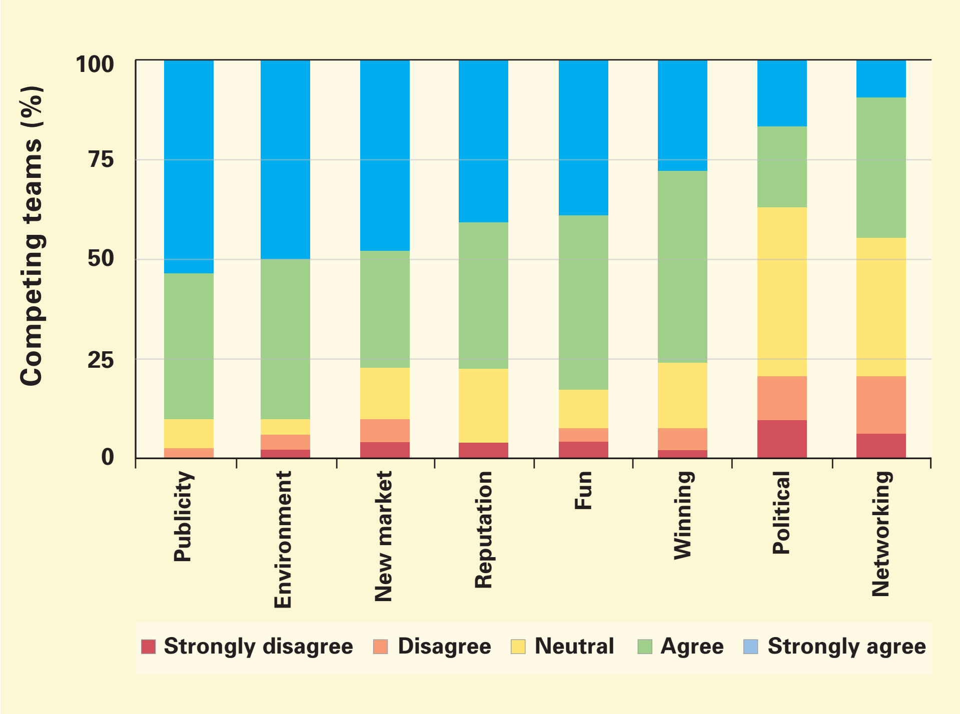
By Nancy W. Stauffer, MITEI

Reasons cited by individuals for participating in PIAXP
(Respondents could select more than one motivation.)



This research was supported by a seed grant from the MIT Energy Initiative. Additional funding was provided by the National Science Foundation. Further information can be found in:

F. Murray, S. Stern, G. Campbell, and A. MacCormack. "Grand Innovation Prizes: A theoretical, normative, and empirical evaluation." *Research Policy,* forthcoming.

G.A. Campbell. *Incentive Competitions as a Policy Tool for Technological Innovation.* SM thesis, MIT Engineering Systems Division, Technology and Policy Program. 2011.

Capturing energy from the sun

Lessons from nature

Dörthe M. Eisele of the Research Laboratory of Electronics (left) and Moungi G. Bawendi of chemistry are investigating fundamental processes in light-harvesting nanotubes and quantum dots with a goal of one day developing a completely new approach to collecting energy from the sun.

This research was supported in part by the MIT Center for Excitonics, an Energy Frontier Research Center funded by the US Department of Energy. See page 24 for a complete list of sponsors.

Photo: Stuart Darsch

MIT investigators are inspired by a deep-sea bacterium that is able to harvest tiny amounts of incoming solar energy with exquisite efficiency. To elucidate the fundamental processes within that photosynthetic masterpiece, the researchers use a less complex model system: an artificial light-harvesting (LH) nanotube. They have demonstrated conclusively that the various interacting parts in their LH nanotube can be treated as separate subsystems—a key step toward modeling nature's highly efficient energy-transfer processes. Using such artificial LH nanotubes, quantum dots, and other building blocks, the researchers hope one day to assemble novel artificial systems that can mimic nature's remarkable ability to collect, transport, and use solar energy.

Much attention is now focusing on natural organisms that have evolved highly efficient light-harvesting capabilities over billions of years. The green sulfur bacterium is perhaps the champion light-harvester. It lives at the depths of the ocean, where light levels are extremely low. But it makes the most of the light it gets: It is able to harvest up to 95% of the solar energy it absorbs.

Research teams worldwide are trying to replicate the capabilities of the green sulfur bacterium. But such natural systems are exceedingly complex. "We'd like to break these systems down into their simpler components and see if we can find synthetic [structures] that mimic them," says Moungi G. Bawendi, the Lester Wolfe Professor of Chemistry. "In the end, we want a set of building blocks that we can assemble to create a more complicated system—perhaps as complex as the natural system but where we have more control, where we can tune some critical parameters."

Key to the light-harvesting success of the green sulfur bacterium is its light-harvesting antenna system. This system consists of long cylinders of closely packed bacteriochlorophyll molecules that absorb solar energy and transfer as much as 95% of it toward the "reaction centers" where critical chemical processes occur. Those cylinders are "perhaps nature's most spectacular light-harvesting system," says Dörthe M. Eisele, postdoctoral associate in the MIT Research Laboratory of Electronics. They could be an ideal building block for a practical device.

But applications are far down the road. The first step is to develop a fundamental understanding of how nature's bacteriochlorophyll cylinders do their job. Chopping individual cylinders out of a bacterium for analysis would destroy their natural functioning. The solution is therefore to create and study an artificial model system that behaves like the *in situ* bacteriochlorophyll cylinders.

A model system—and a challenge

For the past five years, Eisele and her collaborators at MIT's Center for Excitonics, the University of Texas at Austin, Humboldt University of Berlin in Germany, and the University of Groningen in the Netherlands have been working with an artificial system that is similar in size, shape, and function to the natural antenna system in the green sulfur bacterium. The structure consists of molecules of cyanine dye that naturally aggregate and self-assemble, rolling up into long double-walled nanotubes when they are immersed in water (see the diagram on page 22). Each nanotube is about 13 nm wide and thousands of times that long, and each contains two concentric cylinders of closely packed cyanine dye molecules about 4 nm apart. That "supramolecule" with its two cylinders of light-absorbing material closely resembles the natural antenna system in the green sulfur bacterium.

In 2007, Eisele developed a carefully controlled technique to produce well-defined cyanine dye-based nanotubes. In early work, she and her colleagues demonstrated that her nanotubes have highly uniform properties—from tube to tube and also along the length of each one. Because the LH nanotubes are "all the same," she can study their properties from the ensemble in solution with no need to isolate the responses of the individual nanotubes.

Nevertheless, determining how the LH nanotubes collect and transport energy from light is a challenge. Even advanced

Photo: Stuart Darsch

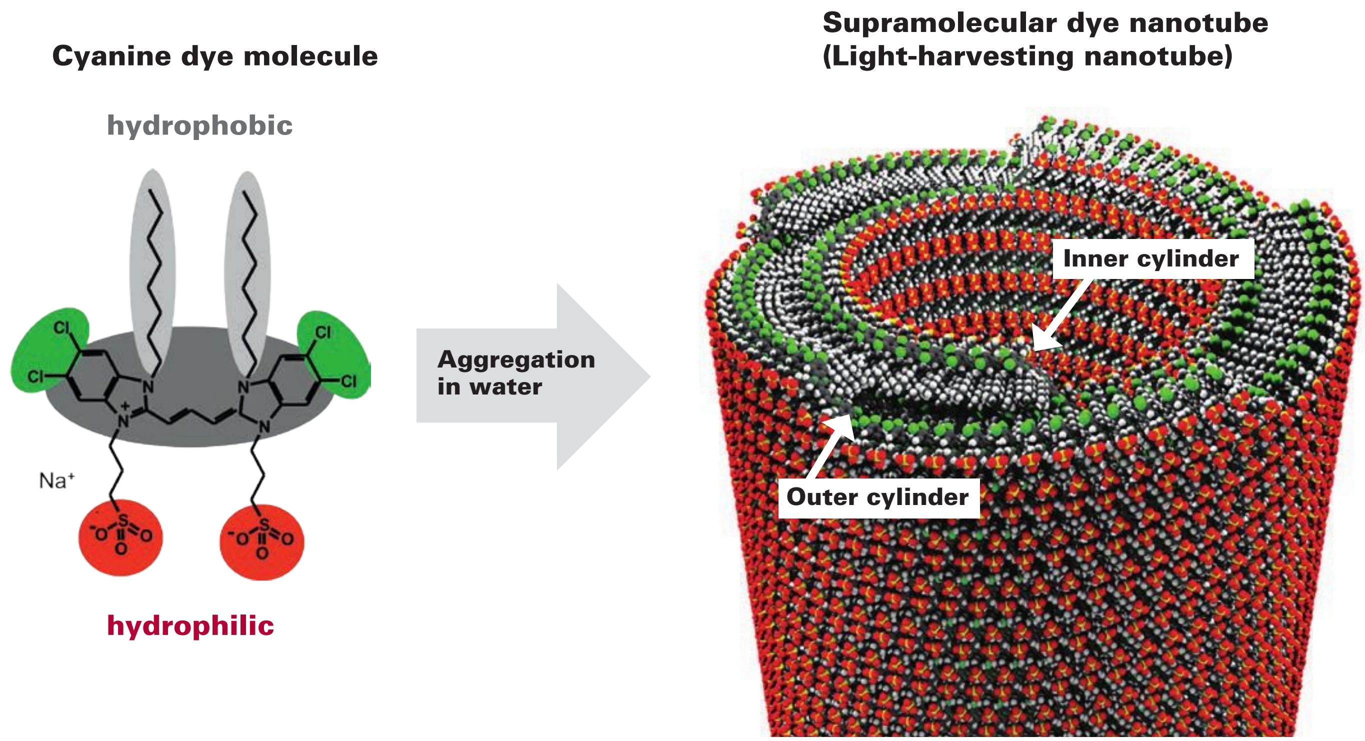
Samples of light-harvesting nanotubes (in the larger vial) and quantum dots that the researchers are synthesizing and studying as they search for novel approaches to collecting, transporting, and using solar energy.

microscopes cannot show the details of their structure, so Eisele turned to another option: their optical spectra. Shine light on a supramolecule made up of closely packed molecules and it will absorb certain wavelengths and not others. The resulting spectrum can be the key to unraveling not only the optical behavior of the supramolecule but also its physical structure.

Early spectral analyses revealed a critical property of such cyanine-based supramolecules. On their own, the individual cyanine molecules have a characteristic absorption spectrum. Yet when they pack together, the supramolecule that results has a dramatically different spectrum—even though the molecules retain their individual structure, do not share electrons, and are held together only by weak attractive forces.

Why? When an individual molecule absorbs energy from the sun, it becomes "excited." But when a supramolecule absorbs solar energy, the closely packed molecules in it "share" their excited states. Because of those shared excited states, the optical properties of the supramolecule are significantly different from those of the individual molecules. "So the unique ability of our nanotubes to harvest light so efficiently arises from the ensemble of closely packed,

Artificial light-harvesting nanotubes



This diagram shows the structure of the artificial double-walled nanotube that the MIT team uses to model the light-harvesting antenna system in green sulfur bacteria. The individual molecule (left)—first synthesized in the 1990s by the late German organic chemist Professor Siegfried Dähne—has at its center a cyanine dye (dark gray). Two side chains hang off, one "water-loving" (hydrophilic, in red) and the other "water-hating" (hydrophobic, in light gray). Suspended in water, these molecules clump together and roll up to form a double-walled nanotube (right). In this structure, the original molecules are closely packed into two layers. The water-hating chains meet in the middle, protected by the water-loving chains on the inside and outside surfaces of the nanotube. With the molecules in that orientation, the cyanine dye ends up in two cylindrical layers about 4 nm apart—much as in the natural antenna system of the green sulfur bacterium.

aggregated molecules," says Eisele. Moreover, the details of how the molecules are packed together strongly affect those interactions, and thus the optical properties of the supramolecule. If the researchers could understand the relationship between the structural details and the optical properties, they might be able to fine-tune the optical behavior by altering how the molecules pack together.

Understanding the spectral evidence

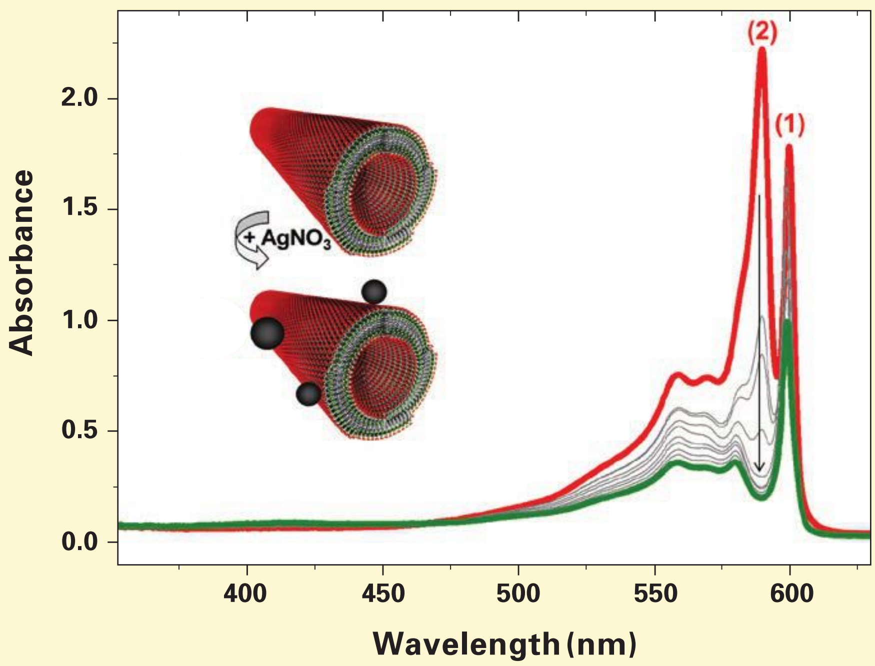
Analyzing the spectrum of the supramolecule would provide valuable insights—but there is a problem. The "electron excitation" is shared between neighboring molecules. But do such molecule-to-molecule interactions occur mainly within the inner and outer cylinders separately or throughout the entire LH nanotube? If the former, then the spectrum of the LH nanotube would show the absorption behavior of the two independent (or at most weakly interacting) cylinders superimposed on one another. But if the latter, the overall spectrum would reflect the combined optical response of the two strongly interacting cylinders.

A solution would be to observe the spectra of the cylinders separately. But using a beam of light to excite selected parts of the LH nanotubes in a vial isn't feasible, and removing the outer cylinder to isolate the spectrum of the inner cylinder won't work. "It's a self-assembling system, and we can't destroy its structure without altering its behavior," says Eisele. "What we can do is change the light-absorption capability of the outer cylinder."

To do that, she oxidizes the nanotubes using silver nitrate. Each silver ion removes one electron from a single molecule of cyanine dye, altering its absorption behavior. Her experimental procedure therefore consisted of simply adding silver nitrate to a vial of suspended nanotubes and then carefully taking the absorption spectrum of the mixture every 30 minutes for six hours as oxidation proceeded.

The results appear in the diagram on page 23. The red curve is the initial absorption spectrum before the start of the experiment; the gray curves are the 30-minute spectra; and the green curve is the final spectrum. Comparison of the curves shows that peak 2 goes down more quickly than peak 1 does—and it ultimately disappears. Eisele and her co-workers were able to show that this fast decrease in intensity of peak 2

Interpreting spectral evidence from double-walled, light-harvesting nanotubes



Experimental results from oxidizing the cyanine-based nanotubes with silver nitrate ($AgNO_3$). The plots show the absorption spectrum of the nanotubes in solution before the $AgNO_3$ was added (red), spectra taken every 30 minutes after it was added (gray), and the spectrum at the end of the six-hour experiment (green). Peak 2 drops down quickly and finally disappears. Peak 1 and other portions of the spectrum change more slowly and drop only in amplitude, not shape. Analysis of the spectral data shows that those two responses reflect the separate behavior of the inner and outer cylinders in the light-harvesting nanotubes. Micrographs show that the outer cylinder is morphologically intact after oxidation but now "decorated" with silver nanoparticles (as shown on the inset above). Isolation of the inner cylinder's spectrum subsequently enabled the researchers to model the detailed supramolecular structure of the artificial nanotubes.

reflects changes in the outer cylinder and that the slower decrease of peak 1 reflects changes in the inner cylinder. The conclusion: Peak 2 can be unambiguously attributed to the outer cylinder, peak 1 to the inner one. Moreover, the portions of the absorption spectrum that drop only in amplitude with no significant change in shape can be traced to the inner cylinder.

Detailed analysis of the experimental data confirmed that the original spectrum is made up of the spectra of two essentially independent chemical species superimposed on one another. The two LH cylinders can thus be treated as two electronically separate systems, with at most weak coupling between them. In addition, images taken with a cryogenic electron transmission microscope clearly showed the double-walled structure of the nanotubes—both before and after oxidation. Indeed, the only difference in the post-oxidation images was that the exterior surfaces of the nanotubes were "decorated with silver nanoparticles," says Eisele (illustrated in the diagram above). Those results confirm that the outer cylinder was still physically present. Only its optical behavior had changed.

The isolation of the inner cylinder's spectrum made possible unprecedented theoretical advances. After three years' work, collaborators led by Professor Jasper Knoester at the University of Groningen, the Netherlands, modeled a structure for the inner cylinder that reproduced the experimentally observed spectrum. The structure has molecules organized in a herringbone fashion—a geometry previously proposed by others but with certain details that are different. For example, each tile is made up of two molecules, and as the tiles wrap around to form the cylinder, they tilt out from the surface at distinctive angles.

Knoester and his group next modeled the structure of the outer cylinder assuming the same packing geometry but adjusted to span the greater circumference. They then calculated the spectrum of a suprastructure formed from their two cylinders that shows remarkable agreement with Eisele's measured absorption spectrum. By combining these experimental and theoretical results, the researchers were thus able to settle a long-standing argument about the geometry of such cyanine-based nanotubes.

Only the beginning

Armed with their new understanding, the researchers at MIT are now continuing their studies. For example, they are examining the nature of the weak interaction between the inner and outer cylinders, and they are looking into what happens when many cylindrical nanotubes cluster together, as they do in nature. Says Eisele, "Now we need to know whether we can think of them as a superposition of individual cylinders—or do they become a totally new system with different optical properties?"

But even a cluster of LH cylinders is just one building block for a future device, says Bawendi. He and Eisele are now working to connect the LH nanotubes to quantum dots (QDs)—nanometer-scale inorganic crystals that fluoresce when stimulated by light. That combination raises exciting possibilities. By controlling the size of the QDs, Bawendi—an expert in this field—will be able to "tune" them to absorb sunlight and then emit a specific wavelength that will generate maximum electron excitation in the LH nanotubes. In the lab, that focused light will enable the researchers to track how the excitation propagates along the LH nanotubes. In a practical device, such tailored QDs could deliver focused energy that LH nanotubes could efficiently transport and deliver to a system—perhaps including more QDs—where chemical reactions might, for instance, produce fuels.

Bawendi stresses that such concepts are very far down the line. "The idea is to create something from building blocks, so first we have to understand the building blocks themselves and how they interact," he says. But if his "grand vision" succeeds, a device integrating such building blocks could one day provide a completely new way to collect energy from the sun—perhaps modeled in part on that solar-harvesting genius, the green sulfur bacterium.

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By Nancy W. Stauffer, MITEI

This research was supported by the MIT Center for Excitonics (see sidebar at right), an Energy Frontier Research Center funded by the US Department of Energy, Office of Science, Office of Basic Energy Sciences, and by the Deutsche Forschungsgemeinschaft, the Integrative Research Institute for the Sciences in Berlin, the National Science Foundation, the Alexander von Humboldt Foundation, the US Army Research Office, and the US Defense Advanced Research Projects Agency. Further information can be found in:

D.M. Eisele, C.W. Cone, E.A. Bloemsma, S.M. Vlaming, C.G.F. van der Kwaak, R.J. Silbey, M.G. Bawendi, J. Knoester, J.P. Rabe, and D.A. Vanden Bout. "Utilizing redox-chemistry to elucidate the nature of exciton transitions in supramolecular dye nanotubes." *Nature Chemistry*, vol. 4, pp. 655–662, July 2012.

B.J. Walker, V. Bulović, and M.G. Bawendi. "Quantum dot/J-aggregate blended films for light harvesting and energy transfer." *Nano Letters,* vol. 10, pp. 3995–3999, 2010.

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B.J. Walker, G.P. Nair, L.F. Marshall, V. Bulović, and M.G. Bawendi. "Narrow-band absorption-enhanced quantum dot/J-aggregate conjugates." *Journal of the American Chemical Society,* vol. 31, pp. 9624–9625, 2009.

Center strives to capture sunlight as plants do

Researchers at MIT's Center for Excitonics are seeking to learn how plants capture, transport, and use energy from the sun. Key to the process is the exciton—a kind of nanoscale packet of energy that is created when sunlight "excites" a chlorophyll molecule. Once created, excitons transfer the solar energy through the leaf and oversee its conversion into electrical energy and chemicals.

By understanding how nature controls the creation, destruction, and migration of excitons during photosynthesis, researchers in the center hope one day to supersede traditional electronics with devices in which excitons mediate the flow of energy. The result could be highly efficient, low-cost solar cells and novel solid-state lighting technologies.

The Center for Excitonics is one of 46 Energy Frontier Research Centers (EFRCs) established nationwide by the US Department of Energy in 2009. Along with 15 other EFRCs, the center receives its funding—$19 million over five years—through the American Recovery and Reinvestment Act. The director of the center is Marc Baldo, associate professor of electrical engineering and a principal investigator in the Research Laboratory of Electronics at MIT. Center activities involve researchers throughout MIT as well as at Harvard University and Brookhaven National Laboratory.

Center-funded research has already produced results including transparent organic solar cells, nanoscale wires tailored for use in LEDs or solar panels, and—most important—an expanding fundamental understanding of excitons that promises to yield a new generation of critically needed energy technologies.

Reducing wasted energy in commercial buildings

Bringing together energy and people

Left to right: Rex Britter, Carlo Ratti, and Prudence Robinson of urban studies and planning and the SENSEable City Laboratory used existing infrastructure in two MIT buildings to detect mismatches between human occupancy and consumption of electricity, chilled water, and steam.

This research was supported in part by a seed grant from the MIT Energy Initiative. For a complete list of sponsors, see page 28.

Photo: Justin Knight

Much energy is wasted heating and cooling indoor spaces when no one or almost no one is present. Now, MIT researchers have used their own campus to demonstrate a means of measuring that energy/occupancy mismatch—a first step toward finding strategies to correct it. Their method uses existing infrastructure, namely, connections on MIT's wireless network as an indicator of occupancy plus energy-use data gathered by sensors that monitor building operations. Analysis of 2006 data from two MIT buildings shows that two-thirds of the variation in electricity levels corresponds to changing occupancy levels. But energy used for heating and cooling shows almost no correlation with occupancy. The MIT team suggests changes in how commercial buildings are designed and used that may help bring energy and people together in time and space.

In the search for energy-saving opportunities, commercial buildings are a good place to look. According to the US Energy Information Administration, commercial buildings account for nearly 20% of US energy consumption and 12% of the nation's greenhouse gas emissions. Yet studies have shown that continuously monitoring and adjusting operations and implementing a small number of energy-efficiency strategies could reduce that energy use by as much as 30%.

One challenge in commercial buildings is providing the "right" amount of heating and cooling. With people constantly coming and going, energy use is frequently either too high or too low for the number of people present. A lecture hall on a college campus provides a striking example. Students flood into the hall for class, and then after 90 minutes the hall is empty—but still being heated or cooled. "It takes a lot of energy to heat up that room, but much of the day nobody's there," says Carlo Ratti, director of the MIT SENSEable City Laboratory and associate professor of the practice in MIT's Department of Urban Studies and Planning (DUSP). "If we can understand that kind of mismatch between energy use and occupancy, we may be able to make changes in how we distribute energy or in how we design or use space that could reduce energy use, costs, and environmental impacts."

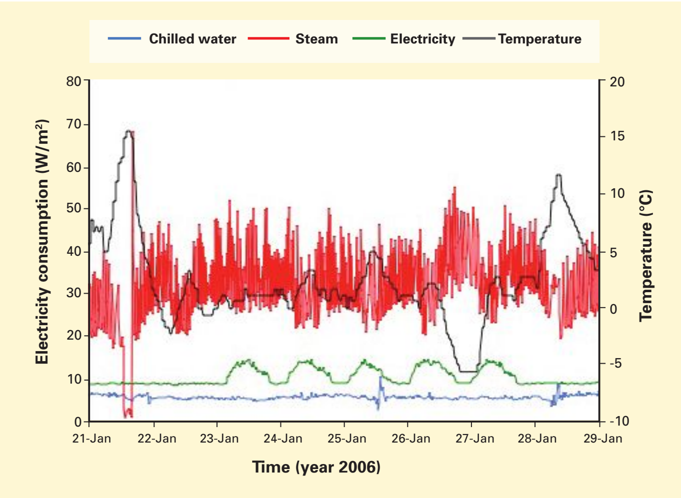
Past studies have examined the relationship between energy use and occupancy, but they have focused on single buildings and yielded inconclusive results. Performing the needed large-scale field experiments could require installing a pervasive system of sensors to collect data on building operations and occupancy—an undertaking that would be both expensive and intrusive.

Using existing infrastructure

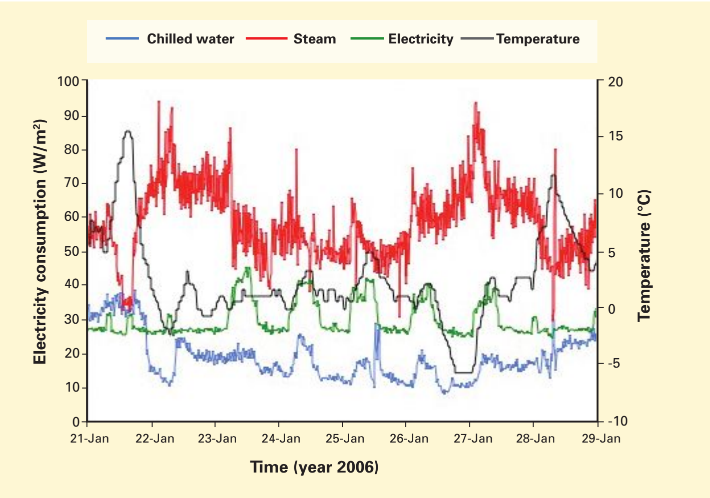
Three years ago, Ratti realized that the needed technology is already in place on the MIT campus. The Institute has a network of more than 100,000 sensors that monitor the functioning of MIT's building automation systems across campus and in turn reveal the per-building consumption of electricity, chilled water for cooling, and high-temperature steam for heating. The campus also has a means of tracking occupancy: via its ubiquitous WiFi network, which includes more than 5,000 hotspots, almost one per room and hallway. In 2005, when the campus-wide wireless network was relatively new, Ratti and his colleagues performed iSPOTS, a project investigating how WiFi was changing the working habits of the MIT community. A legacy of that project is a rich historical database on WiFi use as well as evidence that WiFi connections are a good indicator of where people are and when.

Hourly energy consumption in two MIT buildings plus outdoor temperatures, January 21–28, 2006

Sloan Building (E52)



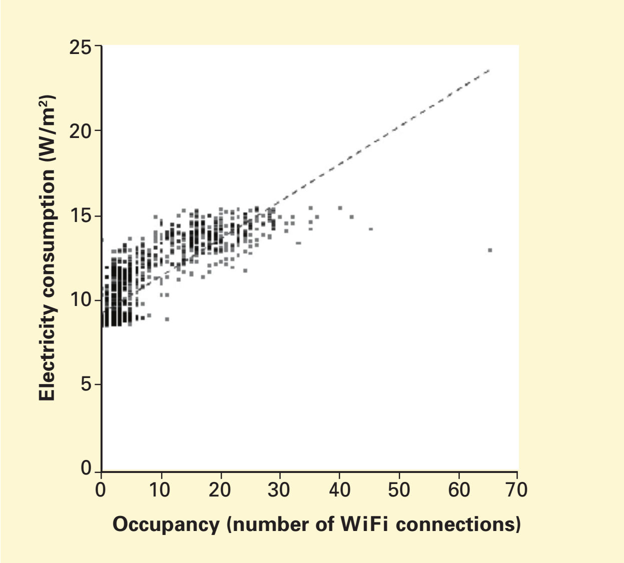
McNair Building (M37)



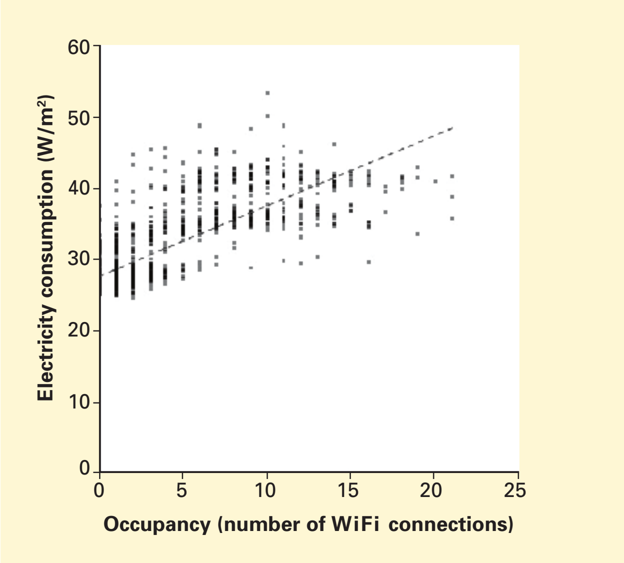
Hourly energy use for chilled water (for air conditioning), steam (for heat), and electricity during eight days in winter 2006 shows distinctly different profiles in two MIT buildings: the Sloan Building, E52 (left), and the Ronald M. McNair Building, M37 (right). Electricity use in both buildings displays steady baseline consumption superimposed by daytime peaks on weekdays. But chilled water and steam consumption in the two buildings show differing trends, sometimes but not always correlating to changes in outdoor temperatures. Notably, all energy use is significantly higher in McNair than in Sloan.

Electricity consumption versus occupancy, January 21–February 3, 2006

Sloan Building (E52)



McNair Building (M37)



Results of an analysis of the correlation between electricity consumption and occupancy based on the full two weeks of data from which the curves on page 26 were extracted. In both MIT buildings, electricity use shows a significant positive correlation with occupancy rate (as measured by WiFi connections). A large proportion of electricity consumption remains constant over time. Even so, 69% of the variation in the Sloan Building (E52) and 63% of that in the McNair Building (M37) can be accounted for by changes in occupancy.

Pairing up the data from MIT's building sensors and WiFi system might provide insights into the nature and extent of the energy/occupancy mismatch. And the MIT campus would be a good "test bed" for trying out that approach. Its many buildings vary in age, construction, and use; and they have unusual "occupancy profiles." In most commercial buildings, groups of workers come and go at fairly predictable times of day. But in academic buildings, people are more likely to enter and exit at irregular times, occupancy can vary widely over short periods, and there may be long stretches of time when buildings are almost—but not quite—empty. Such conditions make the efficient distribution of energy a particular challenge.

For their initial study, the MIT team focused on the Sloan Building (E52) and the Ronald M. McNair Building (M37). The functions of those two buildings are distinctly different. M37 is predominantly composed of laboratories, while E52 is a more typical working space with classrooms, offices, and open reception areas. Drawing on the iSPOTS project, the researchers gathered detailed data on WiFi use in those buildings in 2006. And aided by MIT's Department of Facilities, they obtained the 2006 energy consumption data they needed.

Tracking energy usage and occupancy

The curves on page 26 show data on energy use in the two buildings during eight days in winter 2006. The curves show hourly readings for electricity (green), chilled water (blue), and steam (red). All data are converted to a standardized unit—kilowatts—and then normalized by area—watts per square meter—so the datasets for the two buildings can be compared. The final curve (black) shows outdoor air temperatures measured at Logan International Airport in Boston.

Consumption patterns for the two buildings display both similarities and differences. In E52, electricity use shows pronounced recurring daily cycles, peaking during the daytime and returning to baseline levels at night and on weekends. Similar cycles appear in the M37 data, but the constant background level is about three times higher than in E52, perhaps because the M37 labs contain equipment that must operate continuously and therefore need a constant supply of electricity.

Consumption of chilled water and steam is likewise far higher in M37 than in E52. Chilled water use in E52 is relatively flat, while that in M37 shows considerable variation, including some daytime peaks. Steam consumption in M37 follows variations in outdoor temperature. In E52, steam use rises and falls frequently, sometimes correlated with outdoor temperature, but the overall range of values encompassed is far smaller than in the M37 data.

Analysis of comparable data from spring, summer, and autumn shows little seasonal variation in patterns of electricity use in the two buildings. Far more variation is evident in chilled water and steam consumption. In E52, there are two distinct usage patterns for chilled water and steam, one in winter and spring and another in summer and fall. In M37, similar patterns appear in steam use, but levels of chilled water consumption show no such seasonal difference.

The next step was to examine the relationship between those energy-use patterns and variations in occupancy, using WiFi connections as a proxy. As shown in the figures on page 27, electricity consumption in both buildings demonstrates a significant positive correlation with occupancy rate: WiFi connections can account for 69% of the variation in electricity levels in building E52 and for 63% in building M37. In contrast, the correlation between chilled water and steam use and human occupancy is weak, with WiFi connections accounting for only a small amount of the observed variation.

"We weren't surprised to see that disconnect, but it's good to be able to quantify it," says Prudence Robinson, a DUSP research fellow in the SENSEable City Lab. And Ratti notes that the differing energy use profiles of the MIT buildings are themselves of interest. "It may be no more than a reflection of the different building construction and use," he says. "Further inquiry would likely show all the buildings on campus have their own particular 'signature.' Knowing the signatures across the campus and across the seasons may be enlightening in determining appropriate operating strategies."

Spreading the word, encouraging change

While continuing to gather and analyze data, the researchers are working to spread the word about energy/occupancy mismatching and the significant energy conservation opportunity solving this problem represents. For example, they are developing new ways to present their findings so that people can quickly comprehend what's involved. The figure on page 29 demonstrates their latest data-presentation method. Skimming down a single vertical bar shows how that factor changes on a given day over a year; looking across a bar at one level shows how a particular factor changes over the course of a week; and comparing readings on the four bars at the same level quickly pinpoints where occupancy and energy use match and do not match.

The team also offers some simple energy-saving rules for designing and using buildings. For example, grouping offices together can prevent the loss of heat from occupied, heated spaces to unoccupied, unheated ones. And at times, spaces can be designed to take advantage of "thermal seepage" through internal walls. For instance, that continuously heated lecture hall can be surrounded by heavily used offices so that someone benefits from the warm air even when the lecture hall is empty.

Finally, the group stresses the importance of behavioral change. Rex Britter, a DUSP research scientist in the lab, notes that encouraging people to change their habits may require some creative thinking. As an example, he describes a concept he calls the "weighted thermostat." Picture a large meeting room. When many people are present, they can adjust the thermostat over a wide range to get the room to a comfortable temperature. But if only a few people are present, their ability to regulate the temperature would be more restricted. Over time, small groups would learn to use small rooms. Occupancy and energy use would be better matched, and less energy would be wasted.

"Behavioral change is a huge component that we haven't even scratched the surface of," says Robinson. "This is an area with lots of opportunity to do research—and enormous potential for making a real difference."

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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 National Science Foundation, the AT&T Foundation, the MIT SMART program, General Electric, Audi Volkswagen, Banco Bilbao Vizcaya Argentaria, Société Nationale des Chemins de fer Français, Ente Nazionale per l'Energia Elettrica S.p.A., and the members of the MIT SENSEable City Lab Consortium. Further information can be found in:

C. Martani, D. Lee, P. Robinson, R. Britter, and C. Ratti. "ENERNET: Studying the dynamic relationship between building occupancy and energy consumption." *Energy and Buildings,* DOI: 10.1016/j.enbuild.2011.12.037, 2012.

Visualizing patterns of daily occupancy and energy consumption data for M37 over 2006 (facing page)

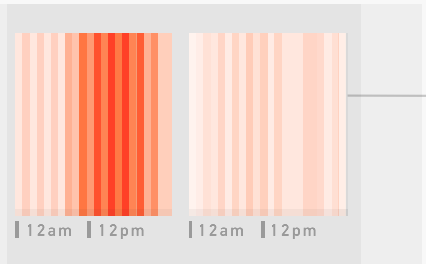
This colorful data-presentation technique enables the observer to quickly see how building occupancy and energy use for electricity, steam, and chilled water change day by day over a week and also over the course of a year. Comparing a given block on the occupancy "ribbon" with corresponding blocks on the other three ribbons sometimes shows a mismatch, with the former color faint and one or more of the others bright. Clearly, energy use does not always correspond to occupancy.

OCCUPANCY & ENERGY CONSUMPTION OF BUILDING M37

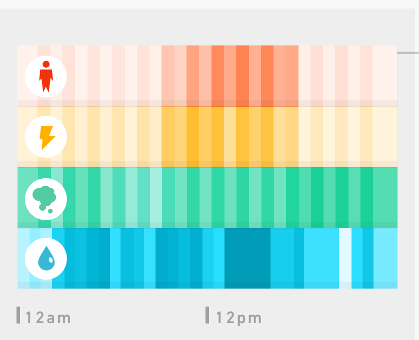
(RONALD M. MCNAIR BUILDING, MIT)

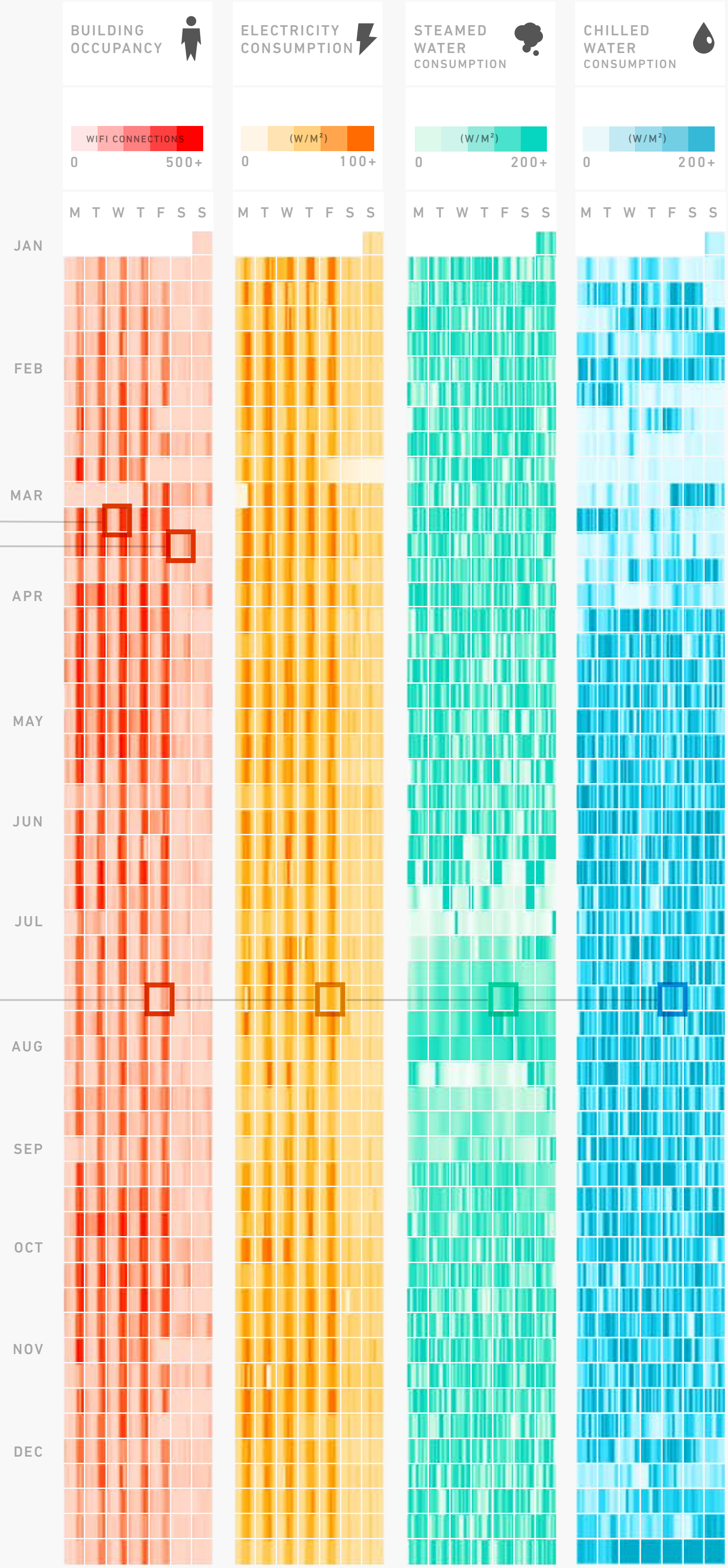
OVER 2006

Wifi connections (used as a proxy for human occupancy) reveal patterns scaled over days, weeks and seasons. People tend to connect from 8am to 8pm during work days. The building is mostly empty during weekends over the summer months.



Electricity consumption is directly correlated to building occupancy, whereas the use of steamed and chilled water is more closely tied with other factors, such as external temperature.





MIT | SENSEable City Lab

Image: Ian Ardouin-Fumat, MIT SENSEable City Laboratory

Robert L. Jaffe: Bringing scientific truths into public discourse

MIT Professor Robert L. Jaffe turned his attention to energy in 2005—after decades spent researching theoretical particle physics—because he saw the need to shine "the clear bright light of knowledge" on energy policy.

"I couldn't stand the level of ignorance that characterizes the public debate about issues of energy," says Jaffe, the Otto (1939) and Jane Morningstar Professor of Physics. "I think listening to talk of the 'hydrogen economy' pushed me over the edge."

Proponents of the "hydrogen economy" posit the replacement of carbon-based fuels with hydrogen fuel extracted from molecules like water—but usually they ignore the energy necessary to break hydrogen free from its source, thus violating the first law of thermodynamics, which states that energy cannot be created or destroyed.

To ensure that MIT graduates are equipped to dispel this and other misconceptions, Jaffe teamed up with fellow physics professor Washington Taylor to start a new MIT subject, 8.21 Physics of Energy. The class centers on the fundamental physical principles underlying energy processes and introduces their practical application.

First offered in 2008, the subject is now part of the core curriculum of the Energy Studies Minor supported by the MIT Energy Initiative (MITEI). But in launching the class, Jaffe says he and Taylor had to start from scratch. "There are essentially no courses like ours—a survey at a scientifically literate level that gives people the operational skills to deal with the science of energy," he says.

Jaffe and Taylor have since begun to compile their course notes into a textbook, *Physics of Energy,* hoping to catalyze the development of similar subjects at other universities. "We wanted a book from which a course like ours can be taught," says Jaffe, noting that the book is forthcoming from Cambridge University Press.

Teaching is of central importance to Jaffe, who credits several of his own teachers with setting him on the road to a career in the sciences. At high school in Connecticut, he was first inspired by an excellent chemistry teacher. And later, at Princeton University, one of his freshman professors steered him into physics—the profession he would ultimately pursue.

Jaffe, who served as director of the Center for Theoretical Physics from 1998 to 2004, might even have become an experimental physicist had it not been for one frightening night the summer following his sophomore year.

It was 4 in the morning, and he was working as the sole operator of Princeton University's cyclotron (an old-fashioned particle accelerator) when suddenly every alarm in the place went off. A hose had popped out and flooded the entire system, destroying $20,000 worth of equipment. "I was completely traumatized and never did another experiment in my life," Jaffe says.

Instead, Jaffe spent decades engrossed in theoretical particle physics, specifically the quark substructure of matter. In the early 1970s, he and MIT colleagues formulated the first consistent description of quark confinement, the "MIT Bag Model." In the 1990s and 2000s, Jaffe helped develop the modern understanding of Casimir forces, quantum forces that can affect the performance of micromechanical systems such as those central to smart phones.

He also taught, founding two MIT classes—Modern Physics and Quantum Mechanics III—and ultimately received MIT's highest award for undergraduate teaching, the MacVicar Faculty Fellowship, in 1998. "I have always loved teaching," Jaffe says. "I find the personal interaction satisfying, and it was a natural outlet for my interest in bringing an understanding of science to the public."

Jaffe traces his interest in policy to his college days in the 1960s. He delivered the valedictory address at Princeton in 1968—within days of the assassination of Sen. Robert F. Kennedy and a few months following that of the Rev. Martin Luther King Jr. The subject of his speech, unorthodox at the time, was student activism.

Later, while attending graduate school at Stanford University, he founded the Stanford Workshops on Political and Social Issues, a series of classes designed both to teach scientific topics and to put research into useful action. SWOPSI, as it was called, lasted for over 20 years and spawned early efforts to address air pollution in California and to stop redwood logging.

"I've always been concerned about social and policy questions—especially as impacted by science," he says. "I'm convinced scientists owe society a responsibility to use their insights into fundamental issues to try to clarify the discussion."

Jaffe's commitment to providing "a clear, plain, factual playing field for analysis" is ultimately what led him to launch the Physics of Energy course and—in a surprising extension—to investigate the use of rare and unusual chemical elements in energy-related applications.

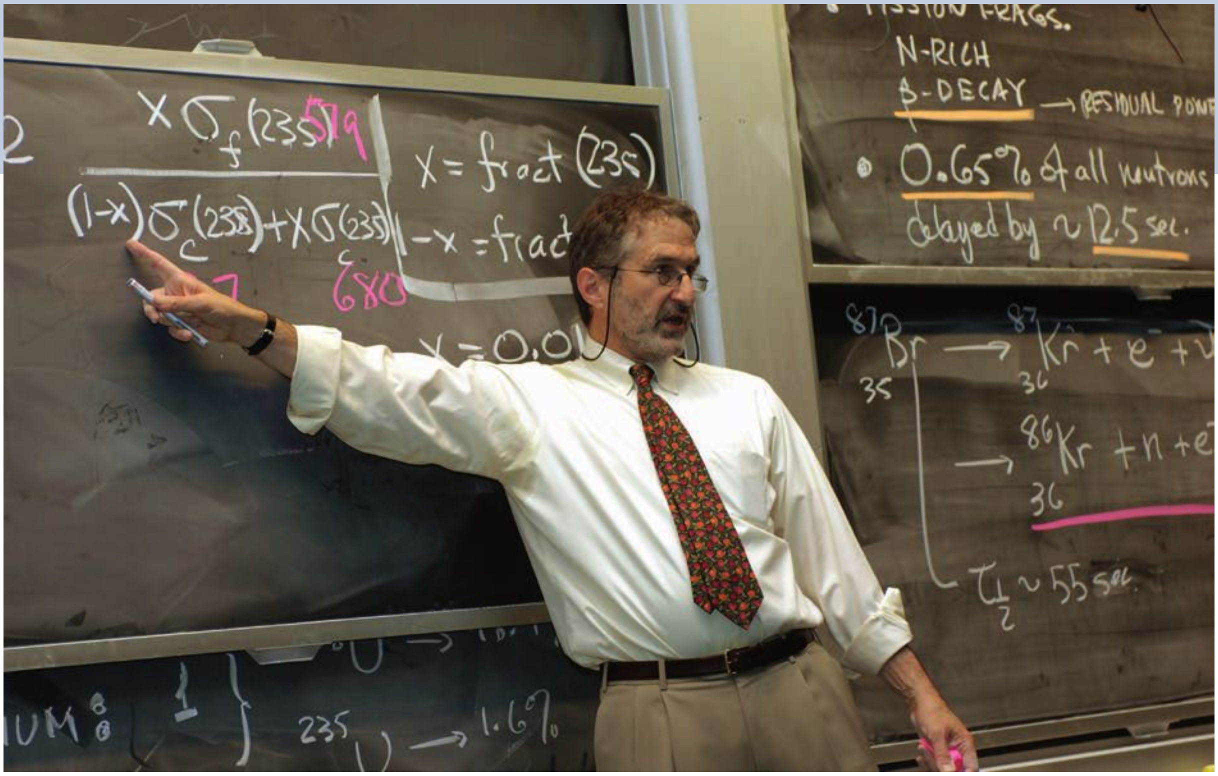


Photo: Donna Coveney

Robert L. Jaffe, the Otto (1939) and Jane Morningstar Professor of Physics at MIT.

"I realized many of the [energy] technologies I taught about were dependent on elements I only knew vaguely about," says Jaffe, who went on to co-chair an April 2010 symposium resulting in the MITEI report *Critical Elements for New Energy Technologies* and to lead work on a February 2011 report for the American Physical Society's Panel on Public Affairs (POPA): *Energy Critical Elements: Securing Materials for Emerging Technologies.*

For example, the classic photovoltaic cells used to convert solar energy into electricity employ silicon, one of the most common elements on Earth, but the leading candidate for newly developed "thin film" photovoltaics uses tellurium, which is rarer than gold.

The POPA report found that it would take 200 metric tons of tellurium to produce 500 megawatts of electric power—roughly the amount generated by a modest US coal plant. "Imagine that much gold," Jaffe says. "How can that possibly be a reasonable economic goal?"

Other examples from the report include the use of neodymium to make powerful magnets for wind turbines and the addition of rhenium to toughen the steel in high-performance gas turbines. Neodymium is not particularly rare but has nevertheless become increasingly costly and difficult to obtain. Rhenium, however, is so rare that only 50 metric tons is produced globally each year.

"We have to look for earth-abundant materials that solve our energy problems," says Jaffe, who has now turned his attention to helping MITEI formulate its upcoming Future of Solar Energy report, which is intended to lay out how solar energy might be deployed at a large scale.

"Energy technologies aren't just little gizmos. These are very large systems. They require long-term investment and need to capitalize on economies of scale," Jaffe says. Noting that the United States—which currently meets just 1% of its energy needs with solar power—would need to cover about 15,000 square kilometers with solar panels to meet all its electricity requirements, he adds: "It's not impossible, but it's a daunting task. What are the barriers to scaling [solar energy] up? How do you deal with the fact that it's intermittent?"

Fortunately, Jaffe does not have to consider these questions alone. "MIT is like having another Internet at my disposal. The expertise here on subjects related to [energy] is phenomenal," he says. "One of the things that makes it all hang together is MITEI, a wonderful clearinghouse that brings people together formally and informally."

Jaffe says, "It's easy to fantasize about solutions to the world's energy needs if you don't worry too much about the laws of nature and the limitations on the other resources Earth provides. The hard part is to find new technologies—from the smallest batteries to the largest solar array—that can work in practice and can be scaled up to the level where they can change the world. Good science has to be integrated into the discovery process from the beginning.... I do believe there are facts in the world and that facts matter."

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By Kathryn M. O'Neill, MITEI correspondent

Discovering solutions: Undergrads take the lead in 10.27

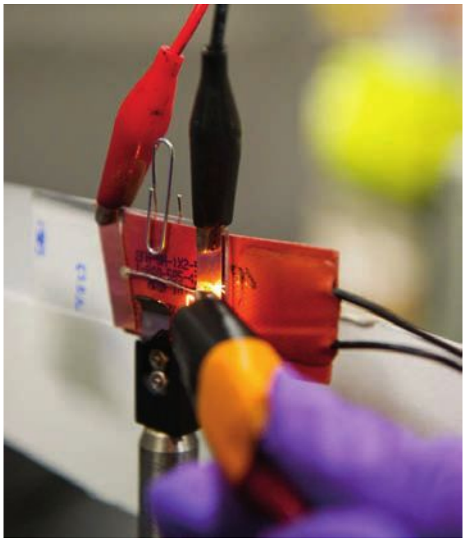
Undergraduates taking 10.27, the Energy Engineering Projects Laboratory, may find themselves far outside their comfort zones, says Clark Colton, a professor in the Department of Chemical Engineering. But Colton would not have it any other way. Students accustomed to homework sets and solutions must instead formulate their own problems and "figure out the best paths to take," says Colton, who shaped this Energy Studies Minor elective. "One of the culture shocks students experience in this class is that there's not always an answer."

10.27 is the latest entry in a grand 75-year-old MIT tradition, according to Colton. The semester-long project class for undergrads is designed not just to stimulate "creative and critical thinking," he says, but to equip students with a host of skills essential for navigating the ambiguities and hurdles of actual engineering ventures. Assigned real problems suggested by industry partners and by MIT's own research faculty, students learn to discover solutions, work in teams, and write reports. In the case of 10.27, which joins project classes on chemical and biological engineering, the focus is energy, "the number one technical topic in our country, which relates to the economy, national security, and the environment," says Colton. "Amongst students, it's a biggie, a very important problem."

Two years since it joined the curriculum, student demand for 10.27 runs greater than available slots for the subject—perhaps because the class offers students a unique opportunity to actually contribute to the field of energy. "It was really exciting to get results and learn about something that no one else had seen," says Marie Burkland '13 of chemical engineering.

Photos: Justin Knight

Marie Burkland '13 of chemical engineering (right) and Jared Forman '13 of chemistry (center) set up a camera to capture images of a thermopower wave being launched by an "electric match" (below), a device they designed and built. Professor Michael Strano of chemical engineering watches from the sidelines. Team member not pictured: Ksenia Timachova '13 of chemical engineering.



She was part of a three-person team investigating a new phenomenon called thermopower waves—a way of converting chemical energy to electrical energy through the use of carbon nanotubes.

Michael Strano, the Charles and Hilda Roddey Professor of Chemical Engineering, was behind the discovery of this phenomenon and served as an instructor for 10.27. He assigned Burkland's group the research goal of trying to improve the energy efficiency of the process—an initial step in deploying thermopower waves in a battery or power source device. There is no "canned solution" to this kind of problem, says Strano. He can "seed students with ideas" and teach them how to make a device to measure electrical power, but "there is still a discovery aspect, because things they are observing are new even to me."

Burkland says her group "bounced ideas off of Professor Strano and his grad student for a couple weeks" to

In their class project, Tshiamo Lechina '13 of chemical engineering (right) and Melissa Showers '13 of mechanical engineering (left) worked with Professor Clark Colton of chemical engineering to develop flow visualization techniques that will permit analysis of fluid dynamics in a process to create new materials for more energy-efficient tires. Here the group adjusts a transparent chamber in which a high-velocity liquid jet mixes with a second, co-flowing liquid. In collaboration with the Edgerton Center, the team made use of a high-speed video camera to capture details of the mixing process at 15,000 frames/second. Team member not pictured: David Campos '14 of chemical engineering.

figure out what areas might prove most fruitful to investigate. "They gave us ideas for where there could be improvements," she says. Burkland found the process highly motivating: "It's exciting; you can make your own rules, take the project in the direction you want." By the end of 13 weeks, Burkland's group had invented a new method for starting a reaction in the carbon nanotubes: "We did it with a resistance wire that gets really hot, is really precise, and all you have to do is touch it to the nanotube device to start a reaction." This innovation not only allows greater control over the amount of energy required to start the wave, notes Strano, but also is very practical because "it is easy to press a button to start this kind of ignition." Says Burkland, "It's a step toward an application in the real world."

"MIT undergraduates are really bright and are able within a short period of time to understand a problem and come up with their own ideas," says Strano. "This is what makes it very different from conventional lab courses. There's no TA telling them what to do." When unexpected obstacles emerged, says Strano, "they had to deviate from plans. They made new objectives and solved some experimental problems that nobody had solved before." In a course like 10.27, it's not just the students who learn. "It's a special space," says Strano.

While 10.27 was "a ton of work," states Burkland, with students often putting in extra lab hours, mastering new technologies, negotiating roles within their teams, and delivering written and oral presentations to other groups, it also was an invaluable experience, she believes. She planned an experiment, collected and analyzed data, generated technical reports—all skills Burkland says she applied last summer in her research job. "I say, wow, I know all this stuff. I don't have to seek help for how to manage a project, document it, and produce results in an effective way."

This is precisely the point of 10.27, suggests Colton: "Every student must learn the details of their application—everyone must learn at the beginning what it's all about, just like real life. When you go to a company you have to start with the basics of that industry, applying what you know. We do it here, in a microcosm." Colton has high expectations for the 60 or so students who have already taken 10.27 and for the next cohort: "I fully expect students in this course to be involved in innovations in industry, solving important problems, becoming entrepreneurs and leaders."

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By Leda Zimmerman, MITEI correspondent

Development and the first three years of delivery of 10.27 were supported by a grant from the S.D. Bechtel, Jr. Foundation.

Energy Fellows, 2012–2013

Photo: Justin Knight

Nicola De Blasio (right), vice president for R&D International Development, Eni, welcomes new Eni-MIT Energy Fellows at a reception in late August.

The Society of Energy Fellows at MIT welcomed about 60 new members in fall 2012. The Energy Fellows network now totals more than 250 graduate students and postdoctoral fellows and spans 20 MIT departments and divisions and all five MIT schools. This year's fellowships are made possible through the generous support of 19 MITEI member companies.

ABB
Xueying Lu Physics
Lisa Pawlowicz Electrical Engineering and Computer Science

Booz Allen Hamilton
Amy Rose Engineering Systems Division

Bosch
Eugene Cho Materials Science and Engineering
Katherine Ong Mechanical Engineering

BP
Philip Arevalo Biology
Kimberly Davis Biology
Maxwell Kaplan Biology/Woods Hole Oceanographic Institution
Levi Lentz Mechanical Engineering
Jennifer Lewis Chemical Engineering
Wei Li Civil and Environmental Engineering
Yuval Tal Earth, Atmospheric, and Planetary Sciences
Arthur Yip Engineering Systems Division

Chevron
David Bierman Mechanical Engineering
Yo Seob Yoon Chemistry

Cummins
Alex Breckel Engineering Systems Division

EDF
Sandra Jenkins Engineering Systems Division

Enel
Jesse Jenkins Engineering Systems Division
Brian Mayton Media Arts and Sciences

Eni
Ashwini Bharatkumar Engineering Systems Division
Michael Chen Civil and Environmental Engineering
Laura Cooper Chemistry
Erik Duhaime Management
Frank Fan Materials Science and Engineering
Aaron Goodman Chemistry
Matthew Klug Mechanical Engineering
Andong Liu Chemical Engineering
Harry Watson Chemical Engineering
Zhulin Yu Earth, Atmospheric, and Planetary Sciences

Ferrovial
Ian McKay Mechanical Engineering
Christopher Smith Urban Studies and Planning

ICF
Michael Davidson Engineering Systems Division

Lockheed Martin
George Hansel Aeronautics and Astronautics
Siping Wang Electrical Engineering and Computer Science

Saudi Aramco
Thanasak Sathitwitayakul Chemistry
Siah Tan Chemical Engineering

Schlumberger
Franco Chingcuanco Civil and Environmental Engineering
Robin Deits Electrical Engineering and Computer Science

Shell
Justin Chen Civil and Environmental Engineering
Nicholas Hagerty Economics
Brett Lazarus Electrical Engineering and Computer Science
Daniel Leithinger Media Arts and Sciences
Junlun Li Earth, Atmospheric, and Planetary Sciences
Yun Liu, PhD Materials Science and Engineering
Shevarl MacNamara, PhD Mathematics
Brian Solomon Mechanical Engineering
Ira Winder Urban Studies and Planning
Xiangyao Yu Electrical Engineering and Computer Science
Ahmad Zamanian Electrical Engineering and Computer Science

Siemens
Parnika Agrawal Materials Science and Engineering
Nazar Lubchenko Nuclear Science and Engineering

Total
Jialiang Chen Civil and Environmental Engineering
Elizabeth M-Y Lee Chemical Engineering
Ketian Zhang Political Science

United Technologies Corporation
Karine Chong Mechanical Engineering
Goksin Kavlak Engineering Systems Division

Weatherford
Michael Gibson Materials Science and Engineering
Arvind Karunakaran Management

Energy alumni: Where are they now?

Photo: Justin Knight

Michael Kearney SM ’11

After earning a master’s degree from the Technology and Policy Program in 2011, Michael Kearney had no time to catch his breath. He had already begun work at Ambri, formerly the Liquid Metal Battery Corporation, a Cambridge startup founded by Donald Sadoway, the John F. Elliott Professor of Materials Chemistry at MIT. Kearney credits this unique career opportunity directly to his experiences while a Hess-MIT Energy Fellow appointed to support the MIT Energy Initiative (MITEI) symposium “The Electrification of the Transportation System: Issues and Opportunities.”

Is this what you expected to be doing after MIT?

I didn’t know much about entrepreneurship when I started graduate school. I assumed I would eventually end up in DC involved in policy. But at MIT my eyes were opened to a world I’d never before imagined, where people were inventing the future they wanted to see.

I first met Professor Sadoway at a symposium on the electrification of transportation, which I had helped organize for MITEI. Several months later, at an MIT Energy Club event, Ambri’s CTO Dave Bradwell asked me to join them getting the company off the ground. They needed me before I finished MIT. There was another complication: I was halfway out the door for a year in China as a Luce Scholar.

There are very few times in life when you have the opportunity to work at a company that could fundamentally change the world. I made the decision to start in April and was at Ambri a week later, still in the throes of writing my thesis.

What’s it like working for a startup?

It’s a little bit of thrilling and terrifying; I don’t get a lot of sleep. I work on everything necessary for setting up a company: human resources, government relations, marketing, modeling our business proposition.

I had no engineering background coming into this, and I’m not working with the technology itself, but I know what we’re doing here is unique. The concept is a new approach to grid-scale energy storage. The key to our plan is ensuring that the liquid metal battery technology achieves a price point that will work in the market. It is the kind of battery that can help integrate renewables like wind and solar into the grid, and ease shortages when power plants have problems meeting demand. We can save money for lots of different players.

What aspects of your MIT education are proving most useful to you?

The opportunities I had through the Energy Initiative were invaluable. My research for the electrification symposium acquainted me with all the related fields: battery technology, electrical grid, the policy side. My MITEI mentors, Ernie Moniz and Melanie Kenderdine, taught me a lot about energy policy, and as an Energy Fellow, I had access to high-level guests in the energy space. I found myself at one point talking about vehicle electrification with the British foreign secretary, David Milliband. These experiences have served me well.


Photo: Donis Perkins

Barbara Brenda Botros PhD ’11

When she left MIT in 2011 with a PhD in energy science and engineering, Barbara Brenda Botros knew she wanted to apply her extensive knowledge of thermodynamics, fluid mechanics, and aerodynamics to “innovative projects whose ultimate goal was making systems more energy efficient.” She landed at United Technologies Research Center. It’s a workplace, says Botros, where researchers are encouraged to investigate areas outside their home disciplines and where, “if you play your cards right, you can make a real impact.”

Did you envision a career in the energy field when you began your education?

After I saw *Apollo 13* as a teenager, I wanted to be an astronaut. I went to McGill University headed for aerospace, and I even interned at the Canadian Space Agency junior year. But while studying mechanical engineering, I developed a passion for thermofluids and then researched detonations and combustions with a terrific professor. I came to MIT still thinking about aerospace and for my master’s conducted Air Force-funded research on reducing the weight of plane engines. I developed the B3 parameter (named for my initials), an innovative design guideline for making compressors more efficient.

But when I began my PhD, I switched back to thermodynamics, which I very much loved. I joined the BP-MIT Energy Conversion [Research Program] on coal gasification with carbon capture. With Professor John Brisson [of mechanical engineering], I researched improving heat transfer processes in coal plants, which led to publishing papers and a patent. During this time, I broadened my horizons around energy research through MITEI conferences and the MIT Energy Club. An entirely new world opened up for me, and I realized that my work in fundamental sciences has so many potential applications in energy.

What is the focus of your current work, and how does your MIT background come into play?

My main focus in the aerodynamics group is developing a new line of high-efficiency compressors in industrial-size Carrier air conditioners for refrigerants with low global warming impact.

I found that because of MIT’s multidisciplinary environment—in research and elsewhere—I began work here well prepared for the demands of my project and knowledgeable about other areas of energy research. I can comfortably approach colleagues about their work and about potential collaborations. I’m not afraid to step outside of my comfort zone to learn something new. I already have some ideas for the center’s innovation pipeline, including ways to reduce noise and emissions in planes.

What kind of impact do you hope to make in your career?

The energy field is broad, and you can make an impact, whether by improving the energy efficiency of existing systems or by coming up with new systems altogether that produce or save energy. I like the idea of looking for the next big thing, the new Facebook or Twitter of the energy domain. I hope to be part of something that revolutionizes the energy sector.

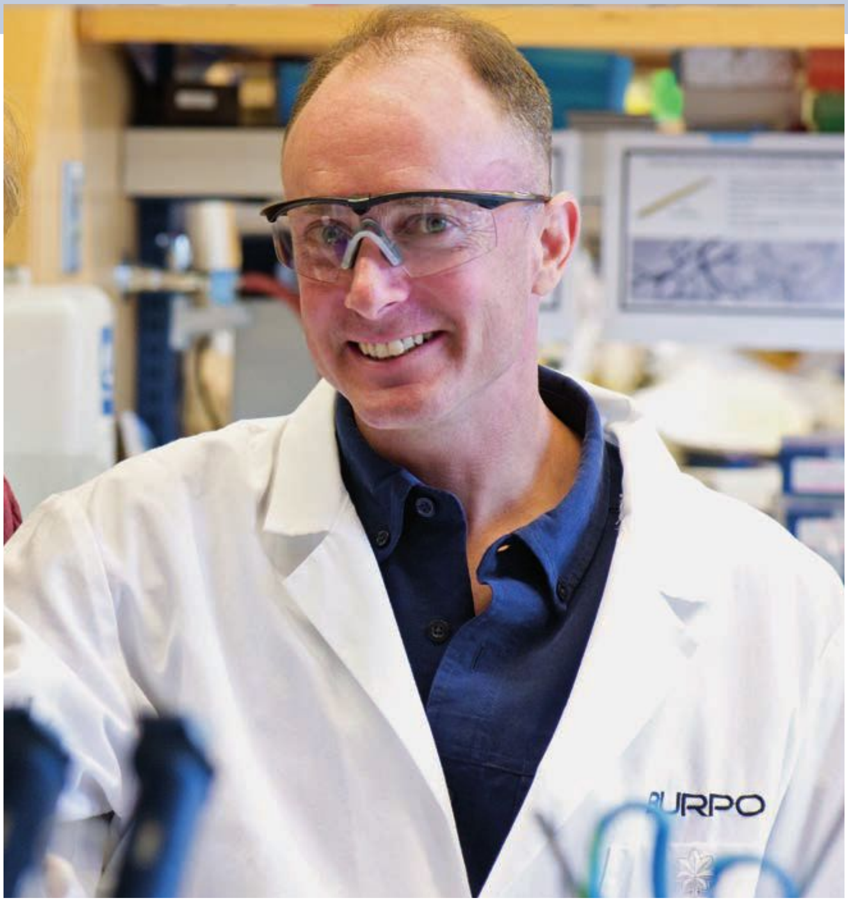

Photo: Justin Knight

F. John Burpo ScD '12

After 20 years, F. John Burpo ScD '12 and Eni-MIT Energy Fellow is returning to West Point, the launchpad for his uncommon career straddling military service and scientific research. A decorated officer with a Purple Heart and Bronze Star, Burpo conducted his principal graduate research in the Biomolecular Materials Group of Angela Belcher, the W. M. Keck Professor of Energy.

You have alternated between field duty and academia. Is it difficult negotiating two such different environments?

It is challenging to be competent and successful in each field, especially when you have to overcome stereotypes and allay concerns. When I showed up in the Army with a master's from Stanford, there was a sense that I might be too smart for what I was doing. In the academic world, I was the guy who jumped out of airplanes and blew things up—maybe a bit of a knuckle-dragger.

After months of combat in Iraq, where our job, euphemistically speaking, was to do bad things to bad people, it was a stark shifting of gears getting settled with my family in Cambridge. I won't lie and say it was easy. I made this transition from combat deployment to academic life by focusing on the very consuming research tasks at hand.

What were your research goals in the Belcher Lab, and in what ways might they address or connect to the energy challenge?

The Belcher lab was a very vibrant, dynamic atmosphere in terms of idea flow and the license to try different things. We worked with a bacteriophage virus, M13, which under the electron microscope looks like a piece of truncated spaghetti. By connecting the virus particles together, you can create a 3D scaffold, a nanoarchitecture for building new things.

My goal was to come up with light-weight energy materials based on this 3D nanoarchitecture, and we successfully created a rechargeable, copper-tin battery system with 3D nanostructure and 3D current connector.

We're trying to achieve materials efficiency and synergies. Imagine a wing for a drone laminated with a battery material to extend its range. My West Point lab will explore different biological platforms for creating new multifunctional materials that could be useful in small- and large-scale device designs. This could start a paradigm shift in the way people think about devices.

What will you bring to West Point from your time at MIT?

I hope to have an impact on a generation of West Point cadets who go on to lead the Army and society at large by honing their thinking skills and scientific understanding. My MIT experience will help me challenge students to think about the interdisciplinary connections beyond the immediate lesson and topic and to imagine solutions not previously envisioned. I will tell students interested in energy careers to talk about their research to everyone they can find, especially people not in their field. If they have an idea that seems crazy, it just may work.

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By Leda Zimmerman, MITEI correspondent

Undergraduates learn the art of posters and pitches

The Poster Scholars Program, now in its third year, equips undergraduates with the basic knowledge and experience needed to successfully present their research. This joint effort of the MIT Energy Club and the MIT Energy Initiative pairs interested undergraduates working in energy with graduate student mentors, who act as guides in the poster-making and pitch-development process. Over three weeks, students hone their posters and their communication skills via practice pitching sessions and mentor guidance on how to create effective visual aids. The program culminates in a poster session during Family Weekend, when visitors get an inside look at a range of energy projects while students practice presenting their work in a low-stress environment (see photos).

Photos: Dominick Reuter

Linh Bui '13 of chemical engineering has been taking part in research to develop new zeolite catalysts. One promising catalyst could lead to a process for converting biomass compounds such as hemicellulose into sustainable liquids useful as high-performance additives to petroleum.

Sam Shames '14 of materials science and engineering has been working on various applications for solar thermal fuels. His poster presents his assessment of the possibility of using solar fuels for de-icing applications.

At left, Kyumin Lee '13 of chemical engineering explains his research on sorghum as a source of starch for conversion to ethanol. Sorghum is attractive because of its drought resistance and relatively low value as a food source. At center, Jean Sack '13 of mechanical engineering takes a question about her work in the MIT Device Research Laboratory on optimizing heat transfer using condensation.

Lisa Liu '14 of electrical engineering and computer science is participating in research on "singlet exciton fission," a phenomenon in which molecules that absorb solar energy share their excited states. Her poster explores potential applications using organic materials, including the creation of highly efficient organic solar cells.

Undergrad project offers glimpse of what MIT is plugging in

This spring, the Department of Facilities tapped one of MIT's greatest resources—its students—to learn more about electricity consumption on campus.

Working with Lecturer Stephen A. Hammer of the Department of Urban Studies and Planning, Facilities tasked a team of undergraduates to conduct a study of plug load on campus—the energy consumed by the appliances and electronic devices plugged into outlets.

Plug load estimates are important in determining the size of a building's heating, ventilation, and air-conditioning (HVAC) system, because lab and office equipment generates heat. Yet Facilities has found that industry standards tend to inaccurately estimate plug load, which can lead to oversizing the HVAC system and paying higher energy costs, according to Peter Cooper, manager of sustainable engineering and utility planning for Facilities and a member of the MIT Energy Initiative's Campus Energy Task Force (CETF).

"The energy consumed via plug load has changed dramatically in the last 20 years," says Julia Ledewitz, sustainability and LEED coordinator for Facilities, who also participates in the CETF. "In classroom and office spaces we're seeing three times what we used to see at the plug load level. The amount is now closer to the energy consumed by lighting and the heating and cooling of spaces."

Photo: Justin Knight

Erica Lai '14 of materials science and engineering (left) and Jennifer Liu '14 of electrical engineering and computer science teamed up to monitor the electricity consumption of various devices plugged into outlets in eight rooms inside MIT's new Sloan building (E62). Their analyses are providing a detailed look at the building's "plug load"—a factor that designers use when sizing heating, ventilation, and air conditioning systems for new commercial buildings.

This uptick has occurred because the use of electronics has skyrocketed—now accounting for an estimated 20% of the electricity consumed in US commercial office buildings. At the same time, plug load has become increasingly important because efforts to insulate buildings and improve lighting systems have reduced other major energy demands.

But the only way to know the exact plug load of a space is to measure it—which is where the students came in.

"This [plug load study] was a very quick and easy, low-cost way to get at this information—while giving students exposure to how one does this kind of field work," says Hammer, who reached out to Facilities to develop this project for a class called Re-Energizing MIT. The class, supported by the S.D. Bechtel, Jr. Foundation and the d'Arbeloff Fund for Educational Excellence, gives students hands-on experience as energy consultants working with MIT to improve campus energy management.

Erica Lai '14, a materials science major who is minoring in energy studies, teamed up with Jennifer Liu '14, an electrical engineering and computer science major, to conduct the study, which involved metering outlets and analyzing usage in E62, the new Sloan School of Management building.

The students tracked all the power consumption in eight discrete spaces—seven offices and a copy room—for one week and found that the average weekday peak load in this densely plugged area did not exceed the average year-round peak load projected for the building. "They found the estimates were a little conservative," Hammer says, suggesting that the building's designers expected higher plug loads than have materialized.

"It's a small sample size, so the findings are still inconclusive, but what's important is that we now have actual field measurements that Facilities can add to over time," Hammer says, noting that the information will help when MIT is designing or retrofitting buildings in the future.

The students also found that computer equipment was the primary driver of plug load, with laptops consuming "between 2 and 13 times less power in a 24-hour period than desktops due to lower usage patterns and the energy-efficient nature of laptops," according to their report.

Laxmi Rao, IT energy coordinator for Information Services & Technology (IS&T) and a member of the CETF, says the students' measurements confirm IS&T's understanding of energy usage. "Across campus there is a noticeable trend toward laptops and energy-efficient monitors that—as they note—will contribute to a significantly lower load factor."

The students presented their work to Executive Vice President and Treasurer Israel Ruiz and other members of the CETF in May, and the work was very well received. "The rigorous, data-driven, student-led research projects open up a myriad of exciting opportunities to expand the good work of the Campus Energy Task Force and increase the range of energy efficiencies on campus," says Ruiz, CETF co-chair. "The students did a great job."

Going forward, Hammer and Ledewitz both say they plan to expand the plug load project to evaluate usage elsewhere on campus. "We'll continue to invite students to conduct these valuable [energy] studies," Ledewitz says. "Each project helps us to understand how the campus and its community are using energy and how best to plan ahead."

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By Kathryn M. O'Neill, MITEI correspondent

Renovation plans offer MIT opportunities to save energy, improve design

After unveiling 11 new buildings in as many years, MIT is turning its attention to renovating existing campus buildings—work that promises both to make the Institute more energy-efficient and to influence design standards in the construction industry, according to the Department of Facilities.

"The major stock of buildings is existing buildings, so that's where the biggest opportunities lie for reducing energy use," says Peter Cooper, manager of sustainable engineering and utility planning for Facilities and a member of the MIT Energy Initiative's Campus Energy Task Force (CETF).

MIT plans to spend $250 million over the next three years on an accelerated Capital Renewal Program. The goal is to do a major building renovation or two each year.

"The Institute is embarking on a program of accelerated capital renewal so that we can begin to address the overall deferred maintenance backlog across campus," says Executive Vice President and Treasurer Israel Ruiz, who co-chairs the CETF. "Sustainability is a key theme in our planning efforts. We constantly strive to incorporate sustainable approaches wherever possible as we make decisions about construction and renewal projects."

MIT is interested in finding ways to improve the efficiency of existing structures not only for its own benefit but also because, as Cooper says, "At MIT there is an expectation that we ought to be smarter about how we do things…and [contribute] to the body of knowledge."

Therefore, while MIT is renewing and retrofitting campus buildings, it is also collecting data that will be submitted to the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE), which sets standards for energy-efficient building design, according to Walter Henry, who was director of Facilities' Systems Engineering Group prior to his retirement in July. "Some of the handbook data now are 20 years old or so; they don't recognize how much better buildings can perform," he says.

MIT's findings could make an enormous impact not only on campus but also nationwide. The building sector is the largest consumer of energy in the country, accounting for about 41% of total energy use, according to the US Department of Energy. Moreover, at least half of today's buildings will still be standing by mid-century, notes the Pew Center on Global Climate Change. As a result, retrofitting structures and upgrading the efficiency and operation of their heating, ventilation, and air-conditioning (HVAC) systems offer an important near-term opportunity to significantly reduce greenhouse gas emissions.

Insulating masonry buildings

Officially, MIT's Capital Renewal Program launched at the start of Fiscal Year 2013, July 1, but the Institute has long been hard at work learning how to make buildings more useful, comfortable, and energy efficient. Just this summer, Facilities tested the results of cutting-edge design work both in the new Sloan School of Management building (E62) and in the newly renovated Arthur D. Little Building (E60) next door—with good results.

MIT's work on E60, a masonry building constructed in 1917, is particularly significant because it challenges the industry assumption that masonry buildings cannot be insulated without risk of damage from moisture, which leaks through brick and can become trapped in walls. If the moisture freezes there, it can deteriorate the wall unexpectedly.

Currently, designers err on the side of caution and don't insulate masonry buildings at all, making them much less energy-efficient than new construction. "The design community needs to know how much [insulating] you can do," Cooper says. "Now they just steer a wide path around the whole issue."

So MIT teamed up with Building Science Corporation, an outside consulting firm with Institute ties, to explore whether insulating E60 might be possible. Building Science has done some groundbreaking research in this area that determined that risk depends on the type of brick and how much moisture it's going to absorb, Henry says. "We had the brick [in E60] tested and determined the risk was low."

Therefore, when MIT renovated E60 in 2011, workers insulated the building with 2 to 2.5 inches of spray foam. Then they added instrumentation to test the effects. Devices are now recording rainfall, insolation (the energy from the sun that hits the building), surface temperatures, wind direction, humidity, and interior humidity and temperature, providing a profile of what the walls are experiencing, according to Joseph Gifun, current director of the Systems Engineering Group.

There are not enough data yet to draw conclusions—especially since last winter was so mild—but the nine months of data accumulated so far have not shown any conditions where the brick was at risk.

Blower-door testing

In addition, a standard "blower-door test" conducted this summer indicates that the new insulation has significantly improved the building's performance. This test involves closing all external windows and doors, sealing HVAC louvers, opening interior doors, and using fans to create a pressure difference between the interior and exterior, enabling the testers to measure the leakage of air through the exterior envelope.

Results showed the rate of air infiltration into and out of the building measured just 0.18 cubic feet per minute (cfm) at a pressure of 75 Pascal—equal to the wind pressure from a moderate breeze. That performance is better than the standard of 0.40 cfm75 set by the US General Services Administration (GSA) and the higher standard set by the US Army Corps of Engineers (0.25 cfm75).

"This is principally due to the use of spray foam insulation and partly due to the new windows," Henry says. "The GSA standard is not considered very aggressive but the Corps standard is, and 30% of the buildings designed to it do not pass. Clearly we have done well."

MIT didn't test E60's performance before the renovation, but Facilities did conduct a blower-door test this summer on E52, a similar masonry building currently in line for renovations. Its high rate of infiltration—0.46 cfm75—indicates how much improvement can be made. "The difference between the E52 and the E60 results demonstrates what can be done with careful detailing and by using spray foam insulation or other effective air barriers," Henry says.

In summer 2012, MIT teamed up with outside experts to perform a blower-door test on MIT's new Sloan building—a means of measuring the leakage of air through the building's exterior envelope. The test involved first sealing up all external openings (including the kitchen fans shown on the facing page) and then using door fans such as those shown above to blow in air while monitoring the pressure buildup inside the building. The measured rate of air infiltration was well below even the strict standards set by the US Army Corps of Engineers, confirming the high performance of the building envelope.

These results will be considered in deciding whether to insulate E52 and will help provide industry with the information needed to make better decisions about renovating masonry buildings in the years ahead. "I'm convinced we're going to change the conventional thinking on this and we're going to do that by the numbers—so people don't just use the rule of thumb and say no, we can't do this," Henry says.

Sloan's performance

Testing conducted this summer at Sloan (E62) is also designed to change the numbers—in this case, those used by industry to determine the level of HVAC needed for new buildings.

"There were many years when energy was cheap....You didn't need to have a fine-tuned building design; you could just put in a bigger heating and cooling system," Cooper says. In recent years, however, demand for energy-efficient buildings has risen dramatically while industry standards continue to lag.

Since MIT has become increasingly sophisticated about designing for sustainability—and Sloan is a premier example—Facilities used a blower-door test to gather hard data on the building's performance for ASHRAE, which will use the information to develop more accurate industry guidelines.

Photos courtesy of Marc Rosenbaum of Energysmiths

E62 includes several features designed to improve its energy performance, including insulation to prevent the leakage of air through the walls of the building and sunshades and screens to reduce solar heat gain. "We think the high quality of the exterior envelope has a lot to do with how the building is performing," Henry says.

These features enabled MIT to downsize the building's HVAC system and helped earn E62 a Gold certification from the US Green Building Council's Leadership in Energy and Environmental Design (LEED) program in 2011. This summer's testing provides hard performance data that MIT's design decisions are paying off.

"The blower test at Sloan was incredibly successful," says Gifun. E62 measured 0.14 cfm75. "This is a way of finding holes in the system, and it didn't leak."

The benefits of these results will accrue to future projects, as MIT's experience with Sloan (and the similarly well-performing new building housing the Koch Institute) is providing evidence that it is possible to downsize HVAC for a fairly airtight building below current industry recommendations.

"Sloan and Koch are good examples. We made the investment in high-performing envelopes, and our design process facilitated downsizing the HVAC systems for offsetting capital cost savings," Cooper says. "And we enjoy the energy benefits forever."

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By Kathryn M. O'Neill,
MITEI correspondent

MIT and Saudi Aramco augment existing collaboration

On June 18, 2012, MIT President Susan Hockfield and Saudi Aramco President and CEO Khalid A. Al-Falih signed a memorandum of understanding (MOU) in Dhahran, Saudi Arabia, providing a framework that will greatly expand the research and education partnership between MIT and Saudi Aramco.

"Our signing today is a solid testimony to the vision of advancing technology and higher education shared between Saudi Aramco and MIT," Al-Falih said. "We have a long history in forging partnerships with world-class institutions. What excites me is the coming together of great minds from Saudi Aramco and MIT to find solutions for the world's challenges while pursuing research of common interest and building human capital at MIT and Saudi Aramco, and contributing to building a knowledge economy in Saudi Arabia."

Several elements of the MOU have been agreed to for implementation. Saudi Aramco has become a Founding Member of the MIT Energy Initiative (MITEI), raising its participation from its current Sustaining Membership. This entails a substantial increase in the scope of research collaboration, encompassing renewable energy; energy efficiency; energy economics; carbon dioxide management and conversion; desalination; advanced materials; and a range of hydrocarbon production areas such as computational reservoir modeling and simulation, geophysics, and unconventional gas. MITEI Founding Members commit to a $5 million-per-year program for a period of five years. Al-Falih also announced Saudi Aramco's plans to create a satellite R&D center in Cambridge, Massachusetts, to enhance the research collaboration and facilitate the exchange of researchers. Also in advance of the signing of the MOU, Saudi Aramco joined the MIT Media Lab and MIT's network of Fab labs.

Photo courtesy of Saudi Aramco

Gathering for the official signing of the MOU between Saudi Aramco and MIT were, from left, Abdullatif A. Al-Othman, former senior vice president, engineering and project management, for Saudi Aramco and now head of the Saudi Arabian General Investment Authority; MIT President Susan Hockfield; Ali I. Al-Naimi, Saudi Arabian minister of petroleum and mineral resources and chairman of the board of Saudi Aramco; Khalid A. Al-Falih, president and chief executive officer of Saudi Aramco; and Ernest J. Moniz, director of the MIT Energy Initiative.

In addition, Saudi Aramco and MIT are working to broaden the Ibn Khaldun Postdoctoral Fellowship program for Saudi Arabian women and to create an engagement with the MIT Venture Mentoring Service aimed at increasing entrepreneurial activity in Saudi Arabia.

Hockfield said, "The relationship contemplated by the MOU would represent another substantial partnership between academia and industry, and serve MIT's commitment to advance research, technology development, and education around the world. We welcome this opportunity to build the scale and scope of our existing partnership and to enhance the transfer of knowledge between our two institutions."

The MOU contemplates extensive additional cooperation in several areas:

- participation by Saudi Aramco in MIT's Master of Engineering in Manufacturing program;
- collaboration in enhanced pre-college teaching in science, technology, engineering, and mathematics through extension of the MIT/BLOSSOMS program;
- collaboration in online education;
- professional development through customized short courses and participation in advancing higher education for women in energy engineering fields;
- capacity building, including possible job fairs and development of career opportunities in Saudi Arabia for suitable graduates;
- entrepreneurship and innovation programs;
- professional development and lifelong learning programs, including joint conferences, workshops, and technical symposia, and customized short courses; and
- cultural exchange and outreach programs involving the King Abdulaziz Center for World Culture, the MIT Program in Art, Culture, and Technology, and the Agha Khan Program for Islamic Architecture.

These cooperative efforts will be developed by a high-level MIT–Saudi Aramco steering committee.

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MIT News Office

Symposium shows women's growing impact in clean energy worldwide

Female leaders are playing a growing role in advancing the development of clean-energy technologies, helping to advance plans for carbon reduction, reduce pollution and greenhouse gas emissions, and foster job creation. Some of these women were honored in a daylong symposium at MIT on September 28, hosted by the MIT Energy Initiative (MITEI) in partnership with the US Department of Energy (DOE). This marked the inaugural event of an initiative, created in 2010 by DOE with eight partner governments, called Clean Energy Education and Empowerment, or C3E. C3E members work to consider ways to promote women in clean energy.

Photo: Justin Knight

The daylong Women in Clean Energy Symposium, hosted by the MIT Energy Initiative on September 28, demonstrated and highlighted women's increasing leadership in energy research, industry, and government.

MIT President Emerita Susan Hockfield opened the symposium, recalling the launching of MITEI as one of her very first acts upon assuming the Institute's presidency eight years ago. "The most important challenge for this generation," she said, "is building a sustainable energy system for the future."

That requires a multipronged approach, she said: "Great technology will never win alone; it needs to be paired with policy." The key, Hockfield said, is "turning ideas into action." When she gives talks on energy, she said, her audiences are largely male. But, she added, "Women are awfully good at turning ideas into action."

Many of the women who were featured as speakers or who received awards at the symposium have embodied those concepts as leaders of companies, as government officials, or as researchers or educators.

One of those leaders is South Africa's minister of energy, Elizabeth Dipuo Peters, who gave a keynote address. "The development of the clean-energy sector will revolutionize the energy sector," she said.

In Africa, while the availability of grid-provided electricity varies greatly, overall "the proportion without access is higher than on any other continent," Peters said. That lack of electricity, she said, "has simply crippled industrialization in Africa." Globally, she said, about 1.5 billion people lack access to reliable electricity, which she called "a fundamental need."

Some 85% of South Africans have regular access to electricity, leading the continent's 54 nations, Peters said, adding, "People follow where the bright lights are shining." But decentralized power systems could leapfrog traditional grids—much as the explosive growth of cellphones in the developing world has bypassed traditional telephone networks.

Nontraditional energy sources could also have a major impact in Africa, Peters said. "The ocean currents along 2,000 kilometers of coastline could meet all of our energy needs," she said. Or, through a widespread deployment of solar power, she said, "South Africa could meet all of Africa's energy needs."

Africa is "poised for change," Peters concluded. "The 21st century is indeed Africa's century, with a bright future."

Other speakers at the symposium echoed that call for innovative energy solutions in developing nations. Richenda Van Leeuwen, director for energy and climate at the Energy Access Initiative Team of the UN Foundation, said that "some developing countries are ahead of where we are here at home" in their efforts to develop decentralized energy systems.

Allison Archembault, president of EarthSpark International, described her organization's work to bring electricity to Haitians, only 25% of whom now have regular access. To remedy that, EarthSpark provides decentralized battery-charging facilities and rents out charged batteries for use in lighting, cellphone charging, and other needs. Some of these customers, in turn, rent out charging capacity to their neighbors for a small fee. By displacing the kerosene most Haitians use for lighting, the organization not only cuts the cost of energy but also eliminates a major source of indoor pollution.

Rhonda Jordan, a doctoral student in MIT's Engineering Systems Division, described a startup called Egg Energy that has been deploying decentralized systems in Tanzania, where only 14% of people have access to electricity. There, she said, the issue is a "last-mile" problem: The country has a widespread electric grid, but alongside a highly inefficient distribution system and prohibitive costs. Egg Energy has been targeting Tanzania's rural homes and small businesses, providing access to power produced either by the grid or by off-grid solar power systems, which are used to charge batteries that can each provide about two days of electricity for household use.

Symposium speakers ranged from those working on small-scale individualized energy solutions to others working at the highest levels of government or corporations. But, these leaders pointed out, with many national and international energy plans stalled, local initiatives often are leading the way. Among other things, energy efficiency has been embraced by some states and cities, forging ahead of national standards.

Henrietta Davis, the mayor of Cambridge, Massachusetts, said that "action on things like energy efficiency is very much on the local level," pointing out that, besides Cambridge, cities including Boston, New York, Los Angeles, and

Photos: Justin Knight

Melanie Kenderdine, executive director of the MIT Energy Initiative and symposium host, introduces the lunchtime ceremony at which the winner of the poster session was announced.

Washington have instituted efficiency programs of their own.

"The time is finally right for energy efficiency to be considered as a national strategy in itself," said Kateri Callahan, president of the Alliance to Save Energy, which works with government officials and corporate and NGO executives to establish strategic energy plans.

One highlight of the symposium was the presentation of a Lifetime Achievement Award to Mildred Dresselhaus, MIT Institute Professor Emerita of Physics and Computer Science and Engineering. She received tributes from two former students, one of whom called her a "bodhisattva, a bringer of enlightenment," and another who said, "Millie changed my life" and has "remained my mentor, even after I left here years ago."

A leader in promoting opportunities for women in science and engineering, Dresselhaus received a Carnegie Foundation grant in 1973 to encourage women's study of traditionally male-dominated fields, such as physics.

In 1973, she was appointed to the Abby Rockefeller Mauze chair, an Institute-wide chair endowed in support of the scholarship of women in science and engineering.

MIT President L. Rafael Reif presented the award to Dresselhaus, citing her significant accomplishments in developing thermoelectric devices. "Everyone who spends a few minutes with her," he said, "knows the brilliance of her mind."

A centerpiece of the day was an award luncheon for the first C3E awards. Six rising leaders in clean energy were recognized for leadership in their field and their contributions to one of six core topics. The winners were selected from more than 160 nominations, and each award included a $10,000 cash prize.

The recipients were chosen by the C3E ambassadors, a group of 30 distinguished senior professionals who have made notable contributions to the clean energy field and who are committed to increasing women's participation in clean energy careers. The ambassadors illustrate the many, varied paths to professional success in clean energy, and they volunteer their time to promote the C3E initiative and to serve as mentors to mid-career professionals.

Each awardee was introduced by a C3E ambassador and had an opportunity to describe her work. The award presenters and recipients were as follows.

Education/Mentorship Award: Presented by Frances Beinecke of the Natural Resources Defense Council to Assistant Professor Tracey Holloway, University of Wisconsin–Madison, of the Nelson Institute for Environmental Studies, Atmospheric and Oceanic Sciences, and Civil and Environmental Engineering.

MIT President L. Rafael Reif (left) presents the Lifetime Achievement Award to Mildred Dresselhaus, MIT Institute Professor Emerita of Physics and Computer Science and Engineering.

Technology Award: Presented by Marilyn A. Brown of Georgia Institute of Technology to Professor Jing Li of the Department of Chemistry and Chemical Biology at Rutgers University.

Corporate Implementation Award: Presented by Merribel Ayres of Lighthouse Consulting Group to Liz Porter, director of energy initiatives at Lockheed Martin.

Developing World Award: Presented by Dymphna van der Lans of the German Marshall Fund to Laura Stachel, founder of WE CARE Solar and associate director of emergency obstetric research for the Bixby Center for Population Health and Sustainability.

Entrepreneurship Award: Presented by Karen Conover of DNV KEMA Energy and Sustainability to Judy Dorsey, president and principal engineer at Brendle Group.

Policy/Advocacy Award: Presented by Melanie Kenderdine of the MIT Energy Initiative to Margaret Downey, assistant county administrator, Barnstable County, Massachusetts.

The C3E symposium also included a poster competition highlighting student research (see sidebar at right). In addition, the event offered opportunities for interacting with the C3E ambassadors, who led small group discussions about key energy issues the evening before the symposium.

Melanie Kenderdine, MITEI executive director and C3E ambassador, hosted the event. She said the symposium was "an informative event, motivating to the participants who are starting out in the energy field." She was pleased with the variety of speakers and panelists and the audience feedback. Kenderdine was encouraged by the networking opportunities and said she heard from many attending the dinners and the symposium that the connections they made were valuable. The symposium brought together distinguished and emerging leaders in clean energy, helping to lay the foundation for a broader, continuing effort to advance women's careers and leadership in clean energy. Kenderdine said she is looking forward to hosting the event again next year.

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By David L. Chandler, MIT News Office, with additional reporting by Rebecca Marshall-Howarth, MITEI

For more about C3E, visit: cleanenergyministerial.org/our_work/women_in_clean_energy/index.html.

Sarah Wood wins poster competition at C3E symposium

Photo: Justin Knight

Sarah Wood SM '12 was voted winner of the student poster competition at the C3E symposium. Her poster, "Philanthropic Capital and Energy Entrepreneurship," outlined her research approach and presented conclusions showing that not-for-profit funding from wealthy individuals and their foundations is widely used to support science and engineering research within the university but is not currently used to fund the translation of those ideas toward greater impact.

Wood graduated from MIT's Engineering Systems Division with a master's degree in technology and policy in September 2012. Her thesis research at MIT, under the supervision of Professor Fiona Murray of the Sloan School of Management, focused on the untapped potential of philanthropic capital to advance many areas of science and engineering that hold solutions to global issues, including energy.

Previously, Wood served as trustee and executive director of the Chesonis Family Foundation, designing and implementing a strategy to use philanthropic resources to address pressing energy and environment challenges not addressed by private enterprise or public capital. Between 2006 and 2010, she oversaw the Chesonis family's $10 million gift to proof-of-concept academic energy research and helped facilitate several equity investments made by the family into energy technology startup companies.

Presidential campaigns offer energetic energy debate at MIT

There could hardly be a more pressing issue than energy policy at a time of global warming, but it has rarely featured in this year's presidential campaign. Until October 5 at MIT, that is, when representatives of President Barack Obama and his Republican challenger, former Governor Mitt Romney, squared off in a crisp debate about energy, revealing significant differences between the candidates. (To watch a video of the debate, go to mitei.mit.edu/news/video.)

At the event, hosted by the MIT Energy Initiative (MITEI) and the MIT Energy Club, Oren Cass, domestic policy director for Romney, emphasized that the former Massachusetts governor believes increased domestic fossil-fuel production should be the principal priority of energy policy, while asserting that government should play a minor role incentivizing energy technology deployment, and dismissing the need for assertive policymaking on climate matters.

There has been a recent "energy revolution" in the techniques used to extract fossil fuels, Cass asserted, making "energy independence on this continent…a potential reality for the first time in decades." The pressing issue, he said, is whether "we embrace the revolution that actually has occurred…or do we attempt to stifle it?"

The Obama administration, Cass charged, has invested too heavily in promoting alternative energy, and has been insufficiently aggressive in backing fossil fuels, by not opening enough public lands and offshore waters for oil and gas drilling and by not yet approving the Keystone XL pipeline, which is intended to deliver oil to the United States from Canada.

"The administration's policies are misaligned with the goal of increased production," Cass said.

Representing Obama, Joe Aldy, a professor at Harvard University's Kennedy School of Government who served as a special assistant to Obama for energy and environment in 2009 and 2010, by contrast made the case that an "all-of-the-above strategy" is needed to address America's energy needs—one that includes increased production, technological innovation, and efficiency.

"When I think about what the American public wants, it's to look for the kind of balanced approach the president is pursuing," Aldy said, adding: "We're going to use every tool we have available. Let's not just focus on fossil fuels. We can do a lot in renewables, whether it's for biofuels, wind, or solar. We need to be creative in how we do this. We need to take advantage of opportunities [for] energy efficiency." While domestic oil production is at a 14-year high, Aldy said, Obama has also signed new fuel-efficiency standards for the nation's automotive fleet that will mandate an average of 54.5 mpg by the year 2025.

Cass and Aldy also presented differing views on the government's proper role in fostering energy innovation. Cass said that Romney supports ARPA-E, the federal government's program to develop new clean-energy technologies, which was first funded with $400 million from the American Recovery and Reinvestment Act—the so-called "stimulus" bill—that Obama signed in early 2009. However, Cass noted a few times, Romney would prefer to see the lion's share of government backing for innovation go toward early-stage basic research.

"Ultimately the biggest source of difference [between the campaigns]…is the question of what is the right way to promote innovation," Cass said, adding that Romney believes in "government support in the very early stages of research, and reliance on the private sector to commercialize technologies to bring down their costs and to hopefully succeed in the market." By contrast, Cass asserted, Obama has supported "massive subsidies for chosen industries…which, in our judgment, has not been a success."

Aldy countered that the Obama administration has not only helped advance clean energy innovation through its ARPA-E grants, but added that the total of $90 billion spent on clean energy in the stimulus bill has created an estimated 250,000 jobs. "We need to continue to diversify…and continue to advance wind and solar," he said, asserting that there is "a lot of job creation going on, it's high-quality jobs in the manufacturing sector."

The 90-minute debate, in front of a crowd of several hundred in MIT's Kresge Auditorium, was moderated by Jason Pontin, editor-in-chief and publisher of *Technology Review*. The campaign representatives hewed closely to their time allowances throughout the debate, and Pontin permitted them a few unscheduled but concise rebuttals to address areas of particular disagreement. In addition to the moderator, three journalists with energy reporting experience in the print and web media, three students from area universities, and an MIT Knight Science Journalism fellow offered questions at the forum.

The campaign representatives laid out contrasting visions about policies regarding climate change. Asked

Photo: Justin Knight

At the presidential energy debate (left to right): questioners Bill Loveless, editorial director of US energy policy for Platts; Steve Hargreaves, senior writer for CNNMoney.com; and Monica Trauzzi, managing editor of E&E Publishing, LLC; moderator Jason Pontin, editor-in-chief and publisher of *Technology Review*; debaters Joe Aldy, assistant professor of public policy at Harvard University's Kennedy School of Government representing President Barack Obama, and Oren Cass, domestic policy director for the Romney for President Campaign representing Governor Mitt Romney; student questioners Lindsay Amico from Northeastern University, Eric Lau from MIT, and Ryan Cook from MIT; and Elana Schor, an MIT Knight Science Journalism fellow.

whether Romney, as president, could forge an agreement with Congress about regulating or taxing carbon emissions, Cass said that the candidate's position was "to focus on innovation, not the pricing of carbon." Cass also repeatedly criticized Obama for not being more direct about his current position on so-called cap-and-trade legislation and a possible carbon tax, among other matters. In response, Aldy noted that, after the House of Representatives passed cap-and-trade legislation in mid-2009, Obama "could not find any Republicans willing to work on a bill in the Senate in 2010" involving cap-and-trade or a Clean Energy Standard, even those who had previously supported such measures.

Another sharp disagreement arose over energy efficiency. Aldy pointed out that the Romney energy plan failed to mention energy efficiency. Cass dismissed efficiency measures as being "most of the time a solution in search of a problem."

The discussion also turned to the environmental effects of energy production. One of the sharpest areas of disagreement pertained to the Environmental Protection Agency's Mercury and Air Toxics Standards, issued in 2011, which regulate emissions from coal-fired power plants.

"The mercury standard makes incredible sense in terms of health," Aldy said, mentioning the EPA's estimate that the law will prevent 11,000 premature deaths per year.

Cass argued that the benefits did not equal the costs of the measure, including the "unemployment of a significant number of workers" at coal plants that could be shuttered on account of the measure. All told, the measure constitutes "one of the most outrageously unjustified regulations the country has ever seen," Cass said.

In his reply, Aldy described that characterization of the regulation as "shocking." He also noted that the alleged war on coal was simply a reflection of low natural gas prices, so that many coal plants are losing out to natural gas in the marketplace.

The two representatives did find common ground on a statement Aldy made early on in the evening's proceedings: "There is a clear choice in this election."

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By Peter Dizikes, MIT News Office

Postscript: As we go to press, President Obama has won reelection. If the MIT energy debate proves to be a good policy indicator, bipartisan support for unconventional gas and oil production will follow, while action on climate change, on energy efficiency programs, and on clean energy technology deployment will be advanced but could face greater challenges as the Congress considers budget options and cuts.

Michael Liebreich: Shift to cleaner energy inevitable

"I'm absolutely confident that solar, wind, geothermal, energy efficiency, smart metering and smart grids will be core technologies in the future energy system, but it's also clear there will be pain along the way," says Michael Liebreich, CEO of Bloomberg New Energy Finance. Liebreich launched New Energy Finance in 2004 to provide analysis and advice on emerging energy technologies and related sectors to utilities, oil, gas, and renewable companies, and governments. He sold it to financial information giant Bloomberg in 2009. In Cambridge, Massachusetts, to speak at the MIT Energy Initiative's 2012 research conference, Liebreich sat down to discuss his take on new energy markets, which currently face major challenges.

Your background includes a degree in thermodynamics from Cambridge University, an MBA from Harvard, experience as an entrepreneur and as a media executive. How did you arrive at new energy?

I got fairly badly burned by the tech boom-bust cycle around the turn of the millennium. Rather than bounce back and try to win Web 2.0, I returned to my roots, which were in energy. I happened to know about databases, modern control technology, and the Internet, as well as nanotech and biotech, because I had been in venture capital for a while. I felt we were going to build the smart grid, not specifically because it helps with electric vehicles or energy efficiency, but because that's just how you'll monitor the condition of the electrical system from generator to user. And it was just obvious that we would eventually switch to cleaner technologies as their costs come down. That's where I came from.

How has the financing landscape for new energy technologies changed since you began monitoring the scene?

It's gone through a number of phases. When I started in 2004, there were only a few idealists wearing suits, some family offices, some visionaries, and an extraordinary level of ignorance about energy technology in the financial community. By 2006, professional venture capitalists, bankers, infrastructure finance people, project financiers, were beginning to pay serious attention. And then in 2007, an enormous amount of money started pouring in. Every asset manager had to have a cleantech fund, a clean energy fund, a climate fund. Valuations went up by factors of four and five. It was irrational, it was ridiculous. And then it was hit hard by the crash.

After that came the "green stimulus" years, 2009–2011. The sector was on a sort of artificial life support, so the amount of investment globally continued to rise. But those years have come to an end, and we've arrived at a cold, hard reality. It's a tough time. What's sustaining the industry now is the fact that its economics are finally coming good. Contrast 2005 to now: The cost of solar photovoltaics is down by a factor of nearly five. We're now in an environment where these technologies are within spitting distance of being competitive without subsidies.

Does it seem paradoxical that as these technologies become increasingly competitive, and global investment in them has increased from $50 billion in 2004 to $280 billion in 2011, we are also seeing new energy firms struggling to secure capital and even going under?

All those asset managers who poured in during 2007–08, now they're all pouring out, saying cleantech and clean energy is over, selling everything they own. The capital markets don't differentiate between technology providers, where there is overcapacity, and technology buyers, getting the advantage of cheap equipment. They are just punishing everyone indiscriminately. Investors are herd animals.

You hear nonsense statistics in political debates on the failure of clean energy companies receiving loan guarantees. Sure, some of the manufacturers supported by the stimulus funds have gone bust. But nobody on the asset build-out side has gone bust. These projects, once they're built, perform well, they become good assets.

Ask Warren Buffet: He sold nearly $1 billion of bonds in his solar projects, and the offer was oversubscribed. We now see more smart investors buying up projects. In Europe, pension funds are buying entire offshore wind farms.

So what kind of setback does the current market represent?

Go back to 1903. There were 500 car companies in the US. By the 1970s, there were essentially three. Some went out of business, some were poorly run, some were acquired and their shareholders did OK. But the car itself was never a stupid idea, and the industry grew. Investors who overreact now should realize that the energy industry is capital intensive, heavily regulated, and it is a difficult space to go from naught to 100 miles per hour quickly. It will go through cycles. This is a tough stage in the cycle.

A lot of things are ugly at the moment, but if we look at them one by one, most will resolve in the next few years, particularly production overcapacity.

There will be some failed technologies. People will shut down uncompetitive lines. With the expiry of the production tax credit, there will be more bankruptcies. But the number of megawatts of wind and solar will increase. Clean energy is not a shrinking industry, it is a consolidating industry. It is not going away.

How does politics affect the situation?

The European crisis has crushed the sector's most important geographic market. How are you going to invest in European projects when there is a question mark over the survival of the Euro? The average commercial bank cannot fund a project in a high-risk country like Spain, Greece, or Portugal, the best countries in Europe for clean energy. But at some point this will resolve: There will be an end to the European pain.

In the US, pre-election uncertainty proved much more corrosive than any of the anti-clean energy statements heard during the presidential campaign. At the end of the day, if clean energy economics are attractive, whoever wins the election will support the industry in some way: perhaps more funding for research, perhaps more for deployment. Or just leave it alone and not create uncertainty.

What's next for new energy?

Technologies continue becoming cost-competitive, whether on- or offshore wind, solar, LEDs, or batteries. The technologies needed to integrate clean energy into the grid also keep becoming cheaper. Engineers are really, really smart and have got the bit between their teeth. They will come up with solutions and drive costs down.

Photo courtesy of Bloomberg New Energy Finance

But in addition to R&D breakthroughs, you need to get technologies out into the market, scale and build a supply chain, and then familiarize financiers with them. You need smart government policies to help break down barriers to market integration—almost more than you need any other sort of support.

What part will clean energy play in the economy?

We're now in a world of perennially high resource and energy prices. Natural gas is currently very cheap in the US because the economy slowed just when shale gas came along. But don't get too used to it—the price will soon be up to where it is no cheaper than onshore wind power. America must create a resource-efficient economy. Renewable energy, together with the smart grid, electric vehicles, and power storage, will be a big part of it, along with gas. If the US lags, it risks ending up buying these technologies from other countries, the way it has ended up dependent on imported oil. Imagine if the revenue from Amazon, Google, and Facebook flowed to Japan and China instead of to the US economy. That's the worry, that US companies won't own the next generation of energy technologies. The next Exxon could be Chinese or Korean.

You privately serve in groups addressing climate change issues, and you executive produced a short advocacy film, *First They Ignore You*. Is it difficult to balance your professional and personal interest in new energy?

At Bloomberg, we provide facts and data for utilities, governments, and corporations, giving them information on risks and options. Grown-up decisionmakers need investment-grade information.

I don't see the film I made as advocacy. Cold, hard analysis shows the cost of clean energy coming down and the cost of conventional energy going up. The inevitable conclusion is that at some point there will be a phase change, and clean energy will be the norm, not the exception. The film was me experimenting with saying the same thing in images, rather than with a PowerPoint presentation.

It is pretty clear as a society we have a choice: We can either invest our money, time, brains, and our brightest students in maintaining the existing energy system, which gets more and more expensive, or we can make the decision to invest in other approaches. I don't feel like an advocate for trying to point this out.

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By Leda Zimmerman, MITEI correspondent

For more about Michael Liebreich, visit liebreich.com. For information about Bloomberg New Energy Finance, go to www.bnef.com. The short film *First They Ignore You* is available at liebreich.com/category/video/.

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 103 seed grant projects across the campus as well as fellowships for more than 250 graduate students in 20 MIT departments and divisions.

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

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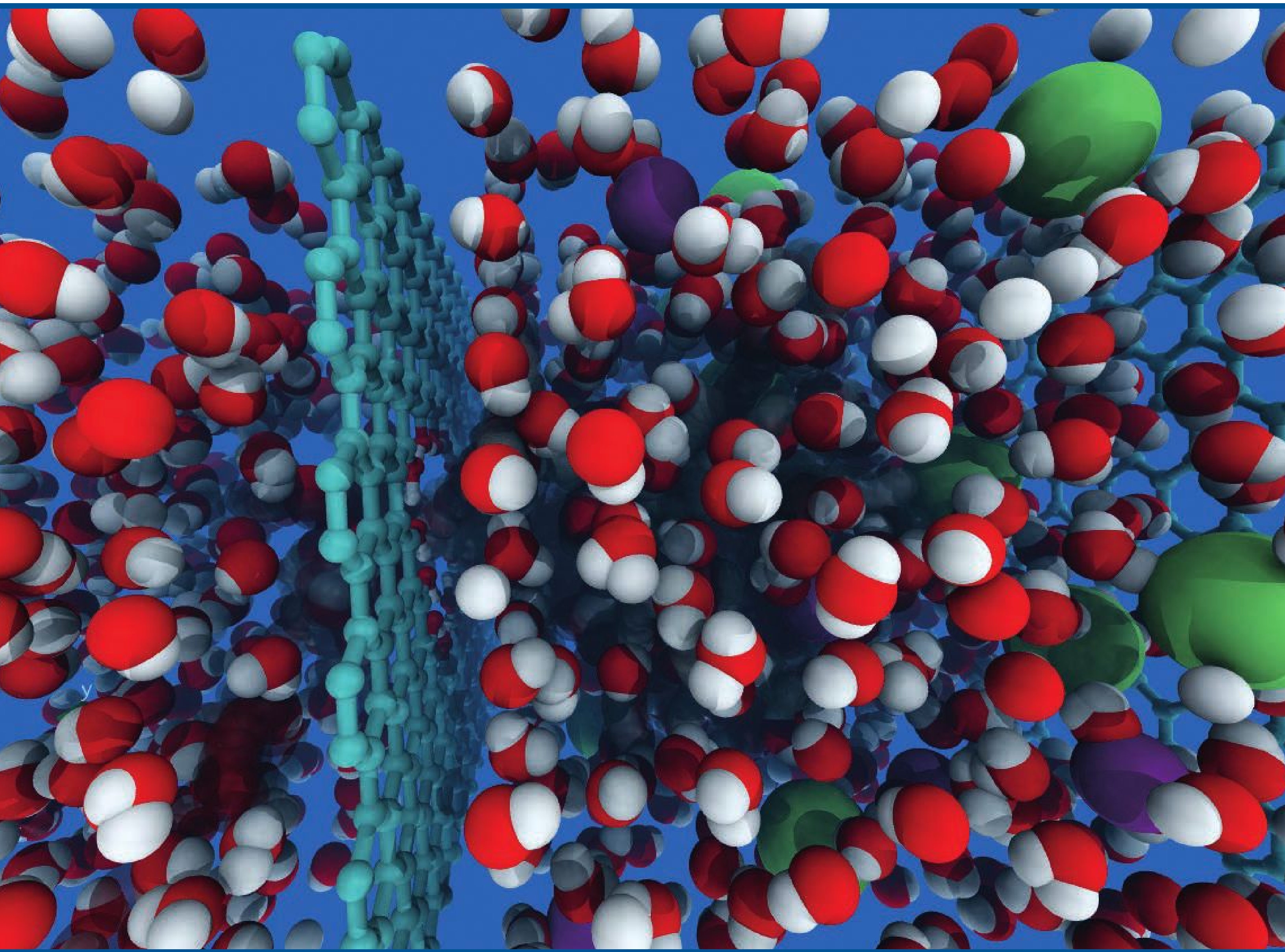

Water desalination: A novel, energy-saving approach

This computer-generated image demonstrates a new MIT approach to desalinating water. The pale blue vertical structure represents a sheet of graphene perforated by holes 1 nanometer in diameter. Approaching from the right is saltwater—a mixture of water molecules (red and white) and sodium and chlorine ions (green and purple). The holes in the graphene are precisely sized so that the water molecules can pass through to the other side, but the sodium and chlorine of the salt are blocked. In computer simulations, the graphene system performed well compared to existing systems, requiring far lower pressures and thus less energy consumption and lower cost. For more details, see page 13.