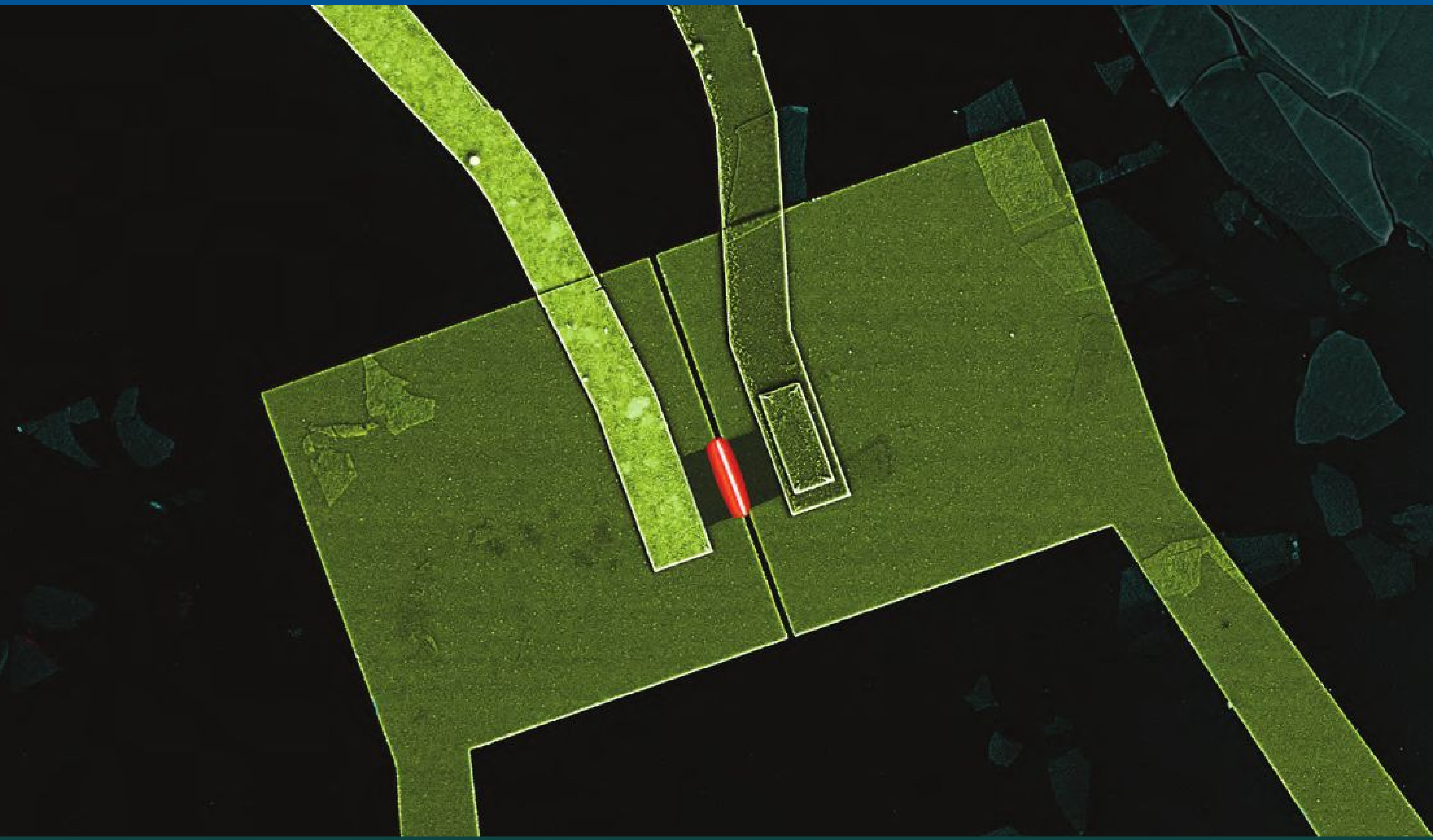
Energy Futures

MIT ENERGY INITIATIVE AUTUMN 2014



New materials, new techniques yield ultrathin LEDs, solar cells

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Energy Futures

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A letter from the director

Dear Friends,

During the past several months, there has been clear evidence of a growing focus on climate change: President Obama has proposed climate regulations; hundreds of thousands of people—including some MIT students—filled the streets of New York during the Climate March in September; and frequent headlines have highlighted the international community's ongoing preparations for the 2015 Paris talks. With the possibility of significant climate action in our future comes the reality that we must prepare our energy system for change—in both the near term and the distant future. But how?

The MIT Energy Initiative (MITEI) already has some answers to that question and is hard at work coming up with more. Since before the launch of MITEI, MIT faculty and research staff have joined hands to produce comprehensive, interdisciplinary analyses focused on our energy future. All of these "Future of…" studies have been predicated on the same basic thesis: Sooner or later, we'll be living in a carbon-constrained world. How do we meet the challenge of increased energy demand in the face of carbon constraints? What technologies can we realistically use? What do we need to do to get those technologies deployed? And what critical policy challenges and opportunities will we encounter?

Our "Future of…" studies attempt to answer those and other questions by assessing various pathways to a low-carbon future. Thus far, our studies have addressed nuclear, coal, geothermal, natural gas, and the electric grid. Early next year, we'll release a "Future of Solar" report. We look forward to unveiling those interesting findings, which include updates on some of the technologies you may have read about in prior issues of this magazine—and will surely read about in future issues as the innovations continue to develop.

Each of these studies is meant to inform policy development, technology choices, and future research. And we believe they have succeeded in doing so. For instance, the US Senate Committee on Energy and Natural Resources held a hearing specifically on the findings of the "Future of Natural Gas" study. And the Obama administration—even before Ernest Moniz left MITEI to become secretary of energy—has largely been implementing our recommendations from that report. Namely, the federal agencies are taking advantage of the natural gas resources we have in the United States and using them to replace coal. (A major factor in the success of this substitution has been the continual innovation in producing shale gas and the resulting competitive price of gas in the marketplace.) At the same time, these agencies continue to invest in developing and deploying renewable energy technologies—a recognition that natural gas must serve as a bridge to a renewable future. This strategy is working. Carbon dioxide emissions have dropped.

While we continue to undertake, evaluate, and update these analyses, we are also embarking on a new project focused on preparing the electricity industry for a dramatically different future. Called "The Utility of the Future," this study is vital because of the many changes impacting the electric power sector. For example, the drive to decarbonize our energy sources is increasing the deployment of energy generation from renewable sources such as solar and wind; breakthroughs in energy storage are creating new opportunities for on-site generation and storage; and changing patterns of electricity use—such as for powering plug-in electric vehicles—are altering demands and broadening what it means to be an electricity consumer and provider.

Photo: Webb Chappell

MITEI's research, education, campus energy, and outreach programs are spearheaded by Professor Robert C. Armstrong, director.

What do these changes mean for the future of the electricity sector? Will a new wave of distributed energy systems take shape? What new business models and regulations will emerge, and how will they transform the sector? With these and many other questions in mind, a team of researchers from across the Institute is working to determine how the electric power sector may evolve and how electricity services will be provided in the coming decades.

Meanwhile, the MIT community is taking the climate challenge and concerns about our future in a warming world very seriously. In fall 2014, the Institute launched an open, campus-wide conversation aimed at seeking broad input from the MIT community on how the United States and the world—and MIT itself—can most effectively address global climate change. Possible activities include a lecture series, panel discussions, and a survey in which all points of view within the MIT community are sought, presented, and discussed. The goal is to gather a list of key suggestions with associated pros and cons and present them in a report to the Conversation Leadership—of which I am a member.

As the community considers how MIT can best contribute, several roles are clear. As always, critical research projects at MITEI are exploring possible solutions for energy challenges all along the spectrum from sourcing to usage to associated environmental impacts. At MITEI, we believe our work is central to building a knowledge base about our future in the context of climate change coupled with significant growth in global energy demand. After all, discovering more efficient, cleaner ways to use the fuels powering much of our world today and developing cleaner energy sources that can power our future are at the heart of what we do.

Equally important is our role in preparing future technology innovators, policy makers, and thought leaders in our classrooms. MITEI's flagship education program, the Energy Studies Minor, graduated its fifth and largest class in June 2014. Thirty-five students joined the ranks of undergraduate Energy Studies Minor alumni, and in so doing elevated the energy minor to third among MIT's largest minor programs. In a survey of 2014 energy minor graduates, more than 95% of students indicated that they felt the minor provided them with an integrated, multidisciplinary perspective on the energy field via a curriculum with an emphasis on real-world problems. The strong reputation of the minor makes us optimistic about its continued growth. In the words of one 2014 graduate: "The fact that MIT has a minor entirely dedicated to the interdisciplinary study of energy was part of the reason I chose MIT, and I was not disappointed."

In the following pages, we present highlights of our work to prepare tomorrow's leaders and to develop the technologies and policies needed for the transition to a low-carbon energy future, while making affordable energy available to more of the world's people. As always, we hope you enjoy this edition of *Energy Futures* and thank you for your continued support and interest.

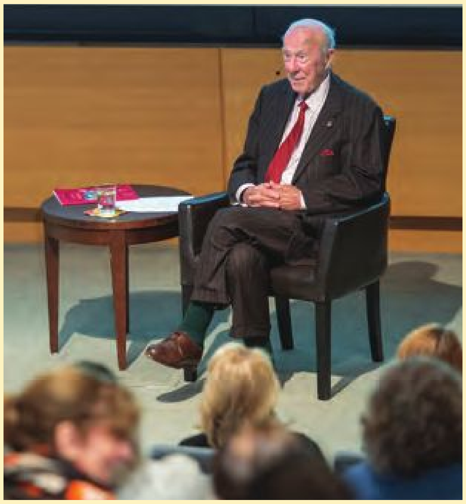
Robert C Armstrong

Professor Robert C. Armstrong
MITEI Director

November 2014

Photos: Justin Knight

During a ceremony on October 31, 2014, MIT President L. Rafael Reif and TJ Wojnar, Jr. (shown above), president of ExxonMobil Research and Engineering Company, signed an agreement under which ExxonMobil became a Founding Member of the MIT Energy Initiative. The company will invest $25 million over the next five years to support faculty and student energy research. The collaboration will focus on improving and expanding new energy sources and finding more efficient ways to produce and use conventional energy resources. See mitsha.re/10VlwtM.



In a talk hosted by the MIT Energy Initiative on September 30, 2014, former Secretary of State George Shultz PhD '49 advocated further policy and research efforts to address climate change and discussed ways to engage people who have not previously supported action on the problem. Watch the talk at mitei.mit.edu/Shultz-video.

Using the sun's heat to make electricity

Novel system will deliver 24/7

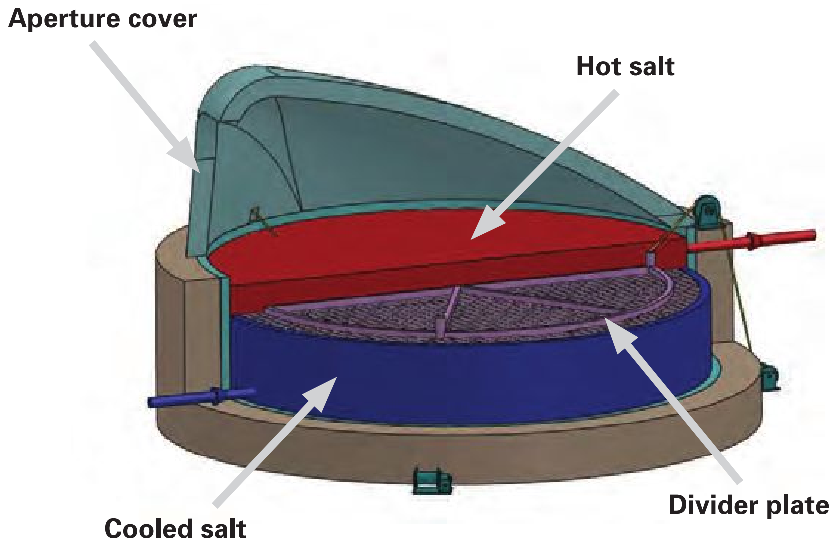
Alexander Slocum of mechanical engineering is working with teams of collaborators from MIT and the Masdar Institute to begin pilot-scale tests of a simple, inexpensive system in which a tankful of molten salt absorbs the heat of the sun, stores it, and delivers it for power generation at any time of the day or night.

This research was supported in part by the MIT Energy Initiative (MITEI) Seed Fund Program and by Lockheed Martin, a Sustaining Member of MITEI. See page 7 for additional sponsors and lists of other participants and publications.

Photo: David Sella, MIT, courtesy of the MIT Industrial Liaison Program

An MIT team has developed a novel system for capturing and storing the sun's heat so it can be used to generate electricity whenever it's needed. The new system is simple, durable, and inexpensive. Mirrors mounted on a hillside reflect sunlight directly into a large tank of molten salt, which absorbs the heat throughout its depth. The system can handle the intense power of the midday sun as well as temperature changes throughout the day and night without structural failure or interruptions in power production. Modeling studies and lab-scale experiments confirm the viability of the concept and the availability of extensive hilly areas suitable for installations. Teams from MIT and the Masdar Institute are now developing a pilot-scale version of the system that will soon be tested at a major experimental facility at Masdar.

CSPonD molten salt receiver/storage system



This diagram shows the large tank of molten salt that is central to the CSPonD system. Sun-tracking mirrors (heliostats) focus sunlight directly through the aperture at the left onto the surface of the salt. Hot salt is withdrawn from the top of the tank and passed through a steam generator for power production. The cooled (but still molten) salt is returned to the bottom of the tank. A movable divider plate at the center of the tank keeps the hot and cold salt separate. As salt is heated on a sunny day, the plate moves down in the tank to make room for more hot salt. When sunlight is unavailable, the plate moves up, making space for the cold salt coming from the steam generator. When the sun returns, the plate moves down, allowing cold salt to pass into the upper region for reheating. At night, the aperture cover is closed to prevent heat from escaping.

Many commercial-scale plants now produce electricity using the heat of the sun—our most abundant renewable energy source. In one popular approach, large arrays of heliostats (sun-tracking mirrors) reflect sunlight to the top of a centrally located tower, where it's focused on tubes carrying heat-absorbing fluid. The heated fluid is then pumped to a steam generator, where it converts water into steam that drives an electricity-generating turbine. But the tower is costly; the piping and pumps are expensive to install and run; and the intensely focused sunlight and the constant cycling between hot and cold challenge most materials. In addition, these "power towers" generally require a separate system to store heat to use when sunlight isn't available.

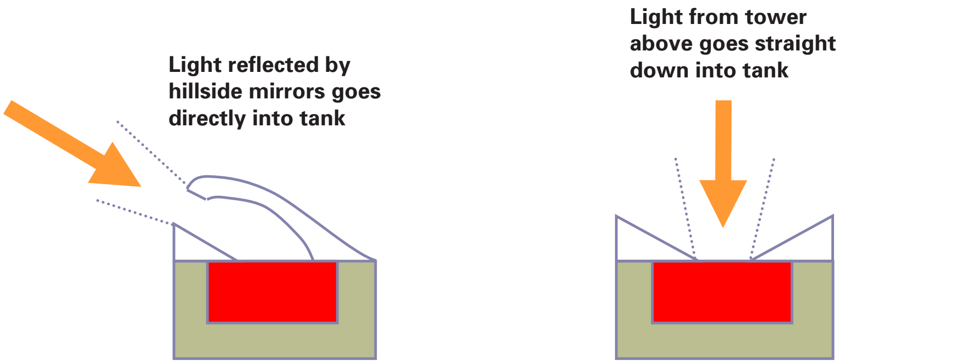
To Alexander Slocum, the Pappalardo Professor of Mechanical Engineering, it seemed that there had to be a better way. Motivated by that belief, he and an interdisciplinary team of colleagues at MIT and the Masdar Institute in Abu Dhabi are now bringing a novel bench-scale system developed by the MIT participants to the next level of testing—at a large-scale experimental facility at Masdar. The system—called CSPonD, for "Concentrated Solar Power on Demand"—both captures and stores the sun's thermal energy, for the most part utilizing known technological elements energetically combined in a new system architecture.

At the core of the CSPonD system is a large tank (illustrated above) that contains molten salt—a substance that can handle extremely high temperatures and has a huge capacity for absorbing heat. An array of heliostats is situated on a hillside, the tank of salt at the foot of the hill. The heliostats focus the sunlight through a small opening in the tank directly onto the surface of the salt (see the left-hand diagram on page 6), where it penetrates the salt and is absorbed throughout its depth. Natural convection disperses the heat through the entire volume of molten salt. During power generation, hot salt is withdrawn from the top and passed through a steam generator; cold, but still molten, salt leaving the steam generator is returned to the bottom of the tank. A movable "divider plate" between the top and bottom regions maintains the upper volume of salt at a constant temperature. At night or when it's cloudy, doors close to reduce heat loss.

This arrangement provides a number of advantages. The sun's energy encounters the working fluid directly—no tubes are needed—and the salt can reach 600°C or even 800°C, which is hot enough for highly efficient power production with either today's most advanced steam systems or future ultra-efficient systems using supercritical carbon dioxide. Because heat is absorbed throughout the molten salt, temperature swings aren't abrupt or extreme, so there's no need to use costly materials that can tolerate all the energy the sun delivers at midday. "You can focus intense sunlight, and you're not going to burn up the receiver because you can't hurt the salt," says Slocum. And the simple salts the team plans to use are well-known in industry. For the past century, companies worldwide have heat-treated steel by submerging it in large open vats of hot salt—similar to the CSPonD tank—and molten salt is regularly used as a heat-transfer fluid in industrial plants.

Finally, the new design can deal with deposits of dust and dirt. When a dust storm brews, the cover on the CSPonD tank can be closed. Any dirt that does land on the molten salt will sink to the bottom where it can be removed later during periodic cleanouts—just the

CSPonD tank configurations



The researchers have designed two versions of the CSPonD tank suited to particular sites. Left: In this version, heliostats mounted on a hillside reflect sunlight into a tank below. The sunlight passes through the aperture in the tank directly onto the salt inside. Right: At Masdar's experimental "beam-down" facility, mirrors on the central tower will reflect sunlight directly down through the aperture into the CSPonD tank.

way molten salt tanks are periodically cleaned in industry. Buildup of dust on the heliostat mirrors is still a concern, as with any solar energy system; but in the short term, the heliostat array can be oversized to ensure that production meets demand—even between cleanings. And unlike conventional systems, CSPonD can handle whatever sunlight is delivered when the mirrors are freshly cleaned and reflecting at full power. In the longer term, better self-cleaning surfaces are apt to be brought to market, especially if demand arises.

Designed for storage

Ensuring that the top layer of hot salt is always available for power production requires keeping the returning cold salt in its place—at the bottom of the tank. Most commercial heat-storage systems prevent mixing by using individual hot and cold tanks connected by hoses and pumps. But the CSPonD system separates hot and cold within the single tank.

A horizontal divider plate (shown in the figure on page 5) is placed in the tank with a gap between its edge and the tank wall. Small actuators (with negligible power consumption) move the loose-fitting, mostly buoyant divider plate up and down to maintain the hot and cold salt volumes required for continuous operation. As sunlight heats the salt, the divider plate is lowered, and cold salt from below moves upward through the gap to be heated. Thus, at the end of a sunny day, the divider plate has moved down, and the hot salt region is fully charged. When sunlight is no longer available and heat is being extracted to produce electricity, the divider plate is slowly raised to allow the cold zone to refill while hot salt is supplied to the steam generator. When sunshine returns, the plate once again descends, allowing cold salt to rise for reheating. Careful control of the plate's position ensures that the hot salt remains at a constant temperature, in effect balancing the solar energy input with the energy that's extracted and stored.

Modeling results, experimental evidence

As an initial test of their concept, the researchers simulated the performance of a CSPonD system that included a tank that's 5 meters deep, 25 meters in diameter, and filled with 4,500 tons (2,500 cubic meters) of molten salt at 600°C. The analysis concluded that the specified system could power a 4 megawatt-electric (MWe) steam turbine 24/7 (based on 7 hours of sunshine and 17 hours of storage)—enough electricity to supply about 2,000 homes. Modest oversizing of the heliostat field to accumulate more solar energy would enable the system to operate for an additional 24 hours (one cloudy day).

An economic analysis using a model from the National Renewable Energy Laboratory concluded that the levelized cost of electricity from the CSPonD system would be between $0.07 and $0.33 per kilowatt-hour. While the higher estimate is currently prohibitively high, the lower estimate would be competitive with the cost of electricity from conventional power sources today. Research now under way will help to better elucidate the actual costs.

The practical feasibility of CSPonD does, of course, hinge on the availability of appropriate hills for heliostat installations. How large would the hills need to be, and would suitable sites be hard to locate? To find out, researchers led by Alexander Mitsos, former assistant professor of mechanical engineering at MIT and now professor of chemical engineering at RWTH Aachen University in Germany, developed a novel algorithm that identifies potential sites using data on topography, solar insolation, and other conditions plus a model of CSPonD system operation.

They then performed two case studies focusing on government military bases at White Sands, New Mexico, and China Lake, California. The analyses showed that 15% of the total 10,000 square kilometers of land at the two bases would be appropriate for CSPonD installations. With 30% of that available land covered by heliostats, installations at each site could continuously generate 20 gigawatts of power. "So those two bases together could provide 40 gigawatts of power, which is somewhere around 4% of the nation's electric need," says Slocum. "And that's just using a little piece of all the hillsides that they have." Slocum adds: "The Army Corps of Engineers is responsible for our nation's seacoasts and waterways to keep commerce flowing and protect our way of life at home, and it makes sense that vast government lands also be used to protect our energy security and combat climate change."

While installing heliostats on hillsides isn't standard procedure, Slocum isn't concerned. "We may need to design and create custom equipment to drive up the sides of hills, popping in heliostats," he says. "But companies have been designing amazing forestry machines that go up much steeper slopes for decades. It's not an issue for the scale of systems that will be needed."

Initial bench-scale experiments indicate that the CSPonD concept is technically sound. For example, in one set of tests, the researchers showed that concentrated sunlight will indeed penetrate and be absorbed by molten salt through a depth of 4 to 5 meters—enough for the CSPonD system to be unperturbed by changes in solar insolation due to passing clouds. In other tests, they designed and built a small-scale CSPonD tank equipped with a movable divider plate and then shone light from a high-flux solar simulator onto the molten salt inside. They found that natural convection in the upper region promotes mixing, keeping the top surface from overheating while maximizing thermal storage in a given volume of salt. And the submerged divider plate successfully separates the hot and cold salt volumes as needed for continuous operation.

Next steps

To test the CSPonD concept at larger scale, the MIT researchers have started work with colleagues at the Masdar Institute who operate a major experimental "beam-down facility" that includes 33 heliostats and a 66-foot tower with mirrors that reflect sunlight down into a central receiver. In upcoming work, the researchers will replace the receiver with a small CSPonD system. The heliostats will focus sunlight directly down into the tank (right-hand diagram on page 6). The initial small-scale system will store enough thermal energy for 25 kilowatt-hours of power generation. "We're going to use it to test our design theories and practical implementation issues," says Slocum. "Then in the next step we can scale up to a much larger machine."

Slocum stresses that he doesn't dismiss other solar technologies and feels diversity is the key to robustness and continual innovation. Indeed, he praises photovoltaic and solar thermal systems "of various flavors" and notes in particular that everyone should at least have a rooftop solar hot water system. But CSPonD may be the best choice for certain locations and thus is a valuable addition to what Slocum calls a "well-balanced diet of options for feeding humanity's ever-growing energy appetite."

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By Nancy W. Stauffer, MITEI

This research was supported in part by the Cyprus Research and Educational Foundation, the MIT Energy Initiative (MITEI) Seed Fund Program, and Lockheed Martin, a Sustaining Member of MITEI. Ongoing pilot-scale work is being funded in part by a cooperative agreement between the Masdar Institute of Science and Technology and MIT. Graduate student fellowships were provided by the S.D. Bechtel, Jr. Foundation, the Chesonis Family Foundation, and the Bill and Melinda Gates Foundation.

Other MIT participants in the CSPonD project are Professor Emilio Baglietto of nuclear science and engineering (NSE), Dr. Daniel S. Codd of mechanical engineering (ME), Dr. Charles W. Forsberg and Dr. Thomas J. McKrell of NSE, and Professor David L. Trumper of ME. Participants from the Masdar Institute include Professors Peter Armstrong and Nicolas Calvet, both of mechanical and materials engineering.

Further information can be found in the following:

D.S. Codd. *Concentrated Solar Power on Demand*. PhD thesis, MIT Department of Mechanical Engineering, June 2011.

D.S. Codd, A. Carlson, J. Rees, and A.H. Slocum. "A low cost high flux solar simulator." *Solar Energy*, vol. 84, pp. 2202–2212, 2010.

A.H. Slocum, D.S. Codd, J. Buongiorno, C. Forsberg, T. McKrell, J.C. Nave, C.N. Papanicolas, A. Ghobeity, C.J. Noone, S. Passerini, F. Rojas, and A. Mitsos. "Concentrated solar power on demand." *Solar Energy*, vol. 85, pp. 1519–1529, 2011.

Recovering natural gas at oil wells

Small-scale system converts it into liquids

Left to right: Angela J. Acocella of the Technology and Policy Program, Daniel Cohn of the MIT Energy Initiative, Leslie Bromberg of the Plasma Science and Fusion Center, and Emmanuel Lim of mechanical engineering are working with others to explore the use of a specially adapted marine engine to convert natural gas into easily transportable liquid fuels—a small, inexpensive setup ideal for use in remote areas and at oil drilling sites.

This research was supported in part by the US Department of Energy through the Advanced Research Projects Agency–Energy and by the Tata Center for Technology and Design at MIT.
See page 11 for more information about funding and publications.

Photo: Stuart Darsch

An MIT team is developing a small-scale system that converts natural gas into easily transported liquid fuels—a design especially suited for use at oil drilling sites where escaping natural gas is now burned or vented. To keep the size and cost down, the researchers are performing a critical step of the conversion process inside a conventional, mass-produced engine. And to minimize cost, complexity, and maintenance needs—important for installations in remote areas—they are focusing on producing methanol, a simple chemical with rapidly expanding uses. Extensive modeling studies and engine experiments confirm the technical viability of the process and show that—in some situations—the cost of producing methanol could be competitive with costs at large conventional methanol plants. A pilot-scale demonstration of the system will begin soon.

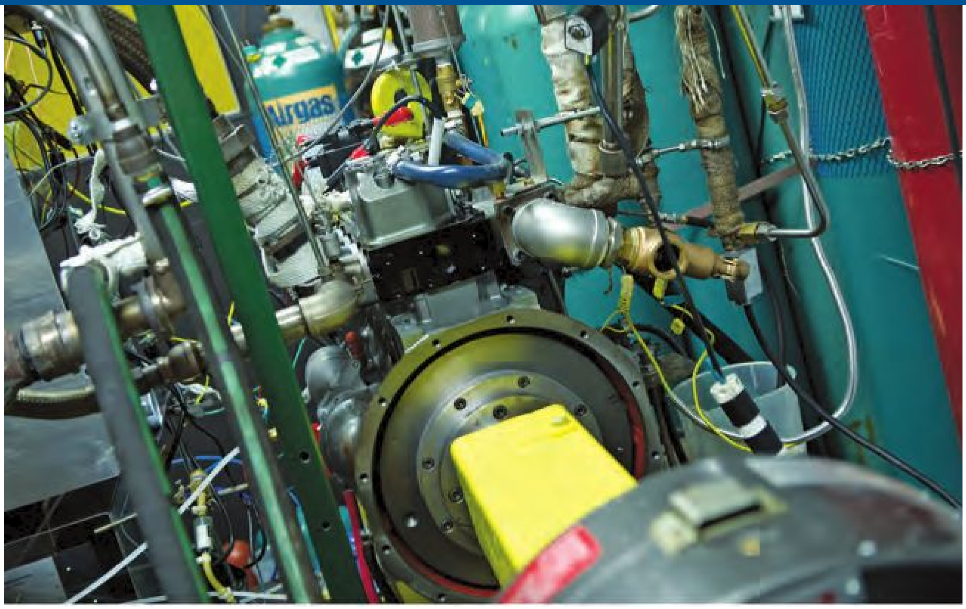


Photo: Stuart Darsch

Key to the small-scale gas-to-liquids conversion system is a mass-produced engine that can convert natural gas into synthesis gas suitable for a methanol-producing reactor. Experiments in the Sloan Automotive Laboratory are confirming that the specially adapted marine engine pictured above can operate under the extreme conditions required to accomplish that conversion.

When natural gas emerges from oil wells, it's often burned off ("flared") because there's no economical way to transport it to market. Worldwide, the total amount of flared natural gas is estimated to equal a quarter of total US consumption. In nighttime satellite images of Nigeria, Russia, and North Dakota, burning gas looks like bright city lights where they don't belong. Flaring puts greenhouse gas into the atmosphere and wastes valuable resources—a special concern when people nearby may be using coal, biomass, or dung for cooking and home heating, often with serious indoor air pollution and health consequences.

Companies now operate plants that convert natural gas into liquid fuels that can be moved by truck, train, or ship. These plants are technologically sophisticated, capital-intensive, high-maintenance, and—to keep product costs down—large in size, especially when producing certain types of diesel. As a result, they're not suited for deployment at remote sites where natural gas yields are small.

To address that problem, Dr. Leslie Bromberg, principal research engineer at the Plasma Science and Fusion Center, Dr. Daniel Cohn, research scientist at the MIT Energy Initiative, and a multidisciplinary team of MIT collaborators are developing a small-scale, low-cost, low-maintenance "gas-to-liquids" conversion system. While economies of scale favor large plants, they're bringing down per-unit cost using a different approach. "Instead of making plants large, we want to save in production costs by using things that we already make lots of," says Bromberg, the project leader.

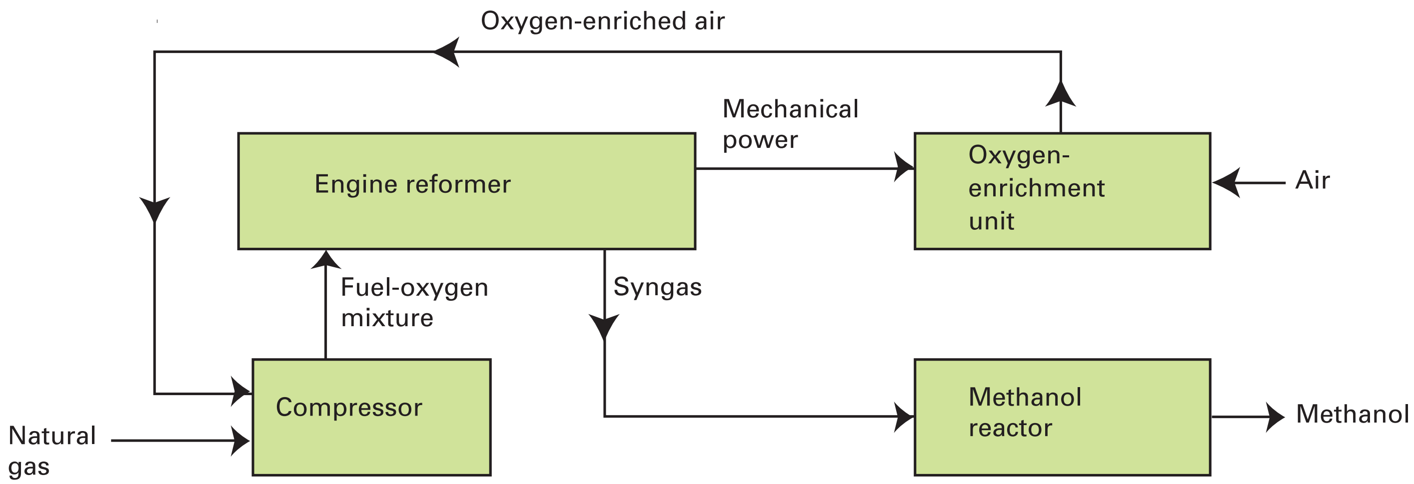
Their target is the reformer, a device that converts natural gas or biogas from organic sources into a mixture of carbon monoxide and hydrogen called synthesis gas, or "syngas"—the feedstock for the chemical reactor that produces the desired liquid product. Their plan: to replace the usual expensive reformers with a small, well-developed technology that's mass-produced—namely, the ubiquitous engine—and utilize "engine reformers" to reduce the costs of other components of the overall system.

Bromberg and Cohn have worked with engines for decades, trying out creative approaches to make them more efficient and cleaner running. To Bromberg, the environment inside the cylinder of an operating engine seemed ideal for producing syngas for a small-scale gas-to-liquids plant: The transient high temperatures and pressures would stimulate the necessary chemical reactions without expensive catalysts. An engine-based reformer would be compact; it could easily be integrated with a small-scale chemical reactor; and it would be inexpensive. "We make hundreds of millions of engines each year," says Bromberg. "So the question is: Can we actualize an engine-based technology for doing the chemical processes needed to turn gas to liquids?"

Initially, the research focused on making diesel, a valuable fuel with many current uses. However, the chemical reactor that turns syngas into diesel involves waxy substances and requires constant monitoring—a nonstarter for a remote installation. So the researchers turned their attention to methanol, the simplest fuel made from methane (the main constituent in natural gas). "Diesel is a mixture of big, complex molecules, so you need a complicated system to deal with all the chemicals involved," says Cohn. "When you make methanol, you just make methanol. The reactor is simpler, more efficient, and requires less monitoring and maintenance."

Demand for methanol is expected to grow rapidly in the next decade. Today, it's widely used as a feedstock for producing other chemicals. In China, it's made from coal and used in vehicles in a low-concentration blend with gasoline. It's slowly gaining attention as an alternative to gasoline, and it can easily be converted into dimethyl ether (DME), which can serve (much like propane) as a clean fuel for cooking and home heating and potentially for operating the trucks and tractors that are so common in parts of the developing world.

Schematic diagram of the novel engine-reformer-based system for methanol production



In this novel system, natural gas is cleaned and fed into a small compressor, where it mixes with oxygen-enriched air. The fuel-oxygen mixture then enters the engine reformer, where high pressures and temperatures inside the engine cylinders drive chemical reactions that form syngas, a mixture of hydrogen and carbon monoxide. After its temperature and composition are adjusted, the syngas is fed into a reactor where it's catalytically converted into methanol, the desired liquid product. Excess mechanical energy from the engine reformer drives the oxygen-enrichment unit and under some conditions a small syngas compressor. The syngas from the engine reformer is relatively close to the pressure required by the methanol reactor, so there's no need for a large, high-cost compressor.

System study

To determine the technical and economic viability of their novel idea, Angela J. Acocella, a graduate student in the Technology and Policy Program, and the MIT team performed an analysis of the engine reformer in the context of the entire methanol-production system. The figure and caption above describe the components and flows in their proposed system.

As a basis for their system study, the researchers assumed an engine reformer that would produce enough syngas to make 30 metric tons per day of methanol (the energy equivalent of 100 barrels of oil per day). That level of operation would require roughly 1.5 million standard cubic feet of natural gas per day. About 40% of all oil wells generate "associated" natural gas at or above that level, so it seemed an appropriate starting point for analysis.

A central question is whether such an engine could produce syngas suitable for the methanol reactor. In standard engine operation, the air and fuel mixture is adjusted so that all the fuel will burn up, producing carbon dioxide and water. But since syngas is the intended product here, the engine must operate with more fuel than air so that combustion is incomplete. The challenge is that running an engine sufficiently "fuel-rich" could cause it to misfire—or it could not fire at all.

Using their models to simulate engine operation, the team—with support from Professor William H. Green of chemical engineering—determined that a conventional spark-ignition (SI) engine could be run with an exceptional amount of excess fuel. The keys to their success: preheating the incoming mixture and raising the fraction of oxygen in the air. According to the analysis, with those changes plus some adjustments in valve and spark timing, the SI engine will run sufficiently fuel rich to obviate the need for a large compressor to pressurize the syngas upstream of the methanol reactor. In addition, the ratio between hydrogen and carbon in the syngas will be close to optimal.

As an added benefit, the mechanical energy produced in the cylinder will be sufficient to compress the syngas as well as to supply electricity for auxiliary components that, for example, enrich the oxygen. The methanol reactor also gives off heat, which can be used for tasks such as preheating the engine intake. "According to the analysis, the electricity and heat coming out more or less balance what is needed for the rest of the system," says Bromberg. "So these units could be self-contained, not requiring utility connections."

Economics and markets

As expected, component costs and operating and maintenance expenses (per unit methanol produced) are higher with small-scale systems than with large, conventional ones. But the small MIT system has an important economic advantage. While large units are specifically designed for a particular site (thus, one-of-a-kind), the small system could be mass manufactured at a central location and then deployed to the site, bringing down construction costs. (According to Bromberg, the units should be small enough to fit in two or three skids.) And, while large plants need constant attention by on-site maintenance teams, the small system could be monitored remotely—again, a considerable savings.

Overall, assuming the present price of natural gas, the projected cost of producing a gallon of methanol using the MIT concept is about $1.70, which is around twice the cost at a large plant. However, at sites where gas is flared, the small system could be supplied with natural gas at substantially reduced or no cost, especially when regulations are put in place to prevent flaring. Assuming free gas, the overall cost of producing methanol using the engine reformer technology drops to about $1.00/gallon, which is lower than the present world market price and lower than the cost of producing diesel fuel (on an energy basis). An additional economic benefit comes from reduced fuel transportation costs when the methanol is used near where it's produced.

Potential markets for methanol and DME—which Cohn calls "emerging" fuels—are another important consideration. "We have a new way of making methanol and DME in small units that's going to get rid of the adverse environmental impact of flaring while making valuable products," he says. "Now, how can those products best be used? For example, methanol could be used as a lower-cost, less-polluting alternative to diesel fuel for decentralized electric power generation and for ship propulsion as well as for powering buses and trucks."

Acocella is now examining potential uses and local production costs for methanol and DME, particularly in developing countries. A major focus is Africa. For example, in Nigeria, large quantities of natural gas are flared and the need for clean fuels is critical. Other collaborators include groups in India and in Australia, where there is significant interest in converting natural gas to DME for use in slightly modified diesel engines.

Engine and system experiments

Encouraged by their early modeling results, the researchers have been performing parallel engine experiments in MIT's Sloan Automotive Laboratory. Working with Wai K. Cheng, professor of mechanical engineering and head of the Sloan Auto Lab, Kevin Cedrone SM '10, PhD '13, a postdoctoral research associate in the Plasma Science and Fusion Center, adapted a power-generating marine engine for the experiments.

In ongoing tests, Cedrone, Emmanuel Lim, a graduate student in mechanical engineering and a fellow in the Tata Center for Technology and Design, and undergraduates Thomas Needham '17 and Raul Barraza '15 of mechanical engineering carefully regulate the injected mixture of methane (the fuel) and air and examine the composition of the exhaust. As predicted in the analysis, they've found that by raising the temperature and oxygen content of the incoming mixture, they can run the engine with substantial amounts of excess fuel. And when they recycle some hydrogen from the exhaust back into the engine, the composition of the product is close to their target.

The team will soon pressurize the incoming fuel-air mixture to investigate performance when producing high-pressure exhaust (needed to avoid the expensive compressors). But even without that adjustment, they're getting close to the product they need—with high productivity and without catalysts.

Meanwhile, Bromberg and his colleagues are ready to take the next step: developing a pilot-scale version of their novel system. The work will be funded by the Advanced Research Projects Agency–Energy (ARPA–E) and will involve investigators from MIT and Columbia University, under the leadership of Research Triangle Institute, a major nonprofit research organization with extensive experience in synthetic fuels production. "Our goal is to have an integrated unit operating at scale within the next two years," says Bromberg. "The thermal integration will not be perfect, but all the components are going to be there to demonstrate that indeed the concept works."

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By Nancy W. Stauffer, MITEI

This research was supported in part by ARPA–E and by the Tata Center for Technology and Design at MIT. Summer support for the two undergraduate participants was provided by the Tata Center through MIT's Undergraduate Research Opportunities Program. Further information can be found in:

A. Acocella, E. Lim, K. Cedrone, L. Bromberg, S. Seethamraju, and D. Cohn. "System and market analysis of methanol production using compact engine reformers." *Proceedings*, ASME 2014 8th International Conference on Energy Sustainability and 12th Fuel Cell Science, Engineering, and Technology Conference. June 30–July 2, 2014.

Assessing the climate impacts of energy technologies

A new accounting of methane's role

Jessika E. Trancik (right) and Morgan R. Edwards of engineering systems have formulated new methods of calculating the future climate impacts of energy technologies that more accurately account for the role played by methane—an approach that reduces the predicted long-term benefits of certain methane-emitting technologies.

This research was funded by the US Department of Transportation through the New England University Transportation Center at MIT.
See page 16 for a list of publications.

Photo: Justin Knight

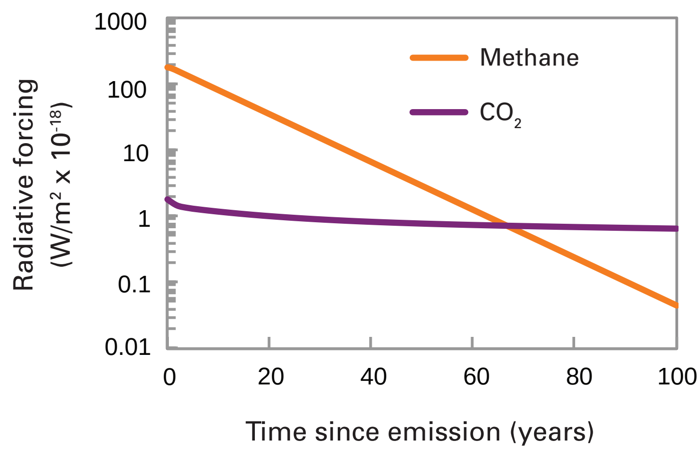
A new MIT analysis shows that the standard method used to determine the climate impacts of promising energy technologies may overestimate the benefits to be gained over the next several decades. The problem? The conventional approach doesn't account for the timing of emissions and as a result doesn't calculate the full impact of methane emitted by many energy technologies. Using novel "dynamic" metrics in a sample analysis, the MIT researchers found that the current advantage of generating electricity with natural gas rather than coal shrinks in half within three decades, and using compressed natural gas in place of gasoline as a transportation fuel is worse for the climate by 2030. The good news is that investments in reducing methane leaks and tracking and regulating methane emissions can significantly improve those outcomes.

Concern about future climate change is motivating major changes in today's energy landscape. For example, electric power producers are switching from coal to natural gas in part to reduce carbon dioxide (CO_2) emissions. But recovering and transporting natural gas gives off methane, which is a relatively short-lived but highly potent greenhouse gas (GHG). Meanwhile, researchers are working to develop new technologies that promise to be more climate-friendly than those we use now. How can we be sure that such investments will provide the predicted climate benefits in the future?

Determining the climate impacts of technology options over the long term is critical, says Jessika E. Trancik, the Atlantic Richfield Career Development Assistant Professor in Energy Studies. "Some components of the energy infrastructure that we're building now will be around for 30 or 40 years, and our research funding decisions today are committing us to…certain technologies that will come online 10 or 20 years in the future," says Trancik. "So we need to assess the impacts of those technologies not just today but also 10, 20, 30 years into the future."

Performing such assessments is tricky. Different technologies emit different GHGs, and those GHGs have varying abilities to trap heat in Earth's atmosphere—a phenomenon called radiative forcing. They also remain in the atmosphere for different lengths of time. For example, a gram of methane (the main component in natural gas) causes about 100 times more radiative forcing than a gram of CO_2 does. But while CO_2 hangs around in the atmosphere for centuries, methane disappears in a few decades.

Radiative forcing of methane and CO_2 over time



These curves show the radiative forcing of single pulses of CO_2 and methane over 100 years. Initially, the methane has 102 times the radiative forcing (per gram) of CO_2. But it decays more quickly. By year 67, the radiative forcing of the two gases is about equal. A climate impact assessment must therefore consider each GHG emitted by a technology and take into account its radiative forcing and rate of decay in the atmosphere.

Global Warming Potential

To determine our best technology options, analysts and modelers generally convert quantities of all GHGs into "CO_2 equivalents"—that is, the number of units of CO_2 that will produce the same climate impact as one unit of the GHG. They can then compare the long-term emissions impacts of technologies (per unit energy produced) on a common scale.

Since the 1990s, analysts have performed such conversions using a metric called the global warming potential, or GWP. Its value is equal to the ratio between the total amount of heat trapped by a given GHG and by the same mass of CO_2 over a set period of time—typically 100 years. Based on such an analysis, the radiative forcing of a gram of methane is 25 times greater than that of a gram of CO_2 over the 100-year time span. The analyst can thus convert each gram of methane in the atmosphere into 25 grams of CO_2, producing a common basis for comparing technologies.

But Trancik argues that we don't have 100 years. "The problem is that now we're actually closer to reaching and potentially exceeding the commonly cited climate targets," she says. "If our time frame for stabilizing radiative forcing is 20 or 30 years, we shouldn't use the 100-year GWP for our analysis."

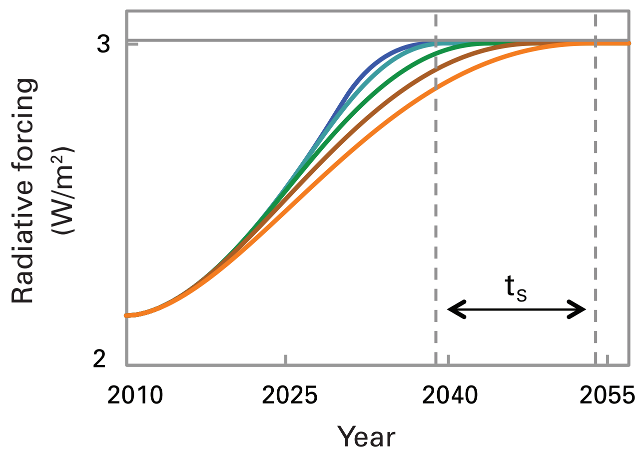
The figure above illustrates her concern. Assume that 1 gram of CO_2 and 1 gram of methane enter the atmosphere at time zero. The curves show the radiative forcing of those initial pulses in each year between the start time and an end time 100 years later. Today, the radiative forcing of the methane pulse is more than 100 times that of the CO_2 pulse. As time passes, the radiative forcing of the initial CO_2 pulse changes very little. But the radiative forcing of the methane pulse decreases rapidly because less and less of it remains in the atmosphere. By year 67, the remaining CO_2 and methane have about the same impact, and thereafter the relative role of the methane continues to decline. So if the point in time at which we intend to stabilize radiative forcing is, say, 50 years in the future, using the GWP conversion factor based on the cumulative impact over 100 years is going to give the wrong answer.

The new, dynamic metrics

To solve that problem, Trancik and Morgan R. Edwards, a graduate student in engineering systems, devised two new dynamic metrics. With those metrics, the conversion factor changes year by year, and—most importantly—each factor depends on how long before the stabilization year the pulse is emitted. Here's why: If a methane pulse enters the atmosphere early in the selected time period, it will have decayed considerably by the end year. But if that pulse is emitted in the stabilization year, it will have no time to decay. The conversion factor for that pulse should be 100, that is, each gram of methane should become 100 grams of CO_2.

Their first metric—the cumulative climate impact (CCI)—takes into account the cumulative contribution over time of a pulse of emission from its release to the stabilization year. The GWP also accounts for a cumulative contribution but—as stated earlier—the GWP conversion factor is constant, regardless of when the pulse of emission occurs. In contrast, the CCI conversion factor changes over time as the stabilization year nears.

Radiative forcing trajectories to stabilize at 3 W/m² under feasible emissions scenarios



Using the new dynamic metrics requires defining an intended stabilization level but not the exact emissions scenario planned for achieving it. Only certain emissions scenarios are practical for achieving a given target, and taken together, they define a finite time frame for performing an analysis with the new metrics. To demonstrate, the researchers selected a stabilization target of 3 W/m² and then examined five possible radiative forcing trajectories reflecting emissions scenarios with a range of start times and emissions growth rates. As the curves above show, the time frame for reaching the stabilization target using any of the scenarios spans just 15 years—from roughly 2040 to 2055.

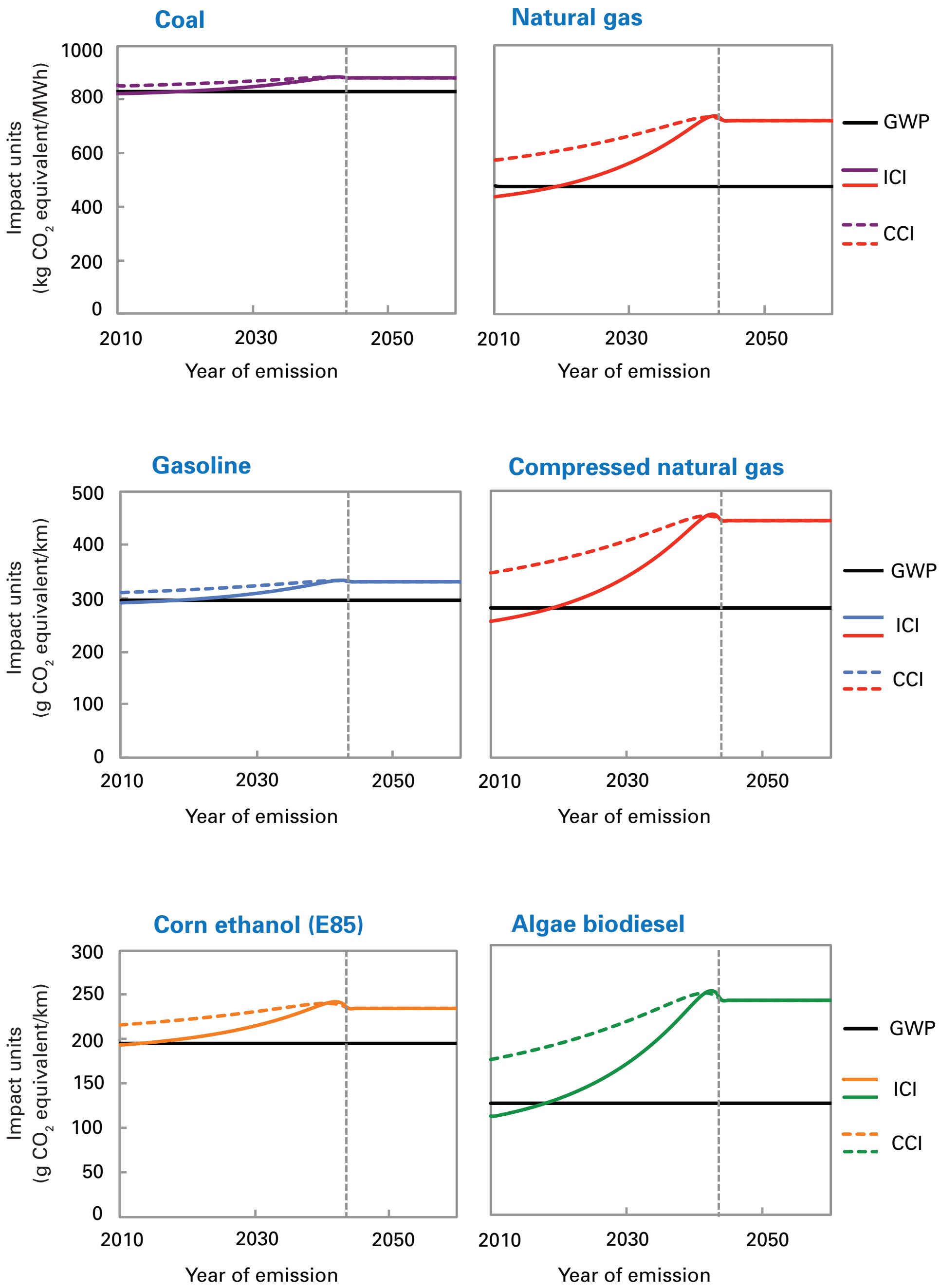
As an example, assume a 30-year time horizon. Take a pulse of methane in year 1 and determine its cumulative radiative forcing over the 30 years (taking into account its decay over time). Follow the same procedure for a pulse of CO_2 in year 1. Divide the two results to get the conversion factor for year 1. Perform the same calculation year by year to get ratios for converting methane to CO_2 equivalents in each year for the 30-year time horizon.

The second metric—the instantaneous climate impact (ICI)—focuses on the radiative forcing in the stabilization year. It is less conservative than the CCI, putting less emphasis than the CCI on emissions in years leading up to stabilization. (The choice of metric should be guided by the policy context.) To determine this metric, take each pulse of CO_2 and of methane in a given year and track their decay in each subsequent year. At the end year, take the ratio between the remaining CO_2 and the remaining methane. That ratio is the conversion factor for the year the pulses were emitted.

Sample technology assessment

As a demonstration, Trancik and Edwards performed a sample technology assessment. To start out, they selected a single input: the radiative forcing stabilization target, that is, the amount of additional heating that occurs at the time when new emissions are exactly balanced by their natural loss. (Says Trancik, "For a metric to be usable, it has to require only limited information about the future—which is inherently uncertain—but still perform well.") For their assessment, they chose a stabilization target of 3 watts per square meter (W/m²), which in equilibrium is associated with a 2°C temperature change—a frequently cited climate policy goal.

Comparisons of technologies using the three metrics



These figures present results of analyzing the climate impacts of six technologies, considering both CO_2 and methane emissions and focusing on a CO_2-emissions scenario designed to bring climate stabilization at 3 W/m² in about 40 years. With the constant GWP conversion factor, the relative impacts of the pairs of technologies do not change over time. With the new dynamic metrics—the CCI and ICI—the conversion factor changes from year to year. In those analyses, by the end of 42 years, the climate advantages of the technologies involving natural gas and algae biodiesel have declined due to their high emissions of methane.

The next step was to translate that target into a time frame for the analysis. They devised five possible emissions scenarios for reaching that target, assuming only CO_2 emissions. At one extreme is a scenario that imposes gradual cuts in emissions starting right away; at the other extreme is one that starts much later and then imposes far more severe cuts in each year. Based on the five emissions scenarios, they determined that the time frame for achieving the stabilization target of 3 W/m² is constrained to a 15-year range—from about 2040 to 2055 (see the figure on page 14). As a result, they can perform their technology evaluation using only the stabilization target and this limited range of years. There's no need to define the exact stabilization scenario to be followed.

Next, they used the CCI and ICI as well as the GWP to assess the climate impacts of several prominent energy technologies. The figures at the left show results from an analysis based on the middle emissions scenario, which brings stabilization at 3 W/m² in about 2042.

Coal-fired and natural gas-fired electricity. The top two figures present results from analyses of using coal and natural gas to generate electricity. (Methane leakage from the natural gas is assumed to be constant in the figures shown here, but this assumption could be adjusted and the same method applied.) The GWP analysis shows that the climate impact of natural gas electricity is about half that of coal electricity over the whole time period. In contrast, the CCI and ICI analyses show that the advantage of natural gas decreases over time. While the climate impact of natural gas is initially about 50% that of using coal, within three decades it grows to 75%. Many experts advocate natural gas as a "bridging fuel" to a low-carbon future, but the new analyses demonstrate the importance of getting to the other end of the bridge relatively soon.

Gasoline and compressed natural gas (CNG). The middle two figures show results for gasoline and CNG used for transportation. Here, the GWP shows that CNG offers some climate benefit over gasoline. The CCI and ICI analyses show that CNG used today ranges from slightly advantageous to slightly disadvantageous, whereas CNG used in 2040 has a significantly higher impact on the climate than gasoline does.

Corn ethanol and algae biodiesel for transportation. The bottom figures show results for corn E85 (a blend of 85% corn ethanol and 15% gasoline) and for algae biodiesel. The latter case is for a production process that involves a biodigester, which emits some methane. The GWP-based analysis shows that corn ethanol provides a significant climate advantage over algae biodiesel. But in the CCI and ICI analyses, the climate impact of algae biodiesel overtakes that of corn ethanol within two to three decades—a change attributable to the methane leakage from the biodigester.

Those sample results demonstrate that the ability of any technology to avert or slow climate change depends in part on methane emissions—not only the quantity but also the timing of their release. "So our findings point to the importance of mitigating methane emissions in addition to CO_2 emissions," Trancik says. "And there are a lot of opportunities for doing that, including reducing methane emissions from biodigesters and cutting methane leaks along the natural gas supply chain." Making those changes will require money and time, so quantifying the potential gains from such investments is critical.

The results also emphasize the importance of more stringent tracking and regulation of methane emissions. Once again, the new metrics can help. The metrics are based on physical emissions and their radiative forcing characteristics. As a result, they can be used to calculate values for "exchanges" on emissions trading markets, and they can help guide the design of emissions-control regulations that will more successfully meet their climate targets than will regulations based on GWP calculations. Exploring the various roles that the new metrics can play in technology- and emissions-related policy making is the subject of ongoing research by Trancik and her colleagues.

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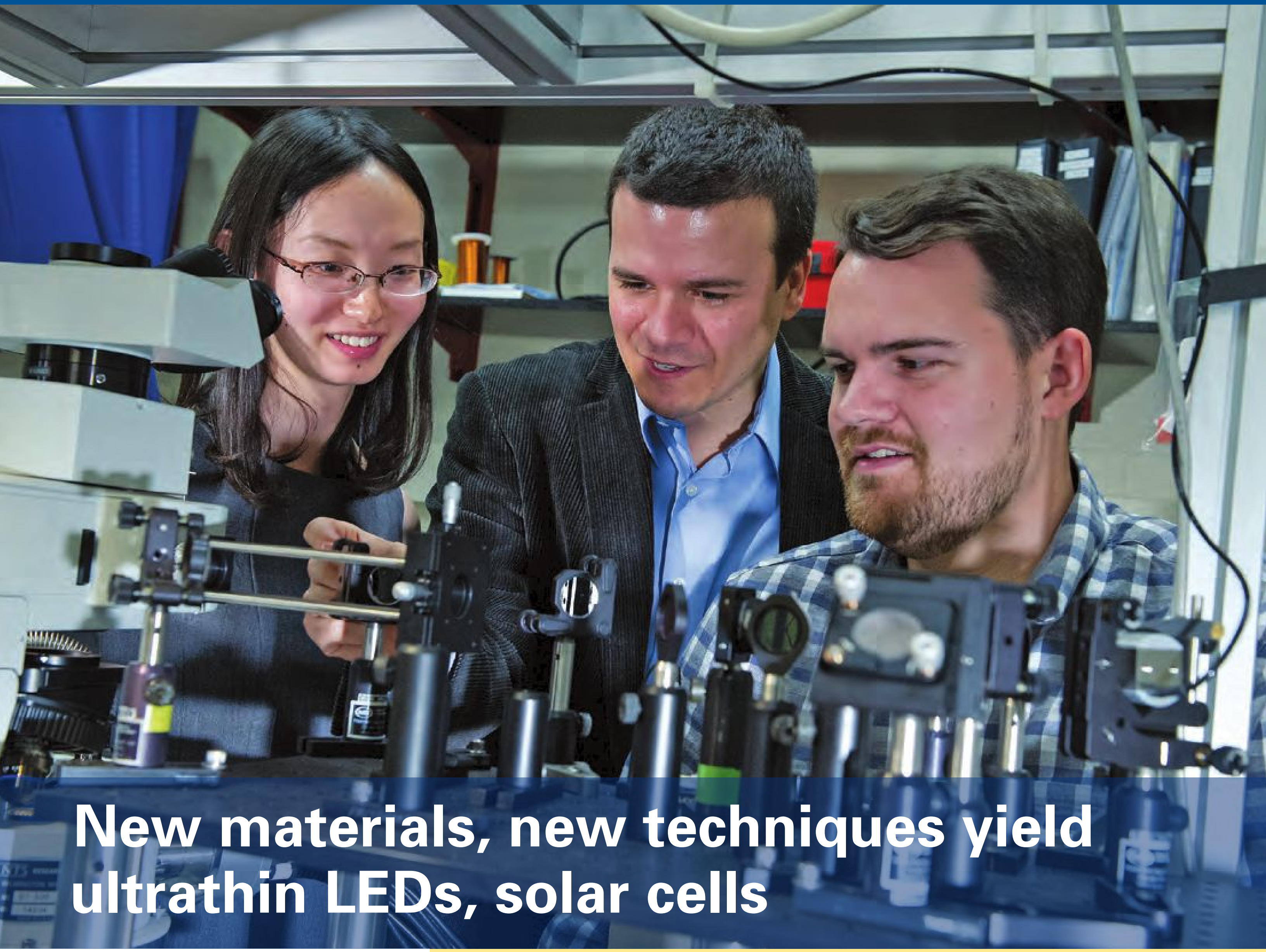
By Nancy W. Stauffer, MITEI

This research was funded by the US Department of Transportation through the New England University Transportation Center at MIT. Current work on this topic, building on the results described here, is being funded by the MIT Energy Initiative Seed Fund Program. Further information can be found in:

M.R. Edwards and J.E. Trancik. "Climate impacts of energy technologies depend on emissions timing." *Nature Climate Change*, vol. 4, pp. 347–352, May 2014.

J.E. Trancik, M.T. Chang, C. Karapataki, and L.C. Stokes. "Effectiveness of a segmental approach to climate policy." *Environmental Science & Technology*, vol. 48, no. 1, pp. 27–35, 2014.



New materials, new techniques yield ultrathin LEDs, solar cells

Left to right: Yafang Yang, Pablo Jarillo-Herrero, and Hugh Churchill of physics with Britton Baugher PhD '14 (not pictured) have developed a novel, inexpensive technique for making semiconductors and diodes and used them to build LEDs, solar cells, and light sensors that are just one molecule thick.

See page 21 for a list of sponsors as well as publications resulting from this research.

Photo: Stuart Darsch

A team of MIT physicists has used a one-molecule-thick material to demonstrate the thinnest LEDs and solar cells in the world. They apply an electric field onto an ultrathin sheet of their special material, thereby making it a semiconductor without adding any chemical "doping impurities"—the irreversible process often used by industry. In their process, by reversing the electric field the MIT researchers can turn the sheet into either of the two important semiconductor configurations— p-type or n-type. When they make one end of it p-type and the other end n-type, the sheet acts as a diode, the basic building block of electronics. Using their diodes, the physicists have built LEDs, solar cells, and light sensors that—once optimized by their engineering colleagues—could become ultrathin, lightweight, flexible devices suitable for mounting on buildings, weaving into clothing, and more.

Since graphene was isolated a decade ago, researchers worldwide have been using this one-atom-thick form of carbon for many potential applications, from faster computer chips to more efficient solar cells and desalination membranes. Four years ago, the research community was again invigorated when a whole family of materials was discovered that could be "exfoliated" in the same way that single sheets of graphene are lifted off chunks of graphite.

Pablo Jarillo-Herrero, the Mitsui Career Development Associate Professor of Physics, describes the phenomenon in terms of cards. A complete deck of cards is the standard "bulk" material. Take off one card and you have a single layer of the same material. "It turns out that the properties of an individual card are very different from the properties of the whole deck, and that's what makes it surprising and fascinating," he says.

For the past two years, Jarillo-Herrero and his team—Britton Baugher PhD '14, graduate student Yafang Yang, and Hugh Churchill, Pappalardo Postdoctoral Fellow, all of the MIT Department of Physics—have been investigating one member of the family of materials, tungsten diselenide (WSe_2). A single layer of WSe_2 is actually three atoms thick: A layer of tungsten atoms at the center is enclosed by layers of selenium atoms above and below. "So the 'monolayer' is like a sandwich, but it's still less than 1 nanometer thick," says Jarillo-Herrero. "That's about 50,000 times thinner than a human hair."

Like graphene, single-layer WSe_2 is semitransparent, flexible, strong, and—unlike bulk WSe_2—it's a good semiconductor. While it doesn't naturally conduct electricity, getting current to flow requires adding just a few more carriers of electric charge, for example, electrons. Given its physical features and its properties, Jarillo-Herrero believes that single-layer WSe_2 could one day make possible a host of new cheap, low-weight, flexible, semitransparent optical and electronic devices. He and his team are using a novel approach to help make that possible.

Making an electrically controlled p-n junction

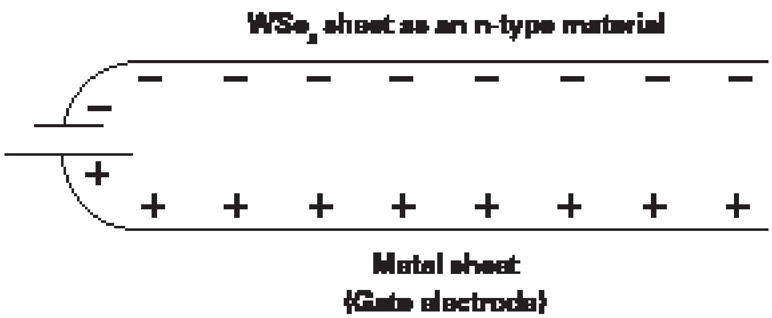
In a pure semiconductor, electrons—negatively charged subatomic particles—are typically trapped within their atoms. Getting them to move along as current is usually achieved by adding a dopant—a few atoms of another chemical. The dopant may add free electrons to the material, giving it extra negative charge and making it an n-type material. Or the dopant may have electrons missing in its crystal structure—vacancies called holes, which effectively add extra positive charge and create a p-type material. As an electron moves from hole to hole, it creates a new hole in its former location, so in essence the negatively charged electrons move one way and the positively charged holes the other way through the material.

The goal of doping semiconductors is, of course, to produce the extra electrons and holes. The chemical dopants are just carriers of those charged particles. But with ultrathin materials like WSe_2, says Jarillo-Herrero, we don't need the chemicals. Instead, he and his team employ a technique that adds electrons and holes to a sheet of WSe_2 using only electric fields.

The top diagram on page 19 shows how it works. Take a sheet of WSe_2 and place a thin sheet of metal under it. Separate them by an insulator and connect them at one end by a battery. (The essential geometry is that of a parallel plate capacitor, where one of the plates is the ultrathin WSe_2.) If the bottom sheet—the "gate electrode"—is sufficiently close to the WSe_2 sheet and a voltage is applied between the two sheets, an electric field is created. Holes move to one sheet, electrons to the other. The WSe_2 sheet is now a doped semiconductor. Moreover, whether it's p-type or n-type depends on which way around the battery is oriented. A negatively charged gate electrode will repel electrons away from the WSe_2 sheet, thus leaving holes on it and making it a p-type semiconductor; a positively charged gate electrode will attract electrons to the WSe_2, making it an n-type semiconductor. Thus, switching from one kind of semiconductor to the other requires simply turning the battery around.

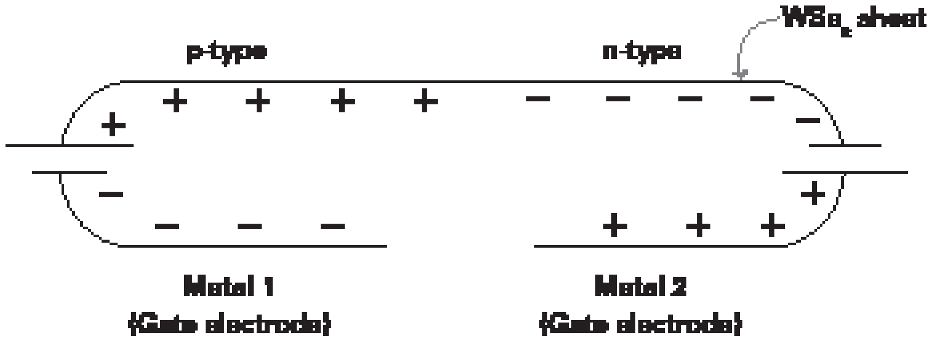
Even more interesting, the researchers can make a sheet of WSe_2 that's half n-type and half p-type. As shown in the bottom diagram on page 19, two separate gate electrodes are connected by batteries to opposite ends of the WSe_2 sheet. With the batteries in opposite directions, the gate electrodes will have opposite charge. As a result, one end of the WSe_2 sheet will become p-type, the other end, n-type. The region of interest is where the p and n sections meet. Called the p-n junction, this interface is where much of the action takes place in semiconductor-based optoelectronic devices, that is, devices that manipulate interactions of light and electricity.

Making an electrically doped semiconductor



Producing a doped semiconductor generally involves introducing a few atoms of another material that add extra electrons or holes (vacancies where electrons are missing)—an irreversible process that permits current to flow. The MIT researchers have developed a novel, reversible way to achieve the same end in their three-atom-thick sheet of tungsten diselenide (WSe_2). They place a sheet of metal beneath the WSe_2 sheet, separated by an insulator (not shown above) and connected by a battery. Applying a voltage between the two sheets, which are in close proximity, induces an electric field, which causes electrons to flow to one sheet and holes to flow to the other. The orientation of the battery determines whether the WSe_2 sheet becomes an n-type material (with extra electrons, shown here) or a p-type material (with extra holes).

Creating a p-n junction



This setup makes half of the WSe_2 sheet a p-type semiconductor and the other half an n-type. Two separate sheets of metal are connected by batteries to opposite ends of the WSe_2 sheet. With the batteries in opposite directions, one end of the sheet receives extra electrons, the other end accumulates extra holes. Where the n-type section and p-type section of the WSe_2 sheet meet is called a p-n junction—the interface at the core of most electronic devices.

A one-way valve for electricity

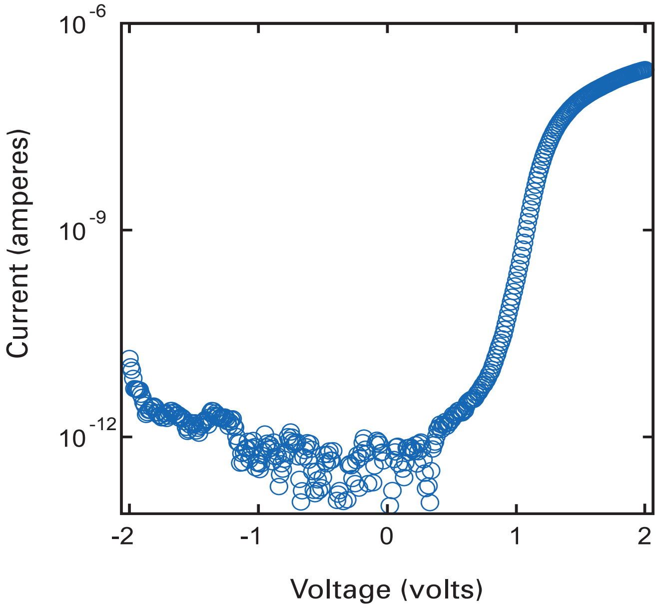
Having realized a p-n junction in their atomically thin material, the MIT team did what researchers have done with conventional p-n junctions for decades: They made a diode. A critical element in electrical circuits, the diode is essentially a switch that allows current to flow in one direction but not the other.

To demonstrate the behavior, the researchers connect an electrical circuit to the WSe_2 p-n device, incorporating another battery to provide the "bias" voltage needed to make it operate. First they set it up with a positive bias voltage, which supplies negative electrons to the n-type end. Since electrons from the n-type end can move across the junction into holes in the p-type end, current flows through the circuit. They then turn the battery around to send current in the opposite direction through the circuit. Now the negative bias voltage sends electrons into the p-type end, but electrons can't move across the junction into the n-type end, so no current flows.

The diagram on page 20 shows results of experiments using the WSe_2 diode set up as a p-n junction. When the bias voltage is negative, there's little or no flow of current. When the bias voltage switches to positive, current begins to flow and soon jumps up by a hundred thousand times. When the p and n ends of the WSe_2 plate are swapped, the shape of the curve showing current flow is almost a mirror image of the one shown in the diagram. The electrically induced p-n and n-p junctions thus act as successful—and flexible—diodes.

According to Jarillo-Herrero, the new diodes have properties that are very close to "ideal," as defined in textbooks.

Tests of the WSe_2-based diode



This figure shows the flow of current through the WSe_2 p-n diode as voltage varies. When voltage is negative, little or no current flows. Changing to positive voltage brings a sudden increase in current. The WSe_2 diode is thus effective as a switch that permits current to flow one way but not the other.

Indeed, they are far closer to the textbook definition of ideal than are diodes made of organic semiconductors—materials now being pursued because they are cheap, flexible, semitransparent, and can be grown over large areas. "Our new diodes aren't meant to compete with traditional semiconductor diodes of silicon or gallium arsenide," says Jarillo-Herrero. "We see them more as possible alternatives to organic electronics, which have many of the same attractive physical characteristics."

Jarillo-Herrero stresses the adaptability of their WSe_2 diodes. "Usually when you make a diode, the p-type and n-type ends are fixed by the chemical impurities that you've added. You can't change a p-n diode to an n-p diode," he says. "We have three batteries—three voltages—that allow us to control the whole thing. We can do anything we want because we electrically tune it with a knob."

Beyond diodes

Given their novel high-performance diodes, the next step was to build optoelectronic devices. There are three basic devices that one can make with a diode: a photovoltaic solar cell, a light-emitting diode (LED), and a photodetector (a light sensor). "We realized for the first time in an atomically thin material all three of those functionalities," says Jarillo-Herrero.

All of their devices work well. For example, their photovoltaic cell converts incoming photons (packets of solar energy) into flowing electrons with notable efficiency, given the small amount of material available for absorbing incoming sunlight. Their LED emits visible light that's focused in a relatively narrow wavelength range—a property that generally correlates to brightness. As shown in the diagram on page 21, WSe_2 emits red light most strongly. But other members of the same chemical family emit other colors, so in principle several could be combined to produce various colors and mixtures. Finally, the response of their photodetector matches that of conventional commercial sensors that are much bigger and bulkier.

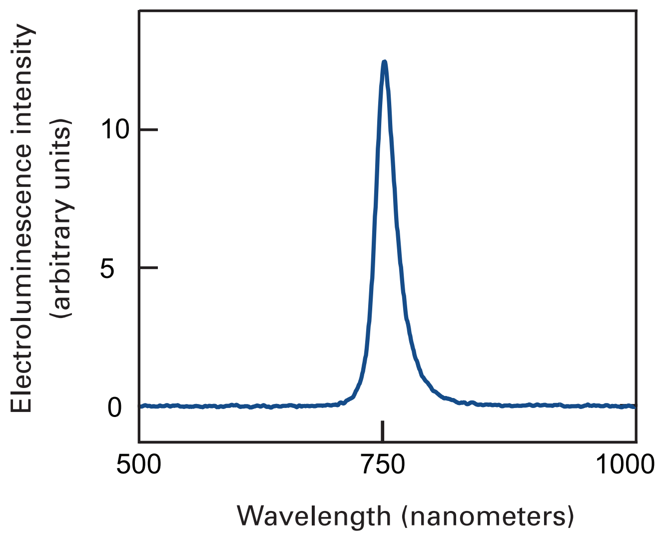
The semiconductor at the core of each of those devices is just three atoms thick. But what about other components? With the exception of the batteries, they could all be made of ultrathin materials, says Jarillo-Herrero. The gate electrodes and the contacts with the batteries could be made of one-atom-thick graphene, and the insulator between the gates and the WSe_2 sheet could be a single nanometer of hexagonal boron nitride. Jarillo-Herrero and his team are beginning to develop some of those components now.

Future plans

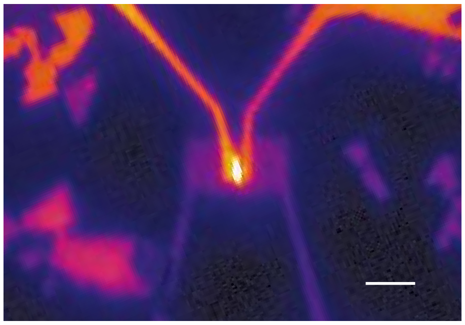
In principle, the novel WSe_2-based devices could one day lead to a new class of commercial electronic and optoelectronic products. Industrial processes exist for making very large-area sheets of WSe_2; and while selenium is far more rare than, say, silicon, the amount of WSe_2 used in the atomically thin devices is so small that thousands of times less material would be needed to make devices of a given size.

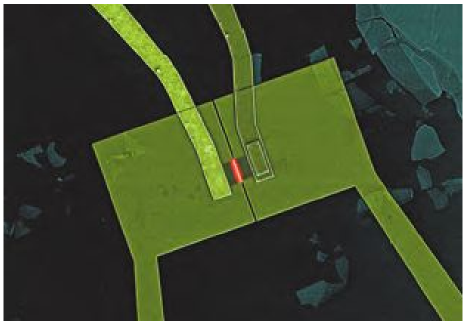
Jarillo-Herrero stresses that "it's still early on, and a lot of research has to be done." Thus far, he and his team have made only proof-of-concept devices. Even so, they were surprised at how well their devices performed in this first trial. "We're physicists, not engineers, so we don't iterate and optimize things," he says. "But I think it's fair to say that already these devices are surprisingly good—and that's why the engineers are jumping on it."

Demonstration of the WSe_2-based LED



This curve shows the intensity of light emitted at various wavelengths by the WSe_2 p-n LED when current passes through it. Intensity peaks at about 750 nm—the red part of the visible spectrum.





Above left: This image, taken through an optical microscope, shows the team's experimental WSe_2 LED. Electricity flows through platinum and gold wires (coming down from the top left and right) to the LED at the center, causing it to glow. The scale bar equals 5 micrometers. Image courtesy of Britton Baugher and Hugh Churchill.

Above right: A scanning electron microscope image of the device. The glow at the LED center has been added for illustration purposes. Image: Felice Frankel and Jarillo-Herrero group.

Photo: Stuart Darsch

At the invitation of Marc A. Baldo, professor of electrical engineering, and Vladimir Bulović, the Fariborz Maseeh Professor of Emerging Technology and associate dean for innovation in MIT's School of Engineering, Jarillo-Herrero and his group have joined the Center for Excitonics, an Energy Frontier Research Center directed by Baldo and supported by the US Department of Energy. Together, the physicists and engineers will investigate these new materials and their atomic properties in greater depth, and they'll optimize the devices to improve their performance and move them toward efficient, inexpensive commercial products that can harvest, emit, and detect light.

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By Nancy W. Stauffer, MITEI

This research was supported by the US Office of Naval Research, a Packard fellowship, and a Pappalardo fellowship. It made use of National Science Foundation-supported facilities. Further information can be found in:

B.W.H. Baugher, H.O.H. Churchill, Y. Yang, and P. Jarillo-Herrero. "Optoelectronic devices based on electrically tunable p-n diodes in a monolayer dichalcogenide." *Nature Nanotechnology*, vol. 9, April 2014, pp. 262–267.

B.W.H. Baugher. *Electronic Transport in Atomically Thin Layered Materials*. PhD thesis, MIT Department of Physics, May 2014.

Left: The researchers use this specially designed optical cryostat setup to examine and test their devices.

DOE renews two Energy Frontier Research Centers at MIT

In June 2014, the US Department of Energy (DOE) announced that two MIT-led Energy Frontier Research Centers (EFRCs) received funding to continue their cutting-edge research. The centers are among 32 projects that were competitively selected from more than 200 proposals as part of a second round of funding for the program.

The EFRC program aims to accelerate transformative energy discoveries by combining the talents and creativity of the nation's top scientists. These integrated, multi-investigator centers conduct fundamental research focused on one or more major energy challenges, such as solar energy, electrical energy storage, carbon capture and sequestration, and extreme environments.

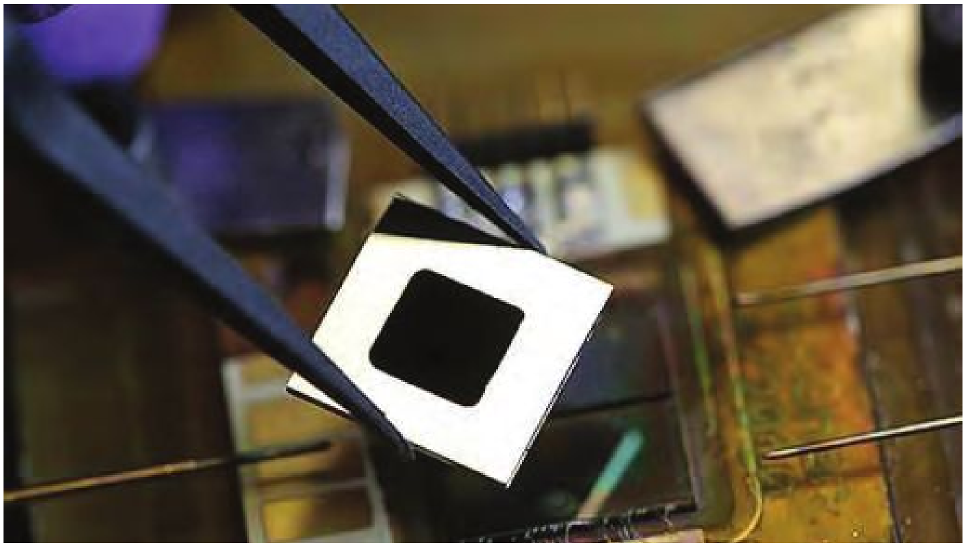
Photo: John Freidah, MIT

Among the innovations coming out of the renewed Energy Frontier Research Centers is this nanophotonic device designed to generate power from solar energy that promises to be both efficient and on demand. It uses sunlight to heat a high-temperature material whose infrared radiation would then be collected by a photovoltaic cell. For more details, go to s3tec.mit.edu.

The MIT-led centers

The Center for Excitonics: Directed by Professor of Electrical Engineering Marc Baldo, this center is working to create new materials for solar energy and solid-state lighting. Since becoming an EFRC in 2009, the center has developed transparent solar cells, a new material for flat semiconductors, a technique that could boost solar-cell efficiency, and more. MIT partners with Brookhaven National Laboratory as well as Harvard University on this project.

The Solid-State Solar-Thermal Energy Conversion Center (S3TEC): Directed by Gang Chen, the Carl Richard Soderberg Professor of Power Engineering, this center designs materials to efficiently convert heat—either from the sun or from a terrestrial heat source such as waste heat from automobiles—into electricity using solid-state devices including thermoelectric, thermogalvanic, and thermophotovoltaic devices. Since becoming an EFRC in 2009, the center has developed advances including a new approach to tap the sun's energy through heat, a method for filtering light waves based on direction, and a new hybrid solar-thermoelectric system. MIT partners on this project with Oak Ridge and Brookhaven National Laboratories as well as Boston College and the University of Houston.

In addition to the two MIT-led centers, MIT is also a partner on one of the centers led by the National Renewable Energy Laboratory: the Center for Next Generation Materials. Gerbrand Ceder, the R.P. Simmons Professor of Materials Science and Engineering, will play a leadership role in this center, and Assistant Professor of Mechanical Engineering Alexie Kolpak will lead a section of the research. The center aims to transform the discovery of functional energy materials.

Since their establishment by DOE, all of the EFRCs together have produced 5,400 peer-reviewed scientific publications and hundreds of inventions at various stages of the patent process. EFRC research has also benefited a number of large and small firms, including startup companies.

Twenty-three of the projects that received funding in 2014 are headed by universities, eight are led by DOE's national laboratories, and one is run by a nonprofit organization.

To learn more about the Center for Excitonics, visit rle.mit.edu/excitonics. To learn more about the Solid-State Solar-Thermal Energy Conversion Center, visit s3tec.mit.edu. To learn more about DOE's EFRC program, visit science.energy.gov/bes/efrc.

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By Vicki Ekstrom, MITEI

New faculty strengthen, broaden MIT's energy expertise

Photo: Vicki Ekstrom, MITEI

Valerie Karplus SM '08, PhD '11

Assistant professor in the Sloan School of Management

Valerie Karplus can trace her interest in international energy affairs to a college course titled Science, Technology, and International Affairs. Her love of the material led the politics-biophysics double major to seek an internship with the Council on Foreign Relations and later to cofound the student-run international affairs magazine The Yale Globalist*. While working on the* Globalist*, Karplus became particularly interested in China. She went on to win a Henry Luce Fellowship for professional study in China post-graduation, and her path took her eastward yet again when she postponed US graduate study to complete a book on China's agricultural biotechnology industry and begin research on China's energy system. Now, Karplus, a newly minted faculty member at MIT Sloan with a PhD in engineering systems from MIT, has found her way back to the classroom.*

Talk a little about your involvement with the China Energy and Climate Project at MIT.

After finishing my PhD, I had the incredible opportunity to start a program on China within the Joint Program on the Science and Policy of Global Change—the China Energy and Climate Project, or CECP—fulfilling a vision that I've had since I first lived in China. Identifying pathways for transitioning to a more environmentally sustainable energy system in China requires a combination of in-country connections, deep understanding of the country's energy system, and solid analytical approaches that can be used to support decision making. The goal behind the whole project is to develop this shared platform.

One of our CECP accomplishments thus far is the development of the Regional Emissions Air Quality Consumption and Health modeling framework, or REACH. Our research involves projecting air pollution emissions for China's provinces under alternative energy policies in a regional energy-economic model and using these projections to simulate air quality outcomes, including ozone and particulate matter, in an atmospheric chemistry model. We can then use the regional energy-economic model to calculate health impacts under alternative scenarios and the magnitude of such damages avoided due to policy. We are currently analyzing the costs and benefits of several energy and climate policies using this framework.

How was your first teaching experience at MIT Sloan last spring?

I thoroughly enjoyed it. Application-oriented classes like my courses on global strategy [15.220 Global Strategy and Organization] and global entrepreneurship [15.395 Global Entrepreneurship Lab: Entrepreneurs Without Borders] are exciting to teach because they tackle current challenges in developing global companies that generate lively discussion and debate. I am enjoying the process of learning how to lead a case discussion, which often encourages students to reason through real-world decisions and adopt different perspectives.

You've made a number of decisions to stay at MIT in your career, even when career opportunities have arisen elsewhere. What have you learned from being immersed in the MIT culture?

MIT provides an ideal laboratory for combining insights from research and practice to solve real-world problems. An important underlying reason is that the MIT culture encourages the formation of dynamic, interdisciplinary teams. With good communication and effective teamwork, you can begin to characterize and tackle large, complex problems—and defining the problem can be half the battle. It is also very important to develop a team whose members really care about each other and want to see everyone on the team succeed. MIT lays the foundation for these kinds of collaborations to develop and thrive, and in the process we challenge our own thinking and test the boundaries of what is possible. It's very exciting, and it's what I love about MIT.

Photo: Tony Pulsone, MIT

A. John Hart SM '02, PhD '06

Associate professor in the Department of Mechanical Engineering

A. John Hart's research interests focus on the science and manufacturing of new materials—in particular, materials with controlled micro- and nanoscale structures—and the pursuit of innovative applications of those materials, including energy conversion and production. His arrival in summer 2013 was something of a homecoming. In the early years of his career, he was a graduate student at MIT, earning both his master's and PhD in mechanical engineering. Prior to returning to MIT, he was an assistant professor at the University of Michigan, where in 2007 he founded the Mechanosynthesis Group (mechanosynthesis.mit.edu). Hart's group is now based at MIT—a place where, he says, the general belief that "anything is possible" inspires him and his research team.

Your particular expertise is manufacturing. Can you tell us why manufacturing is important and what avenues you're pursuing to improve it?

Recently, there has been a lot of important dialogue about advanced manufacturing technologies and their role in the innovation process, both domestically and globally. While industry excels at developing manufacturing technologies at impressive scales, many new materials and devices do not reach the market—or take a long time to do so—because of the challenge of scaling the manufacturing process at appropriate cost. Motivated by that problem, we largely undertake projects that combine expertise in manufacturing processes, mechanical design, and materials processing. At present, our group is working on three main themes: nanomaterials, particularly carbon nanotubes and graphene; additive manufacturing, including machines for high-speed "3D printing" of composites and metals as well as high-precision printing of electronics at small scales; and origami-inspired manufacturing using folding to transform patterned laminates into deployable structures for aerospace and medical applications.

What are some of the energy applications of your work?

We're interested in the use of nanomaterials in energy storage. For example, we're designing high-performance battery electrodes using some of the carbon nanomaterials that we make. Another project involves using nanomaterials to make electrostatic capacitors that can charge very quickly and can operate under extreme conditions, such as close to the engine of a vehicle or at the bottom of an oil well during exploration. We're also creating engineered surfaces using carbon nanotube microstructures that can be useful in energy applications. These surfaces have complex 3-dimensional textures that are robust and electrically and thermally conductive—a combination that's unusual among materials that can be patterned cost-effectively over large areas.

What classes are you teaching?

One is 2.008, the main class on manufacturing processes for mechanical engineering undergraduates. In that class, students learn the fundamentals of manufacturing processes ranging from machining and injection molding to 3D printing, and principles of variation, quality, cost, and scale-up. One class project involves working as a team to design and manufacture a yo-yo—in a quantity of 100! I also teach a new graduate course on additive manufacturing in which students learn the fundamentals of different 3D printing methods and then design an improved 3D printing machine or figure out how to print an entirely new material. Last summer, we offered a new five-day MIT Short Program on additive manufacturing. Nearly 50 participants came to MIT from all over the map, both geographically and professionally, to learn about the reality and potential of additive manufacturing to enable new capabilities for their design and manufacturing operations, ranging from product prototyping using polymers to printing of complex tooling and structural parts from metals and composites. They also asked long-range questions like, Are you going to be printing smartphones in the future, and, Will 3D printing change where manufacturing happens in the world?

Photo courtesy of Rania Ghosn, MIT

Rania Ghosn

Assistant professor in the Department of Architecture

Rania Ghosn's research thrives at the intersection of architecture, geography, urban studies, and energy. She is particularly interested in infrastructures built for energy purposes and how they interact with both a built cityscape and a natural landscape. Ghosn holds a doctorate in design from Harvard University, an MA in geography from University College London, and a bachelor of architecture from American University of Beirut. She was an assistant professor at the University of Michigan, teaching graduate design studios, running thesis studies on the American Corn Belt, and offering a graduate seminar on energy. Prior to that, she served as a Mellon Postdoctoral Fellow at Boston University, where she helped organize the Sawyer Seminar Series on Energy and Society. At MIT, in fall 2014 she taught 4.S26 Landscapes of Energy, a research seminar that proposes a critical spatial inquiry on the relations of energy and space to understand, critique, and ultimately influence choices regarding energy options.

How does energy relate to your work with architecture and city planning?

I use energy as a lens though which to examine how large technological systems underpin the functioning of cities and the transformation of landscapes, regions, and the globe. My work considers systems like waste management, agriculture, and highways and how they relate "hinterlands" to urban centers. Initially, I was drawn into the study of energy almost by coincidence, or geographic proximity. I was looking at one piece of larger infrastructure—a highway being planned in the Middle East—and came to realize that it was being planned to run next to an oil pipeline. My interest in that crude oil pipeline grew till it actually became the subject of my dissertation.

That pipeline is also the subject of one of your forthcoming books, correct?

Yes, there are actually two book projects. The subject of the first one is the Trans-Arabian Pipeline, which operated between 1950 and 1975. It describes how the pipeline that ran for around a thousand miles across the Middle East produced its own geographies—spaces such as pumping station towns, water wells, and health and education facilities. So the book is basically a biography of this piece of infrastructure. It looks at the geographic footprint of something that we usually think of as merely crossing through the landscape and vanishing into the horizon and seeks to unearth the multiple political, economic, and spatial transformations that were part of such an operation. The second book I'm working on, the Atlas of the Corn Belt, looks into the histories and geographies through which corn became the predominant crop—a product that is diversified for multiple industrial uses, be they food additives, livestock feed, or ethanol fuel.

What drew you to MIT?

I was drawn to the MIT School of Architecture and Planning by its interdisciplinary approach to urbanism. The newly established Center for Advanced Urbanism reinforces the significance of urban questions within the Institute as beyond the domain of a single discipline. As I mentioned, I'm very interested in these kinds of intersections, especially between architecture, geography, energy, and, more broadly, environmental questions. The fact that MIT highlights collaboration in its mission really appeals to me. It is my first semester, and I've found that sense of collaboration reflected in things from research centers and dissertation committees to the architecture itself. The idea of having one "infinite corridor" meant to connect all disciplines and foster teamwork was a pleasant surprise to me as a newcomer. The philosophy behind it still means a great deal to me.

Photo: Travis Gray, MIT

Elsa Olivetti PhD '07
Assistant professor in the Department of Materials Science and Engineering

Elsa Olivetti's academic pursuits merge the disciplines of materials science and energy research. Her dedication to energy conservation on MIT's campus began when she was a graduate student in materials science and engineering. In 2006, she and fellow student Jason Jay PhD '10 launched the MIT Generator, an ongoing annual student-driven brainstorming session on how to improve campus energy efficiency. Olivetti was also part of a research team that won one of the first MIT Energy Initiative seed grants in 2008. She joined the faculty in 2014 and now balances commitments among research, teaching, and lending her talents to MIT programs such as the Tata Center for Technology and Design, where she has been collaborating on strategies for reducing waste byproducts for industries in India.

What's the main focus of your current research?

I conduct research on the development of materials and on the technologies that spring from those materials, both from an economic and an environmental perspective. I consider the full life cycle that necessarily goes along with a given material, including extraction, manufacturing, use, and end of life. My group focuses on impact-based discovery; in other words, as researchers develop new materials, our contribution is to understand what the cost and environmental impact would be of new technologies based on those materials at scale, particularly emphasizing processing and manufacturing. Our tools aim to provide insight as early as possible—even when development is still only at lab-scale—into what challenges or opportunities might crop up as the system is scaled up.

Tell us about your work with industry.

The other thread of my research involves system analysis of materials use and the impacts of legislation on industry strategy. Right now, we are working with both the aluminum and paper industries. Currently, this work focuses on identifying ways to improve the way we recycle materials using a combination of methods drawn from economic market models and environmental life-cycle assessment. For example, assume a new regulation requires a certain amount of recycled content in a particular high-grade product. If the supply of recycled material is constrained, a company may shift recycled material it generally uses in lower-grade end uses to make the product described in the legislation. This may lead to an unintended consequence where virgin material is used in lower grade products, resulting in higher overall economic and environmental impact. There's irony in that. Often you have to consider such legislative actions in the context of how they might cause shifts within a materials market resulting in short-term impacts to certain firms or longer-term environmental or economic effects.

What do you cover with your students in class?

With teaching, there's always a balance between breadth and depth. My philosophy in developing my new class [3.081 Industrial Ecology of Materials] has been to talk with students about the foundations first. So we look at the basics of environmental evaluation of materials before we move on to specific applications. If we've built a strong enough foundation, the students can apply their understanding to real-world problems that we don't have a chance to cover in class, given the time constraints of the semester. The students here have a lot of great energy. In particular, in a class on materials processing that I helped teach last spring, there were many students who were really excited to talk about recycling, in particular, and wanted to delve into specific recycling issues in greater depth. Helping enthusiastic students identify their particular passions and apply them to problem solving has been especially rewarding.

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By Francesca McCaffrey, MITEI

MIT's Nancy Rose takes Department of Justice position

Photo: Barry Hetherington

In fall 2014, MIT economist Nancy Rose, the Charles P. Kindleberger Professor of Applied Economics, was appointed by the US Department of Justice (DOJ) as deputy assistant attorney general for economic analysis.

An expert on firm behavior and the economics of regulated industries, Rose served on the Energy Council of the MIT Energy Initiative.

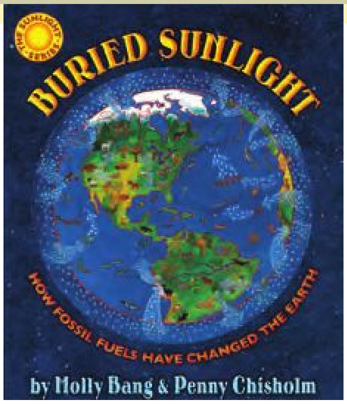
She received her undergraduate degree in economics and government at Harvard University in 1980 and her PhD in economics from MIT in 1985. Her first faculty position was at the MIT Sloan School of Management, which she joined in 1985. She has been on the faculty of the Department of Economics since 1994.

Rose has published extensively on electricity generation and transmission as well as on airlines and other transportation sectors. In 2012, she was named a Margaret MacVicar Faculty Fellow, MIT's highest honor for undergraduate teaching.

On leave from MIT, she now leads a staff of about 50 economists conducting research for DOJ's Antitrust Division, while also working with DOJ leaders in establishing policy priorities.

For the full press release, go to mitsha.re/10VG6eM.

New children's book series sheds "light" on Earth's energy system



MIT's Lee and Geraldine Martin Professor of Environmental Studies Penny Chisholm and illustrator Molly Bang have set out to teach elementary students some of the most basic concepts about how life on Earth works. In a new book, *Buried Sunlight*, the pair describes the role of photosynthesis in creating fossil fuels and how use of this "fossil sunlight" is changing the planet.

The book is part of the "Sunlight Series," their soon-to-be-completed set of children's books focused on the sun's role in the biosphere as the main energy source of life on Earth (see www.thesunlightseries.com). The first in the series, *My Light*, introduces the sun as the narrator and shows how humans change sunlight into electricity. After *My Light*, Chisholm and Bang describe photosynthesis on land (*Living Sunlight*) and in the sea (*Ocean Sunlight*), followed by their newest book, *Buried Sunlight*. Finally, in a book in progress, the two describe the global water cycle and the sun's role in moving water from land to sea and back again.

The authors hope their books will make the critical concept of photosynthesis clear—for adults as well as children—in a way that both makes the information "stick" and leaves the reader in awe of how the Earth functions.

MIT's Sheila Kennedy awarded $100,000 Berkeley-Rupp Prize

Photo: David Sella, MIT

On September 15, 2014, Sheila Kennedy, the first woman to hold the title of Professor of the Practice of Architecture at MIT's School of Architecture and Planning, was awarded the $100,000 Berkeley-Rupp Prize by the University of California at Berkeley College of Environmental Design (rupp.ced.berkeley.edu/2014-sheila-kennedy).

Awarded every two years, the prize honors a distinguished design practitioner or academic who has made significant contributions to advance gender equity in the field of architecture. Kennedy will use the prize to create new designs for contemporary infrastructure in cities, exploring new linkages between digital fabrication and Global Maker Movement communities.

This is the third major prize Kennedy has won recently. Also in September, she and her partner J. Frano Violich received a $25,000 award from the Holcim Foundation for their Chrysanthemum Building, an innovative, low-carbon residential development in Boston. In August, Kennedy was presented with the inaugural Design Innovator Award by *Architectural Record* magazine, a peer-reviewed design program that acknowledges the increasingly visible role of women in the profession.

For more details on Kennedy's awards, go to mitsha.re/10VGnOS.

Energy Fellows, 2014–2015

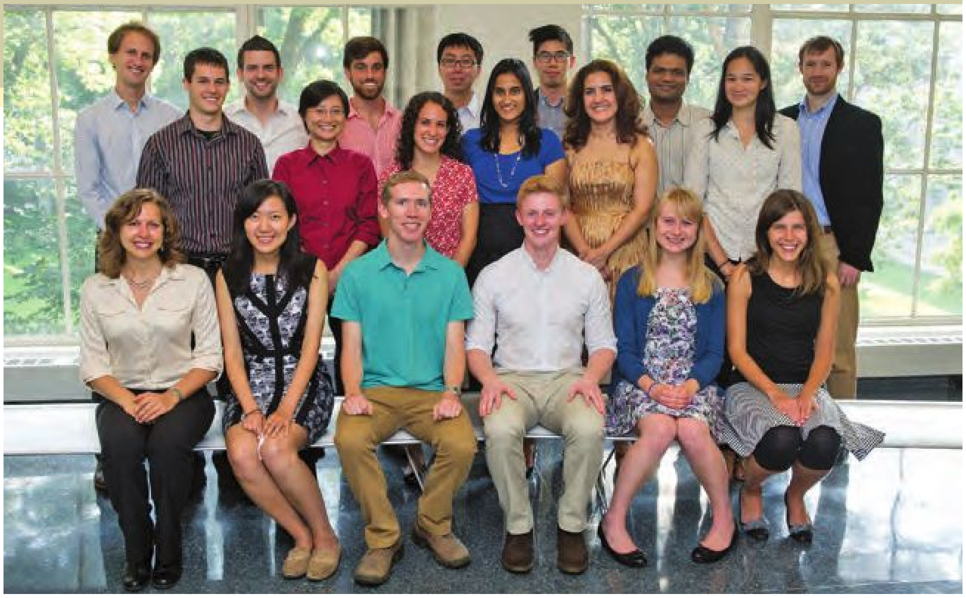


Photo: Justin Knight

The Society of Energy Fellows at MIT welcomed 32 new members in fall 2014. The Energy Fellows network now totals more than 300 graduate students and postdoctoral fellows and spans 20 MIT departments and divisions and all five MIT schools. Fellows now include incoming graduate students and graduate student researchers, teaching fellows, and postdoctoral associates. This year's fellowships are made possible through the generous support of 14 MITEI member companies.

Bosch
Alex Tinguely
Physics

BP
Aliza Abraham
Mechanical Engineering
Vikas Garg
Electrical Engineering and Computer Science
Shweta Mehta
Technology and Policy
Katie Samuelson
Civil and Environmental Engineering/ Woods Hole Oceanographic Institute
Ryan Shaw
Chemical Engineering
Zhenlong Zhao
Mechanical Engineering

Chevron
Jing Zhang
Biology

Eni
Po-Yen Chen
Chemical Engineering
Noemie-Manuelle Dorval Courchesne
Chemical Engineering
Francesca Freyria, PhD
Chemistry
Stephen Zoepf
Engineering Systems

Entergy
Sebastian Luque
Engineering Systems

Ferrovial
Dylan Shiltz
Mechanical Engineering
Qin Zhang
Architecture

ICF International
Michael Davidson
Engineering Systems

Lockheed Martin
Vasant Ramasubramanian
Media Arts and Sciences

Saudi Aramco
Nian Liu
Chemical Engineering
Adam Rieth
Chemistry

Schlumberger
Mirna Slim
Earth, Atmospheric, and Planetary Sciences

Shell
Jayadev Acharya, PhD
Computer Science and Artificial Intelligence Lab
Scott Burger
Engineering Systems
Eva Golos
Earth, Atmospheric, and Planetary Sciences
Danielle Gruen
Earth, Atmospheric, and Planetary Sciences
Chiao-Ting Li, PhD
Joint Program on the Science and Policy of Global Change
Nora Xu
Engineering Systems

Statoil
Gregory Ely
Earth, Atmospheric, and Planetary Sciences
Rebecca Grunberg
Management

Total
Richard McDowell
Economics
Neha Mehta
Civil and Environmental Engineering

Weatherford
Mike Huang
Electrical Engineering and Computer Science
Elise Strobach
Mechanical Engineering

Fellows as of November 1, 2014

"Engrained in the culture": Undergraduate energy education at five years

At MIT, Cecilio Aponte '15 discovered "the perfect ecosystem for an engulfing energy obsession." Priyanka Chatterjee '15 came for ocean engineering, then "fell in love with the energy program." Diego Giraldez '15 realized he could simultaneously explore "crazy, 'what if' questions and cutting-edge energy technologies."

MIT undergraduates are "converting" to energy. As they encounter a wealth of energy-oriented classes, research possibilities, and extracurricular activities, plus a community dedicated to addressing the energy challenge, students are adopting energy as a central and sometimes dominant theme in their education.

Aponte, a materials science and engineering major, says he has taken to heart a line by his favorite rap artist, Watsky: "I'm looking, I'm looking, I'm looking for energy everywhere." These words might serve as a catchphrase for an increasing number of his peers, as the cohort of energy-intent undergraduates swiftly and steadily expands, say MIT administrators.

Take, for example, the Energy Studies Minor. The MIT Energy Initiative (MITEI) launched this specialized course of studies in 2009, and three energy minor students graduated in spring 2010. The curriculum consisted of a handful of courses in the foundational areas of energy science, social science, and energy technology/engineering, and 24 electives. Five years later, the foundational course offerings, especially in social science, have swelled, along with electives, and the Energy Studies Minor is celebrating its largest class ever—35 students. "That's a lovely growth trajectory," says Amanda Graham, director of the MITEI Education Office. It is now the third largest minor at MIT, after economics and management/management science.

There is also the "Discover Energy" FPOP, MITEI's freshman pre-orientation program. Filling nearly all available slots, 22 entering first-year undergraduates arrived in August 2014 to learn about the energy arena at MIT, engaging in seminars, tours, hands-on activities, and discussion with faculty members, current students and staff, and alumni.

Undergraduate research opportunities (UROPs) in energy supported through MITEI have also shown steady growth, rising from eight in 2008 to 47 in 2014 (see the chart on page 30). "What impresses me is the diversity of disciplines represented in [all of MIT's energy-related UROP] research," says Michael Bergren, associate dean of academic and research initiatives. "We're seeing projects not just in engineering fields, but in the sciences and social sciences such as architecture, economics, and policy. These UROPs raise visibility across the entire MIT community about the significance of energy research, and undergraduates see they can make an impact on real energy problems."

A shared pursuit and purpose

The idea of making an impact resonates with many undergraduates, as does joining a community with a shared purpose. By pursuing energy, they can do both at the same time—an insight some students come to early on.

For instance, during her FPOP experience, Chatterjee, an ocean and mechanical

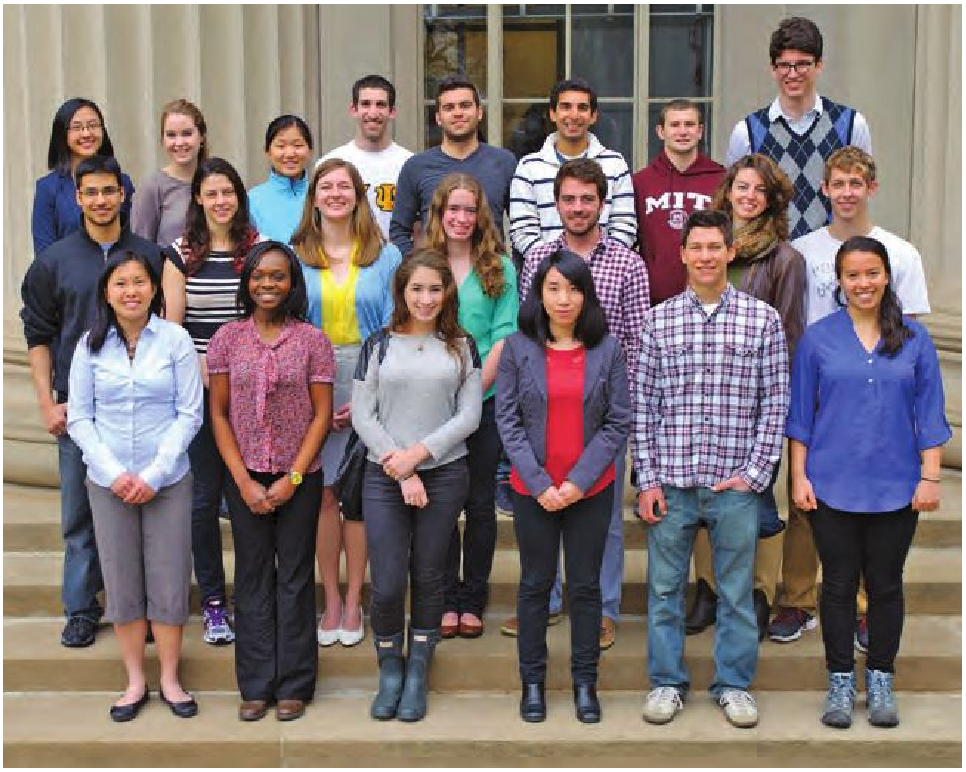
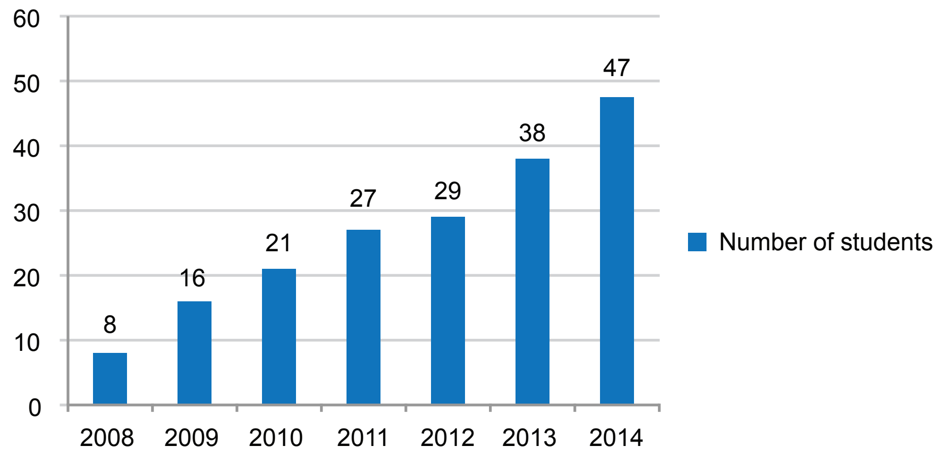


Photo: David Sella, MIT

Students graduating with the Energy Studies Minor in 2014. Launched in 2009, the energy minor is now the third largest minor at MIT.

Number of UROP students, 2008–2014



engineering major, constructed solar cell modules using raspberry juice as a chemical agent and learned about the potential of solar power to revolutionize the energy industry. She also interacted with faculty and students from a diverse range of disciplines. "I saw that there was a big community involved…and I was blown away by how much you can do in the field," she says.

FPOP was also an academic "driver" for Chatterjee, as she recognized that studying energy would enable her "to make an even bigger impact" than sticking exclusively to ocean engineering. As a result, she wasted no time signing up for the Energy Studies Minor.

Giraldez decided soon after his FPOP experience to pursue the minor because it offered the perfect complement to his chemical engineering major. He had arrived at MIT with many "open questions" about energy systems, he says, and while chemical engineering gave him a good basis for understanding these systems, "the minor shows you how they really fit into society— why for instance you can't just build a ton of nuclear power plants."

Aponte says that the minor "grounded my interest in energy and gave me the tools I needed to learn, while still offering the space I wanted to float around and try new things." Among those new experiences were designing and building a biodigester-latrine system for rural El Salvador in D-Lab: Energy (EC.711) and conceptualizing a plan for decentralized solar charging infrastructure in Boston (3.004 Principles of Engineering Practice).

Central to his energy education, Aponte says, was the "community of people to discuss challenges with and learn from." With "like-minded friends" he attended lectures and events, and in such clubs as e4Dev—Energy for Human Development—he found "graduate student heroes" who "have definitely shaped visions of my future."

For Johnathan Kongoletos '14, a mechanical engineering major, energy studies led to community involvement of a different kind: He spent part of the summer of 2014 pedaling a battery-powered, adult-sized tricycle during an MIT-to-Albany trip with the MIT Electric Vehicle Team.

When Kongoletos was not struggling over bumpy country lanes, he was conducting research for MIT's Building Technology Program, helping determine energy efficiency and conservation measures for MIT's next big infrastructure investment, the MIT.nano laboratory building.

This was one in a string of research projects focused on energy efficiency measures for MIT campus buildings. In an earlier UROP, Kongoletos helped assess new high-performing glass being contemplated for renovations in 1917-era Killian Court buildings. "This was research whose impacts I could see," he says.

The defining experience of energy research

Whether on or off campus, undergraduates seek ways to make vital contributions to energy research. Says Chatterjee, "People at MIT really care about making a difference and in a way that connects with their interests."

Chatterjee managed to combine her love of oceans and energy through two MITEI-sponsored UROPs: one on designs for a tidal power generator, which she modeled in a giant water tank in the basement of an MIT building; and another involving the use of laser technology to look for leaks in natural gas pipelines on the ocean floor.

In an engineering laboratory class, Giraldez helped design a toilet for the US Army that uses much less water. Developing a hydrophobic coating for

Photos: Justin Knight

For her summer 2014 UROP project, Alexandria Miskho '17 of chemical engineering examined various approaches to converting food and yard waste into biofuels. Using high-performance liquid chromatography, she analyzed different types of waste samples to measure concentrations of fatty acids, which can be used in yeast-based biofuel production. Here, she prepares a sample for analysis.

During MITEI's 2014 freshman pre-orientation program, students use a Kill-A-Watt power meter to measure the power consumption of various household appliances. Activities included calculating the amount of coal, hydro, uranium, solar, and battery power that would be required to cook their lunchtime pizza. The overall goal: to help the participants develop practical intuition about energy and power.

low-flush toilets would reduce not just the amount of water the Army ships to remote locations around the world, but energy as well.

Hands-on, practical research like this, along with other energy studies classes, Giraldez says, "solidified my desire to enter the energy industry, and made me look at the world in a much different way." An internship as a process engineer at a Chevron refinery in California this past summer sealed the deal for Giraldez, who now hopes to work in the oil and gas industry.

For some undergraduates, energy education is a springboard to a career. For others, it's an essential platform for contemplating a path forward. "I have been exposed to so much more than I could have ever expected," Aponte says. "When I came to MIT, I had no idea what I wanted to do, and now thanks to the community here, I am at least sure it has to do with energy."

With another year to go, Chatterjee has a lot on her plate, including developing an entry for the MIT Clean Energy Prize competition, a project on offshore solar technology. But after three years at MIT, she says, "I see myself, and feel represented, through my interests in energy." While still tailoring these interests, Chatterjee believes that becoming a "social entrepreneur in the environment and energy space would be a dream come true."

Pursuing this dream does not seem far-fetched on a campus full of accomplished strivers supported by top-tier researchers. With the rapid expansion of formal and informal opportunities for energy education and research, and a swelling legion of energy-focused students and faculty, "energy has become engrained in undergraduate culture and intertwined with every discipline," says Chatterjee. "We're becoming a vibrant community inspired by what we can do with energy."

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By Leda Zimmerman, MITEI correspondent

D-Lab offers hands-on lessons in meeting energy needs

Early on in EC.711 D-Lab: Energy, MIT students are put in a dark room and asked to assemble resistors using the equivalent of candlelight. It's a quick, experiential lesson in what many people in the developing world have to cope with every day: insufficient access to energy.

"[The students] are really blown away by how hard it is," says instructor Libby Hsu, MEng '10, SM '11. And that's exactly the point. "If you go to the developing world to talk day-to-day issues, energy is critical. People need lighting [and] fuel to cook with."

To address such needs, Hsu and her fellow D-Lab: Energy instructor, Amit Gandhi SM '14, work with partners in El Salvador and Brazil seeking out energy-related challenges for students to address through technology. This past spring, students explored ways to convert human waste into cooking fuel, investigated how to power an engine with fruit pits, and laid the groundwork for harnessing river power to run a generator.

"We work in one really remote Amazon community [where] … people are spending 30% of their income on [diesel fuel for] generators for electricity," says Gandhi, a PhD candidate in mechanical engineering. "We're looking at ways to use renewable sources."

Accessible technology

The semester-long class developed at MIT's D-Lab (Development through Dialogue, Design, and Dissemination) begins by introducing students to a wide range of energy technologies, from bio-waste charcoal briquettes to wind turbines and solar cells. "There's a lab every week on a different renewable energy. Students actually make solar panels; they make solar water heaters. They're not only learning about the technology but getting shop experience," Hsu says.

Photos courtesy of Maya Ramachandran, MIT

Maya Ramachandran '16 and graduate student Richard Li assemble a kiln to burn acai pits in Brazil. The goal of this task was to turn the pits—a local waste product—into charcoal that could fuel a gasifier, ultimately producing a fuel gas with the potential to run an engine, thereby producing electricity. The community in Brazil currently spends nearly a third of its income on diesel fuel for generators.

D-Lab: Energy also teaches students how to talk clearly about energy options with non-technical people, Hsu says. "We find students have taken a lot of courses but can't necessarily talk about energy at a level others can understand."

These skills are immediately put to use as the students are grouped into teams and assigned projects focused on aiding specific communities in Brazil and El Salvador. After conducting some initial research, the teams spend spring break abroad, talking to community members and investigating the real-world conditions their innovations are designed to address. While generating electricity was the main concern in Brazil, for example, the community in El Salvador had electricity but very limited access to running water.

Maya Ramachandran '16 stands on the raised wooden walkways that make it possible to navigate through the wet and muddy Amazonian region of Brazil. Learning about the challenging conditions common in developing countries was a key lesson of the MIT class D-Lab: Energy.

Photos courtesy of Libby Hsu, MIT

Patricia C. Mayer SB '14 works with Geovany Moreno, an employee of D-Lab partner organization ASAPROSAR, digging the trench for a biodigester in El Salvador. The biodigester will enable a family to convert animal and plant waste into methane gas, which can be substituted for propane as a cooking fuel.

MIT students helped build this bag-style biodigester to provide cooking fuel for a family in El Salvador. The biodigester generates methane gas through the anaerobic decomposition of animal and plant waste within the bag.

"We're very privileged here [in the United States], and to see the conditions there, it put things in perspective," says Patricia C. Mayer SB '14, a graduate student in chemical engineering who traveled to El Salvador.

"The way they live is completely different from anything here," says Maya Ramachandran '16, a double major in biology and management, who visited the Amazonian village in Brazil. "The whole community is houses on the river. … Kids would paddle on boats to other houses."

Learning to adapt to conditions on the ground is an important lesson for students interested in working in the developing world, Gandhi says. "If you forget your pliers here [in the United States], it's easy to get a new one. If you forget one on site, you've got to improvise," he says.

Students also quickly discover that conditions in the field do not always meet expectations. For example, the team working on hydropower arrived in Brazil to discover that the local river currents were too slow to drive their turbines. The students had to adapt the project to use water from a local tilapia farm instead. Another team, working on a system to convert human waste to fuel in El Salvador, discovered that animal waste was also available—which was actually a major plus for their purposes.

"What I learned was, coming up with the technology isn't always the hardest part—it's more communicating with the people who are going to use it," Mayer says.

Fossil-fuel alternatives

After their fact-finding week abroad, the students returned to MIT to finalize their designs and build prototypes of their energy-generating technologies.

This year's teams built:

- A "gasifier" capable of turning charcoal made from acai pits (a local waste product in the Amazon region of Brazil) into carbon monoxide, a fuel gas with the potential to run a modified diesel engine;
- A latrine designed to work with an anaerobic waste management system called a biodigester. The system would enable a family in El Salvador to use the decomposition gases generated by the breakdown of feces and plant waste to produce methane gas as a cooking fuel; and
- A mockup of a simple hydropower turbine that could be used to generate electricity from a Brazilian tilapia farm.

"I really enjoyed this class because it was extremely hands-on," Ramachandran says. "I learned a ton… about energy, about working with people from different cultures, about how to use tools, and how to start a project and see it through from beginning to end."

Ramachandran says the class even changed her career aspirations. "Taking this class made me realize I really enjoy working with the developing world," she says. "I want to stay involved with international work."

Mayer says the class piqued her interest in pursuing an energy-related career. A chemical engineer, she says she is contemplating working with biofuels. "I learned there are many ways to go about producing energy for daily living that don't involve fossil fuels," she says.

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By Kathryn M. O'Neill, MITEI correspondent

Benefits flow from pilot energy internship program

As a Sustaining Member of the MIT Energy Initiative (MITEI), Bosch has engaged in research collaborations with MIT faculty since 2008. But Aleksandar Kojic SM '98, PhD '01, department head of Energy Technologies at the Bosch North America Research and Technology Center, envisioned something more: "We wanted to enhance the collaboration and felt we could strengthen our ties if MIT graduate students worked in our facilities," he says.

Kojic's aspiration was realized in summer 2014 with a successful pilot test of MITEI's US internship program. Three graduate students, selected by Bosch representatives and MIT faculty advisors, dove into energy research projects at Bosch laboratories in Palo Alto, California, and Cambridge, Massachusetts, with MITEI coordinating the logistics of transportation, lodging, and paperwork. "We wanted students to get the most out of their experiences," says Christie Ko, MITEI assistant director for member relations. "Running an internship program is a big undertaking, and in this test drive we aimed to do it right."

Based on the reactions of students and administrators, the trial run of the program did just that. "It was very exciting working there," says Max Zheng Qu, a third-year PhD candidate in mechanical engineering stationed in Palo Alto for the summer. Qu researched modeling and controls for an improved efficiency gasoline combustion engine. After completing the project, he says, "I feel proud because I developed something that can work on real hardware."

Eric Hontz, a fifth-year PhD candidate in physical chemistry, says his Cambridge-based internship changed him. He was engrossed in the details of debugging and extending sophisticated software-

Photos: Justin Knight

Pierre Bi of mechanical engineering discusses his Bosch project, which focused on developing models and parameter estimation algorithms to guide the development of lithium ion cells with higher efficiency and faster charging capability.

computer coding essential to the high-speed computation Bosch requires for developing next-generation, solid-state battery storage. "The internship opened my eyes to a whole other side of computer programming that is pure thought experiment," he says. "It's a kind of problem solving that is truly joy-giving and that I learned I am well suited for."

Pierre Bi, a second-year master's student in mechanical engineering from Switzerland, found the pace of Bosch R&D "very refreshing." His summer work at the Palo Alto facility involved developing and demonstrating software methods for monitoring the state and parameters of lithium ion batteries and ensuring that maximum energy can be extracted from these batteries safely without diminishing their capacity. The research was designed to serve as a building block in his master's studies. Bi relished participating in a fast-moving team focused on product development. "Seeing how research is conducted in industry was my main takeaway from the summer," he says.

Providing a supplement to the academic research experience is one of the primary reasons for undertaking the program. "The internship gives graduate students a lot more relevance to the work they're doing at MIT, showing them it isn't just an ivory tower intellectual pursuit, but research with great application potential," says Dr. Anuradha Annaswamy, senior research scientist in the Department of Mechanical Engineering and Bi's thesis advisor. Her multi-year project with Bosch spawned Bi's thesis work and his internship there. "It gives students more motivation and a rationale for why they're doing what they're doing at MIT, and helps them figure out what their place will be in the larger canvas of research," she notes.

During his Bosch internship, Max Zheng Qu of mechanical engineering worked on physics-based models and control strategies for advanced high-efficiency gasoline engines.

"We [at Bosch] have a driving motivation to build a relationship with MIT students," says Kojic, "both in terms of the specific talents and expertise they bring from a short-term perspective, and because of their potential recruitment in the long term." Through the internship program, Bosch provides graduate students with hands-on experience as well as a preview of a career at Bosch.

Boris Kozinsky BS '00, PhD '07, senior scientist leading the Bosch Research and Technology Center in Cambridge and Eric Hontz's supervisor, attests to the immediate benefits of the internship: "This summer, Eric really ran with the project to develop an automation platform for our battery work, and now we have a new set of capabilities we didn't have before."

This is the kind of progress MITEI Director Robert Armstrong likes to see. "Since MITEI began, we have been working to build a population of students working on energy-related research problems," he says. "Now, in addition to filling the pipeline, there's the additional need to connect students to great careers where they can actually contribute to the creation of new products. Industry is the place for that work, and these internships provide a novel opportunity."

There is little chance that the three MIT graduate students piloting MITEI's US internship program will squander this opportunity. Bi is returning to MIT with the results of his summer work, which will be incorporated soon into his master's thesis. He also carries memories of a "warm and friendly" Palo Alto workplace, which will figure in the coming year as he ponders his professional options. The internship, he says, has brought him to "a crossroads in deciding a career path."

Qu, whose graduate studies revolve around developing adaptive controls for an experimental aircraft, says that his Bosch project gave him "another perspective into areas where my research work can be applied." After this summer's experiences, he says he is "increasingly confident of pursuing an industrial career." An airplane enthusiast, Qu also fulfilled a childhood dream this summer and started flying lessons. His professional goals now involve pursuing "cutting-edge, exciting research" within the aviation industry. His entire California experience paid off, says Qu: "I really cherished my time there."

This year, Hontz will be completing his PhD involving theoretical work on organic photovoltaics and LEDs. But following this summer's internship, he has a different sense of career possibilities. He discovered he really enjoyed delving deep into coding, especially the "quick rewards that come from breaking up problems into well-defined chunks." Hontz realized that academic research, with its sometimes open-ended questions and longer timelines, may not be the best course for him. This was, he says, "a valuable lesson to learn." Now, Hontz says, his "first choice is doing something with programming, in the service of energy." And should Bosch come calling after graduation, he adds, "I would highly consider a position with them."

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By Leda Zimmerman, MITEI correspondent

Eric Hontz of chemistry worked with Bosch on the computational design of materials for electrochemical energy storage, with a focus on crystalline and amorphous materials for lithium ion battery cathodes and electrolytes.

MIT students tackle summer research head-on, together

Every year, large numbers of MIT students participate in the Undergraduate Research Opportunities Program (UROP), seizing the chance to lend their skills to cutting-edge research. During summer 2014, five MIT students—Gloria Hyun, Rebecca Steinmeyer, Jean Bauer, Stephanie Guo, and Amelia Helmick—were supported in their research endeavors by Schlumberger, a Sustaining Member of MITEI. While Helmick worked with Schlumberger on a separate materials-related project, the other four students had the chance to collaborate with each other—an exceptional research opportunity. Each tackled a different facet of a single task: how to monitor and maintain the down-hole structural integrity of oil wells. At an August 14 session at the Schlumberger offices, Hyun, Steinmeyer, Bauer, and Guo presented their findings.

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By Francesca McCaffrey, MITEI

Photos: Justin Knight

Gloria Hyun '15 of civil and environmental engineering studied the preparation and characteristics of varying formulations of cement with the use of expanding agents.

Not pictured: Stephanie Guo '17 of mechanical engineering studied the use of carbon nanotubes as piezoresistive sensors in cement.

Amelia Helmick '15 of materials science and engineering worked independently in the lab on a project related to designing and understanding the properties of advanced materials for oil-field applications.

Jean Bauer '17 of mechanical engineering (left) designed a mathematical model to describe and predict the electrical behavior of cement nanocomposites containing carbon nanotubes. Rebecca Steinmeyer '17 of mechanical engineering worked in the arena of conceptual design. She devoted her energies to seeking an efficient and effective way to run electrical measurements of cement nanocomposites down-hole in a hypothetical oil well.

Cambridge high school students are winners in international Eni competition

Gabe Bamforth and Eric Chan of Cambridge Rindge and Latin School (CRLS) were in the top-scoring group in the international Lab4Energy competition, an educational program run by Eni, a Founding Member of the MIT Energy Initiative (MITEI), and Eni Enrico Mattei Foundation, in collaboration with MITEI. Lab4Energy is designed to promote awareness of energy topics and support students seeking to pursue higher education in energy fields. Bamforth and Chan traveled to Italy with their fellow winners for sightseeing and a visit to Eni's headquarters. Bamforth, currently a senior at CRLS, said the following about his Lab4Energy experience: "I learned so much about the world from [Lab4Energy]… [T]he highlight of the trip for me was living with, talking to, and learning from kids my age from completely different backgrounds. Without [MITEI] and the Lab4Energy program, I would never have discovered the wonderful things I did." Both students are interested in future studies in energy and engineering.

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By Francesca McCaffrey, MITEI

Photo: Amy Bamforth

Left to right: Eric Chan, MITEI Eni representative Nicola De Blasio, Gabe Bamforth, MITEI Director Robert Armstrong, and Cambridge Superintendent of Schools Jeffrey Young pose for a photo at a Lab4Energy reception celebrating the young delegates.

Photo courtesy of Gabe Bamforth

Eric Chan (left) and Gabe Bamforth at the Coliseum in Rome. In addition to sightseeing, the students visited Eni's headquarters on their trip.

Real-time monitoring of building systems saves energy on campus

Designing buildings for top energy performance gets a lot of attention—from articles hailing new green technologies to awards for Leadership in Energy and Environmental Design (LEED). But usage and maintenance are major factors in how energy-efficient any building actually proves to be. That's why MIT has rolled out a new system that monitors the performance of buildings on campus and delivers the gathered data to the Department of Facilities in real time.

"There's a mindset among designers that an efficient building design will lead to an efficient building," says Nick Gayeski SM '07, PhD '10, co-founder of KGS Buildings, which developed the Clockworks software MIT is using to monitor a wide range of performance metrics. "In practice, that may or may not be true. You've got to measure and manage buildings' performance no matter how well designed they are for energy efficiencies."

Launched in 2010, the Clockworks system has already helped the Institute realize $286,000 in annual energy savings in steam, chilled water, and electricity by revealing faulty valves in one LEED-certified lab building that is only 10 years old.

"These realized benefits in a 'newer' building demonstrate the importance of installing these systems in buildings of any age," says Wade Berner, director of systems performance and turnover for MIT Facilities. "As we know, high-performance systems do not always run at peak efficiency; this system provides owners with data to guide adjustments to attain consistent desired performance."

Photo courtesy of KGS Buildings

Left to right: KGS Buildings' chief technical officer, John Anastasio, poses with company co-founders Sian Kleindienst SM '06, PhD '10, and Nick Gayeski SM '07, PhD '10. Co-founder Stephen Samouhos '04, SM '07, PhD '10 is not pictured.

Doing more with data

At MIT, Facilities continually monitors just over 300,000 data points from a wide range of equipment across campus, including everything from air handlers to temperature sensors, according to Aaron Sellers, assistant manager for repair and maintenance in the Department of Facilities. "One air handler may have 20–100 data points associated with it. It depends on the complexity of the equipment design," says Sellers, explaining that most automation systems, even home thermostats, are equipped to capture data about the environment (such as temperature readings), but in practice the data typically aren't used for anything more than the functioning of the individual piece of equipment. "[KGS] came up with this idea to do more with [those] data," he says.

The Clockworks monitoring system provides automated fault detection and diagnostics on a cloud-based platform that enables MIT staffers to see at a glance how equipment is performing. "[These] data [are] immediately available online—we can see the top issues," Berner says, noting that Clockworks presents staff with inferences about where troubles might lie. "Their system narrows it down. At a minimum, you get to the [malfunctioning] piece of equipment."

Clockworks also stores data over an extended period of time—providing "trend data," or the historical record of how well equipment is functioning. Having such data greatly improves staffers' ability to troubleshoot problems and analyze energy efficiency.

"What everyone needed to know was trend data," says Sellers, who worked with the company's founders when they were still perfecting their technology as doctoral students in MIT's Building Technology Program back in 2009–2010. "If something happened that was catastrophic—say a piece of equipment

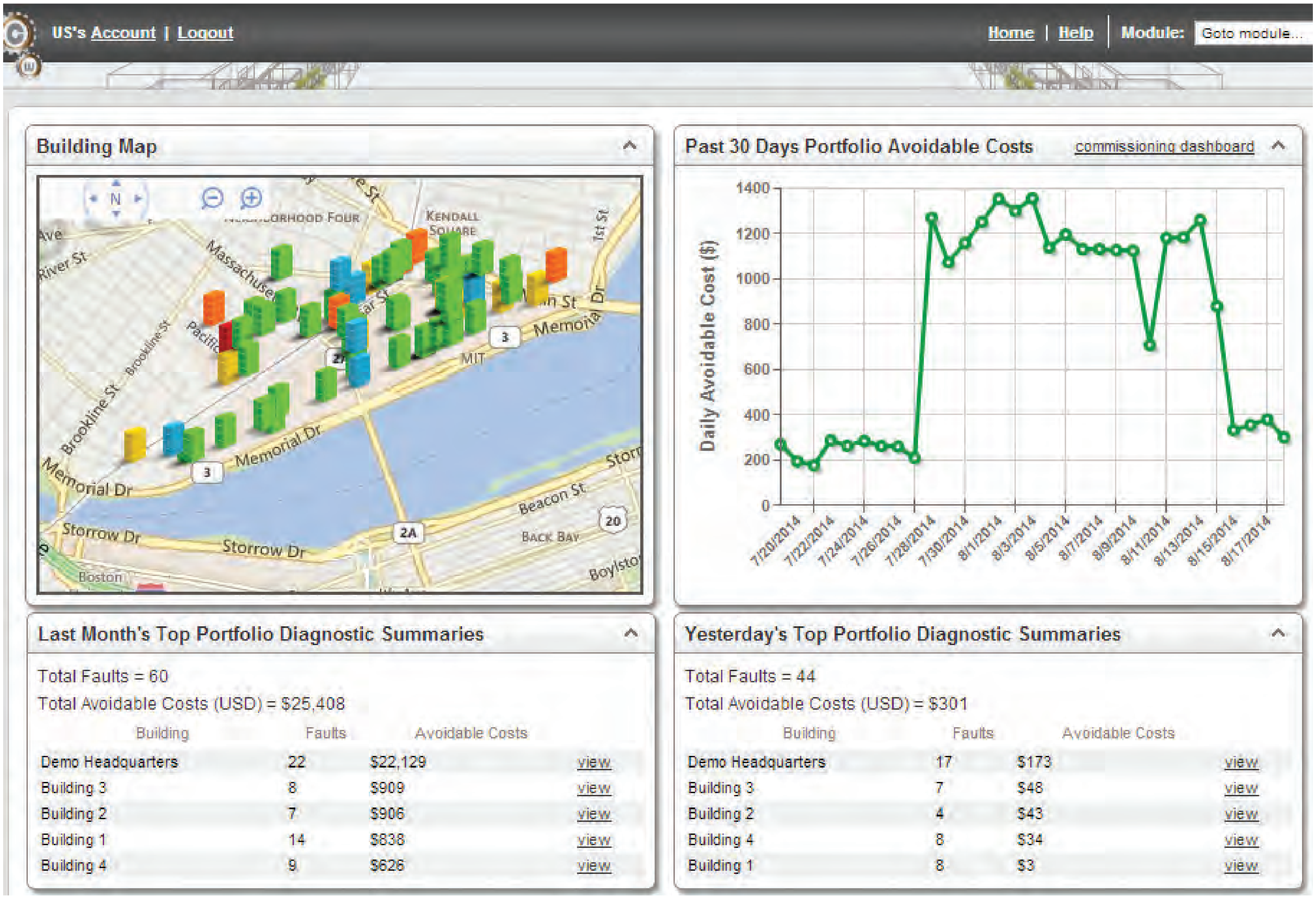

Image courtesy of KGS Buildings

This mockup shows what the Clockworks energy report for MIT looks like online. The numbers shown are for illustration purposes only.

failed on a Friday night of a long weekend—you would come in on Tuesday to find out what happened and wouldn't know because the data trend didn't go back that far," he says. Since KGS stores data for three years, MIT can now trace issues back in time. "That allows us to put together a picture of what happened."

Clockworks also holds promise for streamlining MIT's preventive maintenance program, Sellers says, because real-time monitoring enables maintenance work to be performed based on need rather than a set schedule. "Maybe we don't have to change filters twice a year. KGS could send out data showing they're not dirty until we're nine months out," he says. "Or, it could say they're getting dirty really fast, we should be changing them every three months. That helps the equipment in the long run, and if we can maintain the efficiency of equipment, that equipment will continue to work 20, 30 years down the road."

Improving the efficiency of equipment and quickly repairing system failures ultimately lead to energy savings. MIT is now working with KGS to document these savings in kilowatt-hours. Doing so will enable the Institute to gain extra benefits though Efficiency Forward, a partnership with the utility NSTAR that provides incentives for reducing electricity use.

MIT startup

Energy efficiency is a key mission for KGS, according to its founders—Gayeski, Sian Kleindienst SM '06, PhD '10, and Stephen Samouhos '04, SM '07, PhD '10. The three first worked together on MIT's team for

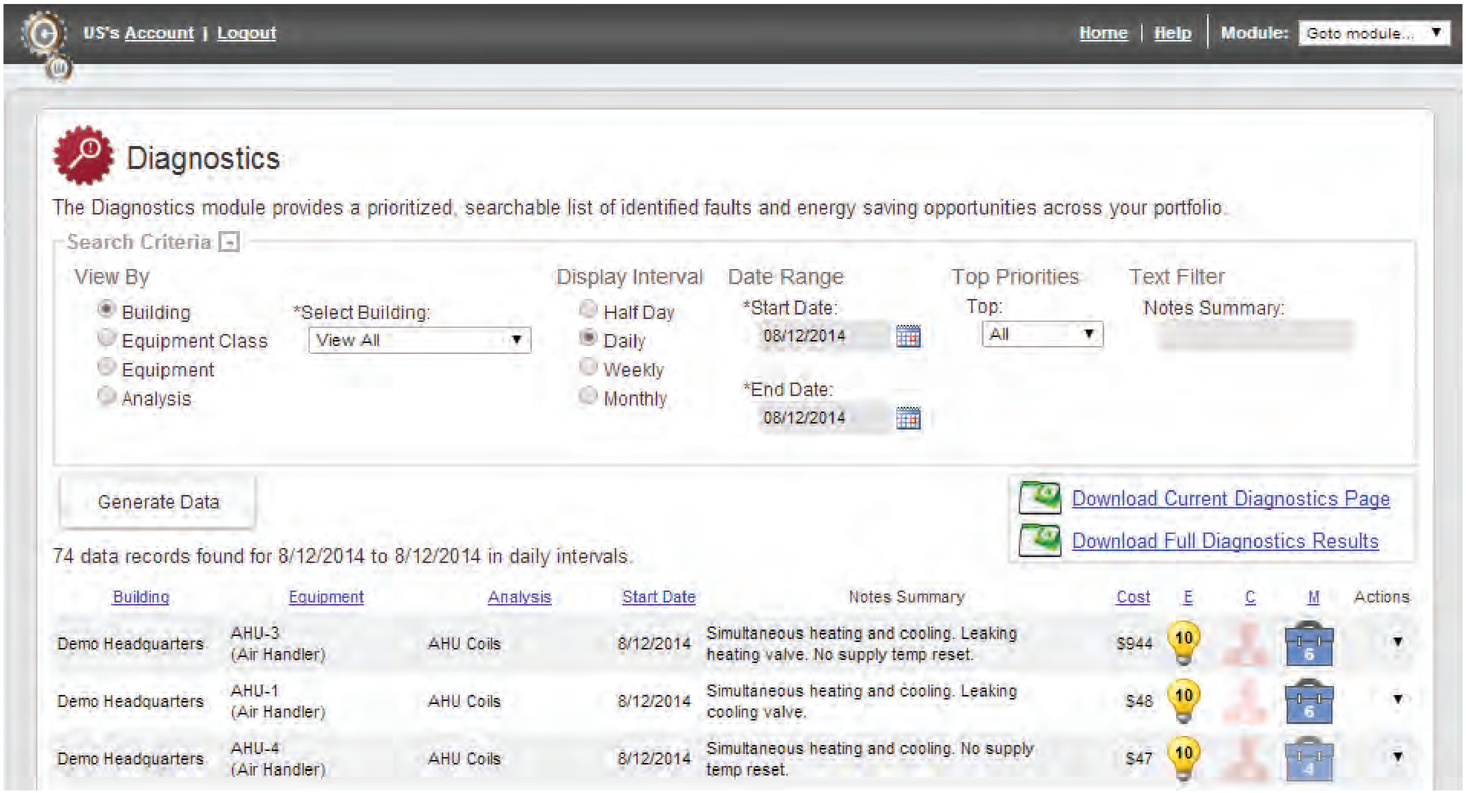

Image courtesy of KGS Buildings

This mockup shows a sample Clockworks report identifying and diagnosing energy waste, uncomfortable conditions, and maintenance issues in selected buildings. The numbers shown are for illustration purposes only.

the 2007 Solar Decathlon, an international solar-powered house competition, and they soon found they shared an ambition—to make buildings better.

"We wanted to have an impact on energy use," Gayeski says. "Why aren't buildings energy-efficient today? It's not all about what can we build. We are in the developed world; these buildings are already consuming energy. So, we decided we'd better deal with existing building stock."

Samouhos was already developing a building systems fault detection program for his PhD research, so the three students began brainstorming ways to expand that idea into a business. MIT worked with KGS to help it pilot the software on one lab building and offered feedback for improving the product. "Every suggestion we made they took to make the data more usable," Berner says.

In 2011, MIT expanded the use of Clockworks to five buildings, then to more than 60 in 2012. Today, KGS monitors 84 buildings on campus and is continuing to expand as a company. Headquartered in Somerville, Massachusetts, the business has a staff of 16, and Clockworks is being used to monitor approximately 350 buildings in 12 countries.

Much of the credit for this success is due to MIT, Gayeski says. In addition to getting practical assistance from MIT Facilities, the three KGS founders received guidance from their academic advisors: architecture professor Leslie Norford (Gayeski), former associate professor of building technology Marilyne Andersen (Kleindienst), and Leon R. Glicksman, who is professor of building technology and mechanical engineering and served as co-chair of the MIT Energy Initiative's Campus Energy Task Force (Samouhos).

"MIT was the place that took a chance on us," Gayeski says.

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By Kathryn M. O'Neill, MITEI correspondent

Class envisions MIT reaching "net zero" emissions growth

What would it take for MIT to stabilize its overall carbon emissions despite projected growth in the Kendall Square area? Could MIT in the long run become a "net zero" community—one in which energy consumption is balanced by renewable energy production and efficiency? MIT students tackled that question last spring—and, while they didn't produce a definitive answer, they did get an education in the kind of work required to find one.

"There are a lot of things to take into account to come up with an energy-saving plan," says Associate Professor Christoph F. Reinhart of architecture, who developed the project for 4.433 Modeling Urban Energy Flows for Sustainable Cities and Neighborhoods. "A good part of the class was dedicated to learning how to model multiple environmental performance aspects of a campus or neighborhood, including energy use in buildings, access to daylight, and walkability."

Getting to net zero is a hot topic these days, particularly in Cambridge where in 2013 citizens petitioned to require new buildings over 25,000 square feet to generate net zero greenhouse gas emissions. But Reinhart says it's not realistic to imagine every building can generate the power it needs with renewables. "If you look at documented net zero buildings, there are less than 400 in the whole world," he says, noting that even a roof full of solar panels cannot meet the energy demands of a large or energy-intensive building.

That's why Reinhart, who heads MIT's Sustainable Design Lab, is investigating the idea of a net zero *community*—one in which power-hungry buildings are balanced by efficiencies or green generation elsewhere in the community.

In 4.433, students specifically explored whether MIT could expand its square footage without adding carbon emissions or depending on off-site green energy generation.

Students initially examined the energy demands of four campus buildings: a lab building, a residence hall, and two office/classroom buildings. "We looked at what kinds of lighting they had, occupancy, what kinds of equipment. These are all inputs that are needed to create an energy model" of a building, says Julia Sokol, a graduate student in mechanical engineering.

"We did the calculation to see what area of PV [photovoltaic] panel you would need to meet the [energy] demand of a specific building," says Nathaniel Jones, a building technology graduate student. Students found the lab building was the neediest, requiring nearly six football fields of PVs to meet its energy demands, Jones says.

MIT-designed modeling tool

The students next estimated each building's energy usage with "umi," a tool developed at the Sustainable Design Lab that links 3-dimensional building geometry with energy modeling. By comparing these estimates with actual usage and adjusting the models for accuracy, they extrapolated the likely usage for all MIT buildings. This enabled them to create a model of campus energy use, which they employed to explore energy performance in a variety of ways. For example, they simulated changing all single-pane windows to double pane, adding more insulation to walls, improving lighting, and adding daylighting sensors.

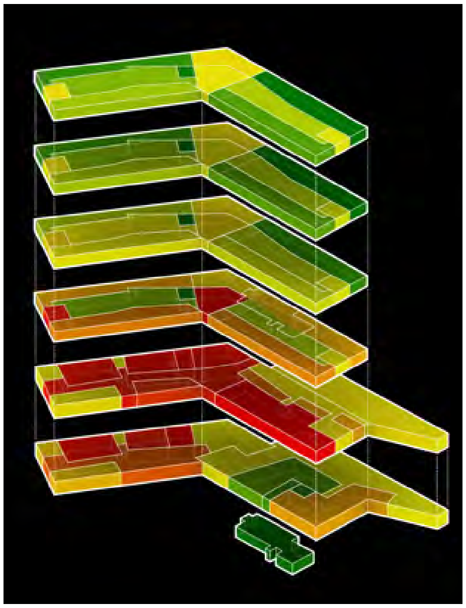

Image courtesy Manos Saratsis, Julia Sokol, Aiko Nakano, and Denise Rivas, MIT

This student-created image illustrates the intensity of energy use in one MIT office/classroom building. The intensity ranges from green (less energy) to red (more energy), as a result of such factors as occupancy and equipment loads.

Students ultimately presented their findings to Julie Newman, director of MIT's Office of Sustainability, and others involved in campus sustainability efforts. "Professor Reinhart's course demonstrated that students can connect theory to real-time sustainability challenges," Newman says. "The findings from the students' project will be shared with the MIT Net Zero working group to inform their recommendations."

"The class was a nice way to get some data into these discussions," Reinhart says.

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By Kathryn M. O'Neill, MITEI correspondent

C3E spotlights women leaders in clean energy careers

Women are accustomed to being in the minority at clean energy sector conferences—and in most science and engineering careers, for that matter. But for participants at the C3E Women in Clean Energy Symposium, which took place at MIT on September 16 and 17, 2014, the tables turned.

"This symposium is about strengthening a network," said Martha Broad, executive director of the MIT Energy Initiative (MITEI), which co-hosted the conference with the US Department of Energy (DOE). "We need each other. And we need smart, collaborative leadership to take us into the next century, because we know we're all confronting the same big challenge: the need for sustainable, affordable, and plentiful sources of clean energy."

For three years now, the C3E initiative—which stands for Clean Energy Education and Empowerment—has worked to advance women's leadership in clean energy, ranging from education, research, and advocacy to business, law, and international development. Launched as part of the Clean Energy Ministerial (cleanenergyministerial.org) in 2010, the C3E program has been led by DOE in partnership with MITEI.

"We know that the transition to a clean energy future requires contributions and support from all members of society," said Ahsha Tribble, senior advisor to the US secretary of energy. "Today, we see many women making a positive impact on the clean energy field, but there are still too few, particularly at top leadership levels. Our C3E initiative is an effort to shift the status quo, to build the talent pipeline of women prepared to contribute to and influence the clean energy field."

Photos: Justin Knight

Martha Broad, executive director of the MIT Energy Initiative, welcomes attendees to the third Women in Clean Energy Symposium. In her remarks, she stressed the need to strengthen and expand the network of women who are working—in academia, industry, and government—on various approaches to providing sustainable, affordable, and plentiful sources of clean energy.

Designed to help women working in the clean energy sector build the skills and professional networks needed to succeed, this year's symposium focused on clean energy issues at the city level. Throughout the two-day event, women participated in panel discussions on topics that included making wise energy investments in an era of constraints; the future grid—increased clean energy integration and reliability; and energy, mobility, and the shape of future cities.

Keynote addresses were delivered by Heather Foust-Cummings of the Catalyst Research Center for Equity in Business Leadership, a knowledge leader on gender, leadership, and inclusive talent management; and by Christine Todd Whitman, former governor of New Jersey and former administrator of the US Environmental Protection Agency.

"Energy hasn't usually been thought of as a woman's field," Todd Whitman said during her speech. "I believe that is something we need to correct because all of us have a responsibility to engage in the debate about our nation's clean energy future."

A highlight of the symposium was the presentation of the C3E awards, which recognize women for outstanding leadership and accomplishments in clean energy. In addition to the recognition, each mid-career award winner receives a cash prize of $8,000 supported by MITEI. This year's

Susan Tierney, a senior advisor at Analysis Group, accepts the Lifetime Achievement Award at the C3E symposium. Tierney, an energy policy and economics expert specializing in the electric and gas industries, has been a longtime leader in energy, environmental, and climate change issues. The Lifetime Achievement Award is presented by the C3E Ambassadors, a group of about 30 distinguished leaders in energy who serve the program as spokespeople and mentors.

Left to right: At a poster session, Caroline Burkhard Golin, a graduate student at Georgia Institute of Technology, describes her research to Joan Wills, a program director at Cummins—a sponsor of the 2014 C3E symposium and an Associate Member of MITEI—and Elena Alschuler, project manager of building technologies at the US Department of Energy. Golin's poster—"Policy Solutions: Resilience, Sustainability, and Improved Societal Outcomes: Water and Energy Strategies for Atlanta"—was among the three winners of the nationwide C3E poster competition. Wills is a C3E Ambassador, and Alschuler moderated a symposium panel on making wise energy investments in an era of constraints.

winners work in a wide range of energy careers and come from a variety of backgrounds—running the gamut from an advocate working to defend the Kansas Renewable Portfolio Standard to a researcher driving progress on smart grids to a community college professor working with educators around the country to integrate sustainable energy into their programs.

The 2014 winners in C3E's eight categories are as follows:

Advocacy Leadership:
Dorothy Barnett
Executive Director,
Climate and Energy Project

Business Leadership:
Zadhya Mohammed
Head of Sales,
Wind Service, Americas, Siemens

Education Leadership:
Debra Rowe
Professor,
Oakland Community College

Entrepreneurial Leadership:
Lisa Dyson
Chief Executive Officer,
Kiverdi, Inc.

Government Leadership:
Ghita Levenstein Carroll, PhD
Sustainability Coordinator,
Boulder Valley School District

International Leadership:
Ashley Murray Muspratt
Founder and CEO,
Waste Enterprisers Ltd.,
Waste Enterprisers Holding
and Pivot Kenya

Law and Finance Leadership:
Phuong Young Phillips
Assistant General Counsel,
SolarCity Corporation

Research Leadership:
Sila Kiliccote
Leader,
Grid Integration Group,
Lawrence Berkeley National Laboratory

In addition, each year C3E honors one woman with a Lifetime Achievement Award. This year, that honoree is Susan F. Tierney, a senior advisor at Analysis Group and former assistant secretary for policy at DOE who has been a bipartisan leader in energy, environmental, and climate change issues for decades in academia, government, and business.

More information on the award winners is online at c3eawards.org/winners. Go to C3Enet.org to watch a video of the 2014 C3E symposium and to join the online community of women working in clean energy worldwide.

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By Caroline McGregor, DOE Office of International Affairs, and Vicki Ekstrom, MITEI

The 2014 C3E Women in Clean Energy Symposium was sponsored by Chevron, Cummins, GE ecomagination, Lockheed Martin, Massachusetts Clean Energy Center, National Grid, SolarCity, and Walmart.

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 129 seed grant projects across the campus as well as fellowships for more than 300 graduate students and postdoctoral fellows 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; and outreach activities, including seminars and colloquia.

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Learning first-hand the challenges of meeting energy needs in developing countries

In spring 2014, students in a class called D-Lab: Energy learned to analyze, design, and build prototypes of alternative energy technologies for the developing world. Their projects aimed to convert human waste into cooking fuel, to power an engine with fruit pits, and to harness river power to run a generator. During spring break, they traveled to selected communities in Brazil and El Salvador, where they talked to residents and investigated the real-world conditions their innovations were designed to address. While there, they experienced some of the special challenges of working in developing countries. Here, Maya Ramachandran '16 stands on raised wooden walkways that make it possible to navigate through the wet and muddy Amazonian region of Brazil. For more details, see page 32.
Photo courtesy of Maya Ramachandran, MIT