Energy Futures

MIT ENERGY INITIATIVE   MASSACHUSETTS INSTITUTE OF TECHNOLOGY   AUTUMN 2017

Upcoming events

Mark your calendars for these upcoming MITEI seminars. All are held on the MIT campus. Please visit energy.mit.edu/events for the latest information about these and other MITEI activities.

December 12, 2017

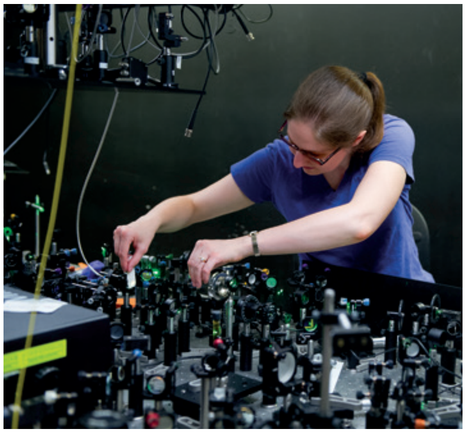
"Achieving the Paris climate goals: The engine of ambition"
Nathan Hultman
Associate professor at the School of Public Policy
University of Maryland

March 6, 2018

Daniel Kammen
Professor of energy and resources and of public policy
University of California, Berkeley

April 10, 2018

Michael Wasielewski
Clare Hamilton Hall Professor of Chemistry
Northwestern University



On the cover
In Professor William Tisdale's lab, Rachel Gilmore PhD '17 prepares a specially built ultrafast laser setup for tests of quantum dot materials that she and her colleagues are designing for high performance in solar cells, LEDs, and more. See page 11. Photo: Stuart Darsch

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Energy Futures

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MITei
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A letter from the director

Dear friends,

Welcome to the newly redesigned *Energy Futures*. As you'll read in this issue, MITEI is celebrating our first 10 years and looking ahead to the coming decades. Reflecting on the research, student engagement, and contributions to policy dialogue that have made MIT's energy community so extraordinary, we wanted this publication to showcase these dedicated people and their innovative projects as vividly as they deserve.

With this redesign, we're also reaffirming our commitment to bringing you compelling articles that we hope not only inform but inspire: stories of researchers advancing technologies and methodologies that can help tackle the dual challenges of climate change and affordable energy access; students and alumni who are making valuable contributions locally and abroad; and initiatives here at MIT that are aimed at furthering public understanding of the most urgent energy and climate issues of our time.

Our cover story for this issue is a prime example of MIT researchers' work to advance energy-related technologies for a low-carbon future. Professor William Tisdale and his team have been working on quantum dot materials that can—in theory—be tuned for high performance in specific energy devices. But engineering the necessary nanoscale structure has proved challenging. Now, the team has produced films made of quadrillions of nanocrystals in a configuration that will allow the rapid flow of current through solar cells as well as through thermoelectric systems that turn waste heat into electricity (page 11).

MITEI's research, education, and outreach programs are spearheaded by Professor Robert C. Armstrong, director. Photo: Kelley Travers, MITEI

Translating energy research and data into actionable information for industry and policymakers is another core element of MITEI's mission. Jennifer Morris, a research scientist with the MIT Joint Program on the Science and Policy of Global Change, has developed a tool that can help planners in power companies decide what kinds of new generating facilities to build, given the uncertainty around future limits on carbon emissions. Her analyses show that including non-carbon generation in the mix will reduce the long-term economic risks of decisions made today (page 17).

In this issue, you'll also hear from faculty members like Ruben Juanes, whose new class helps students visualize complex energy processes and applications with a hand-held "laboratory-on-a-chip" (page 39), and students whose summer energy internships with leading companies took them to Germany, India, and Spain (page 42). Assistant Professor David Hsu shares a preview of changes that will make the Energy Studies Minor more flexible and accessible to all undergrads (page 37), and Low-Carbon Energy Center co-directors discuss the work of the advanced nuclear energy systems and electric power systems research centers (page 8), to mention a few of the articles in this issue.

We hope you enjoy our new look and the articles herein. Please get in touch with any feedback or thoughts for future issues, and thank you, as always, for reading about the work of our energy community.

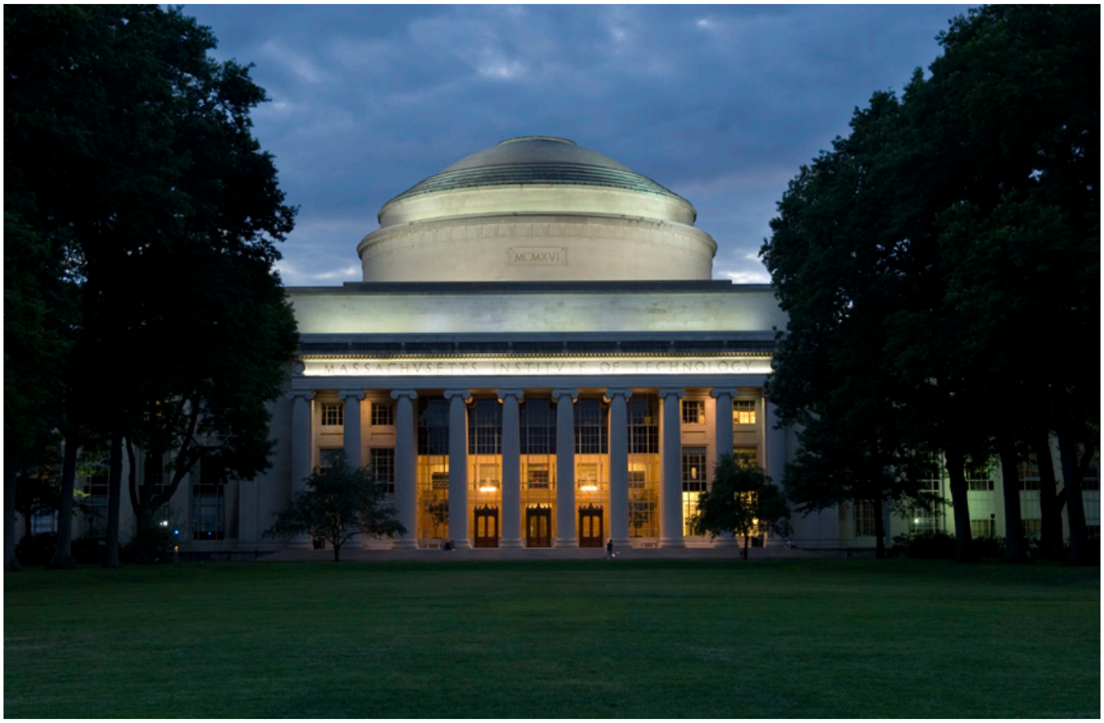
Warm regards,

Robert C Armstrong

Professor Robert C. Armstrong
MITEI Director

November 2017

CELEBRATING 10 YEARS



Strong current of energy runs through MIT

Celebrating 10 years of MITEI

Kathryn M. O'Neill, MITEI correspondent

On any given day at MIT, undergraduates design hydro-powered desalination systems, graduate students test alternative fuels, and professors work to tap the huge energy-generating potential of nuclear fusion, biomaterials, and more. While some MIT researchers model the impacts of policy on energy markets, others experiment with electrochemical forms of energy storage.

This is the robust energy community at MIT. Developed over the past 10 years with the guidance and support of the MIT Energy Initiative (MITEI)—and with roots extending back into the early days of the Institute—it has engaged more than 300 faculty members and spans more than 900 research projects across all five schools.

Photo: Christopher Harting, courtesy MIT Image Library

In addition, MIT offers a multidisciplinary energy minor and myriad energy-related events and activities throughout the year. Together, these efforts ensure that students who arrive on campus with an interest in energy have free rein to pursue their ambitions.

Opportunities for students

"The MIT energy ecosystem is an incredible system, and it's built from the ground up," says Robert C. Armstrong, a professor of chemical engineering and the director of MITEI, which is overseen at the Institute level by Vice President for Research Maria Zuber. "It begins with extensive student involvement in energy."

Opportunities begin the moment undergraduates arrive on campus, with a freshman pre-orientation program offered through MITEI that includes such hands-on activities as building motors and visiting the Institute's nuclear research reactor.

"I got accepted into the pre-orientation program and from there, I was just hooked. I learned about solar technology, wind technology, different types of alternative fuels, biofuels, even wave power," says graduate student Priyanka Chatterjee SB '15, who minored in energy studies and majored in mechanical and ocean engineering.

Those who choose the minor take a core set of subjects encompassing energy science, technology, and social science. Those interested in a deep dive into research can participate in the Energy Undergraduate Research Opportunities Program (UROP), which provides full-time summer positions. UROP students are mentored by graduate students and postdocs—many of them members of the Society of Energy Fellows—who are also conducting their own energy research at MIT.

Students are at the heart of MIT's vibrant energy community. Here, incoming freshmen take a MITEI-sponsored tour of a local wind turbine facility. Photo: Chelsey Meyer, MITEI

For extracurricular activities, students can join the MIT Energy Club—among the largest student-run organizations at MIT, with more than 5,000 members—and compete for the MIT Clean Energy Prize, a student competition that awards more than $200,000 each year for energy innovation, among many other opportunities.

The Tata Center for Technology and Design, now in its sixth year, extends MIT's reach abroad, supporting 65 graduate students every year who conduct research central to improving life in developing countries—including lowering costs of rural electrification and using solar energy in novel ways.

Students have other opportunities to conduct and share energy research internationally as well. Valerie Karplus, an assistant professor of global economics and management, says, "Over the years, MITEI has made it possible for several of the students I've advised to engage more directly in global energy and climate policy negotiations. In 2015, I joined them at the Paris climate conference, which was a tremendous educational and outreach experience for all of us."

Holistic problem-solving

"What is important is to provide our students a holistic understanding of the energy challenges," says MIT Associate Dean for Innovation Vladimir Bulović. Karplus adds, "There's been an evolution in thinking from 'How do we build a better mousetrap?' to 'How do we bring about change in society at a system level?'"

This kind of thinking is at the root of MIT's multidisciplinary approach to addressing the global energy challenge—and it has been since MITEI was conceived and launched by then-MIT President Susan Hockfield, a professor of neuroscience. While energy research has been part of the Institute since its founding (MIT's first president, William Barton Rogers, famously collapsed and died after uttering the words "bituminous coal" at the 1882 commencement), the concerted effort to connect researchers across the five schools for collaborative projects is a more recent development.

"The objective of MITEI was really to solve the big energy problems, which we feel needs all of the schools' and departments' contributions," says Ernest J. Moniz, a professor emeritus of physics and special advisor to MIT's president. Moniz was the founding director of MITEI before serving as US Secretary of Energy during President Obama's administration.

"Great technology by itself can't go anywhere without great policy," says Hockfield. "It's the economics, it's the sociology, it's the science and the engineering, it's the architecture—it's all of the pieces of MIT that had to come together if we were going to develop really impactful sustainable energy solutions."

This multidisciplinary approach is evident in much of MIT's energy research—notably the series of comprehensive studies MITEI has conducted on such topics as the future of solar energy, natural gas, the electric grid, and more.

"To make a better world, it's essential that we figure out how to take what we've learned at MIT in energy and get that out into the world," Armstrong says.

A look at 10 years of the MIT Energy Initiative, by the numbers. Graphic: Jenn Schlick, MITEI

Fostering collaborations

MITEI's eight low-carbon energy research centers—focused on a range of topics from materials design to solar generation to carbon capture and storage—similarly address challenges on multiple technology and policy fronts. These centers are a core component of MIT's five-year Plan for Action on Climate Change, announced by President L. Rafael Reif in October 2015. The centers employ a strategy that has been fundamental to MIT's energy work since the founding of MITEI—broad, sustained collaboration with stakeholders from industry, government, and the philanthropic and nongovernmental organization communities.

"It's one thing to do research that's interesting in a laboratory. It's something very different to take that laboratory discovery into the world and deliver practical applications. Our collaboration with industry allowed us to do that with a kind of alacrity that we could never have done on our own," Hockfield says.

For example, MITEI's members have supported more than 160 energy-focused research projects—representing $21.4 million in funding over the past nine years—through the Seed Fund Program. Projects have led to follow-on federal and industry funding, start-up companies, and pilot plants for solar desalination systems in India and Gaza, among other outcomes.

What has MIT's energy community as a whole accomplished over the past decade? Hockfield says it's raised the visibility of the world's energy problems, contributed solutions—both technical and sociopolitical—and provided "an army of young people" to lead the way to a sustainable energy future. "I couldn't be prouder of what MIT has contributed," she says. "We are in the midst of a reinvention of how we make energy and how we use energy. And we will develop sustainable energy practices for a larger population, a wealthier population, and a healthier planet."

MORE ONLINE

Want to learn more about the history and future of energy research at MIT? Find more content and view our video at energy.mit.edu/10.

MITEI Director Robert C. Armstrong: The past and future of energy research at MIT

To reflect on the last 10 years since MITEI was founded as MIT's hub for energy research, education, and outreach, *Energy Futures* asked MITEI Director Robert C. Armstrong what he sees as some of the most significant research impacts the MIT energy community has made over the past decade and what he finds most exciting for the decades to come. Here's what he shared.

LOOKING BACK…

While the horizon for the majority of energy research we do here at MIT is generally at least several decades, some researchers have already been able to translate their research into technologies and start-up companies—many with early funding support from MITEI member companies and donors. A few examples include:

- **Flexible, thin-film solar photovoltaics** that can be printed on nearly any surface—developed by Vladimir Bulović and colleagues
- **Khethworks**, a Tata Center for Technology and Design spinoff that is developing affordable irrigation for the developing world—co-founded by Katherine Taylor SM '15, Victor Lesniewski, and PhD student Kevin Simon SM '15
- The **solar-powered village-scale electrodialysis desalination system** developed by PhD candidate Natasha Wright with Professor Amos Winter to provide clean drinking water to rural, off-grid villages in India—another project originating from the Tata Center
- **Energy storage companies** including Professor Yet-Ming Chiang's 24M and Baseload Renewables, Professor Donald Sadoway's Ambri, and FastCAP Systems (which was co-founded by Riccardo Signorelli PhD '09 and Professor Joel Schindall)

Khethworks, a Tata Center for Technology and Design spinoff, is building reliable, solar-powered irrigation systems that enable customers to farm year-round.
Photo: Tata Center for Technology and Design

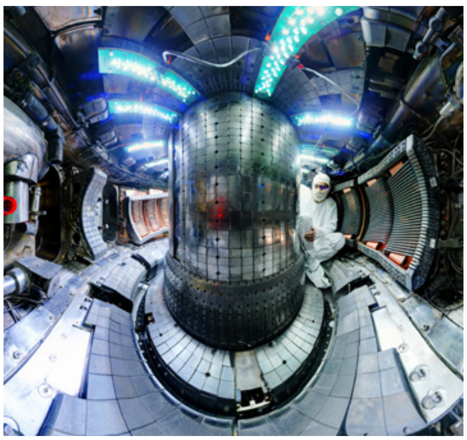
- **Keystone Tower Systems**, co-founded by Eric Smith '01, SM '07, Rosalind Takata '00, SM '06, and Professor Alexander Slocum, which has made it possible to fabricate wind turbine towers on location, making taller towers economically feasible
- Professor Kripa Varanasi's research on **engineering slippery surfaces to eliminate waste from manufacturing and consumer products**, which has led to two start-ups: LiquiGlide, focused on consumer goods and packaging applications, and Dropwise, which is developing coatings for power plants and industrial machinery to improve efficiency—co-founded with Associate Provost Karen Gleason
- The MIT-developed **tokamak fusion research reactor**, which set a record for plasma pressure and has paved the way for future fusion reactors
- **Multidisciplinary studies** such as "The Future of Solar Energy" and "Utility of the Future" that have taken a comprehensive, system-level approach to energy challenges, with recommendations for policymakers, regulators, and industry.

Professor Kripa Varanasi and his group have engineered novel surfaces and coatings that can improve the efficiency of steam turbines and desalination plants, keep ice off airplane wings and power lines, and more.
Photo: Bryce Vickmark

LOOKING AHEAD…

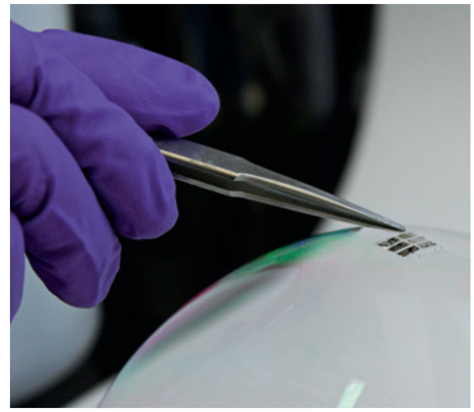
Our faculty and students are working on projects with great potential for the future. Among those that could have transformative implications for our energy system are:

- **Next-generation solar technologies** that lower manufacturing and system integration costs
- **Long-term energy storage technologies** to enable wind and solar deployment at scale



While it was in operation, the fusion experiment Alcator C-Mod at MIT (interior shown above) confined plasma hotter than the center of the sun using high-intensity magnetic fields. During its final run in fall 2016, the C-Mod reactor broke the plasma pressure record for a magnetic fusion device, producing data that are still yielding dividends. Photo: Bob Mumgaard/Plasma Science and Fusion Center

- **Design and implementation of more robust electric grids** for developing and developed nations—complemented by analysis and outreach that encourages innovative policies, regulations, and business models
- **Energy- and climate-conscious urban planning** to reduce the intrinsic energy needs of new cities and neighborhoods, helping to mitigate climate change and increase resilience while making communities more livable—from materials like less carbon-intensive concrete to renewable energy and energy efficiency technologies
- **Research into how transportation will evolve** with developments in technology, fuel, infrastructure, policy, and consumer preference, currently being examined through MITEI's "Mobility of the Future" study, expected to be published in 2019
- **New approaches to fusion** that could begin to come to fruition, such as the small-scale reactor currently being designed at MIT
- Development of **advanced nanoscale materials** engineered for high performance in devices—for example, quantum dot materials for solar photovoltaics, light-emitting diodes, and thermoelectric systems, and carbon nanotube electrodes for capacitors, batteries, and water desalination systems
- **Student and alumni research, technology, and policy development.** While we may not even know yet where our current or future students' research will take them, or what our alumni may achieve in industry, government, or academic roles, I am confident that we're preparing future innovators to meet energy and climate challenges.



To demonstrate how thin and lightweight their new flexible solar cells are, Professor Vladimir Bulović and his team draped a functional cell on top of a soap bubble—without popping the bubble. Photo: Joel Jean and Anna Osherov, MIT

A team led by Professor James Kirtley developed a portable, laboratory-scale model of a power plant for classroom use. Students can use the setup to explore how a grid behaves when use shifts and when power comes from different sources. Photo: Justin Knight

Student researchers who co-authored MITEI's *Utility of the Future* discuss the report's findings in Washington, DC. Photo: Francesca McCaffrey, MITEI

Q&As with Low-Carbon Energy Center co-directors

Kathryn M. O'Neill, MITEI correspondent

The MIT Energy Initiative continues to develop and expand its eight Low-Carbon Energy Centers, which facilitate multidisciplinary collaboration among MIT researchers, industry, and government to advance research in technology areas critical to addressing climate change. Below, the directors of the Center for Advanced Nuclear Energy Systems and the Center for Electric Power Systems Research discuss their vision for transforming the energy system. This feature is the latest in a series of Q&As with directors of the centers.

Center for Advanced Nuclear Energy Systems

Directors: Jacopo Buongiorno, TEPCO Professor of Nuclear Science and Engineering, and John Parsons, senior lecturer in the MIT Sloan School of Management

How can advanced nuclear energy systems research help the world reach its goal of reducing carbon emissions?

Today, fossil fuel–based power generation and transportation systems are major contributors to the all-time-high levels of atmospheric carbon dioxide (CO_2). To address the potentially devastating impacts of climate change, future systems will need to produce very low or even zero carbon emissions—and scale up within a short time horizon: less than 35 years.

Nuclear fission is uniquely positioned to help meet this challenge because it has the highest energy density of any power source and its growth potential is not limited by resource availability. Nuclear power can also scale up quickly to fulfill high demand with zero carbon emissions.

The potential applications are wide-reaching. Not only can nuclear power be harnessed to meet the world's growing demand for electricity, it could be used to decarbonize the transportation sector by providing the power and heat necessary to operate electric cars or produce synthetic fuels.

"Innovations occurring in non-nuclear disciplines, such as robotics, artificial intelligence, and advanced construction technologies, if cleverly applied to nuclear energy systems, can potentially reduce their cost and enhance their performance. It is central to the mission of the Center for Advanced Nuclear Energy Systems to leverage MIT's broad expertise and infrastructure in such disciplines to realize this potential."

—Jacopo Buongiorno

What are the major challenges to the expanded use of nuclear energy, and how will the Center for Advanced Nuclear Energy Systems (CANES) address them?

While nuclear fission is already a leading source of zero-carbon energy, providing approximately 12% of power generation worldwide, progress toward expansion has been stymied by several factors. There are substantial capital costs and regulatory hurdles associated with contemporary reactor designs; rare but serious accidents have exacerbated concerns about plant safety—in spite of the industry's robust safety record; and questions regarding waste and proliferation continue to temper the public's enthusiasm for nuclear energy.

CANES aims to address these issues by hastening the development of new and transformative technologies, materials, and methods that will make nuclear fission more affordable and more rapidly and securely deployable. Building upon MIT's already extensive capability in nuclear fission-related innovation, the center supports work across the entire technology development arc—from basic materials research through to reactor design, manufacturing, and the fuel cycle.

The center also pairs its innovative research with a dedicated techno-economic and systems analysis program focused on how best to overcome the challenges involved in expanding nuclear power. An MIT team is conducting technology assessments, economic modeling, and analyses of the regulatory, financial, and political aspects of siting, designing, constructing, operating, and decommissioning nuclear facilities.

What kind of research is currently under way at the center?

CANES research centers on the real-world needs identified by MITEI's partners in industry and builds upon established tools of nuclear research, including our on-campus 6-megawatt research reactor and state-of-the-art experimental facilities.

"Lowering the cost of nuclear energy is a vital tool for reducing carbon emissions while enabling economic development around the world."
—John Parsons

Projects currently under way range from advances in reactor design, materials, and operation to regulatory innovations that will continue to ensure a robust level of safety for nuclear systems, accelerate the nuclear innovation cycle, and promote private investment in new nuclear technologies.

Recent examples of MIT work include advances in light-water-reactor materials that can help increase the reliability and decrease the operating costs of existing plants; research into the possibility of permanently sequestering high-level radioactive waste in deep granite bore-holes; and development of a risk-informed, performance-based regulatory framework that could facilitate the licensing of innovative new reactor designs. MIT researchers are also developing a design for an offshore floating nuclear plant that promises to be less expensive and easier to deploy than today's land-based plants.

Center for Electric Power Systems Research

Directors: Christopher Knittel, George P. Shultz Professor of Applied Economics, MIT Sloan School of Management, and Francis O'Sullivan, director of research, MIT Energy Initiative

Why is research into electric power systems necessary to reduce carbon emissions worldwide?

Fueling global economic development and powering the lives of billions who lack access to modern energy sources will require a dramatic expansion of the world's electricity system. At the same time, efforts to mitigate global climate change depend on making drastic CO_2 emissions cuts—moving even larger portions of the transportation, heating and cooling, and industrial sectors away from fossil fuels and toward cleaner power sources that generate electricity.

Accommodating these changes will require the electric power sector to undergo an unprecedented transformation. The sector is already highly complex, requiring the precise integration of hardware, operations, and market and regulatory structures. Going forward, the deployment of renewable and increasingly distributed energy resources such as wind, solar, storage, and demand response will challenge the planning and reliable operation of the system. Simultaneously, the much-expanded digitalization of power systems necessary to support a much more decentralized grid will result in increasing cyber risks.

Transforming the sector will require cross-disciplinary research spanning engineering, science, economics, and policy, as well as real-world input from stakeholders in industry, government, and nongovernmental organizations. This is the work of the MIT Energy Initiative's Low-Carbon Energy Center for Electric Power Systems Research.

How is the electric power systems center addressing these research challenges?

The center draws upon MIT's extensive existing research capability in a broad range of relevant fields—from power system modeling to market and regulatory design, and from cyber security to power systems technology—to advance a system-level understanding of the power sector and the transformation it is undergoing.

The center develops new methodological approaches, in-depth policy evaluations, and advanced modeling and analysis tools to represent the complex and dynamic behaviors of power systems. The goal is to make justified, insightful assessments of how such systems will evolve over time and to determine how regulatory and policy innovations can facilitate the transformation to a decarbonized power sector.

"The power system is undergoing unprecedented changes on the technology, market, and regulatory fronts. Understanding and shaping this transition requires expertise ranging from materials science and digital signal processing to economics and political science—areas of expertise that are central to the electric power systems center."

— Christopher Knittel

Can you provide an example of the kind of research currently under way at the center?

The *Utility of the Future* report, released in December 2016, is a great example of the in-depth research going on here. Developed over several years in collaboration with the Institute for Research in Technology at Comillas Pontifical University, *Utility of the Future* provides a toolkit for businesses, policymakers, and regulators to navigate the unfolding changes in electric power systems and develop robust, efficient alternatives.

The study paired research in quantitative economic and engineering modeling with a sophisticated understanding of the complex interactions that characterize the electric power industry. The team included MIT faculty with decades of experience in advising governments, corporations, and institutions on regulation and market design. In addition, we tapped industry stakeholders and other market participants to contribute insights from their real-world experience.

The research revealed that in order to ensure that distributed and centralized energy resources are integrated efficiently, electric power systems in the United States, Europe, and other parts of the world will need major regulatory, policy, and market overhauls.

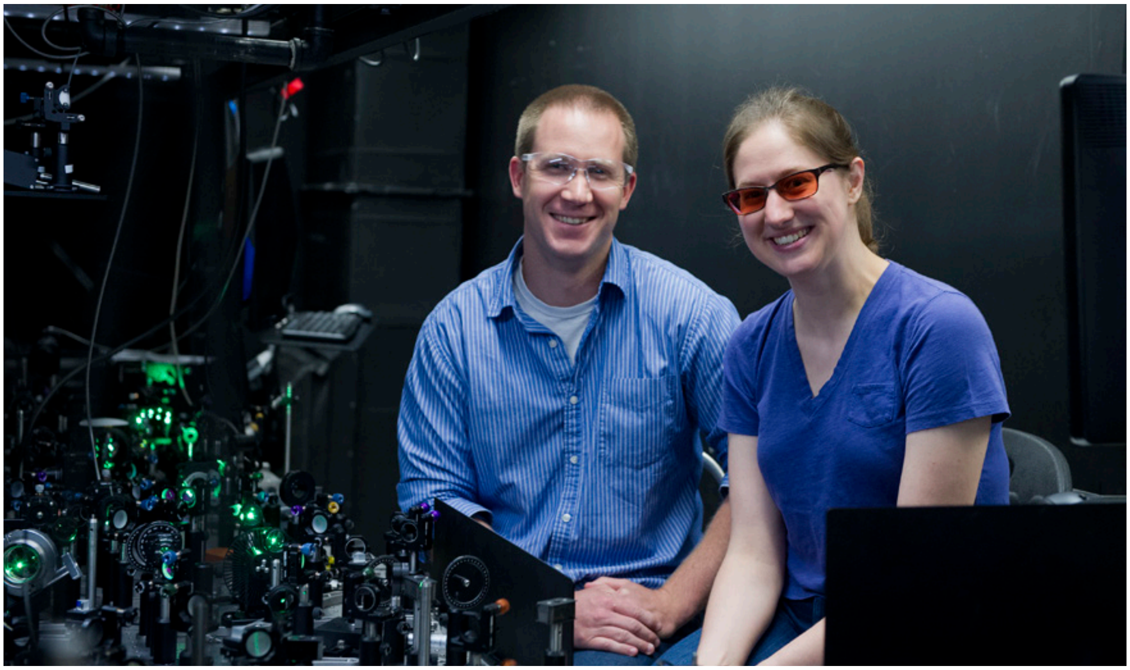
Going forward, the center will be analyzing potential policy and regulatory changes while also tackling many of the other impacts and opportunities likely to emerge from the greater decarbonization, decentralization, and digitization of the power system. These include the challenge of understanding how new and emerging technologies can be effectively integrated into existing power structures. Since wind and solar aren't entering the system in the same way in Massachusetts as in New Delhi, for example, we are looking at the system's evolution within a plethora of contexts.

We are also developing a variety of technical and economic modeling tools as well as new market theories to address the system's extraordinary complexity. In sum, we are working to devise strategies that will enable cleaner, more reliable, and more cost-effective power system solutions in the future.

"The relative impacts of decarbonization, decentralization, and digitalization vary greatly from place to place. We're interested in understanding those impacts and devising cleaner, more reliable, and more cost-effective power system solutions."

— Francis O'Sullivan

Photos
Buongiorno: Susan Young, MIT
Parsons: courtesy of MIT Sloan
Knittel: courtesy of MIT Sloan
O'Sullivan: Dominick Reuter



Quantum dot materials

Optimizing nanostructures for energy devices

Nancy W. Stauffer, MITEI

IN BRIEF

For quantum dot (QD) materials to perform well in devices such as solar cells, the nanoscale crystals in them need to pack together tightly so that electrons can hop easily from one dot to the next and flow out as current. MIT researchers have now made QD films in which the dots vary by just one atom in diameter and are organized into solid lattices with unprecedented order. Subsequent processing pulls the QDs in the film closer together, further easing the electrons' pathway. Tests using an ultrafast laser confirm that the energy levels of vacancies in adjacent QDs are so similar that hopping electrons don't get stuck in low-energy dots along the way. Taken together, the results suggest a new direction for ongoing efforts to develop these promising materials for high performance in electronic and optical devices.

In recent decades, much research attention has focused on electronic materials made of quantum dots (QDs), tiny crystals of semiconducting materials a few nanometers in diameter. After three decades of research, QDs are now being used in TV displays where they emit bright light in vivid colors that can be fine-tuned by changing the sizes of the nanoparticles.

But many opportunities remain for taking advantage of these remarkable materials. "QDs are a really promising underlying materials technology for energy applications," says William Tisdale,

Above Professor William Tisdale (left), Rachel Gilmore PhD '17, and their colleagues are developing novel methods of synthesizing quantum dot materials for use in solar cells, LEDs, and more. Testing confirms that their new techniques enable them to control the nanoscale structure of their materials—the key to high performance in energy devices. Photo: Stuart Darsch

ARCO Career Development Professor in Energy Studies and associate professor of chemical engineering. QD materials pique his interest for several reasons. QDs are easily synthesized in a solvent at low temperatures using standard procedures. The QD-bearing solvent can then be deposited on a surface—small or large, rigid or flexible—and as it dries, the QDs are left behind as a solid. Best of all, the electronic and optical properties of that solid can be controlled by "tuning" the QDs. "With QDs, you have all these degrees of freedom," says Tisdale. "You can change their composition, size, shape, and surface chemistry to fabricate a material that's tailored for your application."

The ability to adjust electron behavior to suit specific devices is of particular interest. For example, in solar photovoltaics (PVs), electrons should pick up energy from sunlight and then move rapidly through the material and out as current before they lose their excess energy. In light-emitting diodes (LEDs), high-energy "excited" electrons should relax on cue, emitting their extra energy as light.

With thermoelectric (TE) devices, QD materials could be a game-changer. When TE materials are hotter on one side than the other, they generate electricity. So TE devices could turn waste heat in car engines, industrial equipment, and other sources into power—without combustion or moving parts. The TE effect has been known for a century, but devices using TE materials have remained inefficient. The problem: While those materials conduct electricity well, they also conduct heat well, so the temperatures of the two ends of a device quickly equalize. In most materials, measures to decrease heat flow also decrease electron flow. "With QDs, we can control those two properties separately," says Tisdale. "So we can simultaneously engineer our material so it's good at transferring electrical charge but bad at transporting heat."

Making good arrays

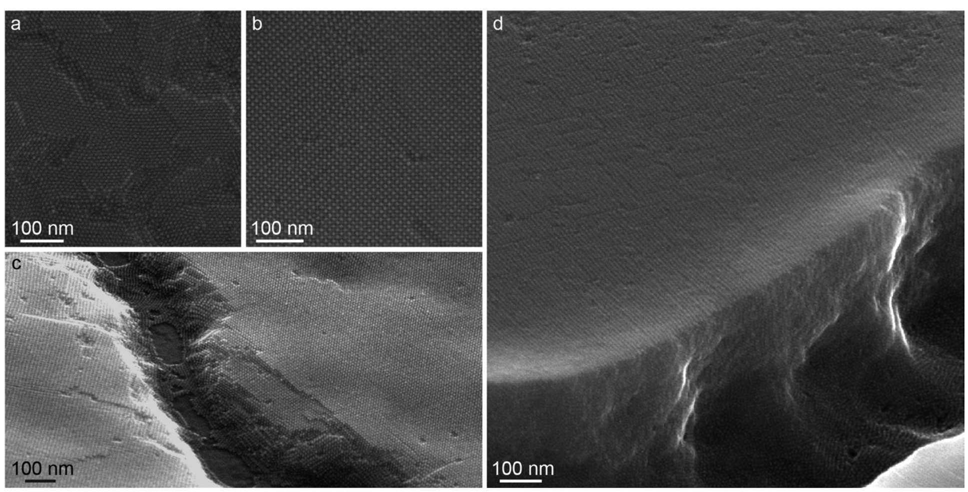
One challenge in working with QDs has been to make particles that are all the same size and shape. During QD synthesis, quadrillions of nanocrystals are deposited onto a surface, where they self-assemble in an orderly fashion as they dry. If the individual QDs aren't all exactly the same, they can't pack together tightly, and electrons won't move easily from one nanocrystal to the next.

Three years ago, a team in Tisdale's lab led by Mark Weidman PhD '16 demonstrated a way to reduce that structural disorder. In a series of experiments with lead-sulfide QDs, team members found that carefully selecting the ratio between the lead and sulfur in the starting materials would produce QDs of uniform size. "And as those nanocrystals dry, they self-assemble into a beautifully ordered arrangement we call a superlattice," says Tisdale.

The figure below shows scattering electron microscope images of those superlattices taken from several angles. Images a and b are taken from the top and show lined-up, 5 nanometer (nm)-diameter nanocrystals on the surface. Images c and d show edges of superlattices and display the depth and long-range ordering of the QDs.

For a closer examination of their materials, Weidman performed a series of X-ray scattering experiments at the National Synchrotron Light Source at Brookhaven National Laboratory. Data from those experiments showed both how the QDs are positioned relative to one another and how they're oriented, that is, whether they're all facing the same way.

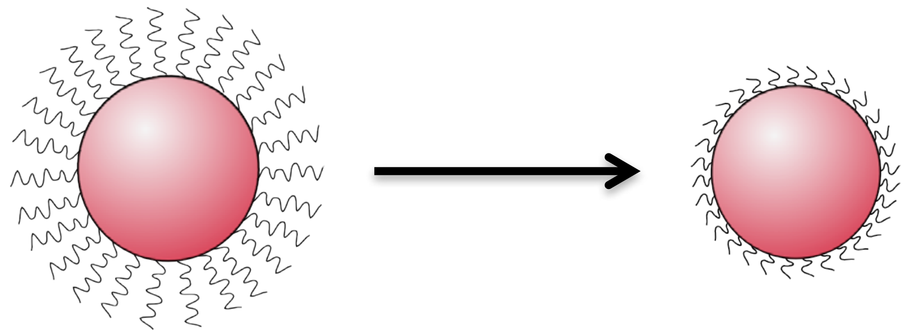
The results confirmed that QDs in the superlattices are well ordered and essentially all the same. "On average, the difference in diameter between one nanocrystal and another was less than the size of one more atom added to the surface," says Tisdale. "So these QDs have unprecedented monodispersity, and they exhibit structural behavior that we hadn't seen previously because no one could make QDs this monodisperse."



Micrographs of lead-sulfide quantum dot (QD) materials These images show scanning electron micrographs of sample QD films. The dark spots are the individual quantum dots, each about 5 nanometers (nm) in diameter. Images **a** and **b** show the consistent size and alignment of the QDs at the surface. The exposed edges in images **c** and **d** show depth and long-range ordering of the nanocrystals.

Controlling electron hopping

The researchers next focused on how to tailor their monodisperse QD materials for efficient transfer of electrical current. "In a PV or TE device made of QDs, the electrons need to be able to hop effortlessly from one dot to the next and then do that many thousands of times as they make their way to the metal electrode," explains Tisdale.



Structure of a quantum dot As shown these schematics, at the center of a quantum dot (QD) is a core of a semiconducting material. Radiating outward from that core are arms, or ligands, of an organic material. The ligands keep the QDs in solution from sticking together, and they determine the spacing between the dots in the solid product. Replacing the long ligands on the left with the short ones on the right allows the QDs to pack more closely together.

One way to influence hopping is by controlling the spacing from one QD to the next. As shown in the schematics on this page, a single QD consists of a core of semiconducting material—in this work, lead sulfide—with chemically bound arms, or "ligands," made of organic (carbon-containing) molecules radiating outward. The ligands play a critical role: Without them, as the QDs form in solution, they'd stick together and drop out as a solid clump. Once the QD layer is dry, the ligands end up as solid spacers that determine how far apart the nanocrystals are.

A standard ligand material used in QD synthesis is oleic acid. Given the length of an oleic acid ligand, the QDs in the dry superlattice end up about 2.6 nm apart—and that's a problem. "That may sound like a small distance, but it's not," says Tisdale. "It's way too big for a hopping electron to get across."

Using shorter ligands in the starting solution—like those in the right-hand schematic—would reduce that distance, but they wouldn't keep the QDs from sticking together when they're in solution. "So we needed to swap out the long oleic acid ligands in our solid materials for something shorter" after the film formed, says Tisdale.

To achieve that replacement, the researchers use a process called ligand exchange. First, they prepare a mixture of a shorter ligand and an organic solvent that will dissolve oleic acid but not the lead sulfide QDs. They then submerge the QD film in that mixture for 24 hours. During that time, the oleic acid ligands dissolve, and the new, shorter ligands take their place, pulling the QDs closer together. The solvent and oleic acid are then rinsed off.

Tests with various ligands confirmed their impact on interparticle spacing. Depending on the length of the selected ligand, the researchers could reduce that spacing from the original 2.6 nm with oleic acid all the way down to 0.4 nm. However, while the resulting films have beautifully ordered regions—perfect for fundamental studies—inserting the shorter ligands tends to generate cracks as the overall volume of the QD sample shrinks.

Energetic alignment of nanocrystals

One result of that work came as a surprise: Ligands known to yield high performance in lead-sulfide-based solar cells didn't produce the shortest interparticle spacing in their tests. "Reducing that spacing to get good conductivity is necessary," says Tisdale. "But there may be other aspects of our QD material that we need to optimize to facilitate electron transfer."

One possibility is a mismatch between the energy levels of the electrons in adjacent QDs. In any material, electrons exist at only two energy levels—a low "ground state" and a high "excited state."

If an electron in a QD film receives extra energy—say, from incoming sunlight—it can jump up to its excited state and move through the material until it finds a low-energy opening left behind by another traveling electron. It then drops down to its ground state, releasing its excess energy as heat or light.

In solid crystals, those two energy levels are a fixed characteristic of the material itself. But in QDs, they vary with particle size. Make a QD smaller, and the energy level of its excited electrons increases. Again, variability in QD size can create problems. Once excited, a high-energy electron in a small QD will hop from dot to dot—until it comes to a large, low-energy QD. "Excited electrons like going downhill more than they like going uphill, so they tend to hang out on the low-energy dots," says Tisdale. "If there's then a high-energy dot in the way, it takes them a long time to get past that bottleneck." So the greater mismatch between energy levels—called energetic disorder—the worse the electron mobility.

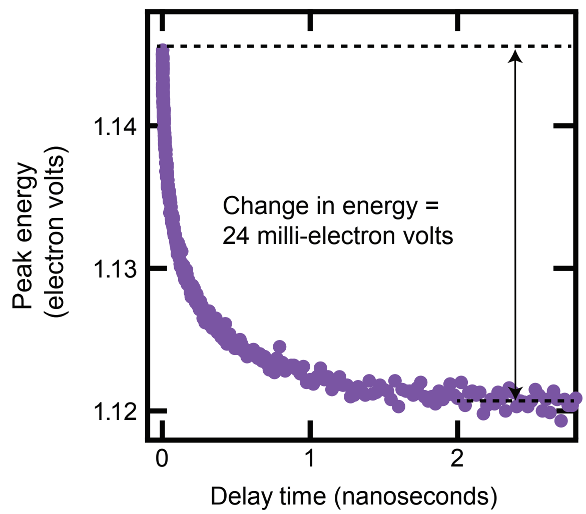
To measure the impact of energetic disorder on electron flow in their samples, Rachel Gilmore PhD '17 and her collaborators used a technique called pump-probe spectroscopy—as far as they know, the first time this method has been used to study electron hopping in QDs.

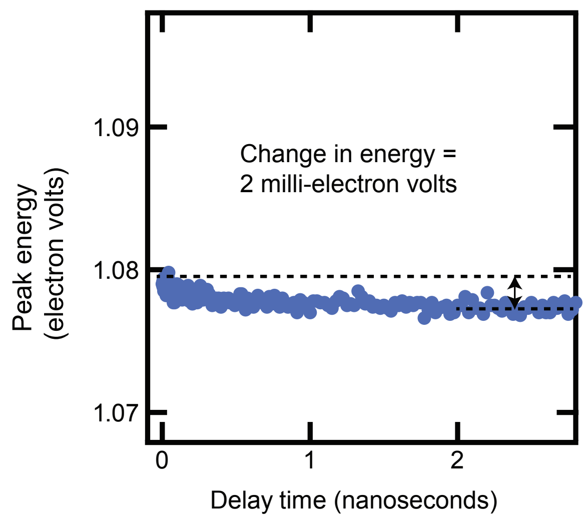
QDs in an excited state absorb light differently than do those in the ground state, so shining light through a material and taking an absorption spectrum provides a measure of the electronic states in it. But in QD materials, electron hopping events can occur within picoseconds—10^{-12} of a second—which is faster than any electrical detector can measure.

The researchers therefore set up a special experiment using an ultrafast laser, whose beam is made up of quick pulses occurring at 100,000 per second. As described in the caption for the photo on page 15, their setup subdivides the laser beam such that a single pulse is split into a "pump" pulse that excites a sample and—after a delay measured in femtoseconds (10^{-15} seconds)—a corresponding "probe" pulse that measures the sample's energy state after the delay. By gradually increasing the delay between the pump and probe pulses, they gather absorption spectra that show how much electron transfer has occurred and how quickly the excited electrons drop back to their ground state.

Sample results appear to the right. The top figure shows data from a QD sample with standard dot-to-dot variability. The bottom figure shows results from one of the monodisperse samples. In each case, the dotted lines indicate the starting and ending energy. In the sample with high variability, the excited electrons lose much of their excess energy within 3 nanoseconds. In the monodisperse sample, little energy is lost in the same time period—an indication that the energy levels of the QDs are all about the same.

By combining their spectroscopy results with computer simulations of the electron transport process, the researchers extracted electron hopping times ranging from 80 picoseconds for their smallest quantum dots to over 1 nanosecond for the largest ones. And they concluded that their QD materials are at the theoretical limit of how little energetic disorder is



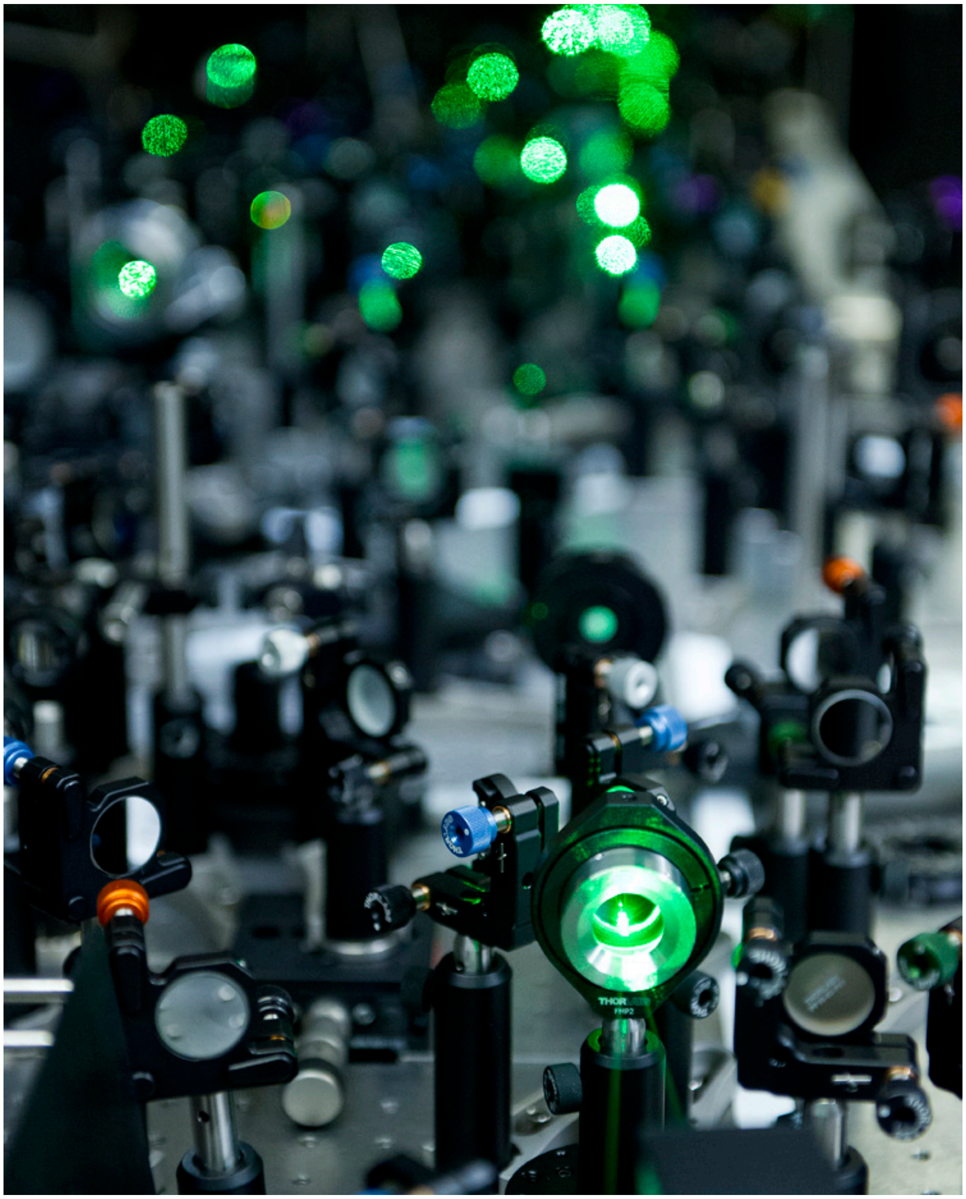


Results from ultrafast laser experiments These graphs show electron energy measurements in a standard QD film (top) and in a film made from monodisperse QDs (bottom). In each graph, the data points show energy measurements at initial excitation—indicated by the top dotted line—and over the subsequent 3 nanoseconds. In the standard sample, the electrons rapidly lose their excess energy. In contrast, in the monodisperse sample, the energy level remains fairly constant—an indication that the energy levels of the QDs are essentially uniform.

possible. Indeed, any difference in energy between neighboring QDs isn't a problem. At room temperature, energy levels are always vibrating a bit, and those fluctuations are larger than the small differences from one QD to the next. "So at some instant, random kicks in energy from the environment will cause the energy levels of the QDs to line up, and the electron will do a quick hop," says Tisdale.

The way forward

With energetic disorder no longer a concern, Tisdale concludes that further progress in making commercially viable QD materials will require better ways of dealing with structural disorder. He and his team tested several methods of performing ligand exchange in solid samples, and none produced films with



Critical to the ultrafast laser tests is the ability to create pump and probe pulses by subdividing a single pulse of laser light and creating a delay between when the two parts reach the sample. To achieve that effect, the researchers mount a partially reflective mirror on a motorized, moveable stage. They send part of the laser beam straight through the sample and divert the other part so that it passes through the sample after a fixed time delay measured in femtoseconds (10^{-15} seconds). The spectrum taken at a given pump pulse measures light absorption of electrons in their excited state; the spectrum at the corresponding probe pulse shows their energy state after the delay. By adjusting the location of the mirror and thus the time delay, the researchers can determine how much electron transfer has occurred as well as how quickly the excited electrons drop back to their ground state. Photo: Stuart Darsch

consistent QD size and spacing over large areas without cracks. As a result, he now believes that efforts to optimize that process "may not take us where we need to go."

What's needed instead is a way to put short ligands on the QDs when they're in solution and then let them self-assemble into the desired structure. "There are some emerging strategies for solution-phase ligand exchange," he says. "If they're successfully developed and combined with monodisperse QDs, we should be able to produce beautifully ordered, large-area structures well suited for devices such as solar cells, LEDs, and thermoelectric systems."

NOTES

QD synthesis and spectroscopy were supported by the US Department of Energy, Office of Basic Energy Sciences. Structural studies of QD solids were supported by the MIT Energy Initiative Seed Fund Program. Mark Weidman and Rachel Gilmore were partially supported by a National Science Foundation Graduate Research Fellowship. Measurements were performed at the Center for Functional Nanomaterials at Brookhaven National Laboratory, the Cornell High Energy Synchrotron Source, and the MRSEC Shared Experimental Facilities at MIT. Further information can be found in:

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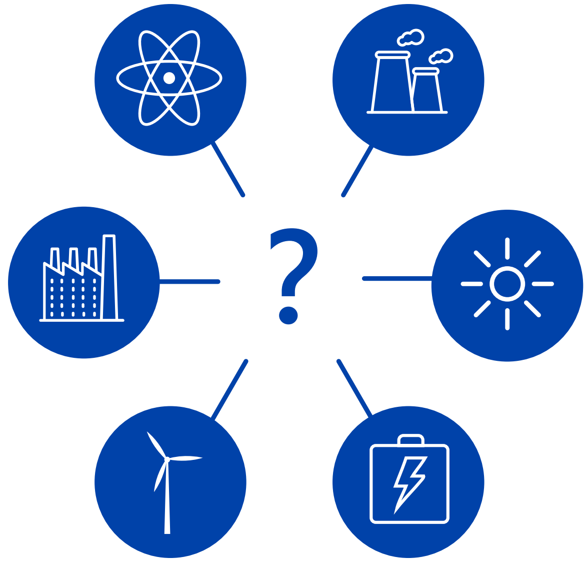


Reducing risk in power generation planning

Why including non-carbon options is key

Nancy W. Stauffer, MITEI

IN BRIEF

An analysis by MIT researchers shows that when electric power companies are planning to invest in new generating facilities but face the possibility of future limits on carbon emissions, they can reduce their long-term economic risk by having at least 20% of the new generation come from non-carbon systems such as solar and wind. Coal or natural gas plants are less expensive initially, but they might have to be shut down prematurely if a carbon cap is put in place in the coming decades. Non-carbon systems are more costly to build, but they're relatively inexpensive to operate, so companies will continue to run them, even if there's no restriction on carbon emissions. The researchers' novel method of incorporating expectations about future emissions policies into the decision-making process identifies an investment strategy that can as much as halve cumulative costs to the US economy, potentially saving more than $100 billion over the long term.

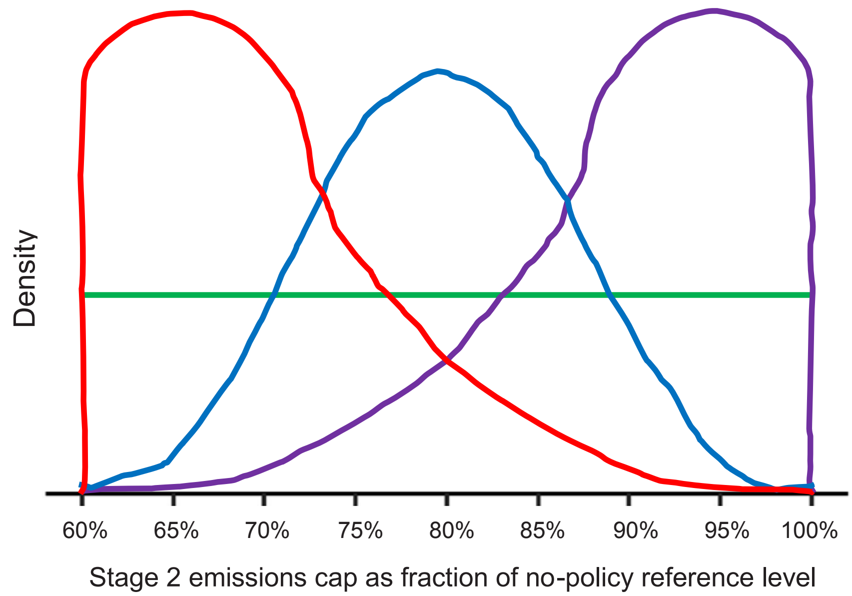
When planners in an electric power company need to add new generating capacity, they may consider building a plant that burns coal or natural gas. After all, such fossil fuel–fired facilities are relatively inexpensive and should run for 40 years or more. But if future policies impose strict limits on carbon emissions, they might need to shut down their fossil fuel plants and build non-carbon systems such as solar or wind in a hurry—two extremely expensive propositions. On the other hand, if they build the more expensive non-carbon systems now and emissions policies aren't enacted, they may have spent that extra money unnecessarily. Deciding to build

Facing page Jennifer Morris SM '09, PhD '13 and her collaborators have developed a tool that can help planners in power companies decide what kinds of new generating facilities to build, given uncertainty around future limits on carbon emissions. Their analyses show that including non-carbon generation in the mix will reduce the long-term economic risk of decisions made today. Photo: Bryce Vickmark

Above Power company planners can choose from a variety of technologies, as suggested in this illustration. But comparing costs is tricky. While the present cost of building a facility may be known, any climate policy enacted during its lifetime can significantly impact the long-term value of the initial investment. Graphic: Jenn Schlick, MITEI fossil plants or choosing to invest in non-carbon generation—either decision has economic risk, given the uncertainty about long-term emissions policy.

To help with such decision making, planners often use modeling tools that identify the best option based on various assumptions about the future. For example, one model may assume that today's conditions will continue; another may assume perfect foresight of how the future will unfold; and yet another may call for analyzing different possible scenarios and then picking one—most likely the one in the middle. "But an important piece that's often left out is explicit consideration of uncertainty, often because it can be difficult to incorporate or even to characterize that uncertainty, much less how it should impact your decision," says Jennifer Morris SM '09, PhD '13, a research scientist in the MIT Joint Program on the Science and Policy of Global Change and the MIT Energy Initiative.

For the past five years, Morris and her Joint Program colleagues—John Reilly, co-director of the Joint Program and a senior lecturer at the Sloan School of Management; Mort Webster, former MIT associate professor of engineering systems and now associate professor of energy engineering at Pennsylvania State University; and Vivek Srikrishnan, a PhD candidate at Pennsylvania State University—have been developing an approach that explicitly incorporates uncertainty into the decision-making process. "You don't know exactly how the future is going to unfold, but you have an idea—you have an expectation—of the probability of different futures," says Morris. "Our goal is to enable you to use that long-term expectation to inform what action you should take now."



Expectations about emissions policy actions in the future The illustrative probability density functions (PDFs) presented above define four sets of expectations about the likelihood of emissions caps at varying levels being enacted in the future. The reference case is defined as 100%, meaning that there's no cap on emissions. Other caps are presented as percentages of that reference level (e.g., 80% means a 20% reduction relative to reference emissions). The farther left on the X-axis, the tighter the emissions cap; the higher the curve at a given cap, the more likely that cap is believed to be. The horizontal line represents the expectation that all emissions caps are equally likely in the future.

Modeling the economy

At the core of their approach is a computable general equilibrium (CGE) model—a type of simulation that tracks the flows of goods and services and the corresponding monetary flows among all sectors of the US economy. "Enactment of a climate policy will affect all sectors, and by using a CGE model, we can track ripple effects throughout the economy and measure the economy-wide impacts," says Morris.

Performing an uncertainty analysis can require running tens of thousands of simulations, so for this study Morris developed a simplified CGE model that captures key sectors, among them electric power, and uses aggregated US data. She included two types of electricity generation—conventional fossil (coal and natural gas) and a generalized non-carbon electricity (wind, solar, advanced nuclear, and carbon capture and storage). She assumed an aggregate cost for the non-carbon electricity sources that's 50% higher than the cost of conventional sources. Why such a high cost? "Our CGE model looks at system costs," she explains. "Once we account for the variability and intermittency of renewable power generation and the need for backup capacity or storage and additional transmission and distribution, the current systemwide cost of the non-carbon options comes out that much higher."

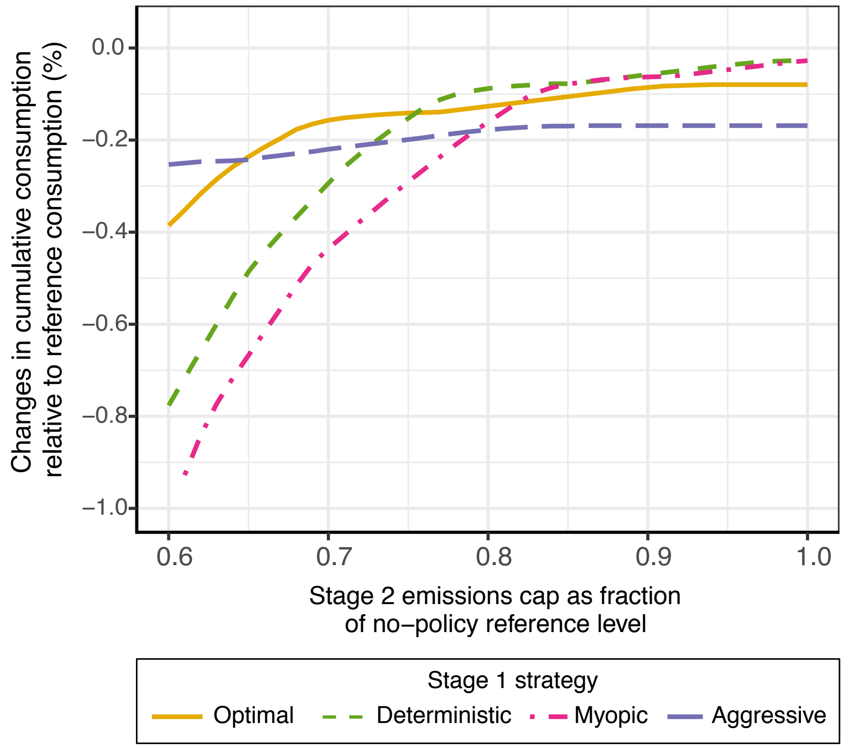
The optimal investment choice is defined as the one that will minimize costs and thereby maximize welfare in all economic sectors over two time periods—now (when the decision is being made) and later (when a policy has—or hasn't—been enacted). To factor in the uncertainty of future policy, Morris put the CGE model into a dynamic programming framework and then defined two time periods for analysis—2010 to 2020 and 2020 to 2030. This two-stage framework determines the overall welfare effect by calculating the cost in the first stage plus the expected cost in the second stage.

Defining policy expectations

To perform an analysis, Morris first defines quantitatively a range of expectations about the most likely policy action in the future. The figure on page 18 shows four examples, presented as probability density functions, or PDFs. The X-axis shows possible second-stage emissions caps reported as percent reductions in cumulative emissions from the electric power sector from 2015 to 2030 below a reference scenario that assumes no limits on emissions. Thus, 100% indicates that no new emissions cap is expected in 2020, 80% foresees a policy that calls for cutting emissions by 20%, and so on.

Each PDF shows a different view of how likely those values are. The horizontal line represents the view that all possible emissions caps are equally likely in the future. In the other examples, the highest point is the value deemed most likely—the one receiving the most votes, if you will—and the lowest point is the value seen as least likely. Accordingly, the familiar bell curve deems the middle caps most likely and the more extreme policies (unrestricted emissions and severely constrained emissions) unlikely. In the other two curves, the highest section is skewed toward the right or toward the left, indicating that future emissions are more likely to be unrestricted or more likely to be severely constrained.

Given a single PDF, the simplest approach would be to pick the highest point—thus the future cap deemed most likely—and determine the best level of non-carbon investment accordingly. But while the highest point is the most likely future cap, there's still some chance that the cap could end up elsewhere—maybe even on the tails of the curve reflecting a strict policy or no policy at all. Morris's modeling system takes all of the possible outcomes into account, weighting the levels according to their likelihood.



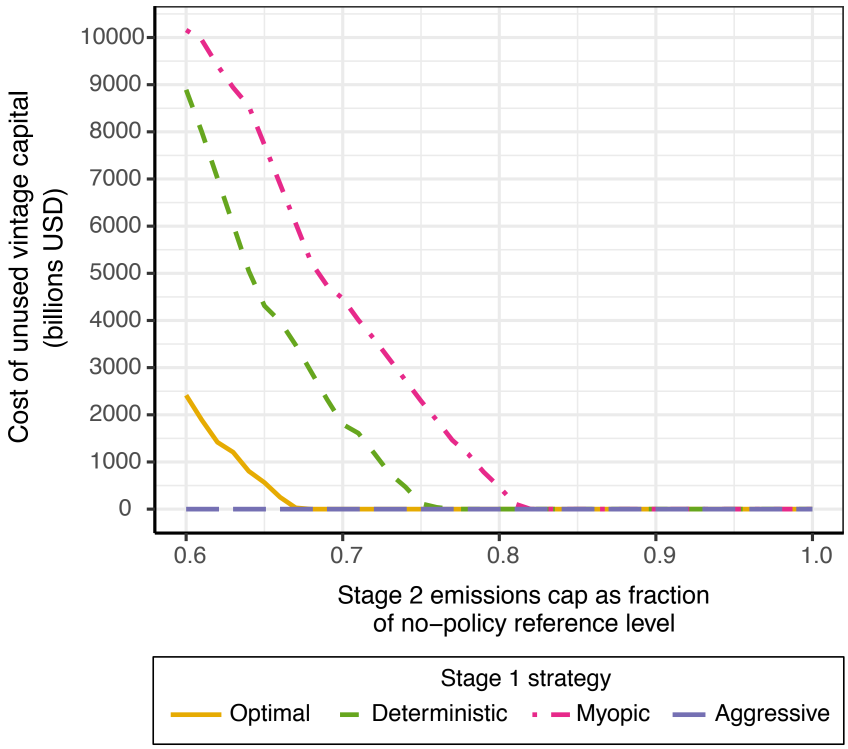
Cumulative economy-wide cost under different investment strategies These curves show the cost—defined as the change in cumulative economy-wide consumption (2010–2030) relative to the reference no-policy consumption level—at various levels of second-stage emissions caps based on first-stage investment choices made using four decision-making strategies. The aggressive approach, which calls for high non-carbon investment, does better than the other strategies if the second-stage cap is stringent. The optimal strategy does well under all but the most stringent emissions caps, while the deterministic and myopic approaches do best when caps are more lenient or non-existent.

To identify the optimal non-carbon investment decision for a given PDF, the system first draws random samples from the possible second-stage policy caps. Because of the sampling method used, more of the selected samples will be the caps deemed most probable, but at least some will be "less likely" points on the tails of the curve.

The system then considers one possible investment level—say, 5% non-carbon generation—and calculates economy-wide consumption over the two time periods for each randomly selected sample. It then considers another investment level and performs the same calculation. By examining many investment levels, it identifies the one that maximizes welfare for the policy expectations represented by that PDF.

Using that procedure, the researchers identified the optimal non-carbon investment level that maximizes welfare under a series of PDFs. Remarkably, they found substantial overlap between the best investment choices. For most of the PDFs they considered, the optimal investment in non-carbon generation was between 20% and 30%. And if the costs of non-carbon alternatives were lower, then an even higher level of investment in non-carbon generation would be optimal.

"So the main takeaway of our study is that the risk of underinvesting in non-carbon generation is far greater than the risk of overinvesting," says Morris. Why the imbalance? If a company doesn't have enough non-carbon generation in place to meet strict emissions limits, it will incur high costs as it both abandons its existing fossil systems and rushes to build new non-carbon capacity—without prior



Cost of unused capital as a function of second-stage cap These curves show the cost of capital equipment—both fossil and non-carbon—that must be scrapped under the four decision-making strategies at various second-stage caps. The costs under the optimal, deterministic, and myopic strategies reflect fossil generating capacity that can't be used when emissions caps are tight. Under looser caps, the cost of unused capital drops to zero because those fossil systems no longer must be abandoned and any non-carbon systems will continue to run. The aggressive strategy incurs no cost from unused capital because the non-carbon generating equipment is never shut down.

experience and knowledge. In contrast, if a company has built non-carbon systems, it will continue to use them regardless of future policy action or inaction because the cost of operating them is low. "So fossil capital is shut down under tight caps, but non-carbon capital is never abandoned under loose caps," says Morris. "It's never economic to leave non-carbon generating capital unused." As an added benefit, early investment in non-carbon technologies enables a company to develop the capacity and the infrastructure needed to scale up non-carbon generation quickly if a much higher share is needed in subsequent decades.

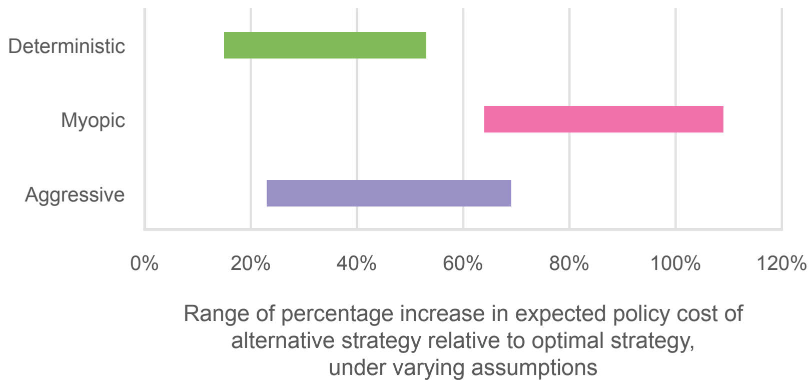
Benefits of optimal analysis

How do Morris's results compare with results from using other strategies to determine the best investment level? To find out, she looked at three other common approaches. "Deterministic" assumes that the most likely value of the PDF will be the certain outcome and calculates the best investment based on that assumption; "myopic" doesn't consider the future but just responds to present conditions; and "aggressive" seeks to avoid the worst possible outcome so in this case calls for a high level of non-carbon investment. Using each of those decision strategies, Morris calculated the best first-stage investment decision. While the optimal strategy results in 20% investment in non-carbon generation, the deterministic and myopic both end up with 5% and the aggressive with 50%.

For each of those four outcomes, Morris performed CGE simulations to determine the likely impacts on cumulative cost (2010–2030) at different levels of a second-stage emissions cap. Results appear in the figure on page 19. If the second-stage cap is stringent (toward the left in the diagram), the deterministic and myopic approaches bring large welfare losses. The optimal decision cuts off most of those losses, while the aggressive strategy is most successful—a result of its risk-averse high investment in non-carbon generation. As the emissions cap becomes less stringent, costs under the optimal decision quickly decrease and then level off; and after a considerable lag, the deterministic and myopic decisions do the same. The aggressive approach protects against the worst-case loss at strict emissions caps but otherwise costs more than the other strategies.

The figure on this page shows how costs under the four strategies are affected by the need to shut down existing generating capacity in order to meet newly imposed emissions caps. The costs here include any system—fossil or non-carbon—that must be scrapped. The most striking result is that the aggressive strategy never incurs costs for unused capital. In contrast, when emission caps are stringent, the deterministic and myopic strategies—and to some extent the optimal strategy—incur high costs for fossil generating capacity they can't use. As the cap eases, the cost of unused capital drops to zero. Even though all the strategies call for some level of investment in non-carbon generation, the systems that are built never turn into costly unused capital.

Morris recognizes that her analytical approach requires more effort and far more computer time than other commonly used methods of decision making. To measure the value of including uncertainty, Morris looked at total long-term costs associated with sample results from the four techniques. Under one set of assumptions, the expected overall cost to the US economy of using the optimal approach was $150 billion. Costs were 53% higher with the deterministic approach, 109%



Expected value of including uncertainty To test the value of explicitly incorporating uncertainty, the researchers calculated the total long-term costs of investment choices determined by the four strategies under a variety of assumptions. This figure shows percentage increases in those costs as a result of using the deterministic, myopic, or aggressive strategies rather than the optimal strategy. While the percentage increase varies with the assumptions used, the optimal strategy always does best.

higher with the myopic strategy, and 23% higher with the aggressive approach. The percentage added cost varied under different assumptions, as shown in the figure on this page, but it was always higher. "So the incremental cost of choosing a non-optimal investment strategy by explicitly neglecting uncertainty can be significant," says Morris.

Good news—but new challenges

Morris notes that over the last decade, about 19% of new US power generation has come from non-carbon systems. "So the good news is that the industry has been on track with what our study shows is the optimal amount of investment," says Morris. "A question for the next decade is, are we going to be able to maintain and even increase that pace?"

Past growth in non-carbon generation has taken place while policies such as production tax credits for renewables and other statewide initiatives were in place. But some of those incentives are going to expire soon. In addition, the current US administration has pulled out of the Paris Agreement, challenged the Clean Power Plan, and taken other steps that are inconsistent with encouraging investment in non-carbon generation.

"Should the current administration's decisions impact your optimal near-term investment in non-carbon generation?" asks Morris. "Only to the extent that you believe they're going to persist through the next 30 to 40 years—the lifetime of your investment. If you think that in the next four to eight years we're going to get back on track and rejoin the global effort to confront climate change, then you should continue with the optimal investment choice, putting 20% or more of your investment dollars into non-carbon sources."

NOTES

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J. Morris, V. Srikrishnan, M.D. Webster, and J.M. Reilly. "Hedging strategies: Electricity investment decisions under policy uncertainty." *The Energy Journal*, 2018. Preprint online at www.iaee.org/en/publications/ejarticle.aspx?id=3028.

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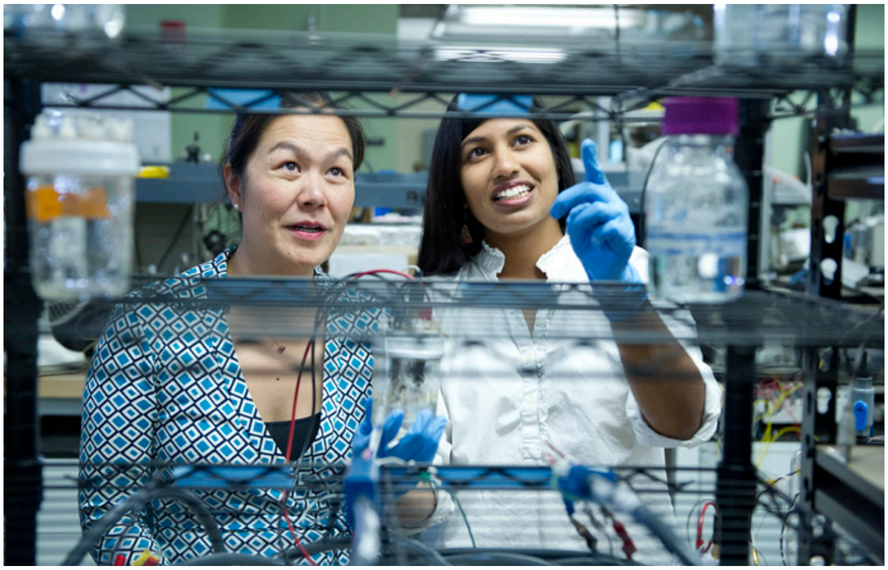


Carbon-nanotube electrodes

Tailoring designs for energy storage, desalination

Nancy W. Stauffer, MITEI

IN BRIEF

Using electrodes made of carbon nanotubes (CNTs) can significantly improve the performance of devices ranging from capacitors and batteries to water desalination systems. But figuring out the physical characteristics of vertically aligned CNT arrays that yield the most benefit has been difficult. Now an MIT team has developed a method that can help. By combining simple benchtop experiments with a model describing porous materials, the researchers have found they can quantify the morphology of a CNT sample—without destroying it in the process. In a series of tests, they confirmed that their adapted model can reproduce key measurements taken on CNT samples under varying conditions. They're now using their approach to determine detailed parameters of their samples—including the spacing between the nanotubes—and to optimize the design of CNT electrodes for a device that rapidly desalinates brackish water.

A common challenge in developing energy storage devices and desalination systems is finding a way to transfer electrically charged particles onto a surface and store them there temporarily. In a capacitor, for example, ions in an electrolyte must be deposited as the device is being charged and later released when electricity is being delivered. During desalination, dissolved salt must be captured and held until the cleaned water has been withdrawn.

One way to achieve those goals is by immersing electrodes into the electrolyte or the saltwater and then imposing a

Above Professor Evelyn Wang (left) and Heena Mutha PhD '17 have developed a nondestructive method of quantifying the detailed characteristics of carbon nanotube samples—a valuable tool for optimizing these materials for use as electrodes in a variety of practical devices. Photos: Stuart Darsch

Facing page Critical to their method are simple benchtop experiments in electrochemical cells such as the one shown here. Three electrodes—one of them a CNT sample—are immersed in an electrolyte, and current flow and other measurements are taken as voltage is pulsed into the system.

voltage on the system. The electric field that's created causes the charged particles to cling to the electrode surfaces. When the voltage is cut, the particles immediately let go.

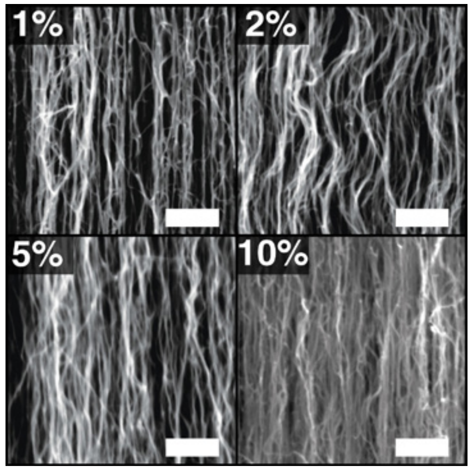
"Whether salt or other charged particles, it's all about adsorption and desorption," says Heena Mutha PhD '17, now a senior member of technical staff at Draper. "So the electrodes in your device should have lots of surface area as well as open pathways that allow the electrolyte or saltwater carrying the particles to travel in and out easily."

One way to increase the surface area is by using carbon nanotubes (CNTs). In a conventional porous material such as activated charcoal, interior pores provide extensive surface area, but they're irregular in size and shape so accessing them can be difficult. In contrast, a CNT "forest" is made up of aligned pillars that provide the needed surfaces plus straight pathways so the electrolyte or saltwater can easily reach them.

However, optimizing the design of CNT electrodes for use in devices has proven tricky. Experimental evidence suggests that the morphology of the material—in particular, how the CNTs are spaced out—has a direct impact on device performance. Increasing the carbon concentration when fabricating CNT electrodes produces a more tightly packed forest and more abundant surface area. But at a certain density, performance starts to decline, perhaps because the pillars are too close together for the electrolyte or saltwater to pass through easily.

Designing for device performance

"Much work has been devoted to determining how CNT morphology affects electrode performance in various applications," says Professor Evelyn Wang of mechanical engineering. "But an underlying question is, how can we characterize these promising electrode



Scanning electron microscope (SEM) images of carbon nanotube coatings
These SEM images show samples of carbon nanotube forests at varying volume fractions. At top left is the as-fabricated sample with a volume fraction of 1% (meaning that 1% of the total volume is occupied by nanotubes). The other images show samples that have been densified to volume fractions of 2%, 5%, and 10%. The scale bar on each image is 500 nanometers.

materials in a quantitative way so as to investigate the role played by such details as the nanometer-scale interspacing?" Inspecting a cut edge of a sample under a scanning electron microscope (SEM) provides images like those shown above, but quantifying features such as spacing is difficult, time-consuming, and not very precise. Analysis of data from gas adsorption experiments works well for some porous materials but not for nanotube forests. Perhaps more important, such methods destroy the material being tested, so samples whose morphologies have been characterized can't be used in tests of overall device performance.

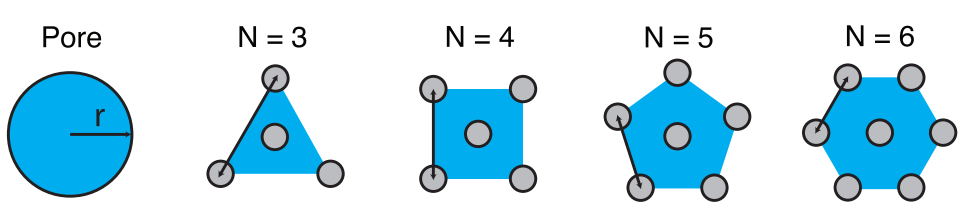
For the past two years, Wang and Mutha have been working on a better option. "We wanted to develop a nondestructive method that combines simple electrochemical experiments with a mathematical model that would let us 'back calculate' the interspacing in a CNT forest," says Mutha. "Then we could estimate the porosity of the CNT forest—without destroying it."

Adapting the conventional model

One widely used method for studying porous electrodes is electrochemical impedance spectroscopy (EIS). It involves pulsing voltage across electrodes in an electrochemical cell at a set time interval (frequency) while monitoring impedance, a measure that depends on both the available storage space and the resistance to flow. The set of impedance measurements at different frequencies is called the frequency response.

The classic model describing porous media uses that frequency response to calculate how much open space there is in a porous material. "So we should be able to use it to calculate the space between the carbon nanotubes in a CNT electrode," says Mutha.

But there's a problem. The classic model assumes that all pores are uniform, cylindrical voids, as shown in the left-hand drawing below. But that description doesn't fit electrodes made of CNTs. Mutha therefore modified the model to more accurately define the pores in CNT materials as the void spaces surrounding



Packing geometry in porous material modeling The classic porous media model—designed for studies of conventional materials such as activated carbon—describes all voids as cylindrical openings, as shown in the left-hand drawing above. In carbon nanotube materials, the open pores are instead the spaces among the solid pillars, and the geometry defined depends on the number of nanotubes (N) that pack together in a repeating cell, as shown in the other four drawings.

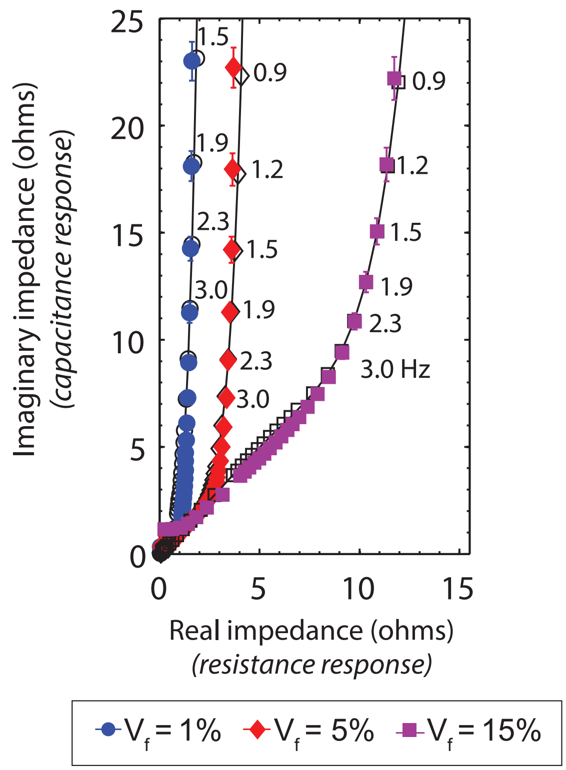
solid pillars, as indicated by the blue areas in the four drawings of different CNT packing geometries. While others have similarly altered the classic model, she took one more step. The nanotubes in a CNT material are unlikely to be packed uniformly. She therefore added to her equations the ability to account for variations in the spacing between the nanotubes—a more realistic representation of the structure inside a CNT electrode.

With this modified porous media model, Mutha could analyze EIS data from real samples to calculate CNT spacings.

Using the model

To demonstrate her approach as an analytical tool for determining CNT spacing, Mutha first fabricated a series of laboratory samples and then measured their frequency response. In collaboration with Yuan "Jenny" Lu SB '15 of materials science and engineering, she deposited thin layers of aligned CNTs onto silicon wafers inside a furnace and then used water vapor to separate the CNTs from the silicon, producing free-standing forests of nanotubes (see the photo below). To vary the CNT spacing, she used a technique developed by MIT collaborators Professor Brian Wardle of aeronautics and astronautics and Itai Stein PhD '16, now a postdoctoral associate in the same department. Using a specially fabricated plastic device,

This 1 centimeter-by-1 centimeter densified sample contains 10^{10} carbon nanotubes with an average interparticle spacing of 80–100 nanometers.



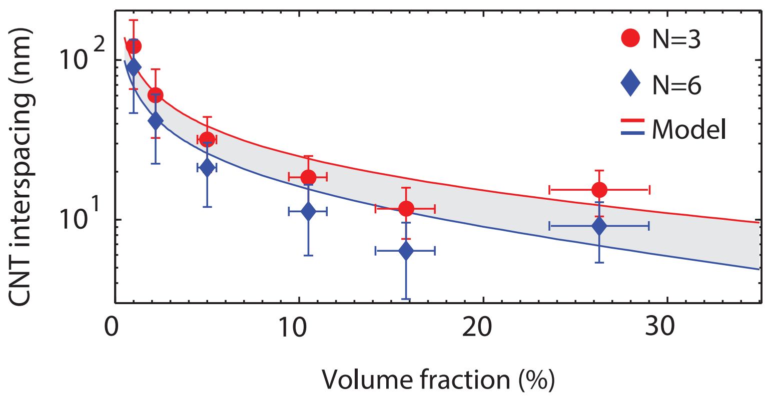
Frequency response of samples with varying volume fractions This figure shows how the impedance response changes as samples of differing volume fractions (V_f) are subjected to pulses of voltage input at frequencies ranging from 3.0 to 0.9 hertz (cycles per second). The colored symbols are experimental measurements; the black lines are model calculations. The measured and calculated values show the same trends, with a gradual transition toward constant resistance as the pulses become less frequent, allowing more time for the voltage to penetrate and the sample to respond.

she mechanically squeezed her samples from four sides, thereby packing the nanotubes together more tightly and increasing the volume fraction, that is, the fraction of the total volume occupied by the solid CNTs.

The SEM images on page 24 show cross sections of four of her samples. The first image shows her original fabricated sample, which has a volume fraction of about 1% (estimated based on density measurements). The other three images show samples with volume fractions of 2% (the sample has been reduced to half its original area), 5%, and 10%. As the volume fraction increases, the spaces between the nanotubes in the forest decrease, and the individual nanotubes become more upright and less curvy.

To test the frequency response of the samples, she used a glass beaker containing three electrodes immersed in an electrolyte. One electrode is the CNT-coated sample being tested, while the other two are used to monitor the voltage and to absorb and measure the current that flows. Using that setup, she first measured the capacitance of each sample, that is, how much charge it could store in each square centimeter of surface area at a given constant voltage. She then ran EIS tests on the samples and analyzed results using her modified porous media model.

The figure above shows her experimental and theoretical results. The impedance response is made up of two components: the resistance response (on the X-axis) and the capacitance response (on the Y-axis). Measurements appear as colored symbols and model calculations as black lines. Frequencies range from 3.0 to 0.9 hertz (cycles per second), as indicated by numbers beside the data points.



Comparing results from EIS analysis and Monte Carlo modeling This figure shows spacing between nanotubes in CNT coatings at various volume fractions. The dots show estimates from the EIS analysis; the solid lines are results from a statistical model that simulates carbon nanotube growth. The studies both considered three-pillar packing (red) and six-pillar packing (blue)—assumptions designed to establish the upper and lower bounds of possible spacing. The results show similar trends until the volume fraction reaches about 26%, when the CNTs in the experimental samples may have buckled during densification.

Results for the three volume fractions tested show the same trends. As the voltage pulses become less frequent, the curves initially rise at about a 45° slope. But at some point each one shifts toward vertical, with resistance becoming constant and impedance continuing to rise.

As Mutha explains, those trends are typical of EIS analyses. "At high frequencies, the voltage changes so quickly that—because of resistance in the CNT forest—it doesn't penetrate the depth of the entire electrode material, so the response comes only from the surface or partway in," she says. "But eventually the frequency is low enough that there's time between pulses for the voltage to penetrate and for the whole sample to respond." Resistance is no longer a noticeable factor, so the line becomes vertical, with the capacitance component causing impedance to rise as more charged particles attach to the CNTs. That switch to vertical occurs earlier with the lower-volume-fraction samples. In sparser forests, the spaces are larger, so the resistance is lower.

The most striking feature of Mutha's results is the gradual transition from the high-frequency to the low-frequency regime. Calculations from a model based on uniform spacing—the usual assumption—show a sharp transition from partial to complete electrode response. Because Mutha's model incorporates subtle variations in spacing, the transition is gradual rather than abrupt. Her experimental measurements and model results both exhibit that behavior, suggesting that the modified model is more accurate.

By combining their impedance spectroscopy results with their model, the researchers inferred the CNT interspacing in their samples. Since the forest packing geometry is unknown, they performed the analyses based on the three- and six-pillar configurations shown on page 24 to establish upper and lower bounds. Their calculations showed that spacing can range from 100 ± 50 nanometers (nm) in sparse forests to below 10 ± 5 nm in densely packed forests.

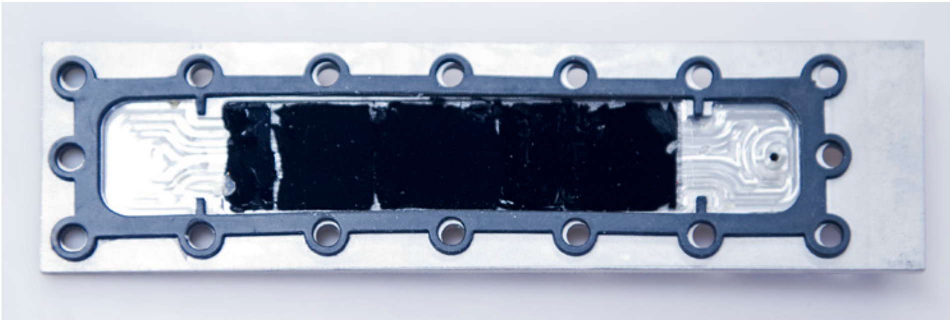
Comparing approaches

Work in collaboration with MIT colleagues Wardle and Stein has validated the two groups' differing approaches to determining CNT morphology. In their studies, Wardle and Stein use an approach similar to Monte Carlo modeling, which is a statistical technique that involves simulating the behavior of an uncertain system thousands of times under varying assumptions to produce a range of plausible outcomes, some more likely than others. For this application, they assumed a random distribution of "seeds" for carbon nanotubes, simulated their growth, and then calculated characteristics such as inter-CNT spacing with an associated variability. Along with other factors, they assigned some degree of waviness to the individual CNTs to test the impact on the calculated spacing.

To compare their approaches, the two MIT teams performed parallel analyses that determined average spacing at increasing volume fractions. The figure on this page shows results from Mutha's EIS analyses (dots) and Stein's simulations (curves), assuming either three-pillar packing (red) or six-pillar packing (blue). The trends they exhibit match well, with spacing decreasing as volume fraction increases. However, at a volume fraction of about 26%, the EIS spacing estimates suddenly go up—an outcome that Mutha believes may reflect packing irregularities caused by buckling of the CNTs as she was densifying them.

To investigate the role played by waviness, Mutha compared the variabilities in her results with those in Stein's results from simulations assuming different degrees of waviness. At high volume fractions, the EIS variabilities were closest to those from the simulations assuming little or no waviness. But at low volume fractions, the closest match came from simulations assuming high waviness.

Based on those findings, Mutha concludes that waviness should be considered when performing EIS analyses—at least in some cases. "To accurately predict the performance of devices with sparse CNT electrodes, we may need to model the electrode as having a broad distribution of interspacings due to the waviness



The researchers tested the use of their CNT electrodes for capacitive deionization, a low-cost approach to desalinating brackish water. They attached CNT electrodes to titanium current collectors—as shown above—and used those prototypes to study the dynamics of salt removal and to optimize device design. By manipulating the volume fraction, height, and surface chemistry of the CNTs, they varied the rate of salt removal and overall system capacity. Photo: Stuart Darsch

of the CNTs," she says. "At higher volume fractions, waviness effects may be negligible, and the system can be modeled as simple pillars."

The researchers' nondestructive yet quantitative technique provides device designers with a valuable new tool for optimizing the morphology of porous electrodes for a wide range of applications. Already, Mutha and Wang have been using it to predict the performance of supercapacitors and desalination systems. Recent work has focused on designing a high-performance, portable device for the rapid desalination of brackish water (see photo above). Results to date show that using their approach to optimize the design of CNT electrodes and the overall device simultaneously can as much as double the salt adsorption capacity of the system while speeding up the rate at which clean water is produced.

NOTES

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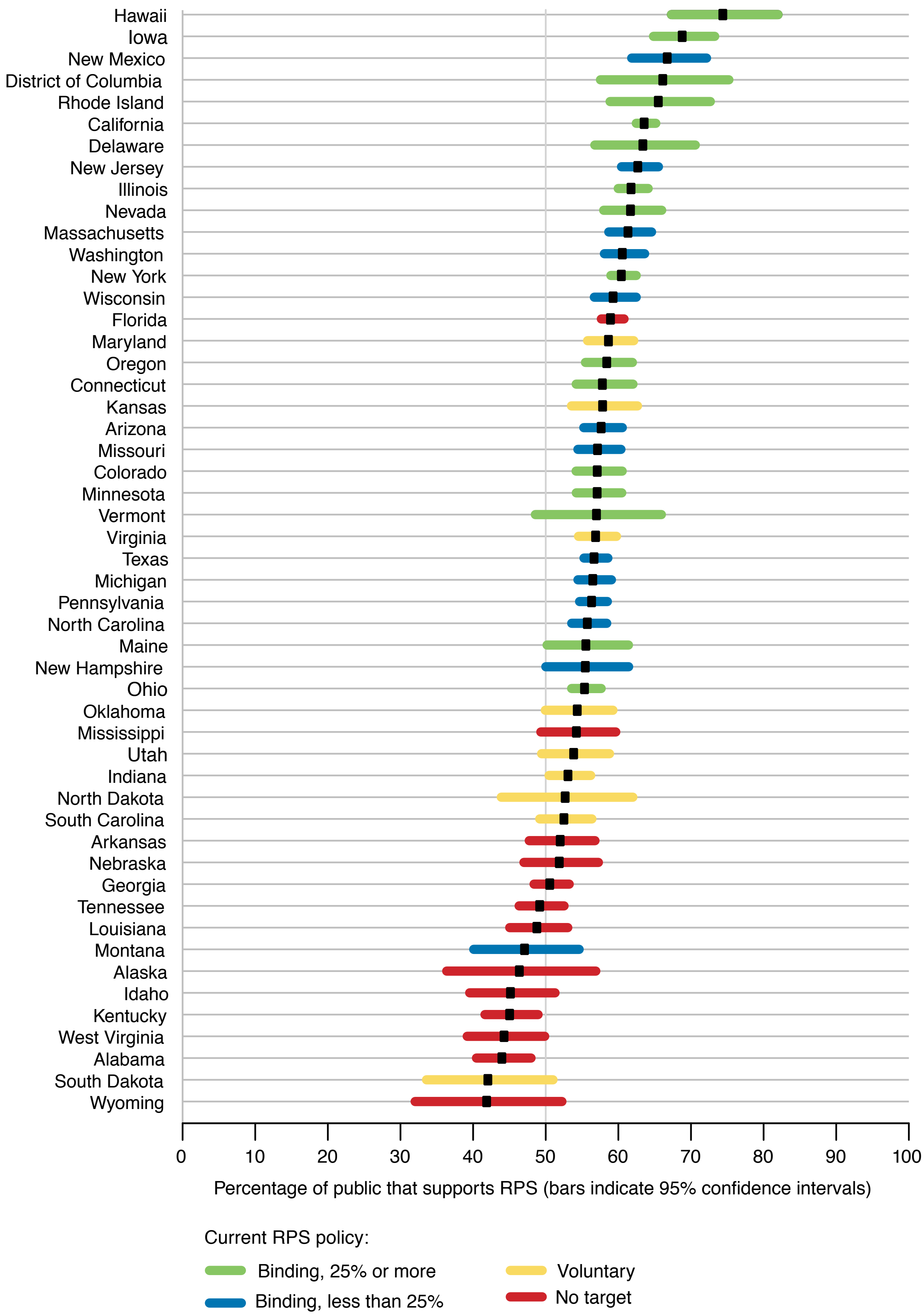
H.K. Mutha, Y. Lu, I.Y. Stein, H.J. Cho, M.E. Suss, T. Laoui, C.V. Thompson, B.L. Wardle, and E.N. Wang. "Porosimetry and packing morphology of vertically aligned carbon nanotube arrays via impedance spectroscopy." *Nanotechnology*, vol. 28, no. 5, 2017. DOI: 10.1088/1361-6528/aa53aa.

I.Y. Stein and B.L. Wardle. "Packing morphology of wavy nanofiber arrays." *Physical Chemistry Chemical Physics*, vol. 18, pp. 694–699, 2017. DOI: 10.1088/1361-6528/aa53aa.

Public support for renewable portfolio standards (RPS) plus current RPS policy, state by state



State-level renewable energy policies

Strengthening critical public support

Nancy W. Stauffer, MITEI

IN BRIEF

In recent years, many US states have been weakening their policies that call for the future adoption of renewable energy. An MIT analysis shows that in this policy arena, state legislators are broadly responsive to public opinion. Based on data from a public opinion survey, the researchers offer practical advice on how to bolster public support for renewable energy policies. Advocates should emphasize the air pollution and job creation benefits of using renewables, have leading legislators speak out in favor of them, and carefully craft any communications about potential added costs for residential customers. Citing climate change benefits doesn't appear to increase public support. However, given the current views of the federal administration, maintaining and strengthening renewable energy policies at the state level may be the best way to make progress on climate change.

Since the 1980s, the United States has often been a world leader in supporting renewable energy technologies at the state and federal levels. Thirty-seven states have enacted binding or voluntary renewable portfolio standards (RPS) requiring that a portion of their electricity mix come from renewable sources by a given date. But since 2011, adoption of such standards has slowed, and in the past several years there have been many attempts—some of them successful—to weaken, freeze, or repeal renewable energy laws.

Given the outcome of the 2016 presidential election, increased federal investment

Facing page An analysis of data from the 2014 Cooperative Congressional Election Study demonstrated that public support for renewable portfolio standards (RPS) within a given state is strongly correlated with the RPS policy now in effect, as shown by these state-by-state results.

Above Working with public opinion survey data, Christopher Warshaw (pictured) and Leah Stokes SM '15, PhD '15 found that certain aspects of how renewable portfolio standards (RPS) are designed and presented can set people's minds for or against such policies. Photo: Stuart Darsch, courtesy of MIT Department of Political Science in renewable energy is unlikely for the foreseeable future. As a result, state-level renewable energy policies will likely be central to driving new deployment. Past research has shown that public opinion plays a crucial role in facilitating a political consensus around new policies in US states. If that's true for renewable energy policies, then people's views may have a major influence on future actions taken by their states.

For the past three years, Christopher Warshaw, a former associate professor of political science at MIT, and Leah Stokes SM '15, PhD '15, an assistant professor of political science at the University of California, Santa Barbara, have been examining the interaction between public opinion and renewable energy policymaking. They have asked, first, is there evidence that public opinion and energy policy align within a particular state? And second, what determines that public opinion? For example, can the design of a given RPS policy or how it's presented to the public—that is, how it's portrayed or framed—increase or decrease support for the policy?

Public opinion and renewable energy policy—state by state

To begin investigating those questions, Warshaw and Stokes turned to data gathered by the Cooperative Congressional Election Study, a major survey supported by 56 universities, including MIT, that has its origins in a survey first funded by the MIT Energy Initiative a decade ago. In the 2014 cooperative survey, 56,200 people were asked whether they supported an RPS policy that "requires the use of a minimum amount of renewable fuels (wind, solar, and hydroelectric) in the generation of electricity, even if electricity prices increase a little."

Using the 2014 survey data, Warshaw and Stokes explored the relationship between public opinion and policy on a state-by-state basis. Their analysis showed that in most states a majority of the public supports renewable energy requirements—although frequently by a narrow margin (see the figure on page 28). In addition, public support within each state is strongly correlated with the RPS policy now in effect. Thirty-seven states plus the District of Columbia have RPS policies that are congruent with the views of a majority of their citizens, leaving only 13 that don't. All 13 states where more than 60% of the public supports an RPS have a binding RPS policy, with varying levels of ambitiousness. As public support drops close to or below 50%, states are much less likely to have a binding RPS.

"Overall, these findings suggest that state legislators are broadly responsive to public opinion on this issue," says Warshaw. "If public support for renewable energy policies increased, we could expect to see more renewable energy laws."

A new experiment

In other areas of policymaking, research has shown that exactly how a policy is designed and presented can significantly impact whether the public supports or opposes it. Thus, it's possible that certain details of RPS policies could be swaying public opinion. "We needed to gauge how the design and framing of renewable energy policies may affect people's support for them across the states," says Warshaw. He and Stokes set out to design a survey experiment that would give them insight into what drives people's opinions of renewable energy policies.

They knew that many factors could influence support for an RPS policy—from possible changes in electric bills to impacts on employment opportunities. A simple survey experiment might involve randomizing one such attribute at a time. For example, one group could be told that the new policy would increase residential electric bills, and the group's response could then be compared to that of a control group that receives no information about added costs.

But the attributes of interest here are independent—they have no impact on one another—so the researchers could investigate all of them simultaneously. This approach enables all the effects of the different attributes to be measured on the same scale. When the results are in, it's easy to see which factors are most important and warrant special attention or concern.

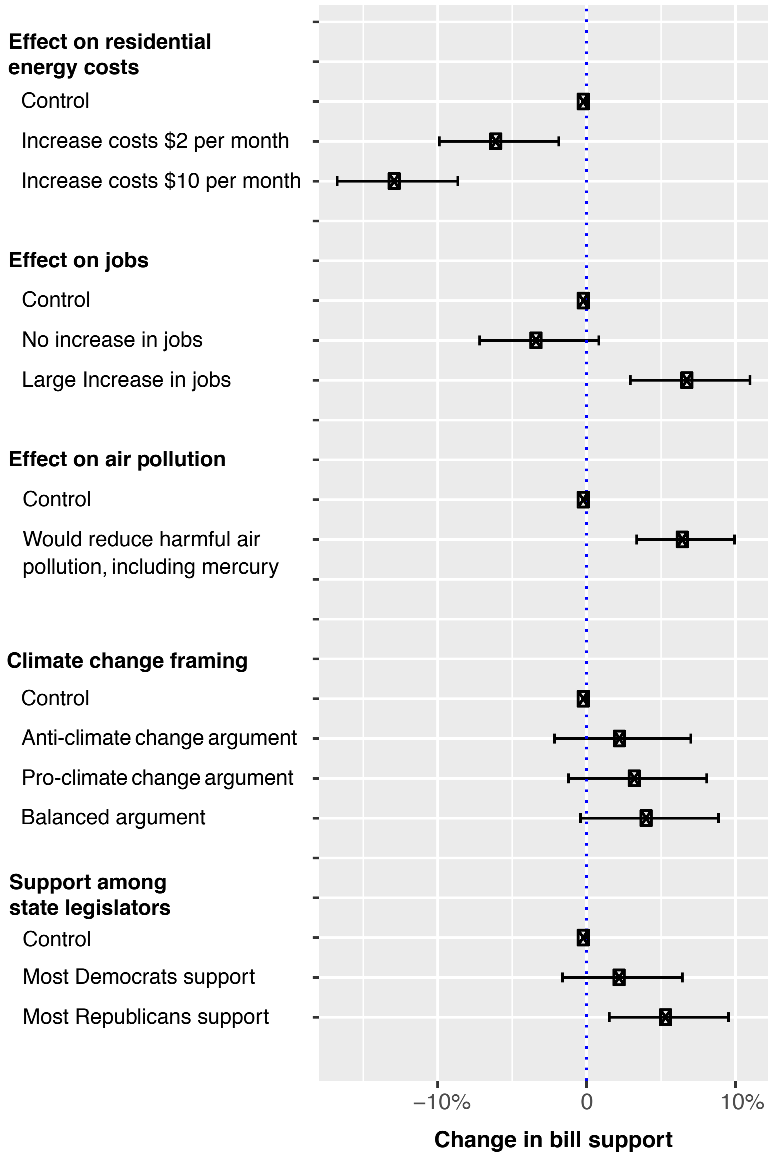
In Warshaw and Stokes's survey, all recipients received a central statement posing the possibility of the recipient's state adopting a new RPS bill requiring that the state meet 35% of its electricity needs with renewable energy sources by the year 2025. Along with that description, they received a variety of additional statements about specific attributes of the bill, randomly distributed among the survey recipients. For each attribute, some (randomly selected) people received no added information, thereby serving as the control group in the experiment.

Warshaw and Stokes received replies from about 2,500 respondents. They then performed a statistical analysis on all the data to determine how much each of the attributes influenced people's views of the basic RPS policy.

The results appear in the chart on page 31. Zero on the X-axis is the baseline for a given attribute, determined by responses from people in the control group. Movement from that baseline shows the percentage change that the added statement elicited either toward greater support (to the right) or toward greater opposition (to the left).

Economic incentives—costs and jobs

A quick look at the chart shows that an increase in residential energy costs has a far greater impact on the outcome than



Effects of design and framing of renewable portfolio standards policies on public support
This figure shows the impact of various policy attributes on survey respondents' support for a renewable energy policy in the respondent's state (with 95% confidence intervals). Zero on the X-axis represents responses from a control group that received no comment about that attribute. A shift toward the left reflects a negative response to the information provided; a shift toward the right reflects a positive response. For example, opposition increases significantly when people learn that their electricity bills will go up. On the other hand, support increases when people find out that many jobs will be created or that air pollution will drop.

any of the other attributes. Adding $2 to the electricity bill decreases support for an RPS policy by about 6%, while a $10 increase decreases support by fully 13%. As shown in the table on page 32, those changes are large enough to flip majority public opinion within some states from supporting to opposing RPS policies. In the $2 case, 13 states shift from supporting to opposing; in the $10 case, 33 states move to the opposing side.

The possible impact on jobs is another big factor—one that can push support either way. Being told that the bill won't create any jobs prompts 3.2% of respondents to oppose the bill. With that change, five states flip from majority support to majority opposition. On the other hand, learning that the RPS policy will probably create several thousand jobs causes 7% of respondents to support the bill, a change that flips eight states from majority opposition to majority support. "So if people think these policies will create a lot of jobs, public support increases enough to lead almost every state—except possibly the most conservative ones—to support RPS policies," notes Stokes.

The results provide some interesting clues about what people believe now. For example, the response to added costs suggests that many people think renewables won't—or shouldn't—cost them anything extra. The prospect of a $2 increase in their electricity bill prompts a shift toward opposition. If people started out thinking renewable standards would cost them something, adding just $2 to the bill probably wouldn't have elicited such a change.

The negative response to learning that the new policy will bring no extra jobs conveys a different message. "It may suggest that in the absence of any added information, people think the new bill will lead to a small increase in jobs—which frankly is generally about right," says Warshaw. Once again, the experiment uncovers starting assumptions that people may have—perhaps without knowing it.

Environmental impacts

Another reason to support using renewable energy may be the promise of environmental benefits. The survey tested that idea by telling some respondents that increasing renewable energy will reduce harmful air pollution in their state, including toxins such as mercury. Learning that air pollution will go down brings almost as large a response as learning that employment will go up: 6.7% of people move to the supporting side. "So emphasizing either job creation or air quality benefits could cause eight of the 10 states where a majority now opposes RPS bills—and where RPS policies largely do not exist—to flip to a majority in support," says Stokes.

	Number of states with majority support for RPS	Change from baseline
Baseline RPS support	40	0
Increases electricity costs $2 per month	27	-13
Increases electricity costs $10 per month	7	-33
No increase in jobs	35	-5
Large increase in jobs	48	+8
Reduces air pollution	48	+8
Democrat elites support	43	+3
Republican elites support	47	+7

Effects of policy attributes on state-by-state majority support More than half the people surveyed in 40 states say they would support a renewable energy bill in their state. But finding out more details can influence those responses enough to flip majority support to majority opposition. For example, learning that the policy would mean a $10 increase in monthly electricity costs shifts support to opposition in 33 of the 40 states. On the other hand, if many new jobs are expected, eight states move from majority opposition to majority support.

Interestingly, linking RPS policies to climate change had no impact on public support. The survey included various statements about the effects of RPS policies on greenhouse gas emissions and about whether or not supporters and opponents believe climate change to be a serious problem. While the added information increased support slightly, the change wasn't large enough to be statistically significant.

Warshaw believes that the lack of impact isn't because people don't know or care about climate change. "I think it's because they already have a pretty strong view on the connection between renewable energy policies and climate change," he says. "Their view is already baked in, so you can't frame the question in a way that triggers a change."

Partisan support

One more factor of interest is the role played by elites in the political parties. Some research suggests that partisanship isn't important for energy policy, even though it has been shown to influence public support in other policy domains. So the researchers added some partisan cues.

They found that when people are told that Democratic legislators support the RPS policy, public support increases by 2.4%, and three states flip from majority opposition to majority support. When respondents are told that Republican legislators support it, public support increases by 5.5%, and seven states flip to majority support. Interestingly, the results show that if an elite affiliated with one political party supports the RPS policy, there is no statistically significant decrease in support by respondents affiliated with the other party.

Warshaw believes that support by partisan elites can have a big impact in part because people's views on renewable energy "aren't super-strongly formed," he says. "On policies they don't know much about, people look to their elected officials to tell them what the right thing to believe is. There's considerable political science evidence that that's true."

Stokes notes that while none of the statements relating to climate change seemed to influence public opinion in the survey, in the absence of a coherent federal policy, state-level RPS policies may actually prove the most effective means of securing climate benefits. That prospect underscores the need for continuing public engagement during the decades-long process of weaning the US energy system off fossil fuels.

NOTES

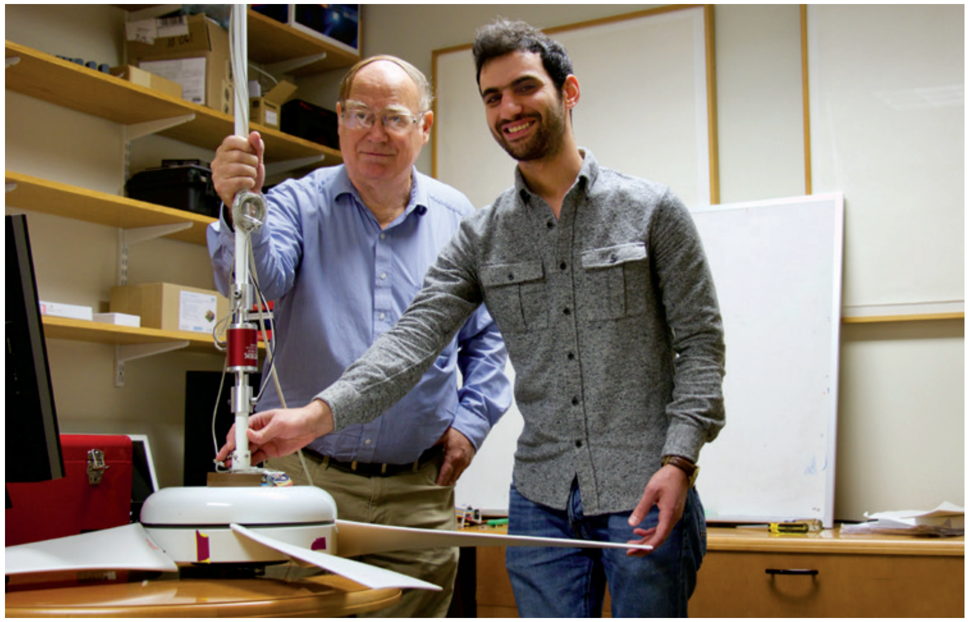
This research was supported by the MIT Energy Initiative Seed Fund Program. In autumn 2017, Christopher Warshaw became an assistant professor at George Washington University and a MITEI affiliate. While at MIT, Leah Stokes SM '15, PhD '15 was a 2010–2011 Siemens-MIT Energy Fellow and a 2013–2014 Martin Family Sustainability Fellow. Logistical support was provided by the MIT Political Experiments Research Lab. Further information can be found in:

L. Stokes and C. Warshaw. "Renewable energy policy design and framing influence public support in the United States." *Nature Energy*, article no. 17107, June 30, 2017.

Making appliances—and energy grids—more efficient

The ceiling fan is one of the most widely used mechanical appliances in the world. It is also, in many cases, one of the least efficient.

In India, these devices have been used for centuries to get relief from the hot, humid climate. Hand-operated fans called punkahs can be traced as far back as 500 BC and were fixtures of life under the British Raj in the 18th and 19th centuries. Today's ceiling fans run on electricity and are more ubiquitous than ever: In 2014 alone, the Indian Fan Manufacturers' Association reported producing 40 million units. The number of fans in use nationwide is in the hundreds of millions, perhaps as many as half a billion.



Professor James Kirtley Jr. (left) and Tata Fellow Mohammad Qasim hold a state-of-the-art ceiling fan that they use as a benchmark for evaluating the performance of their motor designs. A variety of instruments generate measurements they use to calculate how much of the power from the fan ends up actually moving air, thus the efficiency of the device. Photos: Taylor Ko, Tata Center for Technology and Design

James Kirtley Jr., professor of electrical engineering at MIT, has been investigating the efficiency of small motors like those found in ceiling fans for more than 30 years. "A typical ceiling fan in India draws about 80 watts of electricity, and it does less than 10 watts of work on the air," he explains. "That gives you an efficiency of just 12.5%."

Low-efficiency fans pose a variety of energy problems. Consumers don't get good value for the electricity they buy from the grid, and energy utilities have to deal with the power losses and grid instability that result from low-quality appliances.

But there's a reason these low-efficiency fans, driven by single-phase induction motors, are so popular: They're inexpensive. "The best fans on the market in India—those that move a reasonable amount of air and have a low input power—are actually quite costly," Kirtley says. The high price puts them out of reach for most of India's population.

Now Kirtley, with support from the Tata Center for Technology and Design, is working on a single-phase motor design that offers high efficiency at an affordable cost. He says that the potential impact is huge. "If every fan in India saved just two watts of electricity, that would be the equivalent of a nuclear power plant's generation capacity. If we could make these fans substantially more efficient than they are, operating off of DC electricity, you could imagine extending the use of ceiling fans into rural areas where they could provide a benefit to the quality of life."

Mohammad Qasim, a graduate student in Kirtley's research group and a fellow in the Tata Center, explains that the benefits could reach multiple stakeholders: "Having more efficient appliances means a lower electricity bill for the consumer and fewer power losses on the utility's side."

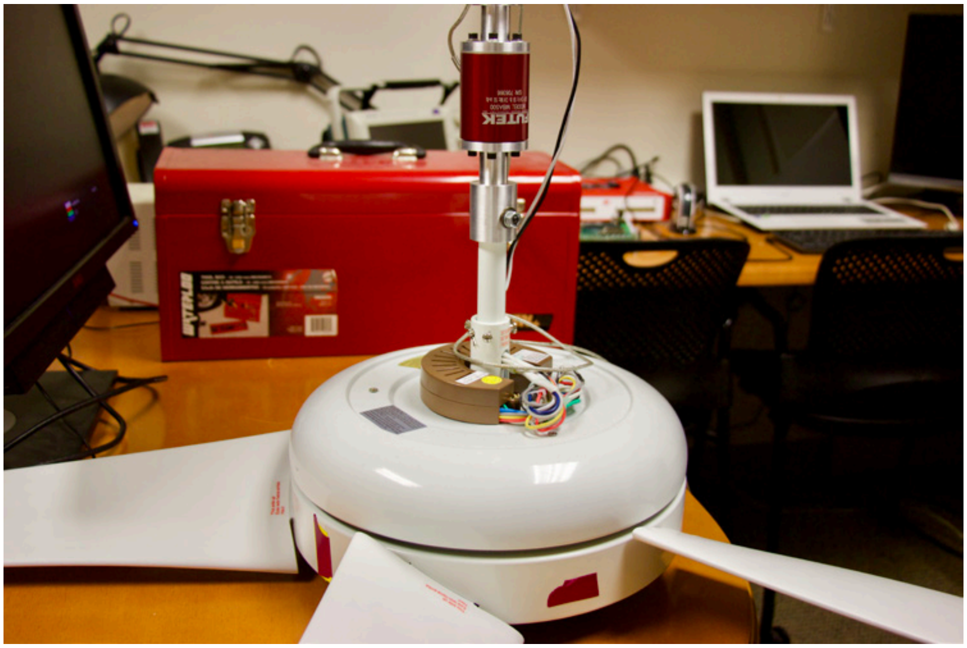
Choosing the right motor

"The idea is to try and hit that high-efficiency mark at a cost that is only a little more than that of existing low-efficiency fans," Kirtley says. "We imagine a fan that might have an input power of 15 watts and an efficiency of 75%."

To accomplish that, Kirtley and Qasim are exploring two approaches: creating an improved version of the conventional induction motor, or switching to a brushless DC motor, which may be more expensive but can deliver superior efficiency.

In either case, they plan to use power electronics—devices that control and optimize the flow of electricity through the motor—to improve the power quality and grid compatibility of the fan. Power electronics can also be used to convert AC electricity from the grid into DC, opening up the possibility of using DC motors in ceiling fans.

Brushless DC motors, the younger technology, use permanent magnets to establish a magnetic field that creates torque between the motor's two main



The base shown here contains the motor and the power electronics being tested. Mounted on the pole above are a dynamometer and sensors that measure torque (turning force) and thrust (forward force). Other instruments include a strobotac that monitors the speed at which the fan turns and a hot-wire anemometer that tracks the movement of the air.

components, the rotor and stator. "You can think of it almost like a dog chasing his tail," Kirtley says. "If I establish the magnetic field in some direction, the magnet turns to align itself in that direction. As I rotate the magnetic field, the magnet moves to align, and that keeps the rotor spinning."

Induction motors, on the other hand, use no magnets but instead create a rotating magnetic field by flowing current through the stator coils. Because they use AC electricity, they are directly grid compatible, but their efficiency and stability can be improved by using power electronics to optimize the speed of the motor.

International collaboration

In determining which path to take—induction or brushless DC motor—Kirtley and Qasim are leaning on the expertise of Vivek Agarwal, professor of electrical engineering at the Indian Institute of Technology, Bombay (IITB), a specialist in power electronics.

"The collaboration with Professor Agarwal's group is so important," Kirtley says. "They can give us a good idea of what the two different power electronics packages will cost. You would typically think of the brushless motor package as the more expensive option, but it may or may not be."

Outside of the lab, on-the-ground detective work is key. When Qasim visited India in January 2017, he hit the streets of Mumbai with one of the graduate students from Agarwal's lab. Together, they visited people across the ceiling fan industry, from manufacturers to repairmen in street-side shops.

"This visit was a big motivation for us," Qasim says, noting that they were able to glean insights that will help them design a more robust and durable motor. "We want to understand the major maintenance issues that cause these motors to break down so that we can avoid common sources of failure. It was important to make the effort to talk to local people who had real experience repairing these motors."

Usha International, an appliance manufacturer based in New Delhi, has been a key advisor in the early stages of the project and helped identify ceiling fans as a critical focus area. Engineers at Usha agree with Kirtley's assessment that there is an unmet need for high-efficiency motors at relatively low cost, and Qasim says the Usha team shared what they had learned from designing their own high-efficiency fans.

Now, Kirtley and Qasim are engaged in the daunting task of envisioning how an ideal motor might look.

"This is a very challenging problem, to design a motor that is both efficient and inexpensive," Kirtley says. "There's still a question of which type of motor is going to be the best one to pursue. If we can get a good understanding of what exactly the machine ought to do, we can proceed to do a good machine design."

Qasim has built a test facility in Kirtley's laboratory at MIT, which he is using to characterize a variety of existing fans. His experimental data, combined with his fieldwork in India, should provide a set of design requirements for the improved motor. From there, he and Kirtley will work with the IITB researchers to pair the machine with an appropriate power electronics package.

In reducing the power demands of the standard ceiling fan by as much as 65 watts, they hope to have a far-reaching, positive effect on India's energy system. But that's only the start. Ultimately, they believe efficient, affordable motors can be applied to a number of common appliances, potentially saving gigawatts of electricity in a country that is working hard to expand reliable energy access for what will soon be the world's largest population.

Ben Miller, MIT Tata Center for Technology and Design

Jing Li: Applying economics to energy technology development and deployment

For the past four years, Jing Li '11 has been studying energy technologies that could help the world move to a low-carbon future. Her expertise is technology diffusion and adoption. Li, fresh out of an economics PhD program at Harvard, says she "loves thinking about how technological progress comes about, how technology is adopted." She's returning to MIT to do that and more—first as a postdoc for a year and then as an assistant professor of applied economics.

Photo: Russ Campbell

Her research focuses on the race to introduce better batteries into the marketplace. The availability of low-cost, high-energy-density, scalable, and safe batteries is critical in both transportation and power generation, two of the most polluting sectors in our energy ecosystem, she points out. Better batteries could mean higher efficiency and lower emissions.

"We're not quite there yet in terms of battery technology that checks all the boxes, but why not? There are many patents out there, but when do we expect to see them on the market?" she says. Li's training in economics allows her to examine each step as a technology progresses from the lab to the marketplace. She hopes her studies will help speed up that process. "Energy is critical to everyday life, and low-carbon energy is critical to addressing climate change concerns," Li says. "At some point, I just started thinking about that, and I couldn't let go."

Li organizes her research on technology adoption around three core questions. First, why aren't adoption rates as high as we'd like or expect for a promising technology? Cost and pricing are sometimes the impediment but not always. Sometimes it's a question of infrastructure, as in the example of electric cars, which Li focused on in her dissertation. Electric cars need a reliable network of charging stations before widespread adoption is possible.

Li's second question deals with the mysteries of technological innovation. She asks, "Is technological innovation a black box, and all we need to do is wait? Or is there scope for government policy to accelerate innovation by addressing inefficiencies?" She studies instances in which more funding for basic research could make a difference, or in which the inventions are ready but firms or consumers need a push in the form of measures such as government subsidies for the product to achieve higher levels of adoption.

The final question driving her research is: How can we meet growing energy demand in developing countries while protecting human health and the environment? Over the course of her education and the beginning of her research career, Li has explored fields from development economics to environmental economics and industrial organization. "If we're going to improve the lives of people in developing countries, energy consumption is going to play a big role," Li says. "But at the same time, how do we make things better for human health by alleviating pollution, improving air quality?"

With her fast-approaching professorship very much on her mind, Li has plans to take a close look at the economics curriculum at the Institute to see if there are any gaps in what's being offered. "There's a history of high-quality energy economics classes at MIT," she says. "I want to learn more about the classes that are being taught currently and bring back some of the really important parts of classes that are no longer around."

She plans to meet with a wide range of students—from Sloan MBAs to undergraduates in engineering, science, and the humanities—to formulate a sense of which energy and economics issues they feel are most important. She's keeping learning outside the classroom in mind, too. She says she benefited immensely from the Undergraduate Research Opportunities Program (UROP) as an undergrad, "learning a lot about the grunt work of research." If the right research opportunity presents itself, she plans to create a UROP for undergrads working in energy economics.

Li looks forward to the chance to give back to her alma mater in this way. "MIT just feels special to me in a way that I cannot even articulate," she says. "To me, it's nerds—in the best sense of the word—coming together to celebrate learning and knowledge."

Francesca McCaffrey, MITEI

FOCUS ON FACULTY

Jennifer Rupp: Engineering ceramics for renewable energy and information applications

Ensuring that her research contributes to society's well-being is a major driving force for Jennifer Rupp. "Even if my work is fundamental, I want to think about how it can be useful for society," says Rupp, the Thomas Lord Assistant Professor of Electrochemical Materials at MIT. Since joining the Department of Materials Science and Engineering (MSE) in February 2017, she has been focusing not only on the basics of ceramics processing techniques but also on how to further develop those techniques to design new practical devices as well as materials with novel structures. Her current research applications range from battery-based storage for renewable energy, to energy-harvesting systems, to devices used to store data during computation.

Photo courtesy of Jennifer Rupp

Rupp first became intrigued with ceramics during her doctoral studies at ETH Zurich. "I got particularly interested in how they can influence structures to gain certain functionalities and properties," she says. During this time, she also became fascinated with how ceramics can contribute to the conversion and storage of energy. The need to transition to a low-carbon energy future motivates much of her work at MIT. "Climate change is happening," she says. "Even though not everybody may agree on that, it's a fact."

One way to tackle the climate change problem is by capitalizing on solar energy. Sunshine falling on the Earth delivers roughly 170,000 terawatts per year—about 10,000 times the energy consumed annually worldwide. "So we have a lot of solar energy," says Rupp. "The question is, how do we profit the most from it?"

To help convert that solar energy into a renewable fuel, her team is designing a ceramic material that can be used in a solar reactor in which incoming sunlight is controlled to create a heat cycle. During the temperature shifts, the ceramic material incorporates and releases oxygen: at the higher temperature, it loses oxygen; at the lower temperature, it regains the oxygen. When carbon dioxide and water are flushed into the solar reactor during this oxidation process, a split reaction occurs, yielding a combination of carbon monoxide and hydrogen known as syngas, which can be converted catalytically into ethanol, methanol, or other liquid fuels.

While the challenges are many, Rupp finds the humanitarian ethos at MIT bolstering. "At MIT, there are scientists and engineers who care about social issues and try to contribute with science and their problem-solving skills to do more," says Rupp. "I think this is quite important. MIT gives you strong support to try out even very risky things."

In addition to continuing her work on new materials, Rupp looks forward to exploring new concepts with her students. During fall 2017, she supported Jeffrey Grossman, the Morton and Claire Goulder and Family Professor in Environmental Systems and an MSE professor, in recitation sessions for his undergraduate materials science and engineering class. In spring 2018, she will begin teaching a new elective for graduate students on ceramics processing and engineering that will delve deeper into making ceramic materials not only on the conventional large-scale level but also as nanofabricated structures and small system structures for devices that store and convert energy, compute information, or sense carbon dioxide or various environmental pollutants.

Rupp has also proposed the first materials science comic strips, which she hopes to develop with the help of students in an extracurricular club. The first iteration is available on Instagram (@materialcomics) and depicts three heroes who jump into various structures to investigate their composition and, naturally, to have adventures. "I think it is important to create interest in the topic of materials science across various ages and simply to enjoy the fun in it," says Rupp. She sees this as an exciting avenue to engage the nonscientific community as a whole and to illustrate the structures and compositions of various everyday materials.

For Rupp, MIT is proving to be a stimulating environment. "Everybody is really committed and open to being creative," she says. "I think a scientist is not only a teacher or a student; a scientist is someone of any age, of any rank, someone who simply enjoys unlocking creativity to design new materials and devices."

Kelley Travers, MITEI

New chair of Energy Minor Oversight Committee envisions changes for Energy Studies Minor

When David Hsu taught his first class at MIT two years ago, he was struck by the curiosity and enthusiasm of his students. Since then, he's made interacting with and supporting students a top priority. In fall 2017, Hsu, an assistant professor in MIT's Department of Urban Studies and Planning, became chair of the Energy Minor Oversight Committee, which guides curriculum development and the creation of educational programs associated with the Energy Studies Minor.

Designed by MITEI, the minor is an undergraduate course of study that encourages students from any department within MIT to expand their knowledge of energy issues across a range of fields, from science and engineering to policy to the humanities.

This year, several changes are on the horizon for the minor. For example, Hsu and his colleagues on the oversight committee are working to make the curriculum more flexible, so that students can take key classes in either the fall or the spring. Another change is an increase in the number of advisors from one in each core area of the minor (science, engineering, and social science) to one in each academic department. Hsu acknowledges that "one of the challenges in the past was making students aware of the classes that are available to them as well as the classes they need to take." These department advisors are a "helpful go-to resource" for students and can provide answers to such questions.

In light of climate change and the current political situation, Hsu believes it is more important than ever for students to study energy. "The issue of climate change is moving quickly, and the interest amongst students is not going away," says Hsu. The popularity of classes within the energy minor that focus on climate change continues to grow. And the increasing number of jobs in energy, especially in the renewables sector, makes energy an attractive field of study for students.

Hsu emphasizes the long-term benefits of building a network of fellow energy researchers while at MIT. Within the energy minor, there are cohort-building activities throughout the year, including special events in the Undergraduate Energy Commons. Hsu also cites exciting opportunities outside the minor, among them MITEI's Solar Spring Break, a volunteer program in which students spend a week installing solar panels on the home of a low-income family in Los Angeles, California.

Since joining the MIT community, Hsu has gained a deep appreciation for the Institute and its emphasis on collaboration between faculty and students. "What is really exciting for students, Energy Studies Minor students in particular, is the opportunity to work with people from across the disciplines," he says. Hsu, who comes from both a natural and social science background, especially appreciates the wide range of classes available within the minor, which allows students to explore and combine their interests, from economics to technology to policy. He says, "Energy is a technical, social, and cultural problem, so tackling it requires a diverse group of people and ideas."

Deirdre Carson, MITEI

David Hsu, assistant professor of urban and environmental planning, chairs the Energy Minor Oversight Committee. Photo: Katherine Shozawa

Energy Minor Oversight Committee, September 2017

David Hsu, Chair
Urban Studies and Planning

William Green
Chemical Engineering

Bradford Hager
Earth, Atmospheric, and Planetary Sciences

Robert Jaffe
Physics

Christopher Knittel
Sloan School of Management

Rajeev Ram
Electrical Engineering and Computer Science

Energy Studies Minor graduates, June 2017

Melanie Abrams
Biology

Andres Alvarez
Nuclear Science and Engineering

Rasheed Auguste
Nuclear Science and Engineering

Hannah Hoffman
Nuclear Science and Engineering

Linda Wei Jing
Materials Science and Engineering

Daniel Kilcoyne
Chemical Engineering

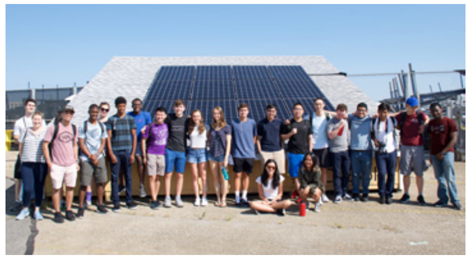
Timothy Manganello
Chemical Engineering

Rachel Osmundsen
Materials Science and Engineering

Carolyn Schaefer
Nuclear Science and Engineering

Rebecca Sugrue
Civil and Environmental Engineering

MITEI welcomes new students to campus



Every year, MITEI invites incoming MIT freshmen interested in energy to come to campus early and spend a week bonding over energy-related workshops and off-campus activities during MITEI's Freshman Pre-Orientation Program (FPOP). Here, the FPOP class of 2017 takes a tour of the Massachusetts Clean Energy Center's Wind Technology Testing Center. Photo: Rhyana Freeman, MITEI

Freshmen Jennifer Fox (left) and Geneva Casalegno explore sustainable energy solutions at the Wind Technology Testing Center. Photo: Rhyana Freeman, MITEI

Assisted by FPOP counselor Srimayi Tenali '20 (right), freshman Jimmy Tran learns how to build his own motor in Professor Steven Leeb's mechanical engineering lab. Photo: Rachel Shulman, MITEI

New textbook on physics of energy

Cambridge University Press is now accepting pre-orders for *The Physics of Energy* by Robert L. Jaffe, the Jane and Otto Morningstar Professor of Physics at MIT, and Washington Taylor, MIT professor of physics and director of the Center for Theoretical Physics. This definitive new textbook provides a comprehensive and systematic introduction to the scientific principles governing energy sources, uses, and systems. It traces the flow of energy from sources such as solar power, nuclear power, wind power, water power, and fossil fuels through its transformation in devices such as heat engines and electrical generators to its uses—including transportation, heating, cooling, and other applications. The flow of energy through the Earth's atmosphere and oceans, and systems issues including storage, electric grids, and efficiency and conservation are presented in a scientific context along with topics such as radiation from nuclear power and climate change from the use of fossil fuels.

This book will be an essential resource for any student, scientist, engineer, energy industry professional, or concerned citizen who has some mathematical and scientific background and an interest in understanding energy systems and issues quantitatively. Its comprehensive but modular form makes it an ideal text for a broad range of courses on energy science.

The book was developed with the support of a grant through the MIT Energy Initiative from the S. D. Bechtel, Jr. Foundation. Publication is planned for March 2018.

Show the flow: Novel hand-held laboratory reveals fluid movement inside rock

When it comes to teaching, seeing is believing, or at least understanding.

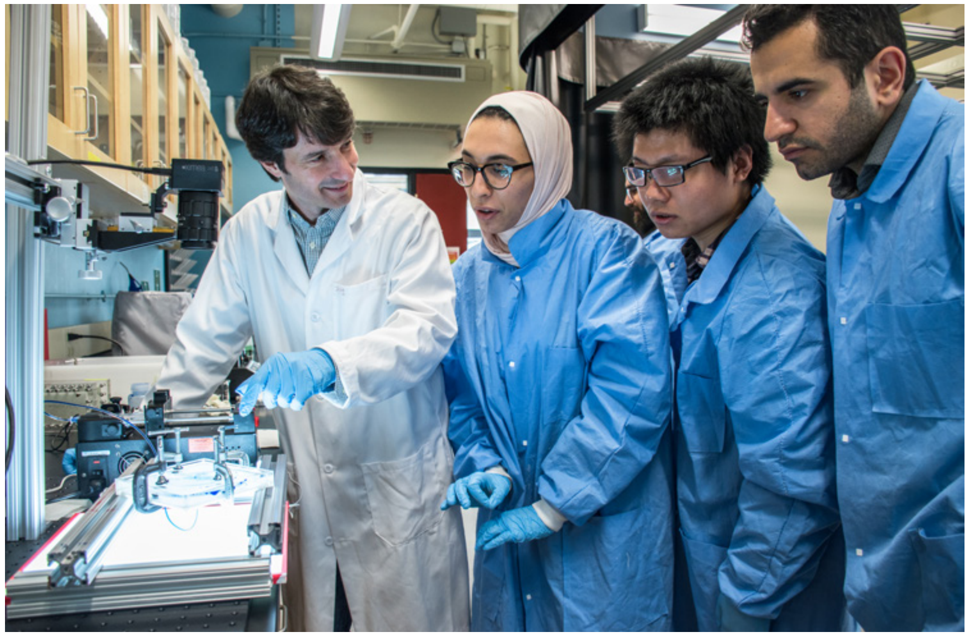
This is the guiding principle of a new class, 1.079 Rock-on-a-Chip, dedicated to exploring multiphase flow in porous media. "This course is an opportunity to teach this subject in a completely different way, by visualizing the physics of flow," says instructor Ruben Juanes, ARCO Associate Professor in Energy Studies.

Juanes introduced 1.079 in spring 2017, aiming to kick-start an energy resources track within the Department of Civil and Environmental Engineering. "The class plays a very nice role in the curriculum, filling a gap in a subject that is crucial to many energy technologies," he says.

Flows in porous media come into play in a range of real-world applications, from oil and gas recovery and groundwater resource management to seismic activity mapping and energy storage technology. These flows are frequently multiphase, composed of gases, solids, and liquids in diverse mixes. For example, hydrocarbon reservoirs simultaneously host water, oil, and gas; and fuel cells feature a porous layer next to the cathode where water vapor may condense into liquid water.

However, the processes by which liquids and gases move underground often take place out of sight. Rainwater infiltrates soil, displacing air. Oil and water compete as they seep through rock reservoirs. It has been difficult to observe and capture in scientific detail what Juanes calls "the marvelous physics and chemistry of multiphase flows."

But recently, Juanes figured out a way of elucidating these subterranean processes. Employing 3D printing and methods borrowed from the field of microfluidics, he created a multiphase flow laboratory on a chip.



Left to right: Professor Ruben Juanes and students Lubna Barghouty, Yunteng Cao, and Ehsan Haghighat discuss the impact of wettability on the patterns of fluid invasion into a porous microfluidic chip, illuminated from below and recorded with a high-speed camera from above. Photos: Kelley Travers, MITEI

The device consists of a microfluidic flow cell patterned with vertical posts using soft lithography, sandwiched between two thin layers of a transparent polymer. When one fluid is introduced to displace another, the chip permits direct visualization of fundamental physical mechanisms at the scale of actual rock and soil pores. Juanes can now study in vivid close-up the critical properties and porous media conditions that hamper, or hasten, underground flows.

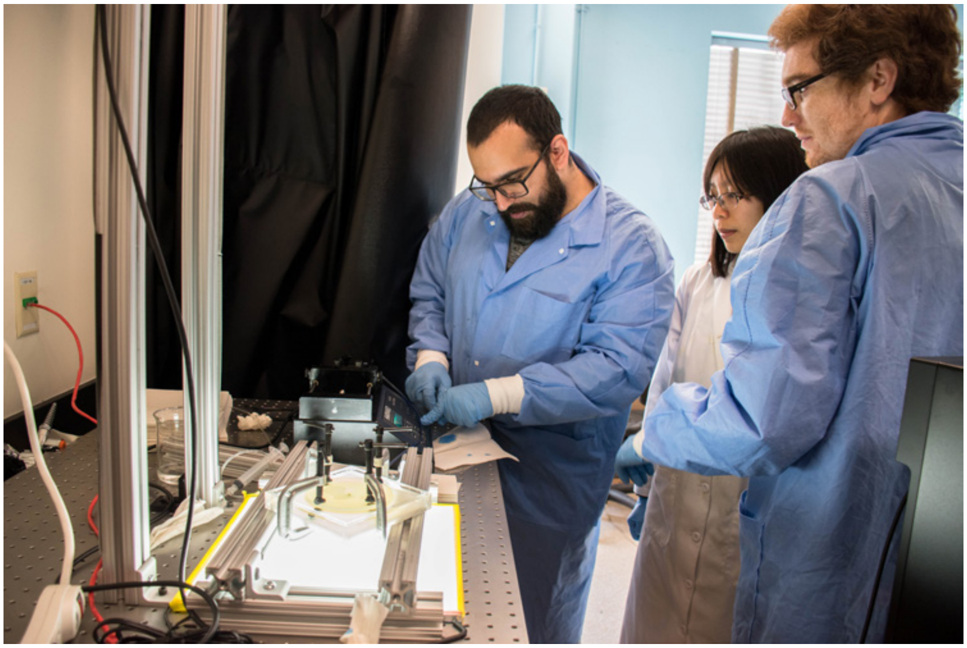
What Juanes calls a "new approach to an old problem" proves especially effective in the classroom. "With transparent porous media, you can demonstrate the process of oil recovery, filtration of water, extraction of gases," he says. "You can't really understand these applications without knowledge of the physics, and here, an image is worth a thousand words."

"I had been reading about the concepts and trying to imagine these phenomena, and finally I was able to see them," says Lubna Barghouty SM '17, whose graduate research focused on predicting the flow of oil from rock reservoirs containing both oil and water. "It's a one-of-a-kind class."

Rafael Villamor Lora, a graduate student in civil engineering and geomechanics, is studying rock permeability and fluid flow inside rock fractures. He found that 1.079 offered "a unique approach to presenting very difficult physics, making it clear and understandable."

Juanes divided class time between lectures focused on theory and labs that brought theory to life, a mix that students found both intellectually challenging and practical.

"I love experimenting and doing things hands-on," says Omar Al-Dajani SM '16,



Students Omar Al-Dajani (left) and Rafael Villamor Lora (right), with teaching assistant Jane Chui (center), set up the fluid injection into a microfluidic device to study fluid-fluid displacement in porous media. Photo: Kelley Travers, MITEI

a petroleum engineer for Saudi Aramco now pursuing a doctoral degree in civil and environmental engineering. But sometimes his experiments failed. "It was amazing how Professor Juanes could change a few things on the fly so the experiment would run successfully," he says. "He goes through derivations, formulates problems in a very elegant way, and comes up with the right solution for whatever problem comes up in the lab."

Barghouty was anxious when she initially discovered that she would be responsible for fabricating her own lab tools. "We did whole experiments from A to Z, including cutting sheets of acrylic glass with lasers and using 3D printers to etch pores in these chips," she says. "I am now confident that I have the skills necessary for experimental work and that I can apply those skills to other kinds of research."

Lab-on-a-chip experiments that required hours of preparation might take mere moments to run. One experiment demonstrated the power of capillary forces. After filling their microfluidic chips with a fluid, students flipped them 180 degrees, expecting the fluid to flow down in response to gravity.

"In my cell, the fluid hung, and my jaw dropped," recalls Al-Dajani. Surface tension made the fluid stick to the many tiny posts inside the chip, fabricated to simulate rock pores. When he added a drop of soap, suddenly the surface tension disappeared and the fluid dropped. "We saw the physics in action, the competition between gravity and capillary forces, which also takes place inside oil reservoirs," he says.

Several labs featured Juanes's research pursuits. "I asked students to change the wettability of the microfluidic cell and to look at displacement of multiphase flow under different wetting conditions," says Juanes. Understanding and altering wettability—a measure of a substance's attraction to or repulsion of water—is essential to fluid extraction applications. "There are ways wettability could be modulated to recover more oil and gas in existing reservoirs," Juanes notes. "There is a big margin for improvement in both fracking and conventional drilling."

While he hopes to drive home the real-world applications of laboratory work, Juanes intends for the class to accomplish a broader pedagogical goal. "When you perform an experiment not knowing the outcome, you are forced to make sense of what happens, especially something unexpected," he says. "Moments like these captivate your attention, really allowing you to dig deep and giving you a better understanding of physics at play."

The Rock-on-a-Chip class was developed with funding from the S.D. Bechtel, Jr. Foundation. It will be an elective for the Energy Studies Minor starting in 2018.

Leda Zimmerman, MITEI correspondent

Energy Fellows, 2017–2018

The Society of Energy Fellows at MIT welcomed 22 new members in fall 2017. The Energy Fellows network now totals almost 400 graduate students and postdoctoral fellows and spans 20 MIT departments and divisions and all five MIT schools. Fellows 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 seven MITEI Member companies.

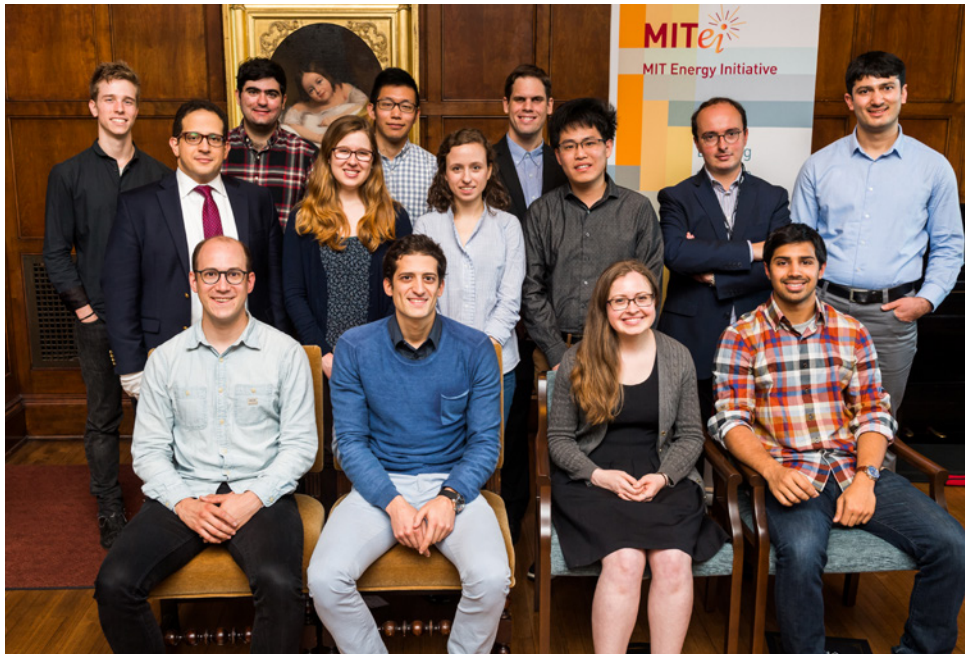


Photo: Justin Knight

Bosch

Eric Fadel
Materials Science and Engineering

BP

Bora Ozaltun
Institute for Data, Systems, and Society
Assignment in Center for Energy and Environmental Policy Research

Christoph Tries
Institute for Data, Systems, and Society
Assignment in Joint Program on the Science and Policy of Global Change

Chevron

Michela Geri
Mechanical Engineering

Eni S.p.A.

Nina Andrejevic
Materials Science and Engineering

Giovanni Azzellino, PhD
Research Laboratory of Electronics

Ulugbek Barotov
Chemistry

Nabeel Dahod
Chemical Engineering

Kunjoong Kim, PhD
Materials Science and Engineering

Lluis Salo
Civil and Environmental Engineering

Sahag Voskian
Chemical Engineering

Seth Wong
Institute for Data, Systems, and Society
Assignment in Center for Energy and Environmental Policy Research

Exxon Mobil

John Leonard Barton
Chemical Engineering

Yuwei Gu
Chemistry

Lisa Guay
Chemical Engineering

Hunmin Koh
Architecture

Andrew Moorman
Architecture

Oles Shtanko
Physics

Youngmin Yoon
Chemistry

GE

Conleigh Byers
Institute for Data, Systems, and Society

Jesse Jenkins
Institute for Data, Systems, and Society

Shell

Nimrod Heldman, PhD
Biological Engineering

Fellows as of November 15, 2017

Undergrads gain on-the-job experience in energy with MITEI member companies

MIT undergraduates who interned with MITEI member companies this summer had the chance to work abroad on a wide range of energy projects, from analyzing fuel additives to evaluating how new technologies might transform energy markets.

Along the way, the interns—all participants in a program called MISTI—learned basic life lessons, experienced other cultures first-hand, and gained insights into the energy industry. This deep dive into the working world overseas is a hallmark of MISTI (MIT International Science and Technology Initiatives), the Institute's renowned program in applied international studies.

"MISTI helped me explore the world and get a global perspective," says Ignacio Ortega '20, who spent eight weeks interning at Iberdrola in Madrid, Spain. "That's something I want to have because in the future I want to start my own company," says the mechanical engineering major, who plans to complete the Energy Studies Minor and enter the energy industry.

This is the fifth straight year that MITEI and MISTI have teamed up to provide interested students with energy internships abroad. This summer, the partnership sent eight students abroad to MITEI members: six to Shell in India, one to Shell in Germany, and one to Iberdrola in Spain.

"MISTI opens the world to MIT students by offering a robust portfolio of possibilities in energy—from looking at solar energy in remote Himalayan villages that have no electricity to working in the R&D heart of Bangalore with global companies such as Shell," says Mala Ghosh, managing director of MIT-India and MIT-South Asia and MISTI liaison for the MISTI-MITEI internship program.

Ghosh notes that the MITEI interns were among roughly 50 MIT students who did energy-related work overseas during summer 2017 through MISTI. Overall, MISTI placed 1,250 students—469 graduate students and 781 undergrads—in internships and research posts around the world this year.

Professional skills for students

"It's been an adventure," says Carissa Skye '19, a physics major working at Shell in Hamburg, Germany. Skye says the MISTI internship provided "a crash course on adult life"—from finding an apartment to filling out German bank forms—and also made it possible to gain professional experience applying machine learning algorithms to the task of predicting the fluctuation of energy-related stock prices.

The data analysis skills acquired for that project will be crucial for a career in physics, Skye says. "Data analysis is more and more important in the world of physics as physics experiments get bigger and more technical," Skye says, noting that a wealth of data is pouring in from CERN and other particle accelerators. "Physics education on the undergraduate level doesn't have a good way of giving us that."

Amy Zhang '20, a computer science major, says working for Shell in Bangalore, India, gave her a new view on her career options. "It was interesting to work in a really interdisciplinary field—using data mining for a company not thought of as a computer science company," she says.

Zhang's main project for Shell was developing a computer program that can identify potential fuel additives. "Long-term screening for fuel additives is really expensive, both in financial terms and in terms of time," she says. "I was part of the computational chemistry team using machine learning to classify molecules on the computer so they wouldn't have to test each fuel with every additive."

Zhang says she enjoyed the MISTI internship in part because she got to work on a project with real-world applications. Since the fuel additives may one day show up in consumers' gas tanks, she says, "what I was working on has the potential to impact a lot of people."

Amy Zhang '20, a computer science major, spent the summer as an intern at Shell in Bangalore, India. Here she takes a break to visit the Taj Mahal in Agra, India.
Photo courtesy of Amy Zhang, MIT

Fresh perspectives

Internships such as these show students that it's possible to work for a corporation and still do experimental research, Ghosh says. And, while students gain new skills and international experience, sponsors gain fresh insights into their own energy challenges.

"MIT students bring their knowledge and intellectual capacity, as well as their innovative spirit, to Shell. This is very much appreciated by our Shell colleagues who are also innovating on a daily basis for more and cleaner energy resources," says Haibin Xu, external research and innovation manager for Shell in the United States.

"We rely on programs like MISTI to help connect us with students from across the globe to not just intern for us but also to teach us their views," says Beatriz Crisóstomo Merino, head of innovation management at Iberdrola. "Iberdrola enjoys the fresh perspective, ideas, hands-on skills, and enthusiasm of MIT students. Students and hosts can contribute to innovative solutions together."

For example, Ortega spent much of his internship working with Iberdrola researchers on a white paper exploring how Iberdrola could use blockchain—a digital ledger technology—for such energy-related transactions as buying and selling energy to the grid. "This would enable the utility to better price energy they're selling based on demand and supply in the market," he says. "It furthers the efficient use of energy."

Skye, meanwhile, found that Shell in Germany is working to meet government regulations that call for an 80% cut to carbon dioxide emissions from the home heating sector by 2050. To that end, Skye worked on a project (in addition to the one that involved data analysis) to standardize the reporting of experimental data related to the efficiency of solar panels.

Carissa Skye '19, a physics major who interned at Shell in Hamburg, Germany, poses at the top of the Hamburg Planetarium. Photo: Noa Knoerl-Morrill

Notably, Skye was surprised to learn that Germans seemed to accept climate change and the need for alternative sources of energy as indisputable facts; in the United States, Skye finds that people are less convinced. "In Germany, they know solar needs to start now, wind power needs to start now. It's interesting to see that cultural difference," Skye says.

While her main project centered on traditional fuels, Zhang was also involved in a smaller project modeling how lithium-sulfur batteries charge and discharge over time—work applicable to the storage needs of such renewable energy sources as wind and solar. "Working in an area that's making the possibility of sustainable energy a reality was pretty cool," she says.

For the companies, sponsoring interns not only advances projects like these. It also provides a platform for recruiting, access to MIT's research community, and opportunities to develop collaborative ventures with MIT faculty and students. "Our host companies are excited to work with our students," says Ghosh. "Our MITEI interns have outperformed expectations."

That's why plans are already under way for MISTI-MITEI to support more internships next year. "Companies are looking to increase their numbers and expand into a variety of countries, including Brazil, China, Mexico, and the UK," Ghosh says.

The bottom line, she says, is: "Senior researchers come back asking for students to continue research remotely while back at MIT, co-author papers, join as full-time hires, and to send more student interns each year. They are impressed with the caliber of work."

Kathryn M. O'Neill, MITEI correspondent

Shell executive describes inevitable transition to carbon-free energy

On September 6, 2017, Harry Brekelmans, the projects and technology director for Royal Dutch Shell, one of the world's leading oil and gas companies and a founding member of the MIT Energy Initiative (MITEI), met with groups of MIT students and faculty members about their work before taking part in a public discussion about energy issues with MITEI Co-founder and Director Robert C. Armstrong.

In the discussion titled "If you had a billion dollars for energy-related R&D, where would you spend it?", Brekelmans addressed that lofty question and many others about the company's, and the world's, energy future.

"For some years already we've been aware of the energy transition," Brekelmans said. It's accelerating, he said, and it's clear that "it's time to act, even more so than before."

Harry Brekelmans, right, the projects and technology director for Royal Dutch Shell, speaks with Robert C. Armstrong, director of the MIT Energy Initiative. Photo: Kelley Travers, MITEI

Already, Shell has made "significant investments in wind, in solar, in biofuels—not all of them successful," demonstrating the need to be careful about how one invests that research money. Because of the complexity of the world's energy systems and demands, he said, "we have concluded that this will be a multi-decade transition."

Shell has long expressed its acceptance of the science of human-induced climate change and its determination to invest heavily in technologies to help enable a global transition to a world of drastically reduced greenhouse gas emissions. As part of that commitment, Shell continues to fund a variety of research projects at MIT and elsewhere related to renewable energy, energy storage, and ways of capturing and storing carbon emissions from fossil fuel.

In introducing the discussion, Maria Zuber, MIT's vice president for research, pointed out that Shell's CEO Ben Van Beurden recently said that with the right mix of policy and innovation, he sees global demand for oil peaking in the early 2030s or sooner—and that his next car will be electric.

Zuber said that MIT's Plan for Action on Climate Change calls for finding solutions for decarbonizing the world's energy systems, aiming for a zero-carbon energy system by the century's end. To achieve that, she said, MIT's view is that "the best chance of success is if a broad range of stakeholders, from industry to government to civil society, engage with each other proactively to address it." One way of doing that, she said, is through conversations such as this one.

Brekelmans said that Shell's approach to energy R&D is two-pronged, working in parallel on both near-term and long-term strategies. For the near term, the emphasis is on finding technologies that already exist in other industries that can be adapted and scaled up to have a rapid impact on energy use. The longer-term work deals with new findings in laboratories that have great potential but that may require many years of work to determine if they can be scaled up to meet a significant portion of the world's energy needs or to improve the performance of existing energy systems.

While the company's investments in low-carbon energy technologies goes back many years, the mix of research projects they support has evolved over time, he said. One change is that much more of the long-term research is now focused on energy storage systems. These are seen as a key enabling technology to allow for increased usage of energy sources that are inherently variable,

Student questions in the morning meeting with Brekelmans focused on carbon pricing, climate change, and long-range R&D planning. Photo: Emily Dahl, MITEI

such as wind and solar power. "It was not part of our portfolio 10 years ago," he said, but is now a significant piece of it.

Another research area of increasing emphasis is capturing and storing carbon emissions from power plants to reduce their climate impact, he said. But other approaches don't necessarily have to be high-tech, he said. "When we talk about offsets, we increasingly talk about simple things like reforestation," he told students during his morning meetings.

Another change, he said, is "in the way we do R&D. Our collaboration with MIT is absolutely fundamental" to Shell's efforts. "We know we can't do it ourselves alone. Much of the progress is happening here and at other institutions." With the company's own technology campus in Kendall Square bordering the MIT campus, "we are hiring people who have no prior experience in oil and gas but who have a knack for innovation," he said. Shell's investments, he said, include providing "seed investments in crazy ideas to help bring them to the next stage."

Despite the company's ongoing commitment to working toward a transition away from greenhouse emissions, Brekelmans said that he and his colleagues "all conclude every year that we're not moving fast enough," and continue to redouble their efforts.

Emphasizing that their reach and their interests are global, he added that Shell has also recently opened a campus in Bangalore, India, which employs almost 1,000 technologists, as an incubator for new technologies and approaches. The world's energy systems and needs are very different and highly localized, he said: "Almost every country is different" in terms of its needs and the most effective ways of meeting them.

Maria Zuber, MIT's vice president for research, introduces the discussion.
Photo: Kelley Travers, MITEI

In the developing world, he said, the company provides aid through the Shell Foundation, helping to bring electricity and other energy supplies to some of the world's 3 billion people who lack access to reliable power. Among other things, these grants are aimed at helping some developing nations steer toward the use of natural gas rather than coal, as a lower-carbon fuel.

Shell "wants to be a voice and a leader" in the world's energy transition, he said. But along the way, he said, the company must "not abandon the economic process that made us a leader," namely the production and distribution of oil and gas.

The company clearly recognizes the need for some kind of pricing on carbon fuels that reflects their real impact on the world, Brekelmans said. Already, the company "internally works with a price on carbon," assuming that this will eventually be part of the economic reality.

As for what form that pricing should take, whether it's a carbon tax, a fee-and-dividend, or a cap-and-trade system, he said, "we are relatively agnostic, as long as we have a price that we can then develop and evolve." Having some such system in place, he says, is "preferable to the almost religious debate over what is the best system."

David L. Chandler, MIT News Office

Energy transition through aesthetics and culture

What does energy have to do with art, literature, happiness? During a MITEI seminar on October 11, 2017, Imre Szeman, professor of communication and culture at the University of Waterloo, addressed this question and engaged in a discussion of "petroculture" with MIT faculty of architecture and humanities, arts, and social sciences.

Left to right: Rania Ghosn, Rosalind Williams, and Caroline Jones joined guest lecturer Imre Szeman for a panel discussion after his talk on ways to shift from "petroculture."
Photo: Deirdre Carson, MITEI

Faculty host Rania Ghosn, assistant professor of architecture and urbanism at MIT, heralded Szeman's talk as a different kind of conversation about energy. She was "delighted," she said, to host an event between MITEI and the School of Architecture and Planning that went "beyond the excellent scientific and engineering research to engage methods and insights from the humanities, aesthetics, and design in conversations on energy and energy transitions."

An intentional energy transition

According to Szeman, "petroculture" "is the name for a society that's been organized around the energies and products of fossil fuels, the capacities it engenders and enables, and the situations and context it creates." He said, "Our expectations, our sensibilities, our habits, our ways of being in and moving across the world, how we imagine ourselves in relation to nature, as well as in relation to each other, these have all been sculpted by and in relation to the massively expanded energies of the fossil fuel era."

Of course, burning fossil fuels has ecological drawbacks, not least of which are its attendant climate-changing emissions. "The fossil economy left much of the world behind," Szeman said. "You were rich because you happened to inhabit a part of the world that was rich in oil." These concerns, as well as increasing calls for diversity and resiliency in the energy sector, are changing the face of the energy landscape. We are on the verge of what Szeman calls an "intentional transition."

The key to this transition, Szeman said, is for people to take a more active role in directing changes in energy consumption, from ensuring that energy comes from diverse, sustainable sources, to fighting for equality in energy distribution. According to Szeman, we also need to rethink our idea of growth. "In the after-oil economy, growth and development are…joined to a new ethics of resilience and sustainability."

The cultural toolbox

A panel discussion moderated by Ghosn followed Szeman's talk. Rosalind Williams, the Bern Dibner Professor of the History of Science and Technology at the MIT Program on Science, Technology, and Society, responded to and challenged Szeman's proposition, taken from novelist Amitav Ghosh, that, even in "an era in which oil has been so important… there are very few novels that speak about oil, that address it directly."

One of the works she noted was Herman Melville's 1851 novel *Moby-Dick*, which she called "the oil-based novel." "The age of sail and wind is turning into the age of oil before your eyes, because you're chasing whales, and you're chasing them for their oil," she said. She pointed in particular to the urgency and detail Melville lent the scenes in which the crew distills the whale blubber to extract oil from it.

Caroline Jones, a professor of art history in the School of Architecture and Planning, discussed a different medium: the visual arts. In the 1960s in particular, she said, "You do begin to get a visualization, or a visibility…for the complex social costs and institutions and infrastructures that are built around energy extraction." She noted Hans Haacke's 1981 sculpture "Creating Consent"—an oil barrel with television antennae attached. Through this piece, Jones says, Haacke creates "an entire narrative around oil industries, extraction industries, funding culture precisely to make their pollution invisible."

According to Szeman, artistic exploration is critical to a successful energy transition. "We need to reexamine the cultural forms that came to life when energy was cheap and abundant," he said. "Transitioning from oil to another energy source will entail the unmaking and remaking of our social worlds."

Francesca McCaffrey, MITEI

Read the full article at bit.ly/ef-szeman. This talk is one in a series of MITEI seminars supported by IHS Markit.

Economist Howard Gruenspecht joins MITEI

Howard Gruenspecht, a prominent economist who has held leadership positions in the US Department of Energy (DOE), has joined MITEI as senior energy economist.

"We are delighted to welcome Howard to the MIT energy community," says MITEI Director Robert C. Armstrong. "His insights and experience leading federal energy data and analysis programs will be invaluable as we analyze economics issues related to storage and other energy topics."

From 2003 through August 2017, Gruenspecht was deputy administrator of the US Energy Information Administration with responsibility for directing its energy data and analysis programs. From 1991 to 2000, he served in leadership positions in DOE's Office of Policy. His accomplishments at DOE were recognized with two Distinguished Presidential Rank Awards, the highest honor conferred on a career senior executive. He has also received the Adelman-Frankel Award, the highest honor bestowed by the US Association for Energy Economics. He holds a bachelor's degree from McGill University and a PhD in economics from Yale University.

"I am very pleased and excited to join MITEI," says Gruenspecht, who started his new role in September. "The opportunity to work with world-class researchers across a wide range of disciplines and to pursue research on policy-relevant energy issues is tremendously attractive."

At MITEI, Gruenspecht will participate in the Initiative's next "Future of…" study, which will focus on energy storage technologies critical to increasing the use of carbon-free wind and solar power generation.

Clean Energy Education & Empowerment (C3E) US initiative announces 2017 awardees

Ten women from various disciplines were recognized for their achievements and leadership in clean energy at the sixth annual Clean Energy Education & Empowerment (C3E) Women in Clean Energy Symposium (c3eawards.org). The symposium, held at MIT in November 2017, was hosted jointly by the MIT Energy Initiative, Stanford University's Precourt Institute for Energy, and the US Department of Energy. C3E was formed under the auspices of the 25-government Clean Energy Ministerial and strives to close the gender gap and increase women's participation and leadership in clean energy fields.

US Senators **Lisa Murkowski**, R-Alaska, and **Maria Cantwell**, D-Washington, were this year's co-recipients of the C3E Lifetime Achievement Award. Murkowski, chairman of the Energy and Natural Resources Committee, and Cantwell, the committee's ranking member, jointly introduced the Energy and Natural Resources Act of 2017. The bipartisan bill featured provisions to save energy, expand supply, modernize and secure the electric grid, bolster the energy workforce, and more.

Eight mid-career women received awards for outstanding leadership and accomplishments in specific areas.

Advocacy: **Anna Bautista** is vice president of construction and workforce development for GRID Alternatives, the nation's largest nonprofit solar installer, which implements solar projects for households in low-income communities.

Business: **Leslie Marshall**, the corporate energy engineering lead for General Mills, executes the company's global strategy for reducing energy usage and emissions at its food processing plants.

Education: **Nicole Lautze** is an associate faculty member at the University of Hawaii at Manoa, where she founded the Hawaii Groundwater and Geothermal Resources Center. Her team is currently developing an updated geothermal resource assessment for Hawaii.

Entrepreneurship: **Emily Kirsch** is the founder and CEO of Powerhouse, an incubator and accelerator dedicated to software-enabled solutions for distributed energy, storage, and grid modernization.

Government: **Chris LaFleur** is program lead for Hydrogen Safety, Codes and Standards at Sandia National Laboratories. Her main research involves evaluating fire risks for emerging energy technologies.

International: **Allison Archambault**, president of EarthSpark International, has led the creation of a town-sized, solar-powered smart grid in rural Haiti and is laying the groundwork for more microgrids.

Law and Finance: **Sarah Valdovinos** is a co-founder of Walden Green Energy, which develops utility-scale renewable energy projects.

Research: **Inês M.L. Azevedo**, principal investigator and co-director for the Climate and Energy Decision Making Center at Carnegie Mellon University, researches how to transition to a sustainable, low-carbon, affordable, and equitable energy system.

Clean Energy Education & Empowerment (C3E)

MIT Energy Initiative Members

MITEI Founding and Sustaining Members

MITEI's Founding and Sustaining Members support "flagship" energy research programs and projects at MIT to advance energy technologies to benefit their businesses and society. They also provide seed funding for early-stage innovative research projects and support named Energy Fellows at MIT. To date, members have made possible 161 seed grant projects across the campus as well as fellowships for almost 400 graduate students and postdoctoral fellows in 20 MIT departments and divisions.

MITEI Founding Members

MITEI Sustaining Members

MITEI Associate Members

MITEI's Associate Members support a range of MIT research consortia, education programs, and outreach activities together with multiple stakeholders from industry, government, and academia. In general, these efforts focus on near-term policy issues, market design questions, and the impact of emerging technologies on the broader energy system. Specific programs include the Mobility of the Future study, the Low-Carbon Energy Centers, the Associate Member Symposium Program, and the MITEI Seminar Series.

Ferrovial

Symposium Program and Seminar Series

Cummins
EDF (Électricité de France)
IHS Markit

Low-Carbon Energy Centers

Aramco
Cenovus Energy
Eni S.p.A.
ENN Group
Exelon
ExxonMobil
GE
Iberdrola
Shell
Statoil
Tata Trusts

Mobility of the Future study

Alfa
Aramco
Bosch
BP
Chevron
ExxonMobil
Ferrovial
General Motors
Shell
Statoil
Toyota Mobility Foundation

MITEI Affiliates

MITEI Affiliates are individual donors and foundations that support MITEI's energy- and climate-related activities across the Institute. Specific programs include the Undergraduate Research Opportunities Program, supplemental seed funding for early-stage innovative research projects, the MIT Energy Conference, the MIT Tata Center for Technology and Design, and the MIT Climate CoLab.

Asociación Nacional de Empresas Generadoras (ANDEG)
Aspen Technology, Inc.
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Bill Brown, Jr. '77
David L. desJardins '83
Cyril W. Draffin '72, SM '73
Patrik Edsparr PhD '94
Jerome I. Elkind '51, ScD '56
S. Jones Fitzgibbons SM '73 and
Michael Fitzgibbons SM '73
Gail '75 and Roy '75 Greenwald
A. Thomas Guertin PhD '60
John Hardwick '86, SM '88, PhD '92
Daniel Harris '68
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Philip Rettger '80
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in memory of Jack C. Scarborough SM '55
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Doug Spreng '65
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Tomas Truzzi
David Wang '00, MNG '00
William Wojeski '71 and Karen Leider '72

Members as of November 1, 2017

MITEI member news

Photo: Iberdrola/Steven Laschever

Iberdrola and MITEI announce $10.3 million collaboration

On June 21, 2017, MIT President L. Rafael Reif (left) and Iberdrola Chairman and CEO Ignacio S. Galán met on MIT's campus to renew and significantly expand the collaboration between the Institute and the global power company.

The $10.3 million, five-year collaboration aims to advance technologies and policies that contribute to the energy transition and the fight against climate change, supporting numerous efforts through the MIT Energy Initiative (MITEI) and related MIT initiatives.

The agreement includes $5 million in funding to create the Iberdrola-AVANGRID professorship at MIT, dedicated to research and education in power systems engineering. In addition, Iberdrola is making a robust commitment to fund energy education opportunities for undergraduate and graduate students through MITEI.

Iberdrola has become a sustaining member of MITEI, committing $5 million over five years to advance key technologies and policies for addressing climate change. As part of its MITEI membership, it has joined MITEI's Low-Carbon Energy Center for Electric Power Systems and will contribute to MITEI's Seed Fund to support early-stage energy research at MIT.

MORE ONLINE

Read the full article at bit.ly/ef-iberdrola.

MIT Energy Initiative
Massachusetts Institute of Technology
77 Massachusetts Avenue, E19-307
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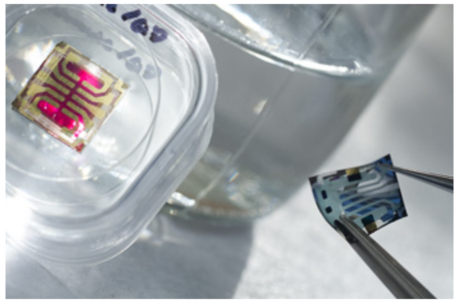

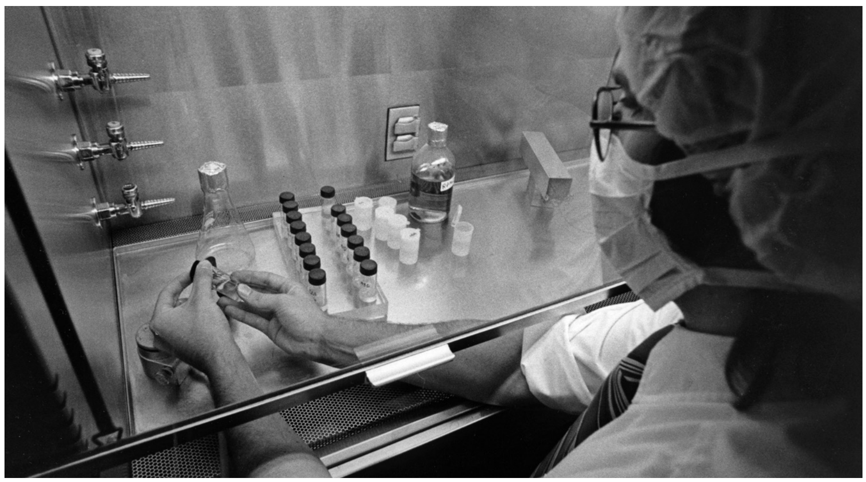

CELEBRATING ENERGY AT MIT

MIT's contributions to energy innovation have led to technological breakthroughs and informed key public policies. This year, we celebrate over a century of energy at MIT and 10 years since MITEI's inception. **To read more, turn to page 3.**

Top row (l-r) Researchers run experiments in MIT Energy Laboratory's Combustion Research Facility, 1990; transparent, flexible solar cell made of nanowires and graphene, 2013; Solar House I, built in 1939.

Middle row (l-r) Researchers in Surendranath lab design catalysts for converting carbon dioxide to fuels, 2016; student in Genetic Toxicology Lab tests for mutations in cells exposed to combustion products, 1978.

Bottom row (l-r) Tata Center for Technology and Design spinoff Khethworks provides affordable solar-powered irrigation systems to the developing world, 2015; Energy Lab researchers examine regenerable sorbents for removing sulfur from coal-derived gaseous fuels, 1990.

Photos (l-r): Jim Harrison, Stuart Darsch, courtesy MIT Museum, Darsch, Ivan Massar, courtesy Tata Center, Harrison.