Energy Futures

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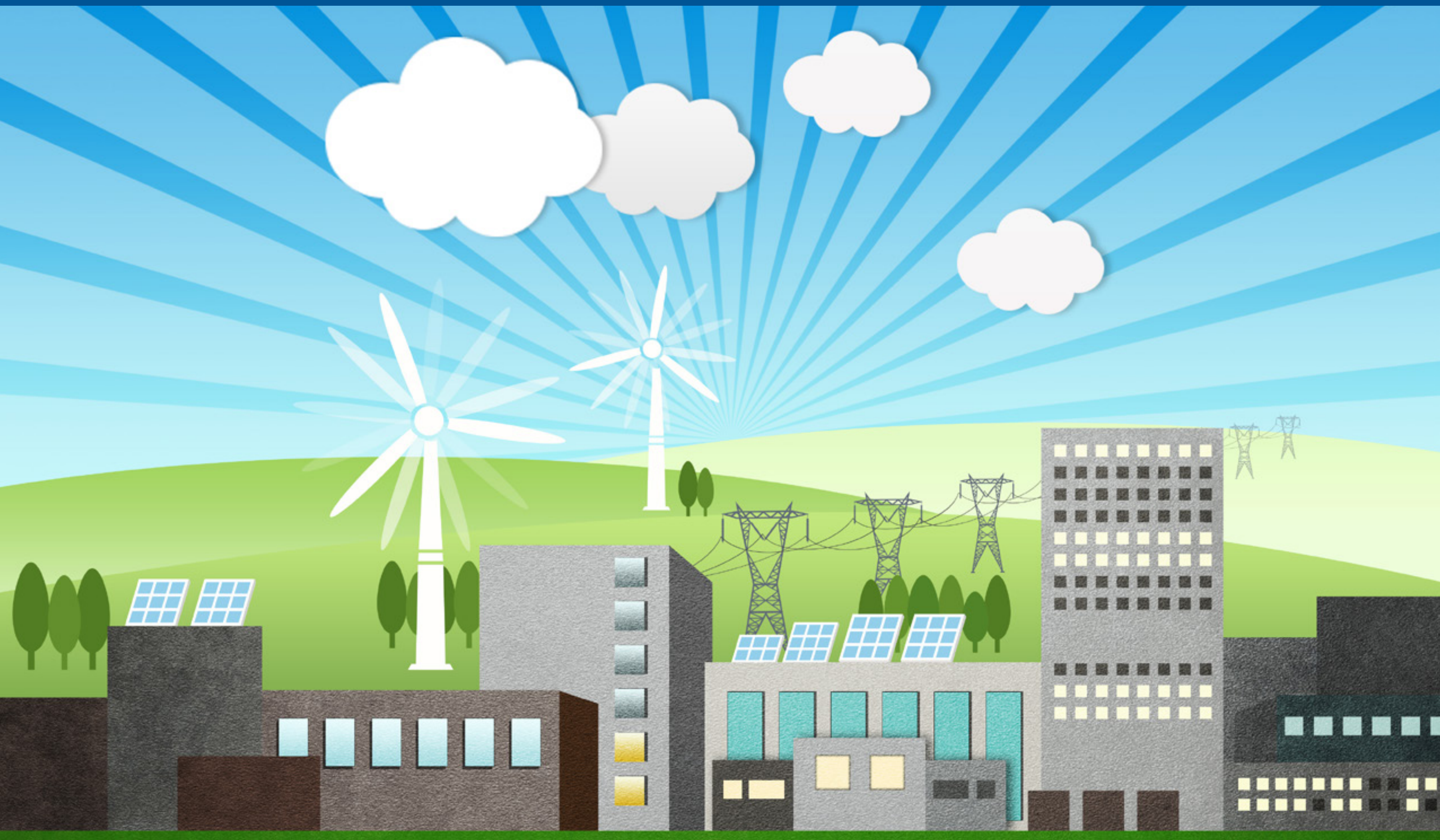

Utility of the Future report: Guidance for an evolving industry

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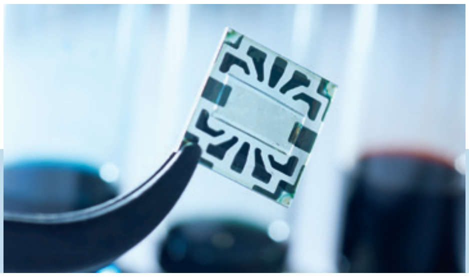

CAMPAIGN FOR A BETTER WORLD

The articles in this issue of *Energy Futures* are a reflection of the MIT Energy Initiative's commitment to addressing global energy challenges and advancing a low-carbon energy future. This vital work would not be possible without the generous support of our friends, members, and alumni. Learn about MIT's campaign to build a better world and join us at **betterworld.mit.edu/health-of-the-planet**.

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Energy Futures

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EDUCATION

OUTREACH

MITEI MEMBERS

A letter from the director

Dear friends,

In December 2016, we released the report from the multiyear Utility of the Future study, a comprehensive examination of the technologies, policies, and business models shaping the evolution of the electric power sector. The report provides a framework for how policymakers and regulators can proactively enable the development of a robust electric grid and a fair system of services that delivers the most value to consumers.

Events held in Washington, DC, to mark the release included a public program in which the study's advisors and authors shared key findings; meetings with policymakers and regulators; and a presentation for MIT alumni. In this issue of *Energy Futures*, we share an overview of the report (page 7) and hear from several of the graduate student co-authors about the insights they gained from the intensive research experience (page 9).

As the Utility of the Future study concluded, our second consortium research study in this series got under way. "Mobility of the Future" brings researchers from various disciplines together to study factors that will drive the way *we* drive (or otherwise get from place to place) in the decades to come (page 27). Like Utility of the Future, this study will take a system-level approach—seeking to identify barriers that policymakers and regulators should remove to improve safety, efficiency, and social equity in urban mobility.

In this issue of *Energy Futures*, you will also read about research breakthroughs in solar technology and energy storage—two key areas for enabling the transition to a low-carbon future. Professor Jing Kong and graduate student Yi Song have developed a new method for producing low-cost, flexible, transparent solar cells using electrodes made of nanometer-thin layers of graphene (page 11). And Professor Yang Shao-Horn and collaborators at MIT and Leiden University in the Netherlands have performed experimental and theoretical studies leading to new guidelines for designing catalysts to speed up the electrolysis of water, a critical process in many energy storage technologies (page 22).

On the policy front, we share MIT research examining international efforts to address climate change. The Joint Program on the Science and Policy of Global Change released its *2016 Food, Water, Energy, and Climate Outlook*, which finds that even if all nations meet their Paris Agreement commitments, the world will exceed the 2°C maximum global temperature increase targeted for 2100 as early as 2050. To avoid this outcome, countries will need to make substantial additional R&D investments to lower technology costs and increase deployment, as Joint Program Co-director John Reilly explains (page 16).

These various research efforts demonstrate that technologies and policies cannot exist in isolation from each other. In the transition to a low-carbon future, as we continue to foster scientific innovation at MIT, we also recognize that well-designed policies and regulations will continue to be essential for ensuring that society can reap the economic and environmental benefits of deploying advanced technologies. Supporting the basic science that underpins breakthrough discoveries will likewise be crucial.

One of the nation's foremost champions of energy innovation has recently returned to MIT: Ernest Moniz. MITEI's founding director, Ernie recently completed an accomplished tenure as US Secretary of Energy during President Obama's second term and has now assumed a part-time role as a professor of physics post-tenure and special advisor to MIT President L. Rafael Reif. Ernie is working on several energy, climate, and nuclear security initiatives with colleagues here and at other institutions and organizations (page 43). I would like to extend MITEI's heartfelt thanks to Ernie for his distinguished service to our country and steadfast dedication to advancing science and low-carbon energy.


Photo: Webb Chappell

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

Here at MITEI, we have continued our tradition of supporting early-stage research by announcing 10 new energy research projects awarded $150,000 each through MITEI's member-supported Seed Fund Program. These projects represent a broad swath of the energy spectrum, from basic science and engineering to policy (page 28).

MITEI has also become an academic and research collaborator in a new national consortium, the Rapid Advancement in Process Intensification Deployment (RAPID) Manufacturing Institute—the 10th institute in the nation's network of Manufacturing USA institutes (MIT participates in seven of these centers). Announced by the US Department of Energy in January, this center convenes MITEI and other academic, national lab, and industry organizations to make important industrial processes more energy-efficient and productive while reducing operating costs and minimizing environmental impacts. Numerous MIT faculty are involved in the initiative (more at mitenergyfutur.es/rapid).

Our Low-Carbon Energy Centers continue to develop as more MIT faculty become involved and member companies join centers that suit their areas of research interest. In this issue, we discuss the missions of the Center for Energy Bioscience Research and the Fusion and Magnet Research Center with their faculty co-directors (page 4). We have welcomed new members Cenovus Energy and ENN Group—both of which have also joined the centers—and have renewed our collaboration with Eni S.p.A., which has been a MITEI member since 2008 and has now joined three of the centers: solar energy; energy storage; and carbon capture, utilization, and storage (see inside back cover).

This spring, MITEI staff and affiliated researchers have shared their work and perspectives at various conferences, among them CERAWeek in Houston, Texas—which was also well-attended by many MIT alumni (more at mitenergyfutur.es/ceraweek2017). We were also pleased to participate in and support the student-run MIT Energy Conference, whose dedicated organizers put together a great program featuring global business and government leaders, including India's minister of petroleum and natural gas, Dharmendra Pradhan (more at mitenergyfutur.es/mitenergyconf2017).

MITEI hosted numerous student-focused events this spring as well, many of which were held at the new Undergraduate Energy Commons. We had record attendance at our Campus Preview Weekend events for accepted students and hope to welcome many of these students back in the fall as they begin their MIT journeys. Nine current undergraduates also took advantage of a new opportunity to spend their spring break installing solar photovoltaic panels for a low-income household in Los Angeles, California, facilitated by a local non-profit solar installer (page 35).

Please don't hesitate to get in touch with us if you have ideas for enriching the experiences of our students, supporting our researchers, or otherwise enhancing the energy ecosystem at MIT. We always appreciate our readers' keen interest in being part of this vibrant community—whether you're here in Cambridge coming to our events or following our work from across the country or around the world.

Warm regards,

Robert C Armstrong

Professor Robert C. Armstrong
MITEI Director

May 2017

Event highlights

Photo: Mary Potts, MITEI

On March 15, 2017, **John Deutch**, Institute Professor Emeritus at MIT and former director of the Central Intelligence Agency, delivered a talk on creating and deploying effective decarbonization strategies. A former chairman of the Department of Chemistry, dean of science, and provost at MIT, Deutch also discussed the challenges of communicating across scientific and policy communities to achieve the kind of full-spectrum systems thinking necessary to solve energy challenges. More at mitenergyfutur.es/deutch3q.

Photo: Kelley Travers, MITEI

Lourdes Melgar SM '88, PhD '92, the Robert Wilhelm Fellow at the Center for International Studies at MIT and Mexico's former deputy secretary of energy for hydrocarbons, delivered a talk on February 14, 2017, outlining Mexico's historic energy reform. An architect of the design and implementation of the reform, Melgar discussed the need for energy reform, the role of private investors, and the remaining challenges for Mexico moving forward. More at mitenergyfutur.es/melgar3q.

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

The MIT Energy Initiative continues to develop and expand its eight Low-Carbon Energy Centers, which facilitate interdisciplinary collaboration among MIT researchers, industry, and government to advance research in technology areas critical to addressing climate change. Below, the directors of two of the centers—those focused on energy bioscience research and on fusion and magnet research—discuss their vision for transforming the energy system. In the autumn 2016 issue of *Energy Futures*, we heard from the directors of the centers on carbon capture, utilization, and storage; energy storage; and materials in energy and extreme environments. Look for Q&As with the directors of the three remaining centers—electric power systems, advanced nuclear energy systems, and solar energy—in an upcoming issue.

Center for Energy Bioscience Research

Photo: Kelley Travers, MITEI

"Biological organisms have existed and evolved for billions of years, but it's only recently that humans have developed both the knowledge and the tools required to manipulate them. We're excited by the potential to use the natural adaptability of biology to engineer solutions to clean energy problems."

Directors **Angela M. Belcher** (left), W.M. Keck Professor of Energy, professor of biological engineering, and professor of materials science and engineering, and **Kristala L.J. Prather** (right), associate professor of chemical engineering

How can bioscience research help the world reach its goal of reducing carbon emissions?

For billions of years, biology has employed an approach to energy generation and the synthesis of materials and chemicals that meets the needs of organisms with minimal production of byproducts that are poisonous to the environment. Bioscience is tapping into this vast toolset to transform today's carbon-centric energy systems by creating new structures, devices, and materials that are significantly less energy-intensive and less harmful to the environment than today's dominant energy technologies.

What's exciting is that, while it took biology 4 billion years of trial and error to develop its extraordinarily efficient systems, modern bioscience techniques enable researchers to conduct a billion experiments in a matter of months. As a result, the field of synthetic biology, which is only about 15 years old, has already produced startling results.

At MIT, researchers working on energy-related applications have successfully engineered microorganisms to make biofuel from an assortment of starting substrates and used viruses to build batteries, sensors, and more efficient solar cells.

How will the new Center for Energy Bioscience Research identify and address the major challenges in this area?

The center partners with a diverse set of private companies, government entities, and nongovernmental organizations to ensure that MIT develops practical biological and biologically inspired energy solutions to a wide range of concerns—from developing cleaner fuel sources to enhancing storage options, and from fueling new transportation alternatives to cleaning up the environment.

Drawing upon MIT's extensive existing research capability in synthetic biology, microbial metabolic engineering, new DNA technologies, and directed evolution, the center plans to rapidly screen, model, design, and synthesize new materials with biological fidelity to harness the power of biology to shape a low-carbon future.

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

One promising development is the biological generation of liquid fuels from natural gas. It has been estimated that the proven reserves of natural gas (methane) in the United States could sustain the transportation sector of this country for the next 50 years. However, methane's low energy density makes it unsuitable for integration into current infrastructure.

MIT researchers are investigating biological processes for the low-cost conversion of methane to liquid fuel molecules with much higher energy density. For example, researchers have developed a novel bioprocess for converting syngas (obtainable from methane) or other waste gases containing carbon dioxide and a reducing gas such as hydrogen or carbon monoxide into biofuel. The process uses bacteria to convert waste gases into acetic acid—vinegar—which is subsequently converted to oil by an engineered yeast.

MIT researchers have also developed a virus that can improve solar cell efficiency by nearly one-third and demonstrated a technique that can significantly increase the photosynthetic activity of plants. Such increased activity could result in faster production of biomass for biofuel production, leading to faster capture and fixation of carbon dioxide from the atmosphere.

On a broader scale, MIT researchers have recently developed a programming language for bacteria that makes it quicker and easier to create designer DNA for genetic parts such as sensors, memory switches, and biological clocks. Such parts can then be combined to modify existing cell functions and add new ones. This work promises to be useful in a wide range of energy applications, such as designing yeast that could ferment biomass into ethanol without toxic byproducts.

Fusion and Magnet Research Center

Photo: Susan Young

Photo: Bryce Vickmark

"It is an exciting time to be at MIT. The rapid progress on high-field fusion, combined with growing collaborative activities at facilities around the world, is positioning our center to be a unique hot spot where fusion education and industry can mix with each other in new and innovative ways."

Directors **Dennis G. Whyte** (left), Hitachi America Professor of Engineering, and **Anne White** (right), Cecil and Ida Green Associate Professor in Nuclear Engineering

Why is fusion research needed to help the world reach its goal of reducing carbon emissions?

It's hard to imagine a more appealing energy source than fusion, which powers the sun and all the other stars by combining light elements into heavier ones. Fusion energy is carbon-free, fundamentally safe, can operate 24/7, produces little waste, and makes few demands on land, water, and other resources. That's why fusion research has enormous potential for catapulting the country—and the world—into a low-carbon future.

What are the major challenges to tapping fusion's potential, and how will the new Fusion and Magnet Research Center address them?

The industrial maturity of high-temperature superconductors has provided a game-changing opportunity. Harnessing fusion power is extremely difficult because it requires the creation and control of extremely hot, charged gases (plasmas) at temperatures above 100 million degrees and insulating them from ordinary matter by using magnetic fields. The stronger the fields, the better thermal insulation they provide. Experiments with a high-field copper device at MIT already achieve the temperatures, pressures, and other conditions necessary for practical fusion reactions on a daily basis. A practical fusion power plant, however, will require magnets built from superconductors; otherwise too much heat would be lost overcoming electrical resistance. High-temperature superconductors uniquely combine the ability to carry current with zero resistance and to operate at extremely high magnetic fields.

The vision for the Fusion and Magnet Research Center is to demonstrate the promise of fusion energy sufficiently to place fusion firmly in the national energy plans of the United States. To reach this goal, the center will focus first on the technologies needed to build the large-volume, high-field superconducting magnets required for fusion applications.

The center's ultimate goal is to incubate a multitrillion-dollar low-carbon fusion industry. To that end, the center will work with industrial partners toward the development of a high-field pilot plant, which could provide significant net electrical power to the grid. A concept for such a device called ARC, based on the new high-temperature superconductors, was recently developed by a class of MIT students. While not a complete engineering design, the students subjected their concept to sophisticated engineering analysis and demonstrated the essential plausibility of this approach.

What research pathway will the Fusion and Magnet Research Center take to accomplish its goals?

The center's three- to four-year timeline for the initial phase of fusion research and development builds on MIT's extraordinary record of breakthroughs in plasma physics, nuclear science and engineering, magnet technology, instrumentation, materials, reactor design, and many other fields.

High-temperature, high-field superconductors are the breakthrough technology that will make it possible to develop smaller, cheaper magnetic confinement fusion devices. Having built and operated the three highest field magnetic confinement experiments in the world, MIT is uniquely positioned to move this area of research forward: The Institute has a long track record of producing record-setting magnets and boasts one of the world's leading groups dedicated to advancing superconducting and conventional magnet technology for large-scale systems.

The next step on the fusion path will involve developing underlying technologies and engineering designs for ARC, with detailed analysis of its mechanics, neutronics, and thermal hydraulics. Safety, regulatory, and siting issues will be addressed along with cost estimates for construction and operation.

The center is also dedicated to identifying and developing other uses for the new superconductor magnet technology in the energy sector. It's extremely exciting that this breakthrough magnet technology can be applied to near-term improvements in electricity generation, regulation, and storage, while synergistically supporting the ultimate goal of providing energy from fusion.

At the same time, the center will continue its strong collaborations with national and international partners in fusion, plasma science, and magnet science. The center's faculty, scientists, and students participate in a broad range of projects around the world aimed at acquiring a deep understanding of the physics behind controlled fusion and creating validated, predictive models to aid in the development of fusion pilot plants.

Throughout this process, the center will endeavor to become a hub for fusion and magnets—bringing together leading experts in fusion science and technology and key stakeholders to identify the real-world technological and engineering needs that must be addressed to propel fusion into position as a major contributor of carbon-free energy.

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By Kathryn M. O'Neill,
MITEI correspondent

Utility of the Future report: Guidance for an evolving industry

Distributed energy technologies—relatively small-scale power sources such as solar, wind, energy storage, and power electronics and control devices—are being deployed rapidly in the global shift toward a low-carbon energy future. To ensure that both distributed and centralized energy resources are integrated efficiently, however, electric power systems in the United States, Europe, and other parts of the world need major regulatory, policy, and market overhauls, says an in-depth report, *Utility of the Future*, released by the MIT Energy Initiative (MITEI) on December 15, 2016, in Washington, DC. The report was developed in collaboration with the Institute for Research in Technology at Comillas Pontifical University (IIT-Comillas), Spain.

“There are great opportunities to deploy distributed energy technologies where they will be most cost-effective and impactful, and also to scale up new information and communications technologies that can provide greater flexibility, control, and cost savings for power businesses and consumers alike,” says Robert C. Armstrong, MITEI’s director and the Chevron Professor of Chemical Engineering at MIT. “Our study does not try to predict the future or prescribe which technologies should prevail; instead, it provides a toolkit for businesses, policymakers, and regulators to navigate the unfolding changes in the system and develop a more robust, efficient system for the future.”


MITei
MIT Energy Initiative
UTILITY OF THE FUTURE
An MIT Energy Initiative response to an industry in transition

Today’s electric power systems were designed, built, and regulated well before distributed energy technologies—small- and medium-sized resources that can provide electricity services, sited in local distribution networks—appeared on the horizon as viable options for widespread use. Now, the businesses and regulatory bodies that determine how power is distributed need a path forward to incorporate these rapidly proliferating technologies and to meet changing consumer preferences while increasing efficiency across the system, with the goal of achieving cost savings and carbon emissions reductions.

“The study’s two overarching recommendations are to establish a comprehensive system of prices and regulated charges that applies to all network users, and to remove inefficient barriers that impede the integration and competition of both distributed resources and centralized resources—such as power sector structures that prevent fair competition and wholesale electricity market design flaws,” says one of the study’s principal investigators, Ignacio Pérez-Arriaga, who is a visiting professor at MIT and a professor of electrical engineering at IIT-Comillas. “Our framework of recommended proactive reforms can enable the efficient evolution of electric power systems into the next decade and beyond.”

Among the study’s recommendations is a set of measures to improve tariff and rate structures for electricity services. For example, electricity services should be priced in a “technology-agnostic” manner that is based solely on how consumers use these services. Making


The Utility of the Future research team presented results of the study at a launch event in Brussels. Here, Executive Director Raanan Miller provides an overview of the research areas covered.

Photo: Benny De Grove

Photo: Samuel Hurd

MITEI Director Robert Armstrong responds to questions from the audience at the Utility of the Future launch at the National Press Club in Washington, DC.

use of "peak-coincident capacity charges" can discourage consumers from drawing on the grid during times of scarcity in generation or network capacities. Prices and charges should also better reflect how the value of services changes at different times of day or at different locations in the grid. Such cost-reflective pricing can open up opportunities for distributed resources—many of which already exist but are not responding to current economic signals—and enable significant cost savings.

Another finding is that for technologies such as solar photovoltaics and energy storage, which can be connected at different voltage levels and at various sizes, understanding trade-offs between locational value and incremental unit costs due to economies of unit scale can help planners identify the ideal locations and applications.

Additional recommendations include improvements to the way distribution network companies are compensated and incentivized to incorporate distributed resources efficiently, re-evaluation of the structure of the electricity industry to allow the creation of new business models, and implementation of robust cybersecurity standards for interconnected energy resources and appliances. Improvements to wholesale market design could also better integrate distributed resources and reward greater flexibility while creating a level playing field for all technologies.

The report emphasizes the urgency of proactive reforms. Electricity users now face unprecedented choices regarding how they get their power and manage their electricity consumption; they need improved economic signals—prices, charges, and other economic incentives—in the near term to guide these decisions.

"The risk of continuing business as usual is immense in terms of system reliability and costs associated with inefficiencies—which many stakeholders in the electric power sector recognize and want to avoid," adds Pérez-Arriaga.

"This report is the result of a multiyear, comprehensive, and rigorous research study in which authors conducted extensive primary research, including data gathering and modeling, and interviews with regulators and business leaders in the electric power sector—including the study consortium members," says the study's executive director, Raanan Miller of MITEI. "We hope that regulators, policymakers, and industry stakeholders find it a useful source of information that helps them weigh decisions and take actions to guide the evolution of the electric power sector."

Research and findings from the Utility of the Future study will inform research taking place through MITEI's new Low-Carbon Energy Center for Electric Power Systems, one of eight MITEI low-carbon energy centers, each of which focuses on advancing key technology areas for addressing climate change.

This report is the first in a new series of MIT consortium research studies focused on the system level and intended to inform industry stakeholders and regulators. The other report currently under way in this new series is the Mobility of the Future study on the evolution of the transportation sector. The consortium members of Utility of the Future are a diverse set of leading international companies with expertise in various aspects of electric power services and technologies. Members provided support, gave regular feedback, and offered insights in a series of workshops; they also participated in the external advisory committee.

Like MITEI's "Future of" studies, *Utility of the Future* is written by a multidisciplinary team of MIT researchers, with research informed by a faculty advisory committee.

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By Emily Dahl, MITEI

To download a copy of the full report, please go to energy.mit.edu/uof. Members of the Utility of the Future consortium are listed on page 44.

Students gain skills, insights working on Utility of the Future study

For graduate students on the Utility of the Future study's research team, the experience of researching and writing the MIT Energy Initiative (MITEI) report proved an extraordinary opportunity—both to learn the inner workings of the power sector and to collaborate with an impressive team of experts.

"Working on the study gave me a chance to really dive in-depth into the rapidly evolving challenges in the electricity sector and as a result come out on the cutting edge of understanding those challenges and being able to speak about them in an academic and in a policymaking context," says Jesse Jenkins, a PhD candidate in MIT's Institute for Data, Systems, and Society (IDSS) and a 2012–2013 Enel-MIT Energy Fellow who served as a researcher on the Utility of the Future (UoF) project.

Jenkins says he particularly enjoyed working with the UoF team, which included both faculty members and researchers from MIT and the Institute for Research in Technology at Comillas Pontifical University (IIT-Comillas) in Spain as well as an advisory committee of top experts from industry and government. "It was a great chance to work with a really interesting team of people with expertise from all over the world," he says. "I think it definitely accelerated our learning process."

Ignacio Pérez-Arriaga, a visiting professor from IIT-Comillas who served as lead principal investigator for the nearly three-year study, says the graduate students' work was central to *Utility of the Future*, MITEI's 384-page final report on the UoF study and a guide to the factors driving change in power systems worldwide.

"The guidance of the faculty in setting priorities, allocating human resources to specific topics, and guiding the herd of cats toward a common objective was of essence, but most of the credit for the value of the study must be given to a group of extraordinarily talented and dedicated students," he says.

Among those students was Ignacio Herrero, a PhD candidate at IIT-Comillas who researched the design of wholesale markets for the report. Trained as an electrical engineer, Herrero says working on the UoF taught him the importance of policymaking. "You learn it's not just about getting the numbers right, and it's not even about developing technology. You need the right regulations in place if any change is to happen," he says.

Another student researcher, Nora Xu SM '15, says she came to MIT with a background in wholesale electricity markets but found that working on the UoF study broadened her knowledge base. "I learned a lot about commercial buildings and their operation, and I learned a lot more about what the big issues are on the distribution side [of the power sector]," Xu says.

Xu, a 2013–2014 Eni-MIT Energy Fellow and 2014–2016 Shell-MIT Energy Fellow, contributed research on thermal modeling for multizoned commercial buildings to the UoF study. As was the case for many of the students involved, Xu used the same research for her master's thesis.

Jenkins, for example, contributed his master's thesis work on the regulation of distribution utilities and also wrote about the value of distributed energy resources using research central to his PhD dissertation.

Now, Jenkins says, he expects his UoF experience will help him in his quest for a tenure-track academic job.

Photo: Samuel Hurd

MIT graduate students join other Utility of the Future participants at the study's launch at the National Press Club in Washington, DC. Here, Ignacio Pérez-Arriaga, lead principal investigator, describes key reforms identified in the study that will enable the efficient evolution of electric power systems into the future.

"[The UoF project has] deepened my expertise and given me an ongoing research agenda to pursue and hopefully positioned me as an expert on these topics," he says.

Ranaan Miller, executive director of the UoF study, says the project provided all the students involved with valuable experience. "This was a multifaceted, very extensive project. The students learned a lot and matured a lot. For example, they learned how to deal with ambiguity and to deliver on a tight schedule," he says.

In addition to researching and writing on their own assigned topics, the students helped review and edit the full report. They also had the chance to present their work to industry experts and regulators, who provided feedback. "Having those inputs was very important," Herrero says. "That's something you don't typically get as a PhD student."

Indeed, Scott Burger, another PhD candidate in IDSS, a 2014–2016 Shell-MIT Energy Fellow, and a UoF researcher, says a major benefit of joining the UoF project was working with "an amazing group of researchers and advisors."

Burger helped develop one of the study's core modeling tools—DR DRE, or Demand Response and Distributed Resources Economics—which the researchers used to examine such questions as: Under what sets of service pricing structures or technology parameters do distributed energy resources complement and compete with each other? "I learned an immense amount about power systems regulation and economics, modeling, and engineering," he says.

Photo: Francesca McCaffrey, MITEI

From left: MIT graduate students Jesse Jenkins, Scott Burger, and Ashwini Bharatkumar participate in a panel at a special Utility of the Future event for MIT alumni during the study's launch in Washington, DC.

Yet it was working with the UoF team that was the highlight for Burger. "Because of [the UoF leaders'] efforts in team building, we now have a solid foundation of researchers that can carry the torch with ongoing work related to power systems here at MIT," he says.

Xu similarly praised the faculty members involved. "Even if I was struggling with some of the research on a day-to-day basis, being able to get advice from them and being able to discuss things with them was really encouraging. They're a great example of professors that don't just want to do good work but also care about their students learning and progressing as researchers," she says.

The UoF study's leaders were equally complimentary of the team's graduate students. Miller says they were "pretty exceptional—in terms of leadership, framing of issues, the quality of the writing, and clarity of thinking." He adds, "It was a creative, talented, highly motivated group of students that was dedicated to this project and contributed their best, and it really showed."

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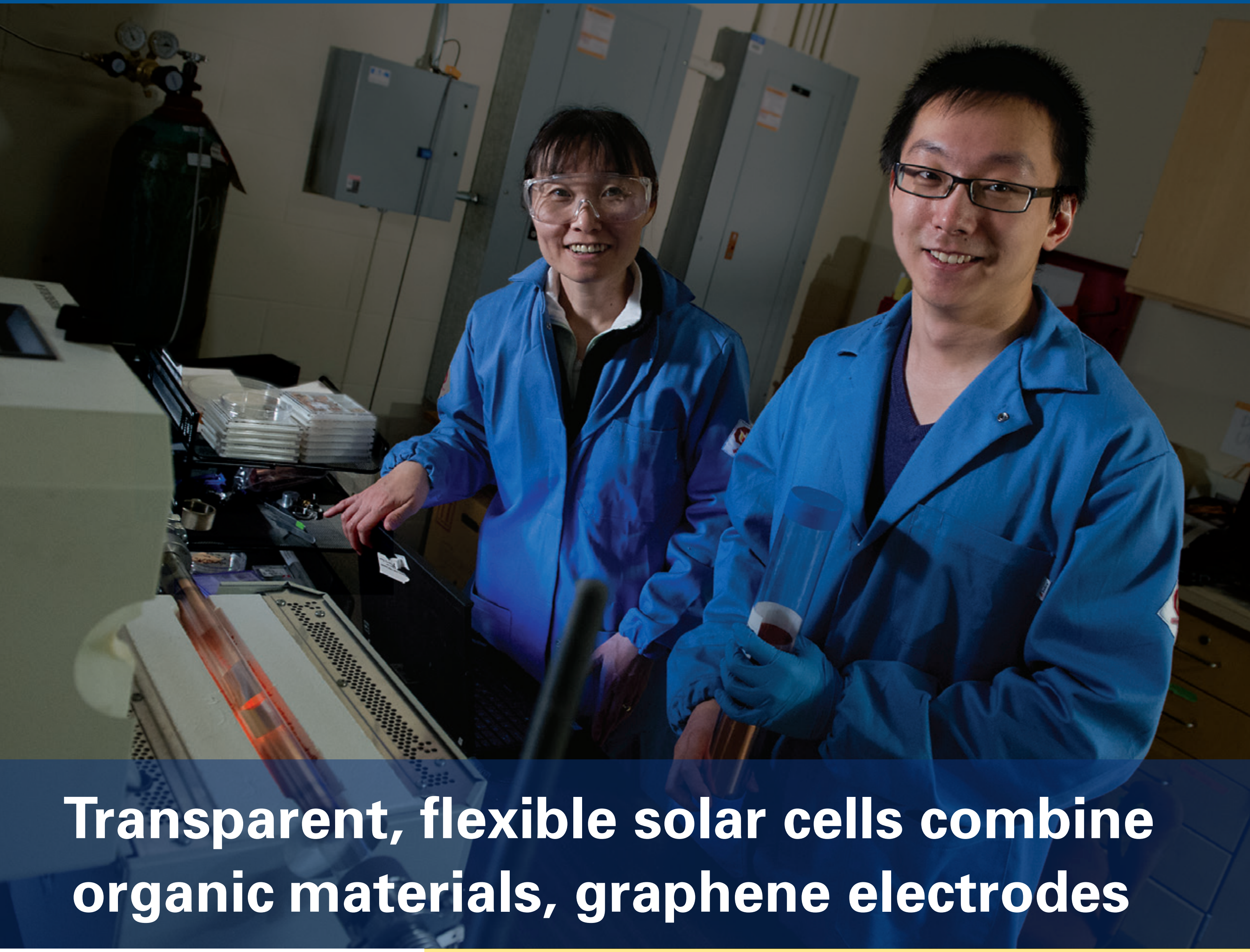
By Kathryn M. O'Neill,
MITEI correspondent



Transparent, flexible solar cells combine organic materials, graphene electrodes

Jing Kong (left) and Yi Song of electrical engineering and computer science fabricate one-atom-thick graphene electrodes and then—using a novel technique—transfer them onto flexible, transparent solar cells that they can mount on surfaces ranging from glass and plastic to paper and tape.

This research was supported by Eni S.p.A., a Founding Member of the MIT Energy Initiative.

Photo: Stuart Darsch

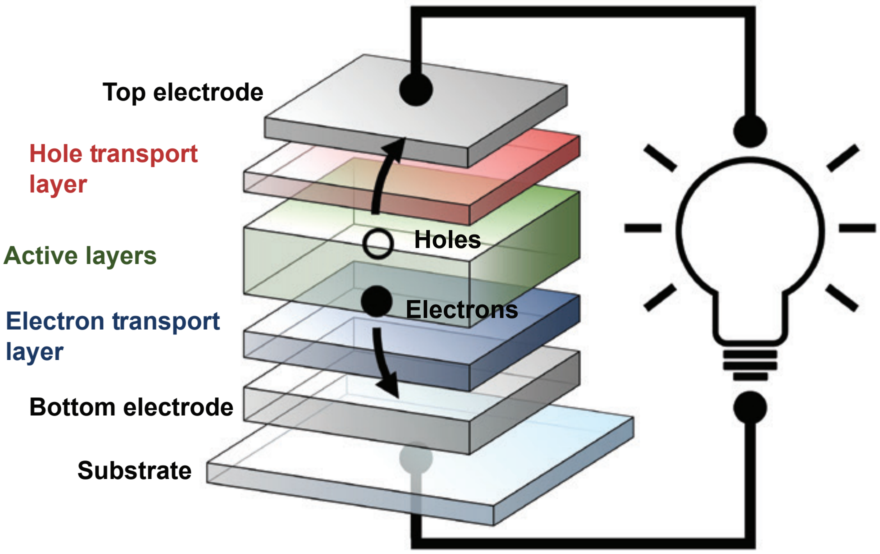
Imagine a future in which solar cells are all around us—on windows and walls, cell phones, laptops, and more. A new flexible, transparent solar cell developed at MIT brings that future one step closer. The device combines low-cost organic (carbon-containing) materials with electrodes of graphene, a flexible, transparent material made from inexpensive, abundant carbon sources. This advance in solar technology was enabled by a novel method of moving a one-atom-thick layer of graphene onto the solar cell—without damaging nearby sensitive organic materials. Until now, developers of transparent solar cells have typically relied on expensive, brittle electrodes that tend to crack when the device is flexed. The ability to use graphene instead is making possible truly flexible, low-cost, transparent solar cells that can turn virtually any surface into a source of electric power.

Photovoltaic solar cells made of organic compounds would offer a variety of advantages over today's inorganic silicon solar cells. They would be cheaper and easier to manufacture. They would be lightweight and flexible rather than heavy, rigid, and fragile, and so would be easier to transport, including to remote regions with no central power grid. And they could be transparent. Many organic materials absorb the ultraviolet and infrared components of sunlight but transmit the visible part that our eyes can detect. Organic solar cells could therefore be mounted on surfaces all around us and harvest energy without our noticing them.

Over the past decade, researchers have made significant advances toward developing transparent organic solar cells. But they've encountered one persistent stumbling block: finding suitable materials for the electrodes that carry current out of the cell. "It's rare to find materials in nature that are both electrically conductive and optically transparent," says Professor Jing Kong of electrical engineering and computer science (EECS). The most widely used option is now indium tin oxide (ITO). ITO is conductive and transparent, but it's also stiff and brittle, so when the organic solar cell bends, the ITO electrode tends to crack and lift off. In addition, indium is expensive and relatively rare.

A promising alternative to ITO is graphene, a form of carbon that occurs in one-atom-thick sheets and has remarkable characteristics: It's highly conductive, flexible, robust, and transparent; and it's made from inexpensive and ubiquitous carbon. In addition, a graphene electrode can be just 1 nanometer (nm) thick—a fraction as thick as an ITO electrode and a far better match for the thin organic solar cell itself.

Organic solar cell structure and operation



When sunlight strikes an organic solar cell, electrons in the organic "active" layers pick up energy and begin moving through the core, leaving behind vacancies—called holes—that essentially move in the opposite direction. The electrons come out of the cell via one electrode, flow along an external circuit—powering a device along the way—and re-enter the solar cell through the second electrode, rejoining the holes they left behind. An electron transport layer and a hole transport layer facilitate the movement of electrons toward one electrode and holes toward the other one, thereby expediting the one-way flow of current.

Graphene challenges

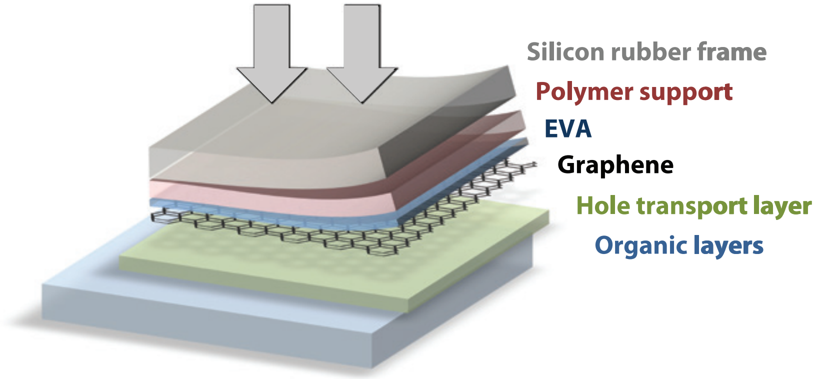
Two key problems have slowed the wholesale adoption of graphene electrodes. The first problem is depositing the graphene electrodes onto the solar cell. Most solar cells are built on substrates such as glass or plastic, as shown in the schematic above. The bottom graphene electrode is deposited directly on that substrate—a task that can be achieved by processes involving water, solvents, and heat. The other layers are then added, ending with the top graphene electrode. But putting that top electrode onto the surface of the so-called hole transport layer (HTL) is tricky. "The HTL dissolves in water, and the organic materials just below it are sensitive to pretty much anything, including water, solvents, and heat," says graduate student Yi Song of EECS, a 2016–2017 Eni-MIT Energy Fellow and a member of the Nanomaterials and Electronics Group, which Kong directs. As a result, researchers have typically persisted in using an ITO electrode on the top.

The second problem with using graphene is that the two electrodes need to play different roles. The ease with which a given material lets go of electrons is a set property called its work function. But in the solar cell, just one of the electrodes should let electrons flow out easily. As a result, having both electrodes made out of graphene would require changing the work function of one of them so the electrons would know which way to go—and changing the work function of any material is not straightforward.

Photo: Stuart Darsch

To prepare the graphene electrodes, the researchers insert pieces of copper foil such as the one shown above into a glowing furnace (as shown in the photo on page 11). With the furnace temperature at 1,000°C, they inject carbon-containing gases until a one-atom-thick layer of graphene forms on the copper foil. The vials contain organic polymers that become the active layers in the assembled solar cells. The white material at the right is ethylene-vinyl-acetate, which plays a key role in achieving tight adhesion between the graphene electrode and the surface of the solar cell.

The dry-transfer stamp



The researchers place the top graphene electrode on the hole transport layer of the solar cell using the "stamp" illustrated above. To create the stamp, they deposit a fine layer of a sticky polymer called ethylene-vinyl-acetate (EVA) on top of the graphene, followed by a thicker layer of another polymer that supports both the EVA and the graphene, keeping them from tearing and folding. On top they place a frame of silicon rubber. Grasping the frame with tweezers, they lift the whole assembly out of the water, dry it, and place it on top of the hole transport layer. The EVA adheres tightly to the surface, pushing the graphene layer beneath it firmly into place.

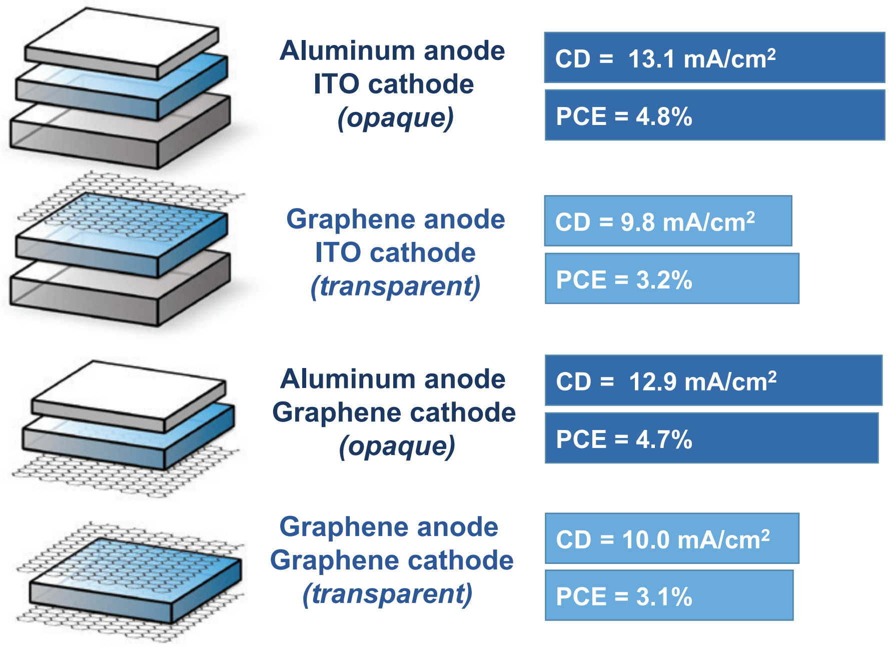
A smooth graphene transfer

For the past three years, Kong and Song have been working to solve these problems. They first developed and optimized a process for laying down the bottom electrode on their substrate. In that process, they "grow" a sheet of graphene on copper foil (as described in the caption at left). They then transfer it onto the substrate using a technique demonstrated by Kong and her colleagues in 2008. They deposit a layer of polymer on top of the graphene sheet to support it and then use an acidic solution to etch the copper foil off the back, ending up with a graphene/polymer "stack" that they transfer to water for rinsing. They then simply scoop up the floating graphene/polymer stack with the substrate and remove the polymer layer using heat or an acetone rinse. The result: a graphene electrode resting on the substrate.

But scooping the top electrode out of water isn't feasible. So they instead turn the floating graphene/polymer stack into a kind of stamp. They press a half-millimeter-thick frame of silicon rubber onto the stack. Grasping the frame with tweezers, they lift the stack out, dry it off, and set it down on top of the HTL. With minimal warming, they can then peel off the silicon rubber stamp and the polymer support layer, leaving the graphene deposited on the HTL.

Initially, the electrodes that Song and Kong fabricated using this process didn't perform well. Tests showed that the graphene layer didn't adhere tightly to the HTL, so current couldn't flow out efficiently. The obvious solutions to this problem wouldn't work. Heating the structure enough to make the graphene adhere would damage the sensitive organics. And putting some kind of glue

Sample solar cells: Structure and performance



To test their graphene electrodes, the researchers fabricated solar cells with top and bottom electrodes (anodes and cathodes) made of graphene, ITO, and aluminum in the combinations shown above. The bars to the right show two performance measures for each type of device. Current density (CD) is the amount of current flowing per unit area, measured in milliamps per square centimeter (mA/cm^2). Power conversion efficiency (PCE) is the fraction of incoming solar power converted to electricity. The performance of devices that combine graphene and ITO electrodes is comparable, demonstrating that the new low-cost, flexible electrodes do as well as the expensive, brittle ones used now. The presence of an aluminum electrode pushes up performance by reflecting sunlight back into the organic core, but the solar cell is no longer transparent.

on the bottom of the graphene before laying it down on the HTL would stick the two layers together but would end up as an added layer between them, decreasing rather than increasing the interfacial contact.

Song decided that adding glue to the stamp might be the way to go—but not as a layer under the graphene. "We thought, what happens if we spray this very soft, sticky polymer on top of the graphene?" he says. "It would not be in direct contact with the hole transport layer, but because graphene is so thin, perhaps its adhesive properties might remain intact through the graphene."

To test the idea, the researchers incorporated a layer of ethylene-vinyl-acetate, or EVA, into their stamp, right on top of the graphene (see the diagram on page 13). The EVA layer is very flexible and thin—sort of like food wrap—so it could easily rip apart. But they found that the polymer layer that comes next holds it together, and the arrangement worked just as Song had hoped: The EVA film adheres tightly to the HTL, conforming to any microscopic rough features on the surface and forcing the fine layer of graphene beneath it to do the same.

The process not only improved performance but also brought an unexpected side benefit. The researchers thought their next task would be to find a way to change the work function of the top graphene electrode so it would differ from that of the bottom one, ensuring smooth electron flow. But that step wasn't necessary. Their technique for laying down the graphene on the HTL actually changes the work function of the electrode to exactly what they need it to be. "We got lucky," says Song. "Our top and bottom electrodes just happen to have the correct work functions as a result of the processes we use to make them."

Putting the electrodes to the test

To see how well their graphene electrodes would perform in practice, the researchers needed to incorporate them into functioning organic solar cells. For that task, they turned to the solar cell fabrication and testing facilities of their colleague Vladimir Bulović, the Fariborz Maseeh (1990) Professor of Emerging Technology and associate dean for innovation.

For comparison, they built a series of solar cells on rigid glass substrates with electrodes made of graphene, ITO, and aluminum (a standard electrode material), paired in the combinations shown in the diagram at left. Two performance measures are shown in the bars to the right of each type of device: Current density (CD) is the amount of current flowing per unit area, and power conversion efficiency (PCE) is the fraction of incoming solar power converted to electricity. The CDs and PCEs for the new flexible graphene/graphene devices and the standard rigid ITO/graphene devices are comparable, but they're lower than those of the devices with one aluminum electrode—a finding they expected. "An aluminum electrode on the bottom will reflect some of the incoming light back into the solar cell, so the device overall can absorb more of the sun's energy than a transparent device can," says Kong.

The PCEs for all their graphene/graphene devices—on rigid glass substrates as

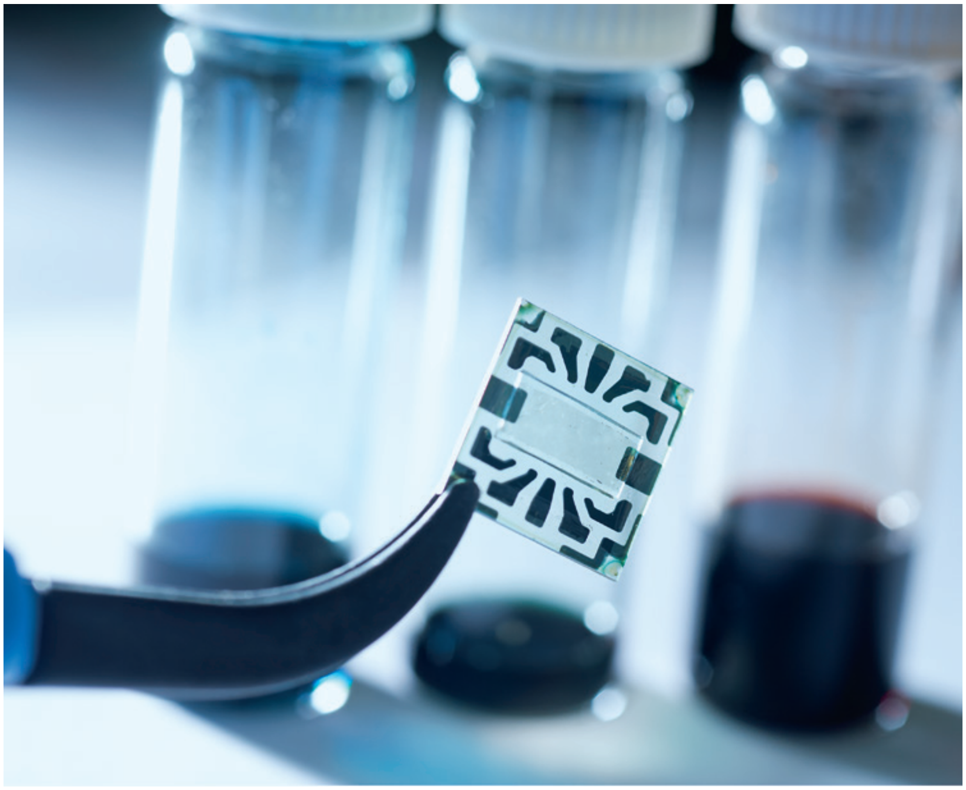


Photo: Stuart Darsch

In this device, the solar cell is the transparent region at the center. Around its edges are metal contacts where probes can be attached during tests of device performance.

well as flexible substrates—ranged from 2.8% to 4.1%. While those values are well below the PCEs of existing commercial solar panels, they're a significant improvement over PCEs achieved in prior work involving semitransparent devices with all-graphene electrodes, say the researchers.

Measurements of the transparency of their graphene/graphene devices yielded further encouraging results. The human eye can detect light at wavelengths between about 400 nm and 700 nm. The all-graphene devices showed optical transmittance of 61% across the whole visible regime and up to 69% at 550 nm. "Those values [for transmittance] are among the highest for transparent solar cells with comparable power conversion efficiencies in the literature," says Kong.

Flexible substrates, bending behavior

The researchers note that their organic solar cell can be deposited on any kind of surface, rigid or flexible, transparent or not. "If you want to put it on the surface of your car, for instance, it won't look bad," says Kong. "You'll be able to see through to what was originally there."

To demonstrate that versatility, they deposited their graphene/graphene devices onto flexible substrates including plastic, opaque paper, and translucent Kapton tape. Measurements show that the performance of the devices is roughly equal on the three flexible substrates—and only slightly lower than those made on glass, likely because the surfaces are rougher so there's a greater potential for poor contact.

The ability to deposit the solar cell on any surface makes it promising for use on consumer electronics—a field that's growing rapidly worldwide. For example, solar cells could be fabricated directly on cell phones and laptops rather than made separately and then installed, a change that would significantly reduce manufacturing costs. And they'd be well-suited for future devices such as peel-and-stick solar cells and paper electronics. Since those devices would inevitably be bent and folded, the researchers subjected their samples to the same treatment. While all of their devices—including those with ITO electrodes—could be folded repeatedly, those with graphene electrodes could be bent far more tightly before their output started to decline.

Future goals

The researchers are now working to improve the efficiency of their graphene-based organic solar cells without sacrificing transparency. (Increasing the amount of active area would push up the PCE, but transparency would drop.) According to their calculations, the maximum theoretical PCE achievable at their current level of transparency is 10%. "Our best PCE is about 4%, so we still have some way to go," says Song. They're also now considering how best to scale up their solar cells into the large-area devices needed to cover entire windows and walls, where they could efficiently generate power while remaining invisible to the human eye.

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By Nancy W. Stauffer, MITEI

This research was supported by Eni S.p.A. under the Eni-MIT Alliance Solar Frontiers Center. Eni is a Founding Member of the MIT Energy Initiative. Further information can be found in:

Y. Song, S. Chang, S. Gradečak, and J. Kong. "Visibly-transparent organic solar cells on flexible substrates with all-graphene electrodes." *Advanced Energy Materials*, July 2016. DOI: 10.1002/aenm.201600847.

Limiting global warming

More aggressive measures are needed

John Reilly and his colleagues in the MIT Joint Program on the Science and Policy of Global Change used a comprehensive set of linked models to demonstrate how dramatically the world's energy system needs to change—within the next few decades—to prevent excessive global warming by 2100.

An MIT analysis of the Paris climate agreement finds that—even if all the participating nations meet their pledges—global warming will exceed the 2°C maximum targeted for 2100 as early as 2050. To determine what else is needed, researchers at the MIT Joint Program on the Science and Policy of Global Change calculated a series of global energy technology mixes that would meet future demand while generating greenhouse gas emissions consistent with the 2°C target. Depending on the assumed costs plus a uniform global carbon price, different technologies dominate, but all the successful combinations are markedly different from today's global energy system. The researchers conclude that substantial R&D investment is needed to lower the cost of key energy technologies and help transform the global energy system—a shift that must be well under way within the next decade or so if the world is to meet its targets.

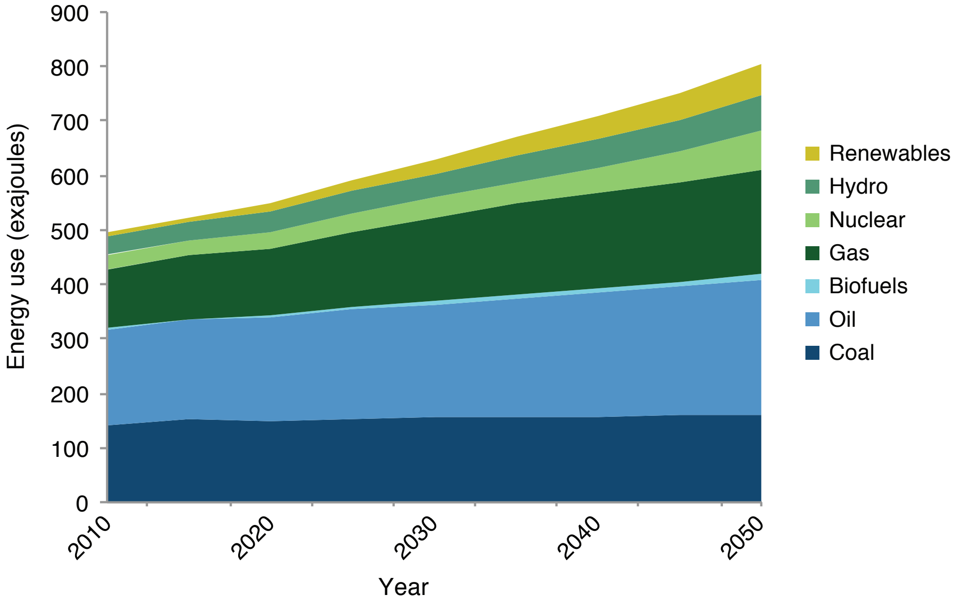
Contributors to this study include the MIT Energy Initiative (MITEI) and BP, a Founding Member of MITEI. Other contributors and sponsors are noted on page 21.

Photo: Dimonika Bray, MIT

At the Paris climate talks in late 2015, almost 200 nations signed an agreement designed to limit warming at the Earth's surface to 2°C or less above preindustrial levels—a long reiterated target intended to avert some of the worst consequences of climate change. But are the nations' individual "Intended Nationally Determined Contributions" (INDCs) pledged under the agreement aggressive enough to put the world on a path to meet the climate target? If not, what will the outcome be, and what other measures may be needed to get us there?

Those questions and more are addressed in *2016 Food, Water, Energy, and Climate Outlook*, the latest in a series of reports published annually since 2012 by the MIT Joint Program on the Science and Policy of Global Change to provide updates on the direction the planet is heading in terms of economic growth and implications for resource use and the environment. New this year is an examination of agricultural and water resource challenges as well as perspectives from experts in the Joint Program, the MIT Energy Initiative, BP, and the Energy Innovation Reform Project on technical and economic barriers and hoped-for breakthroughs in key technologies associated with providing energy and electricity.

Global primary energy use under the Paris Agreement



This chart shows projected energy use worldwide by energy source. The calculations are based on population forecasts from the United Nations and economic growth estimates from the International Monetary Fund, and they assume that policies and measures under the Paris Agreement remain in effect through 2050 (and 2100) but without deeper cuts or broadening participation by more countries. Renewables and nuclear grow, but the world energy mix continues to be dominated by fossil fuels.

The Paris scenario and a risky future

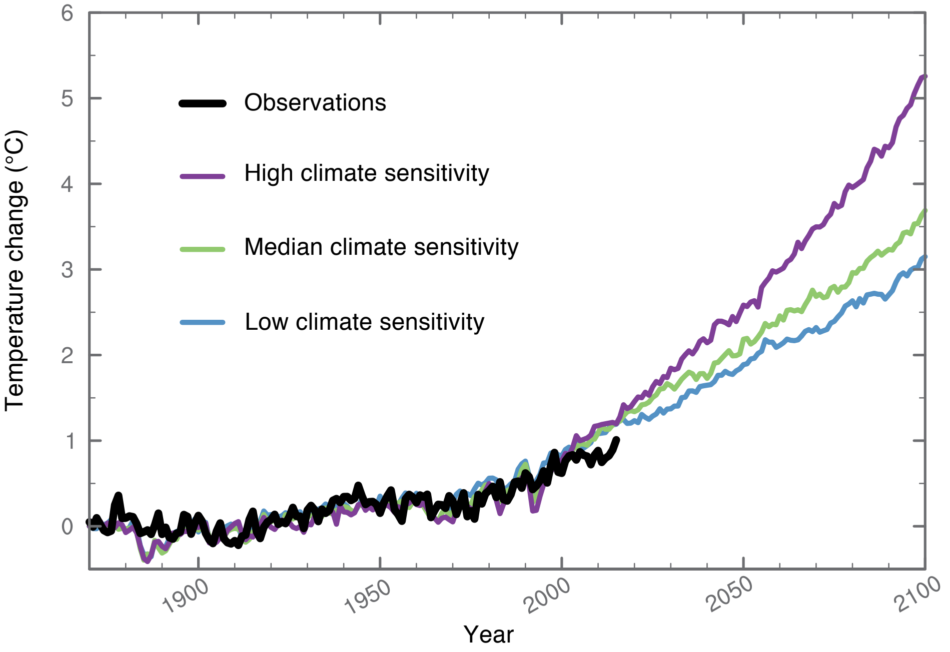
The researchers' first task was to assess the effectiveness of the pledges made in the Paris Agreement. How will they affect the future mix of energy technologies and fuels, what will be the impact on emissions, and what effect will those emissions have on global temperatures?

The team addressed those questions using the Integrated Global System Model (IGSM), a linked set of computer models developed by the Joint Program to analyze interactions among human and Earth systems. The Economic Policy and Projection Analysis component simulates world economic growth as a result of population, productivity, and energy technology choices based on their costs. The MIT Earth System Model simulates chemical reactions in the atmosphere, climate dynamics, and changes in natural ecosystems, including vegetation, soils, and the oceans. Under the IGSM framework, the two models interact to project global environmental changes that may arise from human activities and the impacts of proposed policy measures on those changes.

To examine the impact of the Paris Agreement, the researchers ran the IGSM using future population and economic growth estimates based on data from the United Nations, the International Monetary Fund, and other sources. They introduced policies and measures that they believe reflect the INDCs of the major emitting nations and assumed that all participants would adhere to their pledges through 2025 (and beyond) and that no further measures would be enacted.

The figure above shows the resulting distribution of energy use by different sources between 2010 and 2050. The forecast brings some (seemingly) encouraging news: There's an eight-fold increase in renewables and a three-fold

Change in global mean temperature from preindustrial levels



These curves show MIT estimates of changes in temperature since 1870 (defined as the preindustrial level), assuming that the global climate exhibits low, median, and high sensitivity to atmospheric greenhouse gases. Temperature change is calculated based on the primary energy mix that results from the policies and measures of the Paris Agreement, assuming that they remain in effect through 2100 without deeper cuts or broadening participation by more countries. The 2°C target for 2100 is exceeded as early as 2050.

increase in nuclear power. “But both start out as small fractions of the total, so that growth isn’t enough to drive out fossil fuels,” says John Reilly, co-director of the Joint Program and senior lecturer in the MIT Sloan School of Management. The fossil energy share shrinks from 86% today to 75% by 2050, but the world remains largely fossil-fuel dominated—and in 2100, fossil fuels still claim 58% of the total.

The researchers next calculated the global emissions that would result from that projected energy mix. They accounted for emissions of all types of greenhouse gases (GHGs) from all human sources, including energy, industry, agriculture, waste, and changes in land use. Their results show that total emissions in 2100 are more than 60% higher than they were in 2010, and two-thirds of that total consists of carbon dioxide (CO_2) emitted by fossil fuels.

Finally, based on that emissions outlook, they estimated changes in the global surface air temperature from preindustrial levels. The response of the Earth system to radiative forcing by GHGs is uncertain. As a result, analyses of a given GHG concentration can produce a range of projected temperature increases, some more likely than others. To reflect that uncertainty, the researchers performed separate analyses assuming that the global climate exhibits low, median, or high sensitivity to the presence of atmospheric GHGs. The results appear in the three curves in the figure above. By 2050, the projected temperature rise—depending on the assumed sensitivity—ranges from 1.9°C to 2.6°C, and by 2100, the range is 3.1°C to 5.2°C.

Calculations of the associated impacts on food and water produce equally alarming forecasts. Even if all the pledges in the Paris Agreement are carried out, significant risks still remain for staple crops in major “breadbasket” regions of the world and for water supplies on which most of the global population depends.

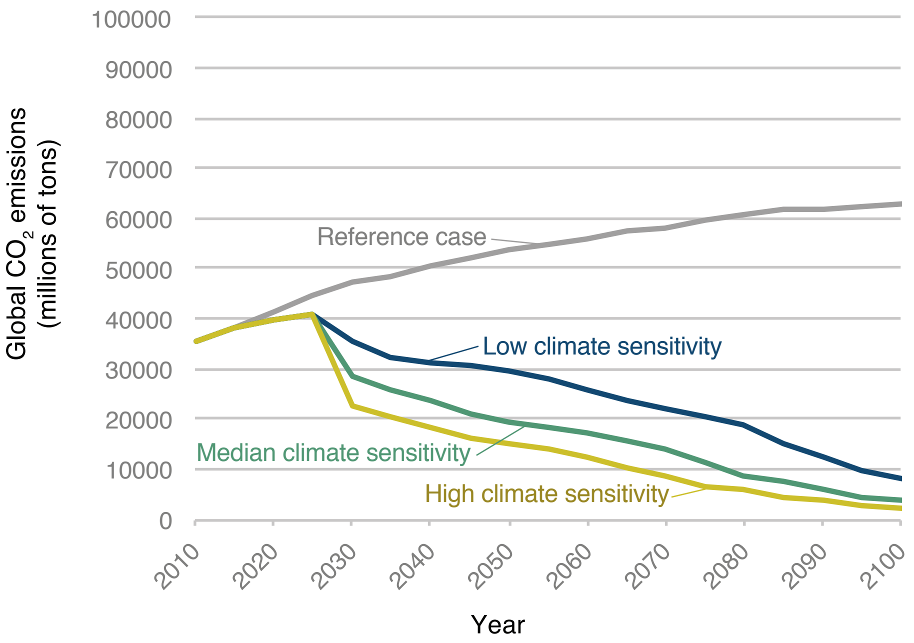
“So even if we’re lucky and the Earth is not very responsive to GHG forcing, by 2050 we’re within a tenth of a degree of the 2°C target,” says Reilly. “We’re obviously not anywhere close to meeting it, and given the risks involved, it’s prudent to pursue more aggressive policies to stabilize climate.”

Emissions and energy scenarios for the 2°C pathway

The researchers next developed emissions scenarios that would successfully keep the temperature increase at or below the targeted level. The analyses assume that the Paris Agreement locks in behavior through 2025, and then in 2025 a globally uniform, rising carbon price is introduced with the starting value set so as to limit cumulative emissions as needed by 2100.

The figure on page 19 shows the results for CO_2 emissions. The top curve is a reference case reflecting emissions in the absence of the Paris pledges. The other three curves show how much emissions must drop to meet the 2°C target, assuming the three levels of sensitivity. Not surprisingly, the higher the climate sensitivity, the lower the required emissions path.

Emissions paths for 2°C warming



This chart shows calculated CO_2 emissions trajectories that would limit warming to below 2°C in 2100, assuming low, median, and high climate sensitivity. The Paris Agreement is in effect through 2025, after which a carbon price is imposed to limit cumulative emissions as needed to meet the 2100 target. The abrupt drop between 2025 and 2030 confirms that the Paris pledges alone are not sufficiently aggressive to produce a path consistent with climate stabilization.

More striking is the abrupt drop between 2025 and 2030. The median case requires a 31% reduction in emissions in those five years. The high-sensitivity case requires that emissions be cut in half.

Despite the high cost and disruption of making such an abrupt correction, the model suggests that it would be economically optimal to do so. Reilly offers an analogy. “If you’re speeding along and suddenly realize there’s a cliff in front of you, you’re going to crank the wheel pretty hard, even if it throws people around the back seat,” he says. “If we continue on our current course and suddenly recognize that we really have to meet the 2°C target, we’ll need to crank the wheel suddenly on our world energy system, regardless of the costs.”

Energy mixes that would work

While drastic changes in the global energy mix are needed, there are various combinations of technologies that could work. To illustrate, the researchers examined a series of scenarios in which—by virtue of assumed costs and other constraints—certain technologies dominate in a future energy mix that meets the target. Results from three of the analyses are shown in the charts on page 20. (All of the analyses assume median climate sensitivity and International Energy Agency [IEA] estimates of technology costs, except where noted.)

Nuclear dominance

To establish a base case, the researchers assumed median IEA costs for all the key energy technologies plus biofuels. The outcome is a world in which nuclear energy rapidly becomes the dominant source of electricity. Bioelectricity plays a minor role, along with hydropower and renewables where they easily integrate into the system.

Nuclear likewise dominates the primary energy outcome. Bioenergy also plays a growing role, with some going to electricity production but much of it into liquid fuels for vehicles. (No breakthroughs in electric vehicles were considered.) Coal disappears quickly, while oil and gas decline more slowly over time. Fossil fuels’ share of global energy falls to 38% by 2050 and 3% by 2100.

A biomass world

A significant global expansion of nuclear energy could prove difficult, given political and other concerns, so the researchers also performed an analysis in which the nuclear option is costly and limited by other constraints. When the cheap nuclear option is taken away, energy conservation and efficiency increase, and total electricity and energy consumption drop.

Bioenergy now dominates the electricity sector, with some help from natural gas with carbon capture and sequestration (CCS) as well as renewables, hydro, and nuclear. Bioenergy is likewise an important source of primary fuel—both for generating electricity and for replacing oil products for transportation.

Renewables rule

For wind and solar to play a dominant role, the researchers had to assume that the intermittency problem would be solved by inexpensive energy storage or advances in grid operation. Otherwise, the cost of maintaining backup capacity—for example, gas

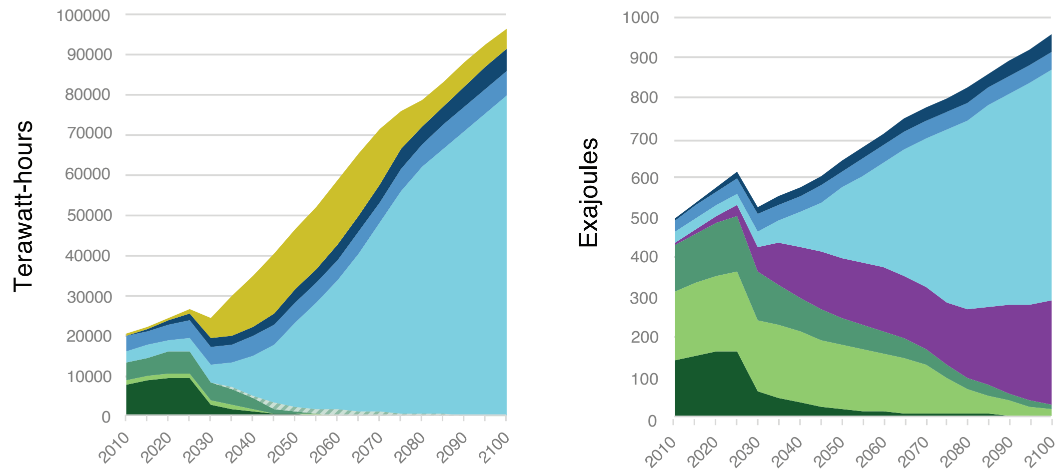
Energy mixes to meet the 2°C challenge

The charts below show three sets of electricity generation and primary energy mixes designed to meet the 2°C target for 2100. They result from analyses in which the researchers assumed a rising carbon price along with costs and constraints such that selected technologies play the dominant role. A fourth analysis assuming inexpensive carbon capture and sequestration (CCS) produces results almost identical to the bioenergy scenario.

Global electricity generation | **Global primary energy**

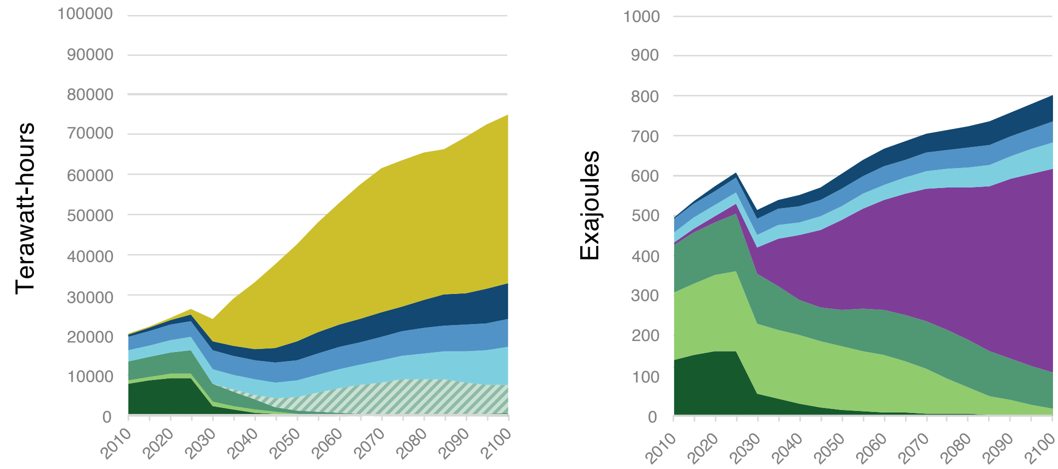
Nuclear

The nuclear scenario results from a base-case analysis assuming the median IEA costs for the key technologies plus biofuels.



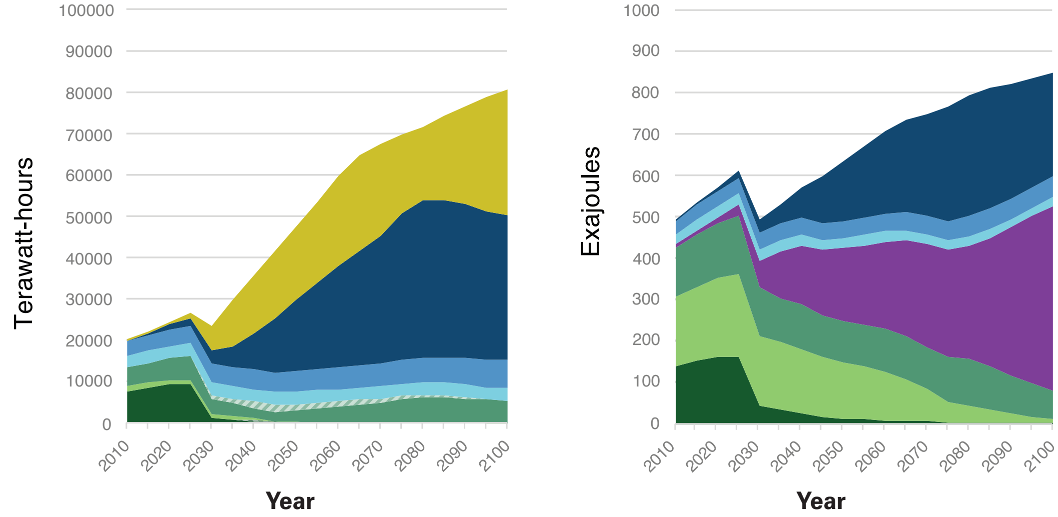
Bioenergy

The bioenergy scenario results from assuming that nuclear power is costly and constrained.



Renewables

In the renewables scenario, nuclear power is costly, and wind and solar power are inexpensive, in part due to the assumption that maintaining backup power is unnecessary.



🟨 Bioelectricity | 🟦 Renewables (wind and solar) | 🟦 Hydro | 🟦 Nuclear | 🟪 Bioenergy | ▨ Gas (w/CCS) | 🟩 Gas (no CCS) | 🟩 Oil | ▨ Coal (w/CCS) | 🟩 Coal (no CCS) turbines or bioelectricity plants—makes the large-scale penetration of renewables economically infeasible.

Given low-cost solar and wind and constrained nuclear, renewables make up about half of all electricity generation, with another chunk coming from bioelectricity. Renewables also play a major role in primary energy, exceeded only by bioenergy, which is used for both electricity generation and liquid transportation fuels.

Carbon capture and sequestration

In another analysis (not shown in the figure), the researchers constrained nuclear energy and dropped the cost of CCS to the low end of the IEA range. Interestingly, the results for electricity generation and primary energy are almost identical to those in the bioenergy case. Even at the low end of the cost estimates, CCS is too expensive to compete. Part of the problem is that the CCS technology captures at most 90% of the emissions, and the carbon price must be paid on the emissions that remain.

Other options and the path forward

The analyses presented in the report don't look at adding CCS to biomass electricity generation—a combination that Reilly considers a kind of magic formula. "You grow the trees, which takes carbon out of the atmosphere," he says. "Then you burn the trees, which releases carbon, but you suck that carbon out of the power plant and put it underground. You get a net-negative." With that arrangement, a power plant would jointly produce carbon reductions and electricity—and would get paid for both. In that scenario, emissions could go to zero or below over the long term, Reilly says.

Reilly stresses the importance of reaching zero emissions. "People think that if emissions stop rising, then we'll have achieved stabilization—but they'll still be building up in the atmosphere," he says. "What we need to remember is that to stabilize concentrations of CO_2 in the atmosphere, we have to get to virtually no CO_2 emissions." And given continuing GHG emissions from livestock, fertilizers, and other critical sources, achieving negative CO_2 emissions somewhere will be needed to get to net zero emissions.

The researchers conclude that the transition to a dramatically different global energy mix must be well under way within the next 10 to 20 years to prevent an excessive temperature increase by 2100. They recognize that such an undertaking will almost certainly require extraordinary political agreement or sudden and unforeseen breakthroughs in technology. They assert that since it's not clear which technologies will take the lead, substantial R&D investment is needed to develop current technologies, explore new ones, and increase the efficiency with which we use energy so less is required in the future. The technological advances and cost reductions that result will help countries move forward on climate change and support the transition onto a 2°C energy pathway as soon as possible.

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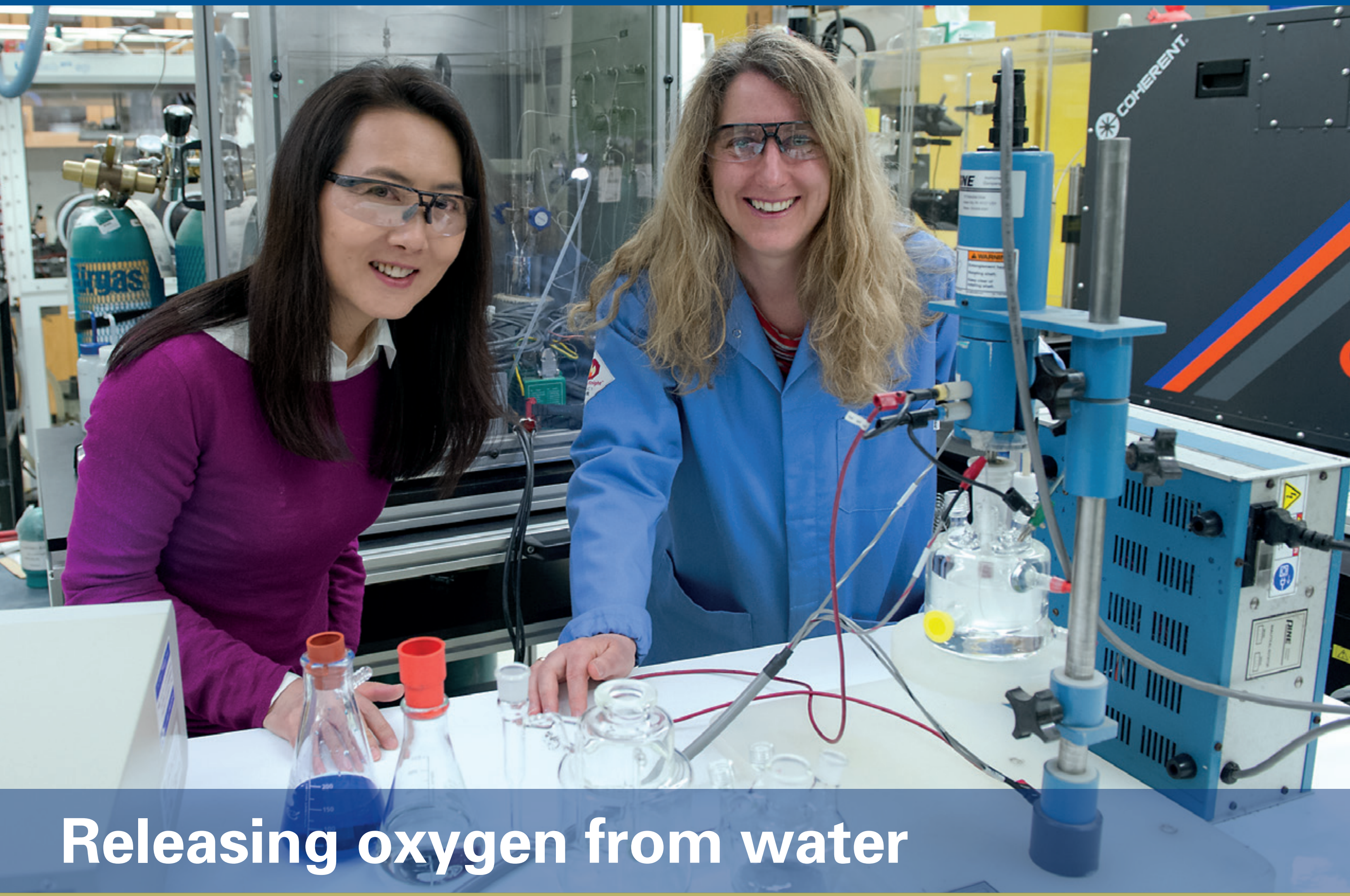
By Nancy W. Stauffer, MITEI

This research was supported by the MIT Joint Program on the Science and Policy of Global Change and its international partnership of government, industry, and foundation sponsors and private donors. Other contributors include the MIT Energy Initiative (MITEI); the Energy Innovation Reform Project; and BP, a Founding Member of MITEI.

Further information can be found in:

MIT Joint Program on the Science and Policy of Global Change. *2016 Food, Water, Energy, and Climate Outlook*. Download the report at mitenergyfutur.es/jp2016outlook.



Releasing oxygen from water

Better catalysts for energy storage devices

Yang Shao-Horn of mechanical engineering and materials science and engineering (left), Livia Giordano of MIT and Milano-Bicocca University (right), and their colleagues have performed experimental and theoretical studies that provide new understanding of why certain catalysts are so effective at encouraging the release of oxygen from water during electrolysis—a key process in many energy storage devices.

Photo: Stuart Darsch

MIT and Leiden University researchers have now produced unambiguous experimental evidence that conventional theory doesn't accurately describe how highly efficient metal-oxide catalysts help release oxygen gas from water during electrolysis—a critical process in many energy storage technologies. Using a special form of oxygen as a marker, they demonstrated that the oxygen gas comes not only from the water but also from the metal-oxide catalyst itself. In parallel theoretical studies, they showed that certain electronic properties of such highly efficient catalysts permit involvement of oxygen from the catalyst. The team is now working to define the sequence of chemical reactions that leads to oxygen release on these special catalysts. Already, their findings provide new guidance in the ongoing search for low-cost, effective materials and designs for these important catalysts.

Many systems for storing energy rely on electrochemical reactions that cause the release of oxygen gas from water. These so-called oxygen-evolution reactions are critical to the efficiency of devices that split water to recover hydrogen fuel and to the performance of regenerative fuel cells, metal-air batteries, and more.

"Oxygen evolution is one universal reaction that's key in developing efficient energy storage technologies by storing electron energy in chemical form," says Yang Shao-Horn, the W.M. Keck Professor of Energy, a professor of mechanical engineering and of materials science and engineering, and co-director of the MIT Energy Initiative's Energy Storage Research Center.

The kinetics of oxygen-evolution reactions are typically slow, so catalysts such as metal oxides are required to speed up the chemical reactions (without being consumed in the process). During electrolysis of water, a metal-oxide catalyst is immersed in a water-based electrolyte. When a potential is applied, the water molecules react on the catalyst, splitting into positively charged hydrogen ions (protons) and oxygen atoms, which form oxygen gas that bubbles out of the system.

Much research has focused on identifying metal oxides that will perform this task. Many compounds work, but the catalytic activity of some is orders of magnitude greater than that of others. After three years of intensive experimental and theoretical study, Shao-Horn and her colleagues in the Electrochemical Energy Lab have developed new insights into why certain metal-oxide catalysts work so well, and they have produced practical guidelines for finding new, more effective catalysts in the future.

Photo: Stuart Darsch

This electrochemical cell is at the core of the experimental setup shown on page 22. At its center, a probe containing the sample catalyst is submerged in the water-based electrolyte. A voltage is applied via the incoming wires, electrolysis commences, bubbles of oxygen gas form on the surface of the catalyst, and the resulting current flow is recorded. The probe spins rapidly to prevent bubbles from accumulating on the catalyst, which would stop the electrochemical reaction.

Experimental evidence: Tracking the oxygen

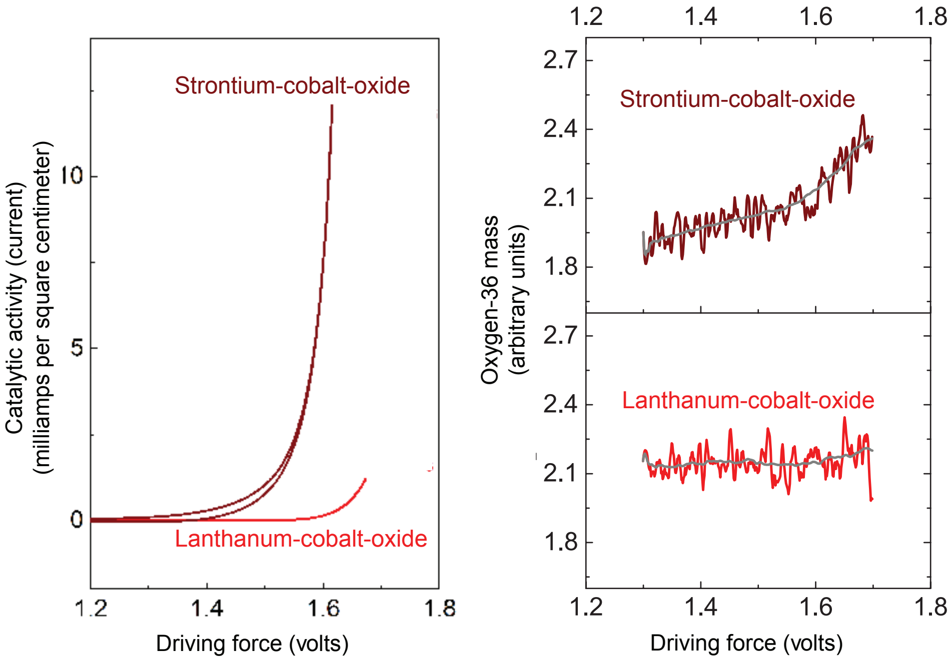
In their work, Shao-Horn, Binghong Han PhD '16, former postdoc Alexis Grimaud, Visiting Professor Livia Giordano from Milano-Bicocca University in Italy, and their collaborators have been exploring a promising class of catalytic materials known as perovskites, which—unlike today's state-of-the-art catalysts—consist of low-cost, earth-abundant materials. To understand what determines catalyst efficiency, they wanted to compare the behavior of two perovskites, one more catalytically active than the other. So they tested catalysts based on the same transition metal—cobalt—in combination with lanthanum and with strontium. The combination of cobalt, strontium, and oxygen is known to exhibit especially high catalytic activity—far higher than the lanthanum mixture.

A first question concerns the source of the oxygen that becomes oxygen gas. The conventional theory of metal-oxide catalysis says that all of the oxygen for the oxygen-evolution reactions comes from the water and that all of those reactions occur on the transition metal atoms—not the oxygen atoms—at the surface of the catalyst. But with certain materials, could some oxygen from the metal oxide itself also be involved in the reactions, adding to the oxygen output? That hypothesis has been widely debated but never resolved.

To address that question, the MIT researchers teamed up with Oscar Diaz-Morales and Marc T. Koper at Leiden University in the Netherlands. Together, they have been performing tests that rely on a special form of oxygen that serves as an experimental marker—the isotope oxygen-18 (oxygen-16 is the form that predominates in ordinary water).

To begin their tests, they first immerse a sample metal-oxide catalyst in "heavy" water containing almost entirely oxygen-18 and then perform electrolysis, instigating reactions on the catalyst. During that process, any oxygen atoms that come out of the crystal lattice of the cobalt-oxide catalyst leave behind vacancies that

Tests with cobalt-oxide catalysts containing lanthanum and strontium



These figures show results of experiments with catalysts of lanthanum-cobalt-oxide and strontium-cobalt-oxide. Left: Here, current flow—an indicator of catalytic activity during electrolysis—is measured as a function of driving force. (Driving force is defined as applied voltage versus a reference electrode, specifically, the reversible hydrogen electrode.) As driving force increases, activity on the strontium-based catalyst far exceeds that on the lanthanum-based catalyst. Right: In the same experiments, concentrations of oxygen-36—formed from oxygen released from the metal oxide lattice—rise significantly with driving force in the strontium tests but remain essentially constant with lanthanum.

are then filled with new oxygen atoms—in this case, by oxygen-18 atoms from the heavy water.

The researchers next remove the catalyst from the heavy water, place it in ordinary water, and perform the electrolysis process again. They then analyze the oxygen gas that forms using a mass spectrometer that separates different isotopes based on their atomic weight. The results measure how much oxygen-18 is present in the product gases—oxygen that must have been stored in the metal oxide in the first part of the experiment.

The researchers performed this test with catalysts made of cobalt and oxygen plus varying proportions of lanthanum and strontium, and the results were markedly different. As shown in the figures above, the versions containing strontium not only showed greater catalytic activity during electrolysis (as measured by current flow) but also yielded different mixes of oxygen products.

In gaseous form, oxygen molecules consist of a pair of oxygen atoms bound together. Analyses of samples collected from experiments with the lanthanum-cobalt-oxide catalyst detected oxygen-32—a combination of two oxygen-16 atoms. The oxygen in the product gases thus came from the water, as dictated by conventional theory.

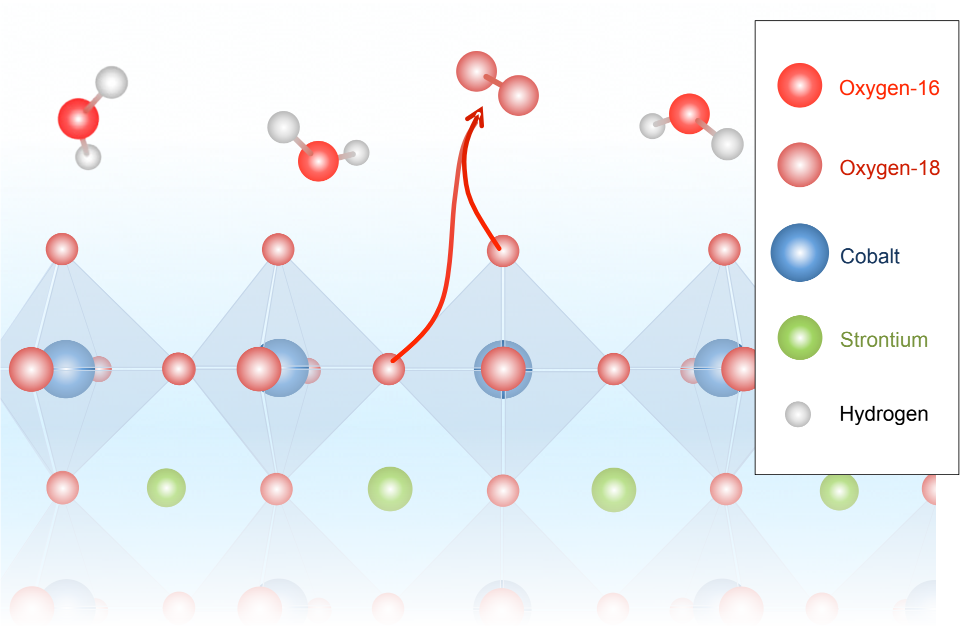
In contrast, tests with the highly active strontium-cobalt-oxide catalyst yielded products containing a significant amount of oxygen-36, that is, combinations of two oxygen-18 atoms—atoms that can only have come from the crystal lattice of the metal oxide (see the schematic on page 25).

Those results show conclusively that oxygen in the crystal lattice takes part in the oxygen-evolution reaction. Interestingly, the combined lanthanum-strontium version of the catalyst produced oxygen-34. In that molecular pairing, one oxygen-16 from the water has combined with one oxygen-18 from the metal oxide lattice.

One possibility is that the oxygen-18 is adsorbed and released only on the surface of the catalyst. To check, the researchers calculated how much oxygen-18 could be contained per volume of the strontium-cobalt-oxide catalyst. They then determined how much material would be required to adsorb and release the amount of oxygen-18 they measured in the oxygen gas. Their analysis confirms that the surface layers wouldn't provide enough storage space. Indeed, the oxygen-18 that's involved must have come from deep within the strontium-based catalyst.

Tests with the strontium catalyst brought another interesting finding: Changing the acidity of the water caused significant changes in the catalytic activity. With most metal-oxide catalysts—including lanthanum-cobalt-oxide—changing the pH of the water doesn't affect the reaction rate. But with the

Schematic showing oxygen evolution from the metal oxide lattice



In this schematic, the octahedrons represent the structure of the strontium-cobalt-oxide catalyst, with atoms of interest at their vertices. Water molecules consisting of hydrogen and oxygen-16 atoms come in from above. During the electrochemical reaction, oxygen-18 atoms are released from within the catalyst and pair up, forming the oxygen-36 detected in the experiments.

highly active strontium-cobalt-oxide catalyst, increasing the pH (that is, making it more alkaline) increased the rate of oxygen evolution.

The figure on page 26 summarizes results of these experiments with the catalysts. The impact of changing the pH is almost insignificant with lanthanum-cobalt-oxide, somewhat greater when strontium replaces some of the lanthanum, and quite pronounced in the strontium-cobalt-oxide tests.

Delving deeper

Clearly, the highly active catalyst doesn't adhere to the conventional wisdom that all the oxygen for the oxygen-evolution reactions comes from the water and that reactions occur only at metal sites on the surface of the catalyst. What makes the strontium-cobalt-oxide catalyst so different from the lanthanum-cobalt-oxide catalyst?

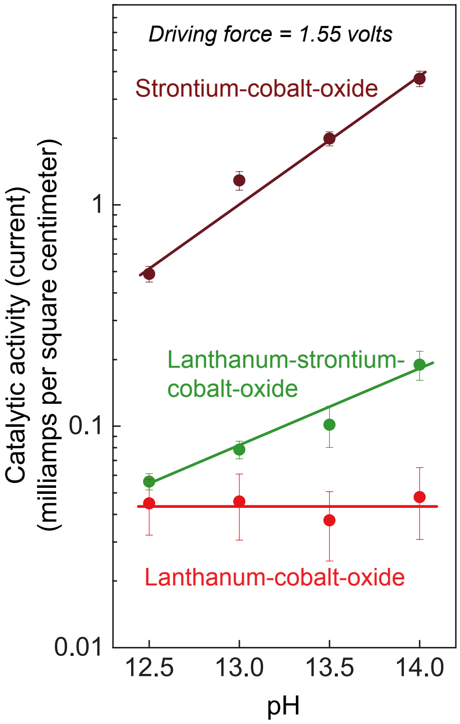
Based on their theoretical simulations, the researchers conclude that the answer lies in the electronic structure of the two metal oxides: In the strontium version, the metal-oxygen bonds are far more covalent. In any material, there are certain energy levels that electrons can occupy, and electrons at the highest energy level are easiest to remove. In metal oxides with record-high catalytic activity—such as strontium-cobalt-oxide—the highest electron energy levels of the metal and the oxygen match up, and the materials are said to be covalent.

"In our strontium-based catalyst, both the metal and the oxygen are able to contribute electrons at the energy level needed to link pairs of liberated oxygen atoms to form molecules," says Shao-Horn. "As a result, both the metal and the oxygen in the catalyst are active sites for oxygen-evolution reactions."

The researchers' findings suggest a need to revise the theoretical reaction mechanism describing the sequence of chemical changes that occurs during oxygen evolution on a metal-oxide catalyst. Converting water to oxygen on a catalyst requires the transfer of four electrons and four protons. The conventional reaction mechanism says that the electrons and protons have to move at the same time. That is, their transfer must be concerted. "But that mechanism doesn't allow for participation of oxygen from the crystal lattice or for pH dependence," says Giordano.

The researchers conclude that when oxygen evolves on a highly active metal-oxide catalyst, there must be non-concerted transfer. Decoupling the transfer of protons and electrons permits involvement of oxygen atoms from the crystal lattice, and it explains why they observed pH-dependent reactivity. "If the mechanism is not concerted—say, a proton goes first followed later by an electron—then the activity can depend on pH," says Giordano. "When we change the pH, we are changing the concentration of protons in our electrolyte, and that will affect the rate of the reaction—but only if protons and electrons can move independently."

Effect of pH on catalytic activity



This figure shows how changing the pH of the water affects the catalytic activity of the cobalt-oxide catalysts. While activity on the lanthanum-cobalt-oxide catalyst is unaffected by increasing the pH, adding strontium to the catalyst changes that outcome. In tests with the strontium-cobalt-oxide catalyst, catalytic activity starts out higher and then rises more rapidly as pH increases.

Design guidance

The new understanding of oxygen-evolution reactions opens up new directions for designing efficient catalysts. For example, researchers can explore other materials—including alternatives to cobalt—to find combinations with higher covalency. "We've shown that evolving oxygen from the metal oxide increases catalytic activity," says Giordano. "So to design particularly active catalysts, we should try to increase the covalency of the metal oxide so as to trigger activation of oxygen in the lattice and enable non-concerted proton-electron transfer." Under those conditions, influencing reactivity by changing the pH of the water becomes another avenue to explore.

Their findings offer one more practical hint. At the outset of the project, a primary goal was to identify the rate-limiting step in oxygen evolution. The rate of any chemical reaction is determined by the rate of the slowest step in the process. Speeding up that step is thus key to speeding up the overall reaction.

With many metal-oxide catalysts, the speed of water electrolysis is limited by how fast oxygen comes off the catalyst. But in their highly covalent material, the transfer of electrons needed to free the oxygen molecules should be quite easy. "So we speculate that getting the protons off the surface may actually be limiting how quickly the reaction proceeds," says Giordano. They can't yet confirm that hypothesis, largely because there's no consensus on how to theoretically simulate non-concerted reaction steps on these complex materials. "It's something we'd really like to do," she says. Their next job is to figure out how.

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By Nancy W. Stauffer, MITEI

The research team for this work also included Wesley Hong PhD '16, former postdoc Yueh-Lin Lee, and Kelsey Stoerzinger PhD '16. The research was supported by the Skoltech-MIT Center for Electrochemical Energy, the Singapore-MIT Alliance for Research and Technology, the US Department of Energy, and the National Energy Technology Laboratory. Further information can be found in:

A. Grimaud, O. Diaz-Morales, B. Han, W.T. Hong, Y-L. Lee, L. Giordano, K.A. Stoerzinger, M.T.M. Koper, and Y. Shao-Horn. "Activating lattice oxygen redox reactions in metal oxides to catalyse oxygen evolution." *Nature Chemistry*, January 2017. DOI: 10.1038/NCHEM.2695.

New study from MIT Energy Initiative will explore the future of transportation

Energy demand for transportation—which today accounts for approximately one-fifth of the world's energy consumption—is expected to rise substantially as a growing middle class in emerging economies demands greater access. But how will such demand be addressed in the years ahead?

As part of MIT's five-year Plan for Action on Climate Change, the MIT Energy Initiative (MITEI) has launched a major study—Mobility of the Future—to explore how consumers and markets will respond to potentially disruptive technologies, business models, and government policies. The scope of this study is ground transportation with an emphasis on the movement of people.

"It is well recognized that transportation is the most challenging economic sector to decarbonize," says Robert Armstrong, director of MITEI and a professor of chemical engineering. "Our three-year Mobility of the Future study is tackling complex questions of how technology advances, consumer choice, new business models, and government policies could change the trajectory of mobility to fundamentally alter the carbon intensity of the future transportation system."

There are many potentially disruptive forces at work in the mobility space, all of which could shape the landscape. MITEI has organized a multidisciplinary team from across MIT to examine the complex interactions among these elements and their implications for the future.

The study team will explore the potential for widespread deployment of advanced powertrains, such as advanced internal combustion engines, hybrid-electric vehicles, all-electric vehicles, and fuel cell vehicles. The study will also examine the consequences of using electricity and fuels such as natural gas, e-fuels, biofuels, and hydrogen to power these vehicles.

Other areas of focus will include research into new mobility business models such as ride hailing and car sharing, and demographic changes such as greater urbanization and the growing middle class in many developing countries. Researchers will use agent-based modeling systems to examine how people travel in metropolitan areas and how these consumers' mode choice decisions are influenced by congestion and government policies. These decisions depend on many factors, including city characteristics, infrastructure, personal income, travel needs, and availability of options including personal car, bicycle, public transportation, and ride-hailing services. The team will also gather data to better understand people's attitudes regarding car ownership and usage, and how these attitudes vary across different cultures and age groups.

Researchers will explore how various government policies—such as those regarding emissions controls and congestion mitigation—can impact prosperity, adoption of alternative modes of transportation, and emissions. The study will also address the important topic of vehicle automation, with a focus on how government policy affects the introduction and use of these technologies.

The study is supported by energy, automotive, and infrastructure companies that are providing industry perspectives on mobility problems that require solutions. Sponsors include Alfa, Bosch, BP, Chevron, ExxonMobil, Ferrovial, General Motors, Saudi Aramco, Statoil, and Toyota Mobility Foundation.

While there is a particular focus on the United States, the European Union, and China, data collection for the study is global in scope. Dalia Research, a Berlin-based mobile research company, is contributing to the study and has already completed surveys with 43,000 participants from across 50 countries to measure perceptions and attitudes toward vehicle technologies, mobility services, and regulations.

"The Mobility of the Future study brings together academia and industry to identify the most compelling questions about the future of mobility and define scenarios that we will simulate with our modeling tools to understand the consequences," says William H. Green, a professor of chemical engineering who is the study's faculty chair. "The multidisciplinary MIT team brings together all of the vital skills for this important study, including city and transportation planning, civil engineering, mechanical engineering, chemical engineering, and economics. We look forward to sharing findings that we hope will inform industry, city planners, and government policies."

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By Emily Dahl, MITEI

For more information about the study, including its eight focus areas and the lead MIT researcher for each, please to go to energy.mit.edu/mof. Statements from current sponsors of the study appear in the press release posted on that website. For information on how to join, contact Randall Field at rpfield@mit.edu.

MIT Energy Initiative awards 10 Seed Fund grants for early-stage energy research

Supporting promising energy research across a wide range of disciplines is a core tenet of the MIT Energy Initiative (MITEI). Every spring for the past 10 years, the MITEI Seed Fund Program has awarded funding to a select group of early-stage energy research projects. This spring, 10 projects were awarded $150,000 each, for a total of $1.5 million.

“Providing support for basic research, especially research in its early stages, has proven to be an incredibly fruitful way of fostering creative interdisciplinary solutions to energy challenges,” says MITEI Director Robert Armstrong, the Chevron Professor of Chemical Engineering. “This year, we received 76 proposals from applicants with innovative ideas. It was one of the most competitive groups of proposals we’ve seen.”

To date, MITEI has supported 161 projects with grants totaling $21.4 million. These projects have covered the full spectrum of energy research areas, from fundamental physics and chemistry to policy and economics, and have drawn from all five MIT schools and 28 departments, labs, and centers (DLCs).

This year’s awardees represent three MIT schools (Science, Engineering, and the Sloan School of Management) and seven DLCs, with research specialties ranging from chemical engineering to management to aeronautics and astronautics. Five out of the 10 awarded projects focus on advancing energy storage technologies, a key area for enabling the transition to a low-carbon future.

Moving forward on clean energy goals

Valerie Karplus, the Class of 1943 Career Development Professor and assistant professor of global economics and management at MIT Sloan, has been awarded a grant for a project focusing on the response of industrial firms to energy-efficiency policies. Using detailed data from firms in China, Germany, and the United Kingdom, she will investigate what characteristics of firms determine how policy affects production costs and firm competitiveness. “We know very little about how policy interventions interact with an organization’s structure and practices to ultimately influence energy use behaviors,” says Karplus. “This project will uncover how the quality of management in energy-intensive manufacturing companies affects the ease of meeting—and potentially exceeding—energy and environmental policy goals.”

Karplus’s fellow Seed Fund grantees are all working toward achieving these goals as well, in a variety of ways. Troy Van Voorhis, the Haslam and Dewey Professor of Chemistry, and Yogesh Surendranath, the Paul M. Cook Career Development Assistant Professor of Chemistry, are one such team. They were awarded a grant to support their development of new, more efficient graphene-based catalysts for fuel formation. If successful, their work could facilitate the clean generation of fuels capable of storing energy in chemical bonds for later release.

Interdisciplinary research applies diverse skill sets to energy challenges

Fikile Brushett, an assistant professor of chemical engineering, and Audun Botterud, a principal research scientist in the Laboratory for Information and Decision Systems, are one of several teams leveraging interdisciplinary collaboration. By combining their expertise in battery technology and in power grid operations, Brushett and Botterud are developing new laboratory-scale methods of testing the performance and economic viability of grid-scale batteries under realistic operating conditions. “Implementation of application-informed methodologies can enable better evaluation of today’s technologies and can guide the development of next-generation battery systems for power grids with increasing shares of renewable energy,” says Botterud.

Another interdisciplinary project from this year’s round of grants focuses on developing novel computational tools that aid the design of new molecules. Based on first-principles modeling and data-driven models that leverage available literature, researchers Heather Kulik, an assistant professor of chemical engineering, and Youssef Marzouk, an associate professor of aeronautics and astronautics, are creating a novel approach that predicts the behavior of new molecules and updates predictions on the fly using recent advances in machine learning and uncertainty quantification. The goal is to use computer simulation rather than laboratory testing to guide the design of molecules optimized for selected uses. Their first tools focus on optimizing lubricant molecules critical to increasing vehicle fuel economy.

Building on past successes

A key goal of the MITEI Seed Fund Program is to provide support that will enable early-stage energy research projects to take root and thrive over the long term. Amos Winter, an assistant professor of mechanical engineering, along with colleagues Ian Marius Peters, a research scientist in the Photovoltaics Research Laboratory, and Tonio Buonassisi, an associate professor of mechanical engineering, won a 2016 seed grant for a cost-optimized solar desalination system. The team has since received additional funding from Tata Projects, the US Bureau of Reclamation, UNICEF, and the US Agency for International Development to further develop their technology, which has led to pilot plants in Chelluru, India, and in Gaza. The goal is to bring clean, energy-efficient, and cost-effective solutions to areas with a lack of clean drinking water. Tata Projects is planning to commercialize the technology.

A seed grant also led to follow-on funding for Noelle Selin, an associate professor in both the Institute for Data, Systems, and Society and the Department of Earth, Atmospheric and Planetary Sciences (EAPS), and Susan Solomon, the Lee and Geraldine Martin Professor of Environmental Studies in EAPS. Under a 2013 seed grant, they identified new ways to evaluate the success of emissions-control measures tailored to reduce particulate pollution. Selin and collaborators are continuing that work under a 2015 grant from the US Environmental Protection Agency.

In some cases, seed grants have catalyzed follow-on funding for different applications of the initial developments. For example, Laurent Demanet, an associate professor of applied mathematics, recently received funding from the US Air Force Office of Scientific Research to support work he has been performing under a 2013 seed grant focused on improving methods of locating subsurface oil and gas reservoirs. In that work, he developed new mathematical techniques for creating maps of the subsurface from passive seismic surveys, where the only source of waves is the ambient seismic noise of the Earth. The Air Force is interested in this line of work because of the potential for using the same mathematical techniques for passive aircraft navigation.

Spinoff companies have also emerged from seed grants. Cambridge Electronics, Inc., for instance, evolved from Tomás Palacios's 2008 seed grant work on nitride-based electronics. "The MITEI seed funding for our gallium nitride power electronics project was key to getting that research effort started in our group," says Palacios, a professor of electrical engineering and computer science. "It allowed us to get some initial results that we then used to win further funding from other sponsors." On graduating, the student leading the project—Bin Lu SM '07, PhD '13—and colleagues started Cambridge Electronics, which Palacios says is "on track to make a real impact on energy use by changing the way electricity is processed in the world."

Funding for Seed Fund grants comes chiefly from MITEI's Founding and Sustaining Members, supplemented by gifts from generous donors.

A full list of the 2017 awarded projects and teams follows.

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By Francesca McCaffrey and Nancy W. Stauffer, MITEI

Recipients of MITEI Seed Fund grants, spring 2017

3D printed ultrathin-wall cellular ceramic substrates for catalytic waste gas converters
Nicholas Fang
Mechanical Engineering

Can small, smart, swappable battery EVs outperform gas powertrain economics?
Sanjay Sarma
Mechanical Engineering

Computational design and synthesis of graphene-based fuel forming catalysts
Troy Van Voorhis
Yogesh Surendranath
Chemistry

Designer electrocatalysts for energy conversion: Catalytic O_2 reduction, CO_2 reduction, and CH_4 activation with conductive metal-organic frameworks
Mircea Dincă
Chemistry

Electrokinetic suppression of viscous fingering in electrically enhanced oil recovery
Martin Bazant
Chemical Engineering

Management capabilities and firm responses to energy efficiency policies
Valerie Jean Karplus
Sloan School of Management

(*continued on next page*)

Combined energy and water system could serve millions

Recipients of MITEI Seed Fund grants, spring 2017 (continued)

Next generation quantitative structure property relationships for lubricants from machine learning and advanced simulation
Heather Kulik
Chemical Engineering
Youssef Marzouk
Aeronautics and Astronautics

PMU data analytics platform for load model and oscillation source identification
Konstantin Turitsyn
Mechanical Engineering
Luca Daniel
Electrical Engineering and Computer Science

Predicting technical performance and economic viability of grid-scale flow batteries
Audun Botterud
Laboratory for Information and Decision Systems
Fikile Brushett
Chemical Engineering

Thin-film metal-organic framework membranes for energy-efficient separations
Zachary Smith
Chemical Engineering

Many highly populated coastal regions around the globe suffer from severe drought conditions. In an effort to deliver fresh water to these regions while also considering how to produce it efficiently using clean energy resources, a team of researchers from MIT and the University of Hawaii has created a detailed analysis of a symbiotic system that combines a pumped hydropower energy storage system and a reverse osmosis desalination plant to meet both needs in one large-scale engineering project. The researchers, who have shared their findings in a paper published in *Sustainable Energy Technologies and Assessments*, say this kind of combined system could ultimately lead to cost savings, revenues, and job opportunities.

The basic idea to use a hydropower system to also support a reverse osmosis desalination plant was first proposed two decades ago by Professor Masahiro Murakami of Kochi University of Technology, but it was never developed in detail.

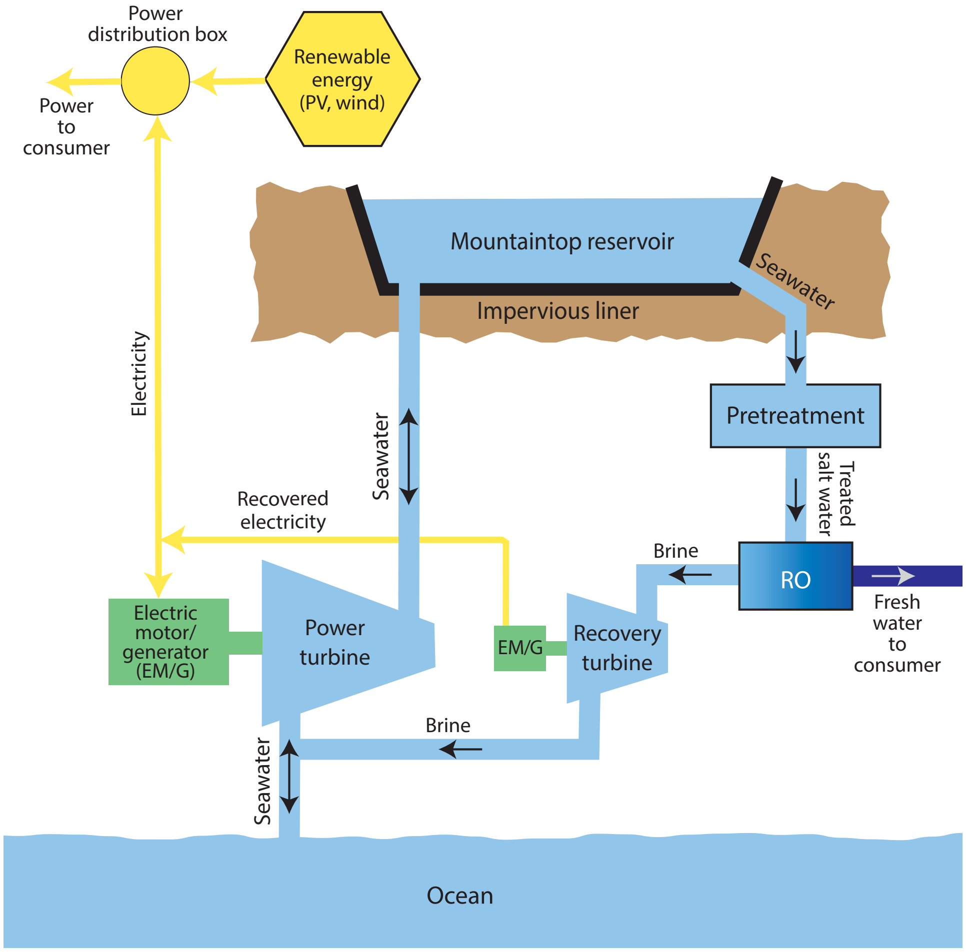
“Back then renewables were too expensive and oil was too cheap,” says the paper’s co-author, Alexander Slocum, the Pappalardo Professor of Mechanical Engineering at MIT. “There was not the extreme need and sense of urgency that there is now with climate change, increasing populations, and waves of refugees fleeing drought and war-torn regions.”

Recognizing the potential of such a concept now, Slocum and his co-authors—graduate student Maha Haji, Sasan Ghaemsaidi PhD ‘15, and research affiliate Marco Ferrara SM ‘05, PhD ‘09, all of MIT; and A Zachary Trimble of the University of Hawaii—developed a detailed engineering, geographic, and economic model to explore the size and costs of such a system and enable further analysis to evaluate its feasibility at any given site around the world.

Typically, energy and water systems are considered separately, but combining the two has the potential to increase efficiency and reduce capital costs. Termed an Integrated Pumped Hydro Reverse Osmosis (IPHRO) system, this approach uses a lined reservoir placed in high mountains near a coastal region to store seawater pumped up to it using excess power from renewable energy sources or nuclear power stations. When energy is needed by the electric grid, water flows downhill to generate hydroelectric power. With a reservoir elevation greater than 500 meters, the pressure is great enough to also supply a reverse osmosis plant and thus eliminate the need for separate pumps. An additional benefit is that the amount of water typically used to generate power is about 20 times the amount needed for creating fresh water, so the brine outflow from the reverse osmosis plant can be greatly diluted by the water flowing through the hydroelectric turbines before it discharges back into the ocean, which reduces reverse osmosis outflow system costs.

As part of their research, Slocum’s team has formulated an algorithm that weighs a location’s distance from the ocean and mountain height to explore areas around the world where IPHRO systems might be sited. Additionally, they have identified possible IPHRO system locations with the potential for providing power and water—based on an American lifestyle of 50 kilowatt-hours per day of energy consumption and 500 liters of fresh water per day—to serve 1 million people. In this scenario, a reservoir at a height of 500 meters would only need to be 1 square kilometer in size and 30 meters deep.

Integrated Pumped Hydro Reverse Osmosis (IPHRO) system



Schematic of potential IPHRO system. Seawater is pumped up into a lined mountaintop reservoir. About 5% of the reservoir water flows through low-pressure pretreatment filters to a reverse osmosis (RO) unit. High-pressure brine flows to an energy recovery unit, where power output is sent to the grid. Low-pressure brine combines with seawater flowing into or out of the pump/turbine depending on whether power is being generated or energy stored by pumping water up to the reservoir.

Their analysis determined that in Southern California, an IPHRO system could meet all power and water needs for 28 million people. An IPHRO system located in the mountains along the California coast or in Tijuana, Mexico, could additionally provide long-term construction and renewable energy systems jobs for tens of thousands of people. Findings show that the cost of building this system would be between $5,000 and $10,000 per person served. This would cover the cost of all elements of the system, including the renewable energy sources, the hydropower system, and the reverse osmosis system, to provide each person with all necessary renewable electric power and fresh water.

Working with colleagues in Israel and Jordan under the auspices of the MIT International Science and Technology Initiatives (MISTI) program, the team has also studied possible sites in the Middle East in detail, as abundant fresh water and continuous renewable energy could be key elements in helping to bring stability to the region. An IPHRO system could potentially form the foundation for stable economic growth, providing local jobs and trade opportunities; and as hypothesized in Slocum's article, IPHRO systems could possibly help mitigate migration issues as a direct result of these opportunities.

"Considering the cost per refugee in Europe is about 25,000 euros per year and it takes several years for a refugee to be assimilated, an IPHRO system that is built in the Middle East to anchor a new community and trading partner for the European Union might be a very good option for the world to consider," says Slocum. "If we create a sustainable system that provides clean power, water, and jobs for people, then people will create new opportunities for themselves where they actually want to live, and the world can become a much nicer place."

This work is now available as an open access article on Science Direct (mitenergyfutur.es/slocumiphro), thanks to a grant from the S.D. Bechtel, Jr. Foundation through the MIT Energy Initiative, which also supported the class from which this material originated. The class was also partially supported by MISTI and the cooperative agreement between the Masdar Institute of Science and Technology and MIT.

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By Kelley Travers, MITEI

Modeling the unequal benefits of US environmental policy

One of the two top air pollutants in the United States, ground-level ozone is harmful not only to your health but also to your bank balance. Long-term exposure to high concentrations of ozone can lead to respiratory and lung diseases such as asthma, conditions that drive up medical expenses and sometimes result in lost income. Ozone exacts a particularly heavy toll on people living in economically disadvantaged areas, where industrial and power plants tend to cluster. While policies have been implemented to reduce ozone emissions across the country, they have not yet addressed built-in inequities in the US economy, leaving low-income Americans at greatest risk for health and economic damages.

Now a study by researchers at the MIT Joint Program on the Science and Policy of Global Change provides the first breakdown of ozone exposure, health effects, and economic impacts by household income across the United States. The study, which appears in the journal *Environmental Science and Technology*, uses a modified version of the MIT Joint Program's US Regional Energy Policy (USREP) model to simulate the health and economic impacts of ozone exposure and ozone-reduction policy on nine US income groups. Comparing a set of policies under consideration in 2014 with a business-as-usual scenario, the researchers found the policies to be most effective in reducing mortality risks among lowest-income (less than $10,000 per year) households, which netted twice the relative economic gains as their highest-income (more than $150,000 per year) counterparts.

"I hope our findings remind decision-makers to look at the distributive effects of environmental policy and how that relates to economic disparity," says the study's lead author, Rebecca Saari PhD '15, a former Joint Program research assistant and engineering systems PhD student who was a 2010–2011 Total-MIT Energy Fellow and a 2013–2014 Martin Fellow and is now an assistant professor of civil and environmental engineering at the University of Waterloo in Canada. "If you ignore those effects, you underestimate the importance of ozone reduction for low-income households and overestimate it for high-income households. Now that we have better tools, we can actually model the differences among income groups and quantify the impacts."

To obtain their results, the researchers combined a regional chemical transport model (Comprehensive Air Quality Model with extensions, or CAMx), a health impacts model (Benefits Mapping and Analysis System, or BenMAP), and a model of the continental US energy and economic system (USREP) into a single computational platform. They then enhanced that platform to simulate ozone concentrations and their health and economic impacts across nine household income categories. Using 2005 US ozone concentration data as a base year, they compared results from two simulations—one representing a baseline scenario in which no new ozone-reduction policy was applied, the other implementing a US Environmental Protection Agency–evaluated suite of policies once planned for the year 2014.

The study determined that ozone exposure—and hence mortality incidence rates—declined with increasing income, with the proposed 2014 policies reducing these rates by 12% to 13%. People earning the lowest incomes were better off economically by 0.2% under the proposed policies—twice as much as those in the highest income group—and were twice as economically vulnerable to delays in policy implementation.

The model could enable today's decision makers to evaluate any new ozone reduction policy proposal in terms of its potential impacts on Americans in all income groups, thereby gauging whether or not it will reduce or exacerbate existing economic inequality.

"Integrating air pollution modeling with economic analysis in this way provides a new type of information on proposed policies and their implications for environmental justice," says study co-author Noelle Selin, associate professor in the MIT Institute for Data, Systems, and Society and Department of Earth, Atmospheric and Planetary Sciences. "This type of approach can be used to help policymakers better identify policies that will mitigate environmental inequalities."

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By Mark Dwortzan, MIT Program on the Science and Policy of Global Change

This research was funded by the US Environmental Protection Agency; the MIT Leading Technology and Policy Initiative; the MIT Energy Initiative Total Energy Fellowship; the MIT Martin Family Society Fellowship; and the National Park Service. Download the journal article at globalchange.mit.edu/publication/16525.

Building bonds in chemistry, laying the foundation for new energy technologies

In 1989, when he was in seventh grade, Troy Van Voorhis, the Haslam and Dewey Professor of Chemistry, describes being jolted by the announcement that researchers had successfully demonstrated cold fusion.

"My science teacher canceled our regular class to explain this remarkable development," recalls Van Voorhis. Although this apparent breakthrough quickly proved to be spurious science, it ignited Van Voorhis's lifelong interest in energy and chemistry. "The idea really captured my imagination, and I was hooked on the possibility that you could produce energy from the physical reactions of chemicals," he says.

Nearly three decades later, Van Voorhis, a theoretical chemist, investigates what he calls "energy-related big questions." He scrutinizes and models the behavior of electrons in research that, among other things, aims to improve the photovoltaic cells used in solar energy; develop new, high-efficiency indoor lighting; and create chemical storage technology for electricity generated by renewable energy technologies.

While his fuse for scientific discovery was lit early on, it took time for Van Voorhis to find his niche exploring the intricate dynamics of molecules involved in processes that produce, transfer, and store chemical energy.

Raised on the north side of Indianapolis by a father who taught junior high math and a mother who was a professor of social work, Van Voorhis was in his own words a "shy, introverted child." In high school, he found theater a constructive way to break out of his shell: "Interacting with an audience was easier than interacting with individuals," he says.


Photo: Justin Knight

Troy Van Voorhis, the Haslam and Dewey Professor of Chemistry.

Van Voorhis also "spent a lot of time playing with mathematics problems because it was something you could do on your own." But he worried about pursuing the subject as a college major because, he says, "it seemed too abstract." Instead, he decided to pair math with another area he excelled in during high school: chemistry.

At Rice University, where he earned his BA as a double major in 1997, and then at the University of California, Berkeley, where he conducted his graduate studies in chemistry, Van Voorhis pursued "curiosity-based science," as he describes it. One area that captured his imagination involved finding better ways to describe mathematically how chemical bonds rupture. "It was a question I thought sounded interesting, a difficult problem," he says, "but it was not something that proved to be useful to other people."

It was not until Van Voorhis landed at MIT, he says, that he understood that his "technical tools might actually solve really important problems." He credits a formative encounter in his early days as an assistant professor with bringing about this revelation.

Pairing up

"I sat down to lunch with the late, great theoretical chemist [and former dean of the School of Science] Robert Silbey and told him I was stuck on a direction to take as I started out," recalls Van Voorhis. "He told me to talk to experimentalists at MIT, who were working on the most exciting problems, ask them how I could help them, and then hitch myself to their wagons."

Wasting no time, Van Voorhis found an eager experimentalist partner in

Marc Baldo, who is now a professor of electrical engineering and computer science. Baldo, who had also recently arrived at MIT, was looking into the application and potential benefits of organic chemicals in light-emitting diodes (LEDs) and solar cells. "I told him my lab worked on simulations involving electrons and chemical bonds and maybe we could help him," says Van Voorhis. "It was the start of a beautiful friendship."

It also launched a fruitful research collaboration. In their very first project together, Van Voorhis provided the computational firepower to help Baldo demonstrate that subtle manipulations of energy states in organic LEDs could improve efficiency in light output. The technical skills that Van Voorhis brought to MIT had found a novel and practical outlet.

Starting in 2005, Van Voorhis and Baldo began focusing on ways to push past longstanding limits in a range of energy technologies, starting with solar power from photovoltaic (PV) cells.

Since the first silicon solar PV panels were invented in the 1960s, they have managed to achieve at best 25% efficiency as they absorb photons from the sun and convert that energy into an electrical current.

Van Voorhis and Baldo demonstrated that it was possible to overcome this limit. Normally, a single photon yields one electron plus waste heat. But by lining solar cells with organic molecules, they figured out how to take a photon and produce two electrons, generating twice as much electricity and less waste heat.

"Marc and I theoretically proved it might be possible to use fission in a device to make a solar cell more than 100% efficient," says Van Voorhis.

Catalyzing brighter solutions

In other domains of research, Van Voorhis and Baldo are testing organic dyes that could help make organic LEDs brighter and perhaps as long-lasting as current-generation conventional LEDs—up to 100,000 hours.

They are also actively investigating chemical-based energy storage in the hopes of helping to bring renewable energy sources such as solar to scale. "The energy content of a normal gas-powered car battery, which weighs 25 pounds, is the same as a quarter-pound Big Mac," says Van Voorhis. "There's a huge incentive to convert electricity into chemical fuels that are energy-dense, but we need to find the right abundant and cheap catalyst for making chemical conversions possible."

One catalyst candidate, a super-thin sheet of graphitic carbon, doped with elements such as nitrogen, boron, or sulfur, presents intriguing possibilities as the basis for a new type of fuel cell. Van Voorhis is running high-throughput computational simulations to figure out the best kind of molecules to pair with graphite for the optimal electrochemical conversion cocktail.

For these research endeavors, Van Voorhis draws inspiration not only from faculty colleagues but also from students. In his primary teaching assignment, the introductory 5.111 Principles of Chemical Science, Van Voorhis incorporates "bits from my research on photovoltaics and alternative fuels, helping students make connections and see the relevance of these ideas," he says. "My greatest pleasure in teaching is seeing the lightbulb go on for students—that instant where a topic goes from a complete mystery to something that is just starting to make sense."

Van Voorhis views mentoring graduate students as a lifelong relationship. "My job as an advisor is to help them become independent scientists, and I find that exposing them to problems of long-range societal relevance like energy or the environment is crucial to them developing into responsible, mature researchers who will be able to devote their skills to problems of significance."

Van Voorhis is heartened to see so many among his MIT students who are "socially conscious and motivated to work on energy questions," including in his laboratory. He finds this engagement reassuring, given that many of the challenges he works on in energy technology may take years to solve. "With problems this big, I have to be comfortable being a cog in a very large machine, where I do the part I'm good at and rely on someone else to do their part, and together we solve the problem."

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By Leda Zimmerman,
MITEI correspondent

For an *Energy Futures* research report about Van Voorhis and Baldo's work on generating more electricity and less waste heat from solar cells, see "Boosting solar cell efficiency: Less wasted heat, more useful current" in the spring 2014 issue of the magazine (online at mitenergyfutur.es/boostingsolar).

MIT undergraduates learn under the sun during MITEI's Solar Spring Break

During the week of March 27, 2017, nine MIT undergraduates chose to forgo a more traditional spring break experience, instead volunteering their time through Solar Spring Break, a new program offered by the MIT Energy Initiative (MITEI) in partnership with GRID Alternatives, a nonprofit whose mission is to provide renewable energy access to all communities nationwide. Accompanied by two MITEI representatives, the students spent the week in Los Angeles, California, installing solar photovoltaic (PV) panels on the home of a low-income family in the Leimert Park neighborhood. The week's programming included solar installation training, a tour of the Los Angeles Cleantech Incubator, networking opportunities, a workshop on solar design, and a complete solar PV system installation. Students also had the opportunity to meet the homeowner and hear firsthand about the impact of their work—an experience that provided valuable insight into some of the social aspects of today's energy challenge.

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By Kelley Travers, MITEI

Photos: Seth Cauman

The Solar Spring Break team, left to right. Front row: MIT undergraduates Allison Shepard and Angela Cai. Second row: Nick Gomez of GRID; undergraduates Tahina Felisca, Gabrielle Ballard, and Rayna Higuchi; team leaders Rachel Kurchin, a graduate student in materials science and engineering and 2016–2017 Total-MIT Energy Fellow, and Aisling O'Grady of the MIT Energy Initiative; Darean Nguyen of GRID. Back row: undergraduates Juan Ferrua, Adedoyin Olateru-Olagbegi, Hilary Vogelbaum, and Gabriel Madonna; Jose Cardenas and David Calhoun of GRID Alternatives.

Left: Secured to the roof by harnesses, the students install "flashings"—black mounts that serve as foundations for the solar panel installations.

Above: With the help of the GRID professionals, the students set one of eight solar PV panels onto a rack they had installed the previous day.

New elective hits sweet spot for energy students

MIT students with an appetite for energy studies enjoy a buffet of options, with classes covering renewable and fossil fuel–based forms of energy production, energy storage, power electronics, and systems optimization as well as energy distribution, policy, markets, and regulation. But in 2015, Konstantin Turitsyn, associate professor of mechanical engineering, realized something was missing from the feast.

“There was no class providing a system-level perspective to help students understand how energy technologies are linked together within a power grid, how that power grid imposes constraints on those technologies, and how that power grid is controlled,” says Turitsyn. A physicist who develops novel mathematical tools for analyzing such large-scale systems as energy networks, Turitsyn was well-equipped to remedy the situation.

With the help of a grant from the S.D. Bechtel, Jr. Foundation, Turitsyn designed 2.S997 Fundamentals of Smart and Resilient Grids, a new elective for the Energy Studies Minor. While it targets mechanical engineering students, 2.S997 aims to provide an introduction to power systems that is accessible to a wide spectrum of undergraduate and graduate students, requiring only a basic background in core physics, math, and engineering. The class debuted in fall 2016 to a warm reception.

“I have been studying generation methods like wind turbines, renewable fuels, and solar panels, but I didn’t fully understand the difference between AC and DC, or how distribution worked,” says Wesley Cox, a senior majoring in mechanical engineering. “This class gave me a basic understanding of the way electricity gets from one place to another, and a solid understanding of grid infrastructure.”

Photos: Kelley Travers, MITEI

Ali Trueworthy, a senior majoring in mechanical and ocean engineering, presents evidence gathered by her team showing that certain electricity-intensive industrial processes could run exclusively at times when intermittent energy sources such as solar are putting more power into the grid than needed to meet current demand.

Senior Ali Trueworthy, majoring in mechanical and ocean engineering, has conducted research on energy-efficient desalination methods as well as on wave energy at the National Renewable Energy Laboratory. Before 2.S997, she says, “I didn’t really get what people meant when they said the grid couldn’t handle fluctuating sources of energy output. Through the class, I gained a good concept of not only how an electric grid works, but also where grid infrastructure needs to go and the steps left for renewable technologies to become integrated in the grid.”

This is precisely the kind of content the energy studies curriculum needs to deliver, says Antje Danielson, director of education for the MIT Energy Initiative (MITEI). “At MIT, we are focused on the future of energy, including tackling the transition from fossil fuel–dominated energy production to the integration of renewables into the grid,” she says. “Offering a class like 2.S997 is crucial.”

This was also a course perfectly suited for one of the MITEI-administered Bechtel Foundation grants, which seek to ensure that energy classes keep pace with the evolving landscape of energy systems, Danielson notes. “We try to identify areas where we don’t have strong representation in the curriculum, ideally aligned tightly with current energy research, and encourage the development of courses with strong and innovative pedagogies,” she says.

Striking the right balance in course design

Turitsyn and his collaborator Petr Vorobev, a postdoctoral associate in mechanical engineering, were eager to design a class with a range of appealing and instructive activities.

They set themselves an ambitious target: introducing the structure and dynamics of power grids, detailing conventional and renewable energy technologies and storage, and describing demand-side management, microgrids, emergency control options, and resilient energy systems.

"Our main challenge was to ensure that students with different backgrounds all got something from the class, so they wouldn't be either frustrated or bored," says Turitsyn. Through lectures and problem sets, the class "focused on short stories, real case studies, that explained core mechanisms, such as voltage stability, the physics of power flows, how energy markets work," he says.

"We explained the technical obstacles associated with photovoltaics and wind—voltage control issues—that can make it difficult to integrate renewables into the grid," says Vorobev. "We also showed on a fundamental level why the price for electricity varies in different places in the same grid."

For some students, the math involved in analyzing these cases proved demanding. "Power systems modeling was really math-heavy," recalls Trueworthy. "I didn't have a strong background in electrical concepts, so I had a lot of catching up to do in terms of understanding voltage and power."

Vorobev recognized that some of the case-based problems he developed were too difficult. "When I carefully wrote down all the solutions so students could check their work, I found that the problems required an enormous amount of time," he says. "We adjusted on the fly when we realized that some material was too ambitious," says Turitsyn.

During a meeting of his new class, Konstantin Turitsyn, associate professor of mechanical engineering, describes some of the technical challenges involved in integrating solar photovoltaics and wind into today's power grid.

Problem-solving projects

In the semester's second half, 2.S997 shifted gears from lectures and homework to projects. This was a pedagogical first for Turitsyn at MIT. "Students here are very mature, and we wanted to give them some freedom to analyze, model, and present real problems in power systems, preferably those related to new technologies," he says. "Groups came up with ideas I hadn't imagined or heard of before."

Cox's group looked at ways of using power generated by solar farms to stabilize the grid in the case of some instability. "In class, I learned that it is shockingly easy to take out an entire grid even if the problem lies with a single facility," says Cox. "And if we want to integrate green energy into the grid, we can't make the argument without bringing in new systems and infrastructure."

In her team's project, Trueworthy identified electricity-intensive industrial processes that could run exclusively during times when energy available from the grid is greater than demand and when prices might also be low. Such opportunities might occur when an intermittent, renewable energy source such as solar is producing more power than can be consumed. "Our project showed this inverse demand response could profit certain kinds of chemical industries as well as help balance supply and demand on the grid."

Skeptical at first that industries could be flexible enough to take advantage of such shifts in grid load consumption, Turitsyn now believes this team found a "viable, promising business opportunity." He notes that the work is a good example of finding a way to integrate and utilize intermittent energy sources such as solar and wind—the kind of case study 2.S997 is built around.

In the next iteration of the class, in 2018, "We want to put more emphasis on these projects, which will get students excited and thinking about new ideas," says Turitsyn. "It's a class I enjoyed, learned from, and now feel passionate about."

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By Leda Zimmerman, MITEI correspondent

Energy Studies Minor alumni: Where are they now?

Photo: Emilia Tou

Maria Tou SB '14, Chemical Engineering

The vision of a sustainable, renewable energy future inspires the work of Energy Studies Minor alumna Maria Tou. She is currently pursuing a PhD at ETH Zurich in Switzerland.

What's the focus of your current research at ETH Zurich?

I'm working on my PhD in a lab that focuses on renewable energy carriers. Most of our research looks at how we can use concentrated solar energy to produce liquid fuels. We imagine diesel or jet fuel or gasoline, but with sun as the energy source instead of digging it out of the ground. We take starting components of water and carbon dioxide, and by using solar energy and running high-temperature thermochemical reactions, we upgrade them back into fuel. One way to think of it is as a reverse combustion process. You take those waste products and you reform them back into useful fuel. You could then theoretically close the carbon cycle.

What drew you to studying concentrated solar power?

What drew me to the research was definitely this ideal picture of being able to take a renewable source like the sun and make something as necessary to everyday life as these liquid fuels that the world is so dependent on. It was very much the renewable aspect, especially as it applies to being able to store energy in more energy-dense carriers.

Did the energy minor at MIT impact your choice of graduate program?

Definitely. Actually, the reason that I am at ETH today is one of the classes I took for the energy minor. Senior year, I took Fundamentals of Advanced Energy Conversion with Professor [Ahmed] Ghoniem. In the class, we had a semester-long project where each group was studying a different kind of energy conversion technology, and my group was focused on the topic of solar fuels. That's when I found out that there's a lab at ETH that works on this. So later when I decided I wanted to do a PhD, I asked for contact information for the professor who directs the lab and then reached out to see if they had any positions. That was a really great opportunity that I got through the energy minor.

Do you have any advice for a current student considering a career in energy?

I guess just go for it! Don't be discouraged by what the current field looks like because, if you're a student right now, by the time you reach the job market, the energy market will have grown and developed. So I would say that if what you're looking for doesn't quite exist, that's not a reason to leave the energy field.

Are there any notable differences between energy use in the United States and Switzerland?

Yes, I was interested in those differences. I even took a class last semester specifically about Swiss energy policy. Because Switzerland is a very small country, the energy in the grid in Switzerland depends a lot on its interconnections with its European neighbors. Energy is much more of an international and hence political issue in Europe because electricity is actively being traded across borders all the time.

Another thing that I've come to appreciate more and more is the importance of geography in defining what makes the most sense for a certain country to pursue. For example, in Switzerland, there are lots of mountains and mountain lakes with which you can build a lot of hydropower dams, both for storage by using electricity in off hours to pump water up into a reservoir, and for generation as the water flows down the mountain.

Photo: James Rudd

Chris Carper SB '10, Mechanical Engineering

Chris Carper is making his mark in the energy industry by focusing on energy use in buildings. From his early career at Honeywell analyzing existing buildings to his current work with new construction at Atelier Ten, he aims to reduce energy use and lower greenhouse gas emissions to sustainable levels.

How did the energy minor at MIT shape your career path?

It exposed me to the breadth of fields that energy studies could encompass. I learned as part of the Energy Studies Minor that buildings use about 40% of all the energy consumed in the United States. That made me curious about how that number could be reduced or optimized in some way.

Can you describe a typical day in your job at Atelier Ten?

A typical day might include developing an energy model of a building to predict how much energy it would use. It might include meeting with members of a design team—the architects and engineers and developers—to review energy analysis results or to go over optimization studies to help the team figure out the best path forward for reducing or optimizing energy consumption. It might include analyzing the potential for a new building to meet LEED standards. It could also involve reviewing a newly built building's energy usage to see if the actual energy consumption matches the predicted energy consumption and, if not, doing some reverse engineering, doing some data mining, to figure out why that mismatch might be happening.

How do you use what you learned at MIT in your job?

Every day, I use the problem-solving and analysis skills that are so core to the education that MIT provides. The mechanical engineering major gave me a solid foundation for the more technical aspects of my job, and the Energy Studies Minor helped me with some of the less technical aspects and seeing other sides of issues—for example, the political side, the economic side—and keeping in mind that all of these things interact with one another and that you can't really look at any problem in isolation.

Some of your early work was as an engineer at Honeywell. What did you learn there?

My background at Honeywell was really useful for what I do now. With Honeywell, I spent a lot of time in existing buildings to understand how they work, how they use energy, how the mechanical systems operate, and how all these components are tied together. And in my current role, I work on new construction, on anticipating the energy use of a building before it's built. It's very helpful to know how buildings typically operate when I make predictions and when I make models. Being able to see a computer simulation and actually look at each component and think about what it does in real life is really helpful for generating a result that's reliable and actually reflective of the real world.

What would you tell students who are thinking of pursuing a career in energy?

I would tell them that it's a great opportunity if you want to tackle a problem that is truly multifaceted— that has technical aspects, regulatory and policy aspects, and economic and business aspects that are all very tightly interrelated. And it's a changing industry. There are always new technologies and techniques that are shaping the landscape, and I think it's something that's going to be important for a long time to come.

Photo: Mark Morand

Brendan Ensor SB '12
Nuclear Engineering

Energy Studies Minor alumnus Brendan Ensor knew he wanted to be a nuclear engineer ever since he was a child growing up near a nuclear reactor. Following a Rickover Fellowship at the US Department of Energy, he is now a senior engineer at the Naval Nuclear Laboratory.

What led you to your current work at the Naval Nuclear Laboratory?

When I was a senior at MIT, I was awarded a Rickover Fellowship. It paid my tuition and provided me a stipend during all of my PhD. In the Navy nuclear world, it was an honor to get that fellowship, and it closely tied me into the Naval Nuclear Laboratory. I spent two summers there as part of my PhD program.

I'm now at the Knolls Atomic Power Laboratory site in Schenectady, New York. We design and support the naval nuclear reactors for the US Navy's submarines and aircraft carriers. I'm a senior engineer in the technology department. The focus of my work is on corrosion of the nuclear fuel cladding, which is the primary barrier that prevents the fuel from getting into the coolant and being released. One of the concerns in a nuclear reactor is that when zirconium alloys used in fuel cladding are exposed to very high-temperature water, they can corrode.

In your opinion, what's the outlook for nuclear energy in the United States?

I think that nuclear has a part to play in the future energy field. I believe that there are a number of factors that look good for nuclear, including the US House and Senate bills on nuclear innovation and licensing, which seek to motivate research and investment in advanced reactor designs and to modernize the regulatory framework of the Nuclear Regulatory Commission; the desire to maintain a diversified energy portfolio; and the potential of small modular reactors (SMRs) in the future. SMRs could be revolutionary for nuclear. With their smaller and tunable energy output, they would be much more successful than large nuclear plants in a future energy grid that incorporates many small, distributed power-generating sources such as solar and wind. Other factors, like future carbon taxes or changes in how electricity is bought on deregulated markets, could also make a difference.

What advice do you have for a current student considering a career in your field?

Be flexible, because technology breakthroughs can happen at any time. When I was coming into my undergraduate years, fracking was just a new thing. Since then, it has completely changed the energy field. So I would say be flexible and broaden your horizons. Have lots of experiences, so when you decide to enter the workforce or your career, you could go down a bunch of different paths and be valuable to everybody. Don't pigeon-hole yourself.

What do you think is the most important role played by the Energy Studies Minor?

The Energy Studies Minor exposes you to a lot of different aspects of the field that you may not be familiar with. I was a nuclear engineer. But I would sit in class with people who were focused on renewables. I would sit in class with people who were focused on policy. That experience is very valuable because it leads you to ask questions like, How does your energy technology fit into the global energy field, and what obstacles does it face?

So the energy minor does a good job bridging the divide between the engineers and the policymakers and the economists. All three play a role, and the better they can communicate and understand each other, the better it will be for the energy future of our country.

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By Mary Potts, MITEI

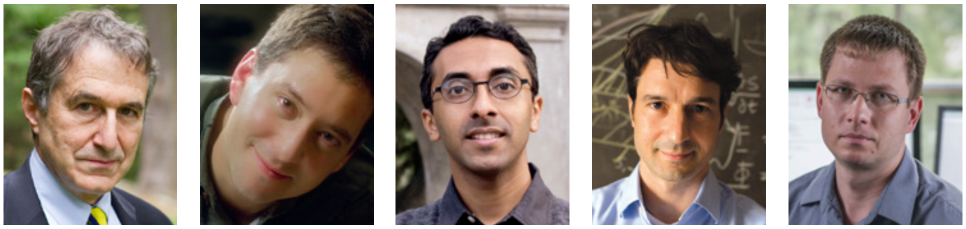
MITEI welcomes five new faculty members to Energy Education Task Force

Five new and returning faculty members were appointed to the MIT Energy Initiative's Energy Education Task Force (EETF) this 2016/2017 academic year. MITEI welcomed Robert Jaffe, Jane and Otto Morningstar Professor of Physics; Steven Leeb, professor of electrical engineering and computer science; Yogesh Surendranath, Paul M. Cook Career Development Assistant Professor of Chemistry; Ruben Juanes, ARCO Associate Professor in Energy Studies, of civil and environmental engineering; and Konstantin Turitsyn, associate professor of mechanical engineering.

The EETF is composed of faculty from all five schools at MIT, as well as graduate and undergraduate student representatives. Under the direction of co-chairs Bradford Hager, the Cecil and Ida Green Professor of Earth Sciences and director of the Earth Resources Laboratory, and Rajeev Ram, professor of electrical engineering and computer science, this task force plays a critical role in shaping energy education at MIT.

“The Energy Education Task Force is one of the many magical features of MITEI,” says Leeb, a returning EETF member who first served on the committee at its inception in 2006. “It affirms that part of MITEI's charter is not just the creation of ideas but also education. We create not just solutions but also problem solvers.”

“Energy studies are intrinsically multidisciplinary, and as such fall outside the normal departmental structure at MIT,” adds Jaffe, also returning to the EETF after a hiatus. “Departments have the resources to build, support, and ensure the continuity of programs in academic areas that interest them. An interdisciplinary program needs a similar organization to gather resources, build curricula, and promote the subject.”



The new and returning members of the Energy Education Task Force are (from left) Robert Jaffe, Steven Leeb, Yogesh Surendranath, Ruben Juanes, and Konstantin Turitsyn.

With the support of the MITEI Education Office, the EETF is tasked with overseeing the curricular evolution of the Energy Studies Minor, creating a connection between energy research and the energy curriculum offered at MIT, and communicating MIT's diverse energy subject offerings and interdisciplinary energy education model. Antje Danielson, MITEI's education director, says that the EETF will be particularly focused in the near term on new graduate-level educational opportunities. The major priorities are the addition of opportunities through the Society of Energy Fellows and the development of graduate-level online MicroMasters programs through edX that will broaden the Institute's mission to make an MIT education accessible to a global population.

Each new EETF member brings a different background, knowledge set, and interest to the group, which will further enhance MITEI's education program. Jaffe is particularly enthusiastic about re-energizing the undergraduate Energy Studies Minor program. He has developed and taught an energy-minor-required course in the foundations of energy science and has just published the accompanying textbook. Leeb teaches hands-on energy-related laboratory classes, and he looks forward to finding ways to connect MITEI member companies with more of MIT's students.

First-time EETF member Surendranath leads a research group that investigates the chemistry of renewable energy, and he will use that background to help design curriculum within the EETF. “Facilitating the transition to a more sustainable energy future is a multigenerational effort, so much of MIT's impact derives from training the next generation of energy scientists,” says Surendranath. “I would like to see the EETF better enable aspiring energy scientists at all levels to develop the network, perspective, and competencies needed to be thought leaders in the field.”

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By Kelley Travers, MITEI

Photo credits
Jaffe: Justin Knight
Leeb: Steven Leeb, MIT
Surendranath: Karthish Manthiram, MIT
Juanes: M. Scott Brauer
Turitsyn: Christian Livingston Welch, MIT

3 Questions: Maria Zuber, MIT's vice president for research, shares her views on climate policy

Maria T. Zuber, vice president for research and the E.A. Griswold Professor of Geophysics, published an op-ed in The Washington Post *on February 24, 2017, that described her personal history growing up in eastern Pennsylvania's coal country and argued for a strategy to support coal industry workers as the world transitions to new, clean energy sources. Zuber spoke with MIT News to share her thoughts on how we can address climate change while also improving the economic fortunes of coal communities.*


Photo: MIT

Q: You grew up in Carbon County, Pennsylvania, a place that got its name because of the discovery of anthracite coal there in the late 18th century. Can you tell us about your experience growing up in coal country and what inspired you to write about it?

A: Both of my grandfathers were coal miners. They both contracted black lung disease, one dying much too young and the other living longer but suffering mightily from both health problems and underemployment. My grandfathers worked in the mines at a time when the coal industry in eastern Pennsylvania was in the midst of a long decline. My hometown, Summit Hill, Pennsylvania, was a place where prosperity and economic opportunity vanished with the decline of the anthracite industry.

During the recent presidential campaign and subsequent to the election, I've read a lot about how the intellectual elite doesn't understand the plight of blue-collar workers who have lost well-paying jobs and, with that, their hope for the future. And I thought, "Wait a minute, that's the story of my family." The more I thought about it, the more I realized that I was in a position to shine a light on this issue and maybe even contribute to improving the situation.

Q: How does this personal history you've described affect the way that you think about climate change?

A: On the one hand, I can really understand why we hear so much about the "war on coal." That's a product of the deep anxiety that people feel when they experience such seismic changes caused by things like changes in the global supply and demand for coal, or automation in mining that makes it possible to get more coal with fewer workers. People do feel like they are under attack, that their way of life is under attack. We need to really try to recognize that.

On the other hand, my life's passion, and my career focus, has been science. And as I've said many times, the scientific evidence is overwhelming: If we keep emitting carbon dioxide into the atmosphere, then global temperatures are going to continue to rise, and that carries with it unacceptable risks — disruptions to food and water supplies, rising sea levels that could put coastal cities at risk, and so on.

So the way I look at it is that we have two responsibilities: We need to take urgent action to address climate change by moving to clean energy, and we also need to take care of the people who do difficult and dangerous work so that we can power our modern economy and enjoy our standard of living.

Q: With this dual challenge in mind, what do you think we should we do for coal communities?

A: The good news is that, in the long run, transforming our energy system so that it emits zero carbon will create more jobs than it destroys. But if we don't plan this transformation in an orderly way, then we will see avoidable negative economic impacts on coal communities.

As a start, I propose three things we can do. First, we should aggressively pursue carbon capture and storage technology, which catches carbon dioxide from coal power plants before it is released into the atmosphere and stores it underground. We'll need to improve capture efficiency, lower the deployment costs, and better understand the environmental impacts. The MIT Energy Initiative has launched a low-carbon energy center focused on these challenges.

Second, we should expand the use of coal for things that, unlike combustion and steel production, do not produce significant carbon emissions. About nine-tenths of coal production is used for electric power. But researchers here at MIT and at other research institutions around the country are exploring whether coal can be used more widely as a material for the production of carbon fiber, batteries, electronics, and even solar panels.

Third, though, we have to recognize that even if carbon capture becomes practicable and we expand other uses for coal, the industry's fortunes will never fully revive, because of factors like cheap natural gas and the rapidly declining costs of wind and solar energy. So we need to support policies that would promote economic development; help coal workers find employment in other industries, including renewables; and preserve healthcare and retirement benefits for retired coal miners. Fortunately, these are all policies with bipartisan support.

The risks of climate change make it clear that we have to stop burning fossil fuels, especially without the use of carbon capture and storage technologies. But we do have choices to make about how we transition to clean energy. We can choose to do it fast enough to head off some of the worst risks of climate change, and we can choose to do it as fairly as possible for communities that have long depended on fossil fuels. These are not impossible challenges, but they do require that we all work together. I think this is the kind of problem that we at MIT are attracted to tackle. We won't solve the climate change problem without solving the jobs problem.

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MIT News Office

Ernest Moniz, MITEI's founding director, returns to MIT

After more than three and a half years of service as the 13th US Secretary of Energy, nuclear physicist Ernest J. Moniz has returned to his roots at MIT, the place where he served most of his professional career.

Nominated to the cabinet by President Barack Obama in March 2013 and confirmed by the Senate on May 16 in a unanimous vote—a rare occurrence in a polarized political atmosphere—Moniz left the office on January 20, 2017, with the arrival of the Trump administration.

Now, he intends to build upon his experience by working on policy proposals for climate solutions through clean energy innovation, and in the area of nuclear security. In addition to serving in a part-time appointment at MIT as professor of physics post-tenure and special advisor to the MIT president, he has been named inaugural Distinguished Fellow of Emerson Collective, co-chair and CEO of the Nuclear Threat Initiative, and a nonresident senior fellow at Harvard University's Belfer Center for Science and International Affairs. He also intends to do additional work in clean energy through a nonprofit organization of his own.

"Over the last few years, the United States and the world saw what we at MIT have known for decades: that Ernie Moniz is a brilliant scientist, a gifted leader, and a tireless advocate for positive change," says MIT President L. Rafael Reif. "I am thrilled that the Institute will again benefit from his wisdom and experience as we continue our critical work to identify practical ways to achieve a sustainable energy future and address climate change. All of MIT is delighted to welcome him home."

Photo: Bryce Vickmark

At the Department of Energy (DOE), Moniz led the implementation of President Obama's commitment to an "all of the above" energy strategy, including the establishment of new programs to foster research on clean, renewable forms of energy and next-generation nuclear power. He also played a crucial role in the negotiations that led to a ground-breaking treaty with Iran to limit that country's development of nuclear materials. He was often called the best-prepared of energy secretaries by members of both political parties.

"One of the things we really accomplished" during his term at the DOE, Moniz says, "was placing innovation at the center of climate solutions." Finding ways to push that emphasis forward—encompassing innovation in policy and economic arenas as well as in technology—will continue to be a major focus of his work in coming years, he says. This emphasis echoes the "Mission Innovation" initiative that was adopted, with the help of a strong push by the Obama administration, at the Paris COP 21 climate conference in 2015.

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Excerpted from an article by David L. Chandler, MIT News Office, with additional reporting by MITEI (see mitenergyfutur.es/monizreturns).

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 more than 375 graduate students and postdoctoral fellows in 20 MIT departments and divisions.

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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 Utility of the Future study, the Mobility of the Future study, the MITEI Low-Carbon Energy Centers, the Associate Member Symposium Program, and the MITEI Seminar Series.

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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.

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MITEI member news

eni

On January 16, 2017, MIT President L. Rafael Reif and Eni CEO Claudio Descalzi met in Rome, Italy, to renew the nine-year collaboration between the Institute and the Italian energy company for another four years. The $20 million agreement includes an extension of Eni's founding membership in the MIT Energy Initiative (MITEI) and research support for MITEI's Low-Carbon Energy Centers in the areas of solar energy; energy storage; and carbon capture, utilization, and storage.

ENN 新奥

Recognizing the critical need for scalable energy storage solutions to develop regional energy systems in China, ENN Group of China has joined MITEI to advance research in this area. With a three-year membership agreement, the ENN Group will participate in the Center for Energy Storage Research, one of MITEI's Low-Carbon Energy Centers.

cenovus
ENERGY

In February 2017, Cenovus Energy joined MITEI with a three-year membership including participation in the Low-Carbon Energy Center for Carbon Capture, Utilization, and Storage. Cenovus is a Canadian integrated oil company committed to applying progressive thinking to safely and responsibly unlock energy resources.

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MIT undergraduates learn under the sun during MITEI's Solar Spring Break

Nine MIT undergraduates spent their spring break taking advantage of an unusual opportunity for hands-on learning: They attended Solar Spring Break, a volunteer program offered for the first time this year through the MIT Energy Initiative. Accompanied by two MITEI representatives, the students volunteered in Los Angeles, California, with GRID Alternatives, the nonprofit that founded the Solar Spring Break program and works with volunteers and job trainees to provide solar photovoltaic (PV) panels and energy efficiency improvements to underserved communities.

During their stay, the students attended a series of workshops and tours, but most memorable was working with the GRID professionals on the complete installation—start to finish—of solar PV panels on a home in Los Angeles. Above: Putting the finishing touches on the solar installation are (left to right) Jose Cardenas of GRID; undergraduates Tahina Felisca, Adedoyin Olateru-Olagbegi, Allison Shepard, and Gabriel Madonna; and Darean Nguyen of GRID. See page 35 for more information and photos. Photo: Seth Cauman