Energy Futures

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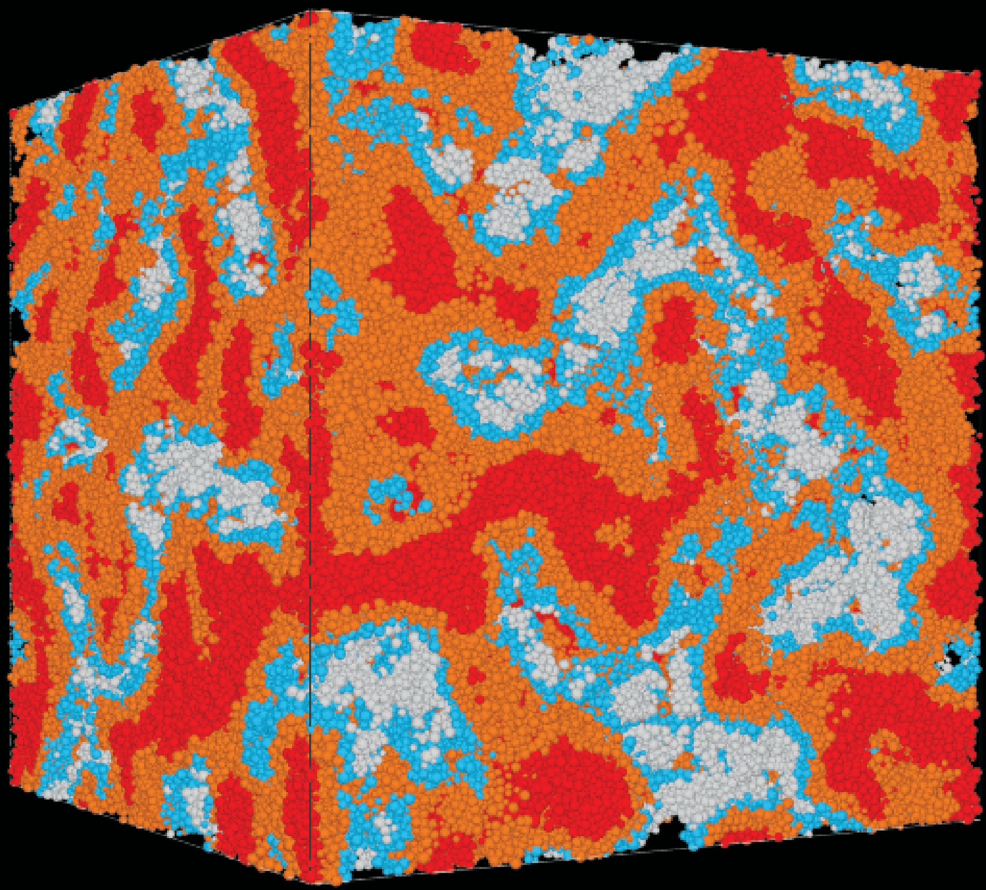

Designing climate-friendly concrete—from the nanoscale up

IN THIS ISSUE

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**.

Energy Futures

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A letter from the director

Dear Friends,

Since the momentous Paris Agreement was reached by 196 parties at the United Nations Climate Change Conference (COP21) in December 2015, a dual narrative of immense possibilities and daunting challenges has emerged.

Certainly, the Paris Agreement represents a turning point. COP21 and the resulting agreement have focused a global spotlight on the urgent need for climate action and on the monumental achievement of reaching consensus among nations with incredibly diverse energy, development, and even survival needs—as in the case of low-lying island and coastal nations and others affected by climate change–influenced natural disasters such as droughts and floods.

At the same time, the agreement itself does not fully address the vast scope of the climate challenge. As MIT Professor Jessika Trancik noted at a post-COP21 event hosted by the MIT Joint Program on the Science and Policy of Global Change, "The emissions reduction commitments that have been pledged are not sufficient for the task at hand, but if implemented, they promise to drive significant amounts of technological innovation." (See page 6 for a report on Trancik's related research.)

Technological innovation is indeed a linchpin of the global effort to mitigate climate change, and programs and policies that further the development of low-carbon energy technologies are equally crucial. US Secretary of Energy Ernest Moniz drove this point home in his keynote address at the MIT Energy Conference, where he discussed the multinational Mission Innovation effort announced at COP21 to accelerate global clean energy innovation (see page 45). Following the keynote, I was delighted to have a fireside chat with Secretary Moniz at the conference to discuss how his perspectives and experiences as MITEI's founding director have shaped his approach to policymaking.

In this issue of *Energy Futures*, we focus on promising research, education, and policy efforts at MIT geared toward addressing climate change. We also include a special section on the MIT community's involvement in COP21 (pages 39–44).

Integral to MITEI's involvement in these efforts is the development of eight Low-Carbon Energy Centers, which seek to catalyze technology innovation in key areas through collaborative research with industry, government, and others. Five of the centers now have named faculty co-directors, and MITEI's newest member, national energy provider Exelon, plans to conduct research through multiple centers (see inside back cover for more on Exelon's MITEI membership). The mission of the centers is described in greater detail on page 3.

Two related system studies that are important to the adoption and deployment of low-carbon energy technologies are also under way. The Utility of the Future study uses modeling and analytical tools to evaluate regulatory frameworks for the evolution of the power sector worldwide. The study is a collaboration between MITEI and IIT-Comillas, with a consortium of industry members. The final report will be released in fall 2016.

The other study, Mobility of the Future—launched this spring—convenes an MIT study team and industry consortium to examine how aspects of transportation, from technologies to business models and policies, will shape the future landscape of mobility. One of the study participants, MIT Professor John Heywood, has studied these issues for decades. His latest report, *On the Road toward 2050: Potential for Substantial Reductions in Light-Duty Vehicle Energy Use and Greenhouse Gas Emissions*, presents findings from about 20 research projects in recent years (see page 4).

Our faculty and researchers have been investigating climate and energy solutions from all angles, from analysis of how emissions-control regulations affect the formation of fine particulate pollution (see page 21) to unlocking the secrets of concrete's structure and examining how it could be refined to be less carbon-intensive (see page 16).

MITEI also recently announced our 2016 Seed Fund awards to nine promising early-stage MIT faculty research projects in areas including fuel cells, solar-powered water desalination, and impacts of electric vehicle charging on the power grid (see page 25). Previously funded projects have led to published research, sponsored research at MIT, federal research funding, and the formation of new clean energy companies.

Among recent developments in energy education at MIT, three new and expanded electives have been launched as part of the undergraduate energy curriculum (see page 31). Programs such as the Energy Studies Minor, the Energy Undergraduate Research Opportunities Program, and the graduate MIT Energy Fellows program have continued preparing future energy leaders; recent energy minor alumni share their stories on page 35.

Expanding student opportunities is one of the core goals of MIT's Environmental Solutions Initiative (ESI) and its recently appointed director, John Fernandez, professor of building technology. As noted in a profile on page 29, Fernandez and his colleagues in ESI and across campus are currently working toward the creation of an environment and sustainability minor for undergraduates. MIT is growing its energy and sustainability education programs as well as research activities every day, and we at MITEI look forward to collaborating closely with ESI and others on campus dedicated to these issues in the coming years.

Over the past several months, we have been fortunate to host world-class guest speakers, including US Department of Energy Assistant Secretary for Energy Efficiency and Renewable Energy David Danielson PhD '07, Stanford University Precourt Institute Co-director Sally Benson, Environmental Defense Fund President Fred Krupp, Nuclear Energy Agency Director-General William Magwood, Exelon Chairman Emeritus John Rowe, and other energy leaders. MITEI also brought a group of faculty members to IHS Energy CERAWeek in February, where they discussed their research toward a low-carbon energy future. Photos from some of these events appear on pages 44 and 47.

I always enjoy connecting with *Energy Futures* readers at events, and I look forward to seeing many of you in the future. We at MITEI are sincerely grateful for our readers' and partners' interest and support as we continue advancing research, education, and outreach to help transform the world's energy systems.

Professor Robert C. Armstrong
MITEI Director
May 2016

MITEI's Low-Carbon Energy Centers

In the Autumn 2015 issue of *Energy Futures*, we shared news about MITEI's new Low-Carbon Energy Centers, which were announced as part of MIT's Plan for Action on Climate Change. Since then, MITEI team members have been speaking with interested industry leaders in the United States and internationally to lay the foundation for collaboration through the centers.

"When we're looking at challenges as complex and vast as addressing climate change while meeting global energy needs, we need to engage experts across all disciplines and sectors," says MITEI Associate Director Louis Carranza, who is spearheading the development of the centers. "Through the Low-Carbon Energy Centers, MITEI is facilitating this vital collaboration. We're enabling faculty members from across MIT to converge around specific technology research areas and providing a program for industry and governments to join us in advancing these technologies and scaling them from the lab into the marketplace."

The inclusive model of the Low-Carbon Energy Centers prompted Exelon to become a MITEI member. As Exelon President Chris Crane said in the February 2016 announcement made at IHS CERAWeek, "We know the energy system of the future will need new technologies such as energy storage, smarter grids, advanced nuclear generation, solar energy, and more. Together with the MIT Energy Initiative, we will actively identify and develop the most promising innovations in our sector, as the centers bring together a perfect trifecta of academia, government agencies, and private organizations to tackle long-term challenges in reducing our carbon footprint and evolving our energy system."

Each center aims to advance research on solutions in a specific technology area: solar energy; energy storage; materials for energy and extreme environments; carbon capture, utilization, and storage; advanced nuclear energy systems; nuclear fusion; energy bioscience; and electric power systems. Centers are led by MIT faculty directors, with broad involvement from researchers across schools and departments, and a Faculty Steering Committee and Advisory Committee that provide guidance. Members can join one or more centers, based on their research needs and interests, and participate by providing financial support as well as offering technical and market expertise.

In our engagements with industry and government, we have learned that one of the greatest inhibitors of moving research forward is uncertainty. This is as true for our faculty, research staff, and students as it is for our industrial partners. To address and mitigate this uncertainty, each center will have a dedicated research team focused on monitoring, tracking, and reporting on the evolving performance and economic potential of emerging technologies. This resource will help provide guidance and definition for the opportunity space that each center will be exploring.

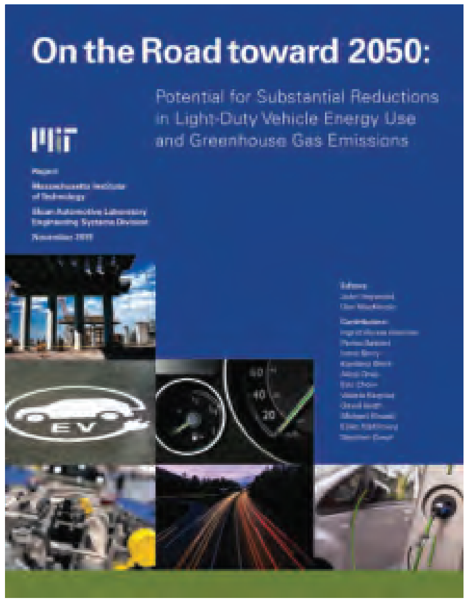
MITEI welcomes conversations with all those interested in engaging with us through the centers, and we invite you to contact Louis Carranza at carranza@mit.edu or 617.324.7029 to begin a discussion.

Transforming the US transportation system by 2050 to address climate challenges

Road vehicles are a key part of the climate change challenge, representing both an important source of petroleum demand and greenhouse gas (GHG) emissions worldwide. Changes to our transportation system—how much we travel, the vehicles we use, and the fuels that power them—offer the potential for substantial reductions in GHG emissions and are necessary to mitigate climate change. Likewise, changes in policy, driving behavior, and the development of alternative fuels and energy sources are required to meet this challenge.

On the Road toward 2050: Potential for Substantial Reductions in Light-Duty Vehicle Energy Use and Greenhouse Gas Emissions, a new report spearheaded by John Heywood, MIT professor of mechanical engineering, identifies three important paths forward for light-duty vehicles (LDVs, i.e., cars and light trucks): improve the existing system and technologies for shorter-term benefits, conserve fuel by changing driver habits for nearer- to longer-term benefits, and transform the transportation system into one that is radically less carbon-intensive for longer-term benefits. Each element is separately important, but all three must collectively be pursued aggressively to achieve necessary emissions reductions. More research, development, and demonstration studies are needed to lay the foundation for such a long-term transformation.

The report addresses topics related to the evolution of vehicle technology and its deployment, the development of alternative fuels and energy sources, the impacts of driver behavior, and the implications of all of these factors on future GHG emissions in the United States, Europe, China, and Japan.



In the United States, LDVs alone currently account for 43% of petroleum demand and 23% of GHG emissions, when fuel production is considered. The United States, Europe, China, and Japan consume over half of the world's petroleum, making these countries particularly critical in efforts to reduce petroleum consumption and the associated emissions.

"Overall, we have substantial opportunities for reducing environmental and climate impacts from light-duty road vehicles," says Heywood. "Achieving reductions in vehicle-related greenhouse gas emissions will require a major global shift towards more efficient personal and freight vehicles—including those powered with alternative, low-carbon energy sources—along with a corresponding reduction in demand for energy-intensive vehicles that is strongly incentivized with supportive policies, and ongoing research towards the technology breakthroughs needed to achieve a transition to a truly low-carbon transportation system."

The results of the report's plausible yet aggressive scenarios for the United States show the potential for technological improvements to more than offset fleet growth and, by 2050, reduce fuel use and GHG impacts by up to 50%. In Europe, the anticipated fleet growth is less, as are the potential reductions from technology improvements, but the overall percentage reduction potential is similar to that in the United States. In Japan, fleet size and use are declining, so the overall reduction in impacts could be larger. In China, though current growth in fleet size is large, reductions in that growth rate and substantial technology improvements over time are expected to level off fleet fuel consumption and GHG emissions by about 2040.

The report makes several recommendations that should be implemented to attain the 40% to 50% reductions in fleet fuel consumption and GHG emissions by 2050 that the overall assessment indicates are feasible in North America, Europe, and Japan. Larger reductions on this time scale will need additional major efforts and would likely require a significant reduction in travel demand and more rapid development and substantial distribution and use of low-GHG-emitting alternative sources of transportation energy, such as electricity and hydrogen.

Recommendations include the following:

- Improving the fuel consumption of mainstream vehicles is the primary nearer-term opportunity for reducing fuel use and GHG emissions. Market-based incentives should be implemented to support the US Corporate Average Fuel Economy (CAFE) LDV requirements.

- The CAFE standard targets for LDVs leading up to the 2025 models need to be clarified as the often-quoted average number of 54.5 miles per gallon will not reflect what most new car buyers should expect to achieve in 2025.
- Vehicle electrification is a potentially promising alternative energy source and propulsion system technology to move toward lower fleet GHG emissions over time. Plug-in hybrids will likely provide the primary path.
- The overall strategy should include conserving energy through changes in travel behavior, improving conventional technologies, and transforming the transportation system to increasingly use lower carbon energy sources.
- Policies should be implemented to enforce a carbon tax combined with an increasing fuel tax; current CAFE regulations should be extended and new regulations should be implemented; and improvements in existing fuels that would achieve fleet-wide GHG emissions reductions should be explored.

On the Road toward 2050 is a synthesis of research conducted in the Sloan Automotive Laboratory at MIT over the past five years, primarily under the direction of Heywood, with support from the MIT Energy Initiative (MITEI) as well as MITEI Founding Member Eni S.p.A. It is the third report in a series that records the research findings of this group; *On the Road in 2020* was published in 2000, and *On the Road in 2035* was published in 2008.

Because MIT has other ongoing research programs in many domains vital to transportation and mobility, MITEI has recently organized a multidisciplinary study team from across the Institute to examine how the complex interactions between engine technology options, fuel options, vehicle characteristics, refueling infrastructure, consumer choice, public transit options, new mobility business models, and government policy will shape the future landscape of mobility. MITEI's study Mobility of the Future will explore these and other questions.

"The question of how to get from point A to point B has driven the development of transportation—but now, the question we need to ask is: How can we get there most efficiently, with the least impact on the environment and climate? At the same time, we need to make these new modes enticing to consumers," says MITEI Director Robert Armstrong. "*On the Road toward 2050* provides an excellent roadmap for answering many of these questions, which MITEI will build on in our Mobility of the Future study."

BP, Chevron, Concawe, the DOE US–China Clean Energy Research Center's Clean Vehicle Consortium, the MIT Joint Program on the Science and Policy of Global Change, and the MIT Portugal Program also provided support for the report.

The study is available at mitei.mit.edu/on-the-road-2050.

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MITEI Office of Communications

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**co-editors of the report*

Reducing emissions, improving technology

A mutually reinforcing cycle

An MIT analysis shows that if countries meet their emissions-reduction pledges to the Paris climate agreement, the cost of electricity from solar photovoltaic systems could drop by 50% and from wind systems by 25% between now and 2030. The reason: To cut their emissions, countries will need to deploy low-carbon technologies, and with that deployment will come technological innovation and lower costs, enabling further deployment. The researchers estimate that if countries reinvest their savings as costs decline, they can increase their solar deployment by 40% and wind deployment by 20%—for the same level of investment. The lower costs of these and other low-carbon technologies will also help developing countries meet their emissions-reduction commitments for the future. Results of the MIT analysis were presented at the White House and referenced by negotiators in Paris.

See page 10 for information about funding and publications.

Photo: Justin Knight

In an invited report and presentation at the White House ahead of the Paris climate negotiations, Jessika Trancik of the MIT Institute for Data, Systems, and Society described an analysis that she and her colleagues at MIT and Tsinghua University performed, including results that demonstrate a mutually reinforcing cycle between emissions-reduction policies and technology development.

In December 2015, much of the world celebrated when 195 nations plus the European Union reached an agreement to address climate change and pledged to meet nationally determined emissions-reduction targets at the United Nations climate talks in Paris. But many experts have observed that the national targets in the Paris Agreement aren't sufficiently aggressive to meet the goal of limiting global warming to less than 2°C. Moreover, they worry that some countries won't be willing—or able—to meet their targets.

Jessika Trancik, the Atlantic Richfield Career Development Assistant Professor of Energy Studies at the MIT Institute for Data, Systems, and Society (IDSS), agrees that the targets as written are too weak to do the job. But she cautions that looking only at those targets doesn't tell the whole story. "There's something else going on below the surface that's important to recognize," she says. "If those pledges are realized, they'll require an expansion of clean energy, which will mean further investment in developing key clean-energy technologies. If good investment and policy decisions are made, the technologies will improve, and costs will come down." Thus, the act of cutting carbon emissions will drive down the cost of meeting current emissions-reduction targets and of adopting stronger targets for the future.

In a recent study, Trancik and her colleagues showed that the impact of this mutually reinforcing cycle of emissions reduction and technology development can be significant. "The return on emissions reductions can be astonishingly large…and should feature prominently in efforts to broker an ambitious, long-term agreement among nations," she notes.

Photo courtesy of the researchers

Jessika Trancik, center, in Washington, DC, with members of her team—left to right, Goksin Kavlak and Magdalena Klemun of IDSS, Patrick Brown of physics, and Joel Jean of electrical engineering and computer science.

The study involved an interdisciplinary team of graduate students—Patrick Brown of physics, Joel Jean of electrical engineering and computer science, and Goksin Kavlak and Magdalena Klemun of IDSS—in consultation with other colleagues at both MIT and Tsinghua University in Beijing, China.

Before the Paris climate talks, the researchers brought their message to Washington, DC. In an invited talk at the White House, Trancik presented the research findings to US policymakers, and the message apparently resonated: US negotiators used the report during the talks to encourage agreement to revisit and strengthen commitments every five years; White House statements on the agreement, including the final press release, cited the mutually reinforcing cycle between enhanced mitigation and cost reductions; and the Paris Agreement cited the benefits of investing in emissions reductions early on to drive down the cost of future mitigation.

Understanding technology development

Trancik is not new to the study of technology development. For the past decade, she has been studying the underlying reasons why technologies improve over time. Of particular interest has been figuring out why the cost of a technology falls as its deployment increases—a phenomenon first observed some 80 years ago.

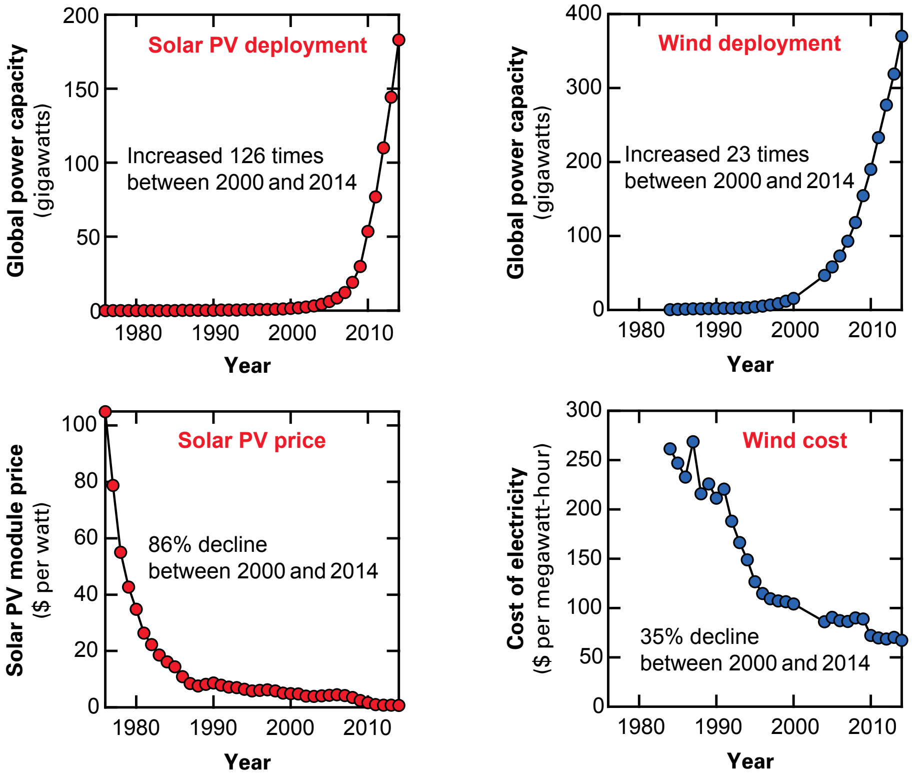
By developing fundamentally new research methods, Trancik has been able to look "under the hood" of solar photovoltaics (PV) and other technologies to model changes over time. The resulting models can be tested against data and then applied to many different technologies to pin down the general drivers of technological improvement. The research has required studying hundreds of technologies, looking for key trends in everything from individual device capabilities and constraints up to macroscale market behavior.

About a year ago, she decided to take a comprehensive look at PV and wind technologies—two low-carbon energy sources that have been improving rapidly and have large potential for expansion. Using her analytical methodology, she asked: How quickly are these technologies improving? How rapidly have costs fallen and why? And what can those insights about the past tell us about future trends—in particular, under the emissions-reduction targets stated in the Paris Agreement?

Expanding markets, falling costs

In recent decades, worldwide solar and wind electricity-generating capacities have grown at rates far outpacing experts' forecasts, and associated

Worldwide deployment and costs of solar and wind energy



Since 2000, the rapidly growing deployment of solar photovoltaic (PV) and wind technologies (top figures) has been accompanied by dramatic declines in their costs (bottom figures). During that period, government policies rewarding the use of emissions-reducing technologies drove market growth, which in turn led to cost reductions due to private company innovation and economies of scale.

costs have dropped dramatically. The charts on this page show those changes. Between 2000 and 2014, global solar PV capacity increased 126 times and wind capacity 23 times. Over the same period, the price of a solar PV module dropped 86% per kilowatt, and the cost of wind-generated electricity dropped by 35% per megawatt-hour. (Changes in solar costs cited here are based on module price because the cost of installation varies so widely from country to country.)

Drawing on Trancik's past research on the drivers of technological improvement, the researchers determined why those costs have been falling. Public funding of research and development has played a role, but a key contributor has been the policies enacted by governments worldwide to reward the use of emissions-reducing technologies. Those policies have caused deployment of solar and wind technologies to ramp up and markets to expand, increasing competition among firms to excel. For example, in-house researchers work to improve product designs and manufacturing procedures. Technicians on solar PV manufacturing lines find ways to waste less high-cost silicon and make processes more efficient. And increased output yields cost reductions from economies of scale.

"Policies to incentivize the growth of markets have unleashed the ingenuity of private companies to drive down costs," says Trancik. "I think that's an important angle that's not always recognized."

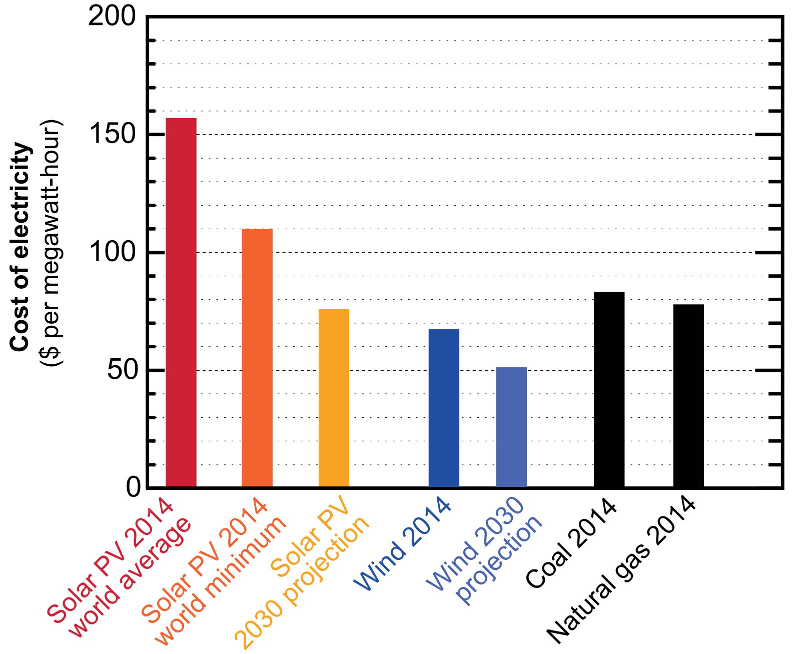
Interestingly, the gains have resulted from a hodgepodge of public policies adopted by a handful of countries in North America, Europe, and Asia. And the leadership role in installing the technologies has shifted over the past three decades. Solar PV deployment was led by Japan and later Germany, while wind deployment shifted from the United States to Germany and ultimately to China. "Effort was not coordinated," says Trancik. "Nonetheless, something resembling a relay race emerged, with countries trading off the leader's baton to maintain progress as efforts from individual nations rose and fell."

Implications for the Paris Agreement

So what do those insights mean for the future under the Paris Agreement? To find out, the researchers first had to estimate how much solar and wind capacity would be deployed under the Intended Nationally Determined Contributions (INDCs) specified by countries in the Paris Agreement. They assumed a scenario that had a "relatively heavy" emphasis on the renewables but also allowed for expanded use of nuclear fission and hydropower, and they took into account any specific commitment to renewables adoption that countries have made. Based on analyses of all the INDCs, they concluded that global installed solar capacity could increase nearly fivefold and wind about threefold between now and 2030.

To forecast how costs will change at those deployment levels, the researchers used models that Trancik had

Current and projected costs of electricity from various sources



These bars show costs (including contributions from construction and operation) for solar and wind in 2014 and projected costs for 2030 and—for comparison—costs of coal and natural gas in 2014. Despite short-term fluctuations, costs of coal- and natural-gas-based electricity have not exhibited long-term downward trends in recent decades and aren't forecast to do so in the coming decades. (Cost estimates are global averages and do not include energy storage.)

developed in her previous research, including methods of dealing with inherent uncertainty and forecasting errors so as to generate robust results. In addition, they incorporated expert opinion into their estimates of the "soft costs" of PV installation—that is, labor, permitting, and on-site construction costs—which vary significantly from country to country. Based on their analyses, they forecast a cost decline of 50% for solar PV and 25% for wind between now and 2030 (and they quantify the expected errors in those forecasts).

The figure above helps to put those costs into context. The bars show electricity costs (including contributions from construction and operation) in 2014 from solar, wind, coal, and natural gas and cost projections for solar and wind in 2030.

The results show that wind is already competitive with coal and natural gas in 2014. Solar PV can compete only with coal and only when the coal cost is increased to account for health-related costs resulting from air pollution (as estimated in the literature). By 2030, solar costs are roughly comparable to the 2014 coal and natural gas costs, even without considering health costs. "So there are already circumstances under which switching from fossil fuels to renewable sources could both abate carbon emissions and reduce the cost of generating electricity," says Trancik, adding that the "development of storage will become increasingly critical over time as intermittent renewables deployment grows."

Of course, an obvious question is whether the coal and natural gas technologies will also improve between now and 2030, eroding the renewables' ability to compete. According to the researchers, the cost of generating electricity with those fuels hasn't followed long-term decreasing trends in recent decades. In both cases, a large fraction of the total cost is buying the fuel. Those fuel costs tend to fluctuate over the short term but trend neither up nor down over the longer term, limiting the cost decline for the technologies that rely on them.

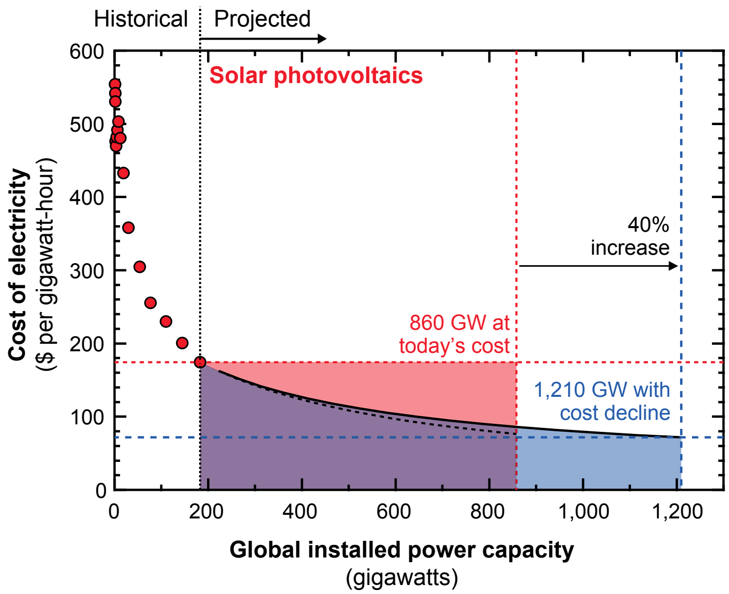
Messages for policymakers

So what does this mean for international climate change efforts? Trancik cites several possible outcomes for the Paris Agreement if pledges are met. One is that the targets are reached, costs fall, and countries are that much better positioned by 2025 or 2030 to commit to further emissions reductions and expanded adoption of low-carbon technology.

Another possible outcome is that the deployment of wind and solar PV could actually outpace the INDC commitments—either due to market forces alone or because of increasingly aggressive public policy. Policymakers may become more ambitious over time because of the ability to deploy more low-carbon energy without additional financial investment. That possibility is demonstrated in the figure on page 10, which plots global installed solar capacity against the cost of electricity. According to the researchers' scenario, the INDCs commit countries to deploying a total of 858 gigawatts (GW) of solar PV by 2030.

But if costs decline as forecast by the MIT team, then investing the same amount of money could fund the deployment of 1,210 GW—a 40% increase. Performing the same analysis for wind shows that the projected cost decline would permit a 20% increase in the amount of wind power deployed for the same investment.

Cost declines enable increased deployment without expanded investment



Under the targets in the Paris Agreement, countries will deploy a total of about 860 gigawatts (GW) of solar PV by 2030. The pink shading indicates the total required investment, assuming today's electricity cost. But if costs decline as forecast—as shown by the downward-sloping solid curve—a 40% increase in deployment is possible for the same investment (shown by the blue shading).

"So if developed countries invest their cost savings back into deployment, they could increase their emissions-reduction commitments without changing the total investment—and the larger those commitments, the faster costs may fall," says Trancik. "If good decisions are made, by the time the least-developed nations are required to cut emissions, technology development may have lowered costs so much that switching to low-carbon energy is a benefit rather than a burden."

Sustaining the momentum

As solar PV and wind power begin to dominate electricity markets, other technologies and practices will be needed to ensure reliable delivery of power. Since electricity generation from solar and wind sources is intermittent, ensuring that supply is available to meet demand will require bulk storage devices, expanded long-distance transmission infrastructure, and methods of shifting demand to times of maximum supply. "We can draw lessons on how to drive innovation in those areas by observing the approaches that successfully grew PV and wind markets," says Trancik. But, she notes, the future is uncertain and we shouldn't "put all our eggs in one basket." Other low-carbon electricity sources—such as hydropower and nuclear fission in some locations—as well as technologies for transportation and heating should also be supported.

On the solar side, a final challenge—and opportunity—is to bring down the soft costs of installation. PV modules and inverters are sold in a global market-place, so cost-reducing advances in that hardware can be shared internationally. But the soft cost components aren't currently traded on global markets, and they're twice as high in some countries as in others. Finding ways to share knowledge and best practices relating to soft costs, or possibly even creating global markets, could significantly reduce total costs, both within some countries and globally.

Trancik and her collaborators offer one last encouraging observation: There appears to be growing recognition among negotiators of the long-term positive contributions their countries can make by supporting low-carbon energy and driving down costs. "I think countries now realize that by supporting the early-stage development of these low-carbon energy technologies, they're helping to contribute knowledge that will last indefinitely and will enable the world to combat climate change, and they take pride in that," says Trancik. "It's something that can become part of their historical legacy—an opportunity that I believe played a role in the latest climate change negotiations."

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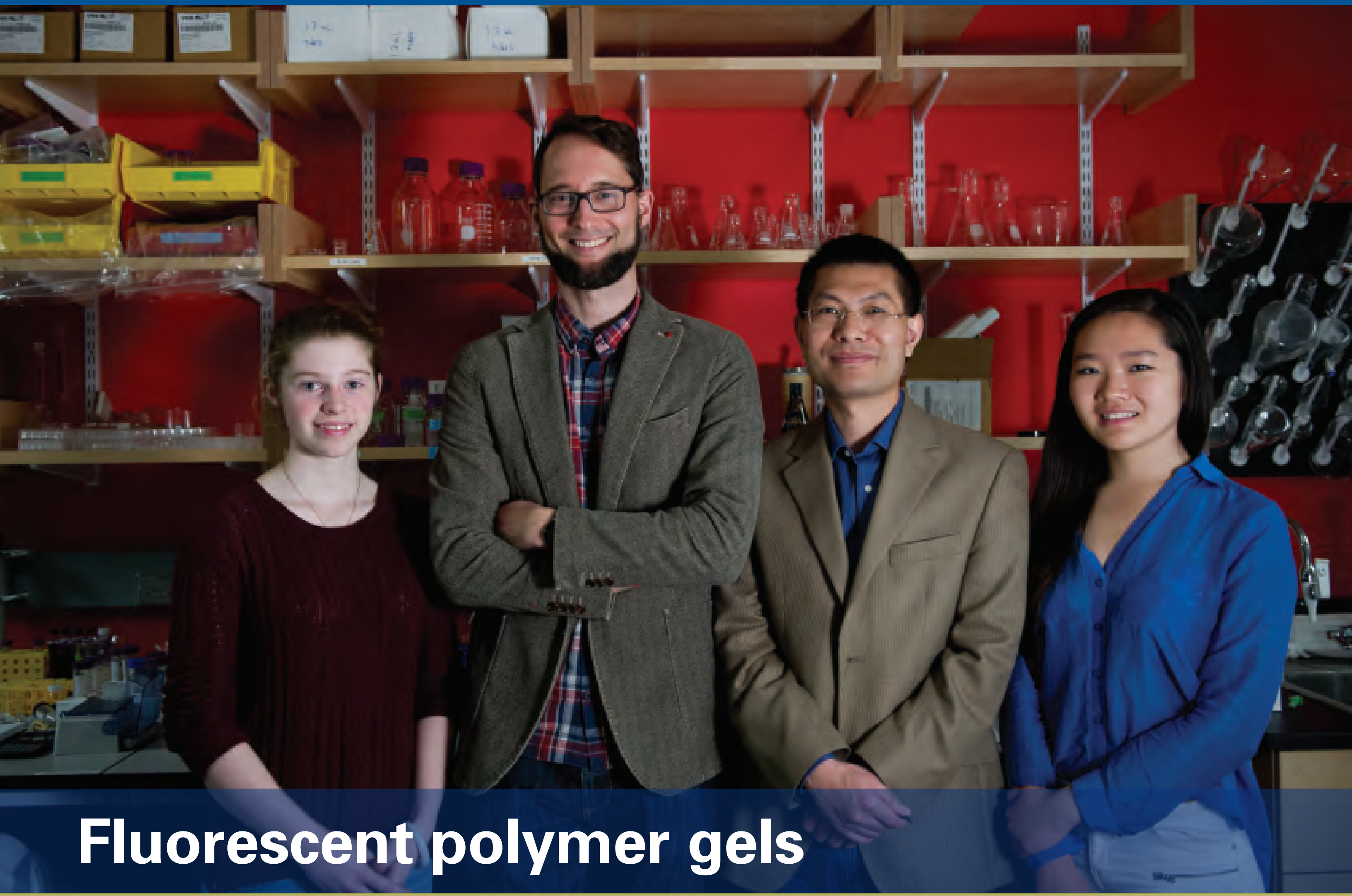
By Nancy W. Stauffer, MITEI

This research was supported by the MIT International Policy Laboratory. Further information can be found online at trancik.scripts.mit.edu/home/publications/ and in the following publication:

J.E. Trancik, P.R. Brown, J. Jean, G. Kavlak, M.M. Klemun, M.R. Edwards, J. McNerney, M. Miotti, J.M. Mueller, and Z.A. Needell. *Technology Improvement and Emissions Reductions as Mutually Reinforcing Efforts: Observations from the Global Development of Solar and Wind Energy.* Cambridge, MA: Institute for Data, Systems, and Society, Massachusetts Institute of Technology, November 13, 2015. (URL: http://hdl.handle.net/1721.1/102237)



Fluorescent polymer gels

Light-emitting sensors that self-repair

Left to right: Rebecca Gallivan, Niels Holten-Andersen, and Pangkuan Chen of materials science and engineering and Caroline Liu of mechanical engineering are creating fluorescent polymer gels that change color when they're disturbed—behavior that could make them effective sensors for detecting structural failure in energy-related equipment.

This research was supported in part by the MIT Energy Initiative (MITEI) Seed Fund Program and by the Energy Undergraduate Research Opportunities Program through MITEI with funding from Lockheed Martin, a Sustaining Member of MITEI. See page 15 for more information on funding and publications.

Photo: Stuart Darsch

MIT researchers are now making fluorescent polymer gels that change color when they're shaken, heated, exposed to acid, or otherwise disrupted. Given that response, these novel materials could be effective sensors for detecting changes in structures, fluids, or the environment. To create the gels, the researchers combine a widely used polymer with a metal that fluoresces and a chemical that can bind the two together. Mixed into a solvent, the metal and binder instantly self-assemble, grabbing the polymer molecules and pulling them together to form a gel. By using different metals, the researchers can control the physical properties of the gel as well as the color of light it emits. In a series of tests, the gels emitted a color-coded response to a variety of subtle external stimuli and later returned to their pre-stressed state and color.

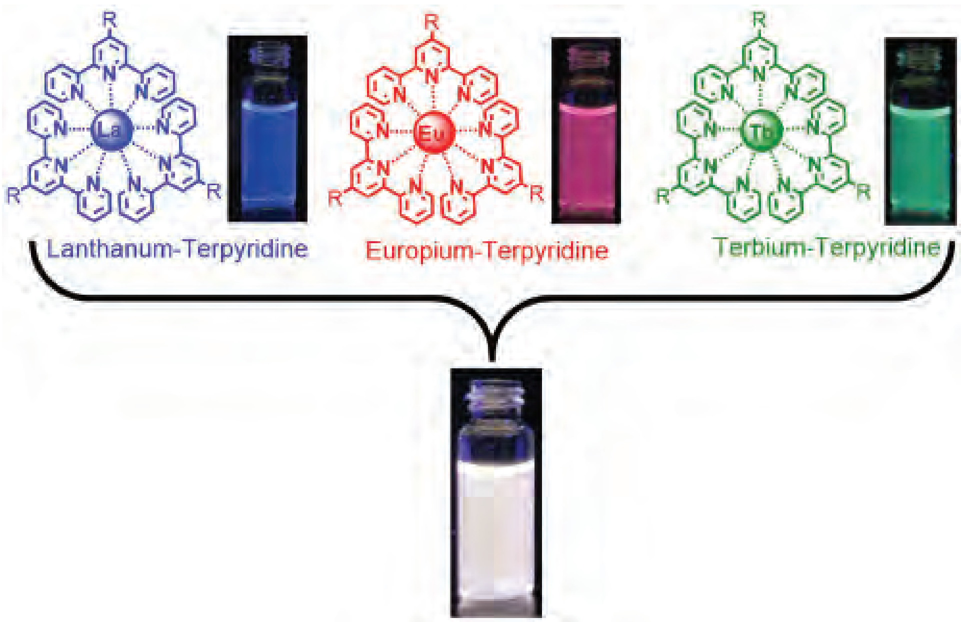
Natural organisms display some remarkable behaviors. The mussel, for example, produces strong fibers that allow it to attach tightly to boats, rocks, and other underwater surfaces. But those fibers are changeable. Pull on an attached mussel, and the stiff fibers become stretchy. Let go, and the fibers go back to their original stiff state, "self-repairing" any damage that's occurred. In contrast, man-made materials are typically not very dynamic, and when they break, the damage is irreversible.

Niels Holten-Andersen, assistant professor of materials science and engineering (MSE) and the Doherty Professor in Ocean Utilization, has long been interested in mussel fibers and the component that's key to their success—the metal coordination complex. This structure consists of a single metal ion (a charged particle) with several chemically bound arms, or "ligands," radiating outward. The ligands are made of organic (carbon-containing) molecules and can attach to other molecules, enabling the complex to serve as a crosslink that binds materials together. Given that capability, the metal coordination complex plays an important role in many biological systems, including the human body, where it catalyzes enzyme-controlled reactions and binds oxygen to hemoglobin in blood.

Holten-Andersen says he's always been fascinated by the way that nature assembles materials, putting together proteins and sugars and fatty acids in creative ways to form complex dynamic structures. "We can't copy nature's materials. For example, it's difficult to synthesize proteins in the lab," he says. "But we can see how nature builds its materials and why they work the way they do. We can then try to mimic the way nature has done it but using simple, inexpensive building blocks that we know how to make."

To Holten-Andersen, polymer building blocks seemed like a good bet. "We know how to make simple, cheap, green polymers in large quantities," he says. So four years ago, he decided to try making polymer gels held together by metal coordination complexes built on transition metals—a family of elements he'd frequently seen in biological settings. Initial results were promising. The polymer molecules, metals, and ligands instantly self-assembled into gels, and the mechanical properties and emitted colors of the gels depended on the transition metal used.

Using lanthanides to synthesize light-emitting fluids of controlled colors



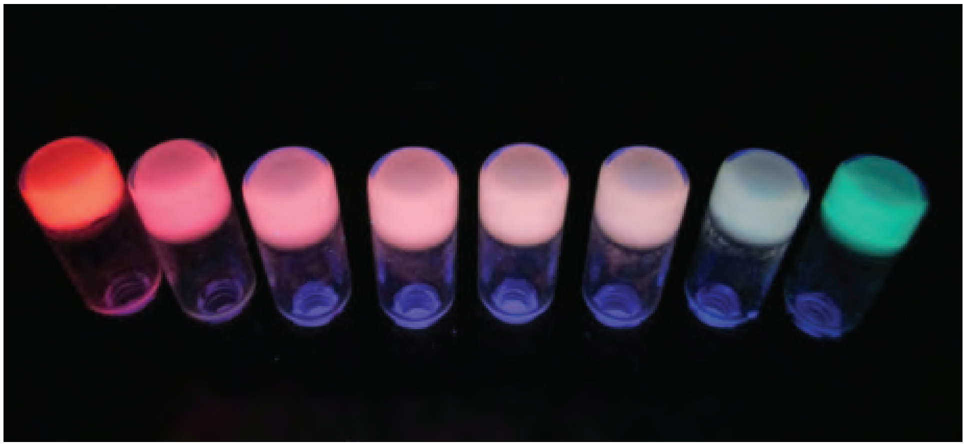
These samples show the effect of mixing different lanthanide ions with a ligand material called terpyridine in a solvent. In the top three vials, the lanthanides used are (left to right) lanthanum, europium, and terbium. The fluids display the characteristic colors of those elements. The white-light-emitting fluid in the lower vial was formed by mixing together equal volumes of the blue, red, and green samples above.

Adding fluorescence

Encouraged by those results, he decided to try a different family of metals—the lanthanides. Like the transition metals, the lanthanides—often referred to as the rare earth elements—provide a host of interesting and complicated behaviors. But they have one additional intriguing characteristic: They fluoresce. Shine ultraviolet light on a lanthanide, and it becomes excited and emits light at a characteristic wavelength.

"By using the lanthanides, we could still control the properties of our gels, but now we'd have light emission that would reflect any changes in those properties," says Holten-Andersen. "With those two features intimately

Polymer gels with tuned luminescence



These gels were synthesized by mixing a polymer (polyethylene glycol) and a ligand (terpyridine) with two lanthanides—europium and terbium—in varying ratios. The red sample at the far left contains only europium, while the blue-green sample at the far right contains only terbium. A white-light-emitting gel forms when the mixing ratio of terbium to europium is 96 to 4.

coupled, any time the physical properties were disturbed—say, by a change in the temperature of the nearby air or the pH of the surrounding water—the color emitted would change." Such a polymer gel could report on its own state and serve as an excellent sensor. For example, it could be used as a coating that monitors the structural integrity of pipes, cables, and other underwater structures critical to offshore oil and gas and wind farm operations.

Testing in liquids

Before beginning to work with polymers, Holten-Andersen wanted to confirm—as others had shown—that mixing lanthanide ions and ligands in a solvent would produce light-emitting fluids. Accordingly, he and his team in the Laboratory for Bio-Inspired Interfaces—Pangkuan Chen, postdoc in MSE; Qiaochu Li and Scott Grindy, both MSE graduate students; and Rebecca Gallivan '17 of MSE and Caroline Liu '18 of mechanical engineering—combined terpyridine, a commercially available ligand material, with selected lanthanides in a solvent. As the top three photos on page 12 show, the mixtures produced liquids that fluoresce under ultraviolet light in the characteristic colors of the three lanthanides: blue for lanthanum, red for europium, and green for terbium.

Those results confirm that the complexes formed as expected. But a mixture emitting pure white light would make a far better sensor: It's easier to see white light turn slightly green than it is to see green light become a little less green. To their surprise, the researchers found that producing a white-light-emitting fluid was simple. Since white light is actually a combination of many colors, they just needed to mix together their blue, red, and green light-emitting fluids. As shown in the bottom photo on page 12, putting together equal parts of the three colored fluids produced a glowing white liquid.

The researchers next exposed their white-light-emitting fluid to a series of external stimuli to see if they'd get a color-coded response—and they did. For example, when they gently heated the fluid from room temperature to 55°C, the emitted light gradually changed color. When they let it cool down, the white light returned. The ligand and metal ions had come apart when they were heated and then reassembled when they were allowed to cool. The fluid also proved sensitive to wide-ranging changes in pH. "So we found that this simple blue-red-green approach to making a white-light-emitting system indeed leads to materials that respond to a variety of stimuli, and with that response comes a change in color," says Holten-Andersen. The fluids might therefore serve as good sensors for detecting chemical variations within a liquid or for observing velocity gradients in fluid flow experiments—differences in flows that now must be determined indirectly by simulation.

Adding the polymer

In the next series of tests, the researchers tried incorporating their lanthanide ions and terpyridine ligands into a widely used polymer called polyethylene glycol, or PEG. At the beginning of the experiments, the polymer molecules coupled with ligands were free-floating in a solvent. "We then mixed in one of our lanthanide metals, and after some gentle shaking, the mixture changed from a fluid to a fluorescent gel," says Holten-Andersen. The metal ions and ligands had self-assembled, linking the polymers together.

Once again, they found that gels based on different lanthanides emitted different colors, and combining them in various ratios produced shifts in color. The photo on page 13 shows a series of gels made using europium and terbium. (It turned out they didn't need lanthanum because the ligand itself emits blue.) The sample at the far left is all europium, therefore red; the one at the far right is all terbium, therefore blue-green; and those in between are made with various ratios of the two. Bright white luminescence appears in the second sample from the right, when the mixing ratio of terbium to europium is 96 to 4. The samples demonstrate the simplicity of designing "metallogels" with a broad spectrum of colors.

Like the fluids, the gels proved to be sensitive detectors of changes in temperature and pH. But perhaps the most dramatic response came when the gels were sonicated, that is, disrupted by exposure to high-frequency sound waves. The photos on this page show changes in the white-light-emitting gel during immersion in an ultrasonic bath. In the sample taken after 5 minutes, the gel is partially broken down into a fluid. The gel that remains retains its white luminescence, while the fluid gives off blue light—emitted by the now-unbound ligands. After another 11 minutes of shaking, the conversion of the sample from gel to fluid is complete, and the blue light of the ligands dominates.

And again, given time, the white-light gel reassembles. "When we let the blue fluid rest overnight, the polymers found each other again, and it turned back into a gel and made white light," says Holten-Andersen. "That was very exciting for us because it really shows in principle that as a proof-of-concept, our approach works under these conditions. We can make a material that emits white light, reports its own failure, and then recovers. So it's a self-reporting material that's also self-healing."

Looking ahead

Holten-Andersen and his team are now investigating the use of their materials as coatings that can sense structural failure as well as pH and temperature changes—a capability that will be valuable in many energy and environmental systems. Current work focuses on coatings for underwater cables used to transport electric power from offshore wind turbines to shore.

The researchers are also planning more fundamental studies. There's a lot of interest in making materials that can change in response to various outside stimuli and then autonomously repair, returning to their original state. The availability of such self-healing materials would reduce the need to fabricate replacements for them over time.

Knowing how to build self-healing materials, however, requires knowing how those materials fail and repair in the field, and that's difficult to study, says Holten-Andersen. He hopes their new materials may help. The chemical bonds in the metal-coordinate crosslinks have a remarkable ability to break and then re-form—and to announce that activity with changes in light emission. Guided by those light changes plus high-resolution imagery, the researchers may be able to get new insights into when, where, and how the material breaks and then comes back together.

Holten-Andersen stresses that we still have lots to learn from nature. "We're just scratching the surface in understanding nature, given the technology we now have to look at it," he says. For example, he believes that we're far from finding all the metal coordination complexes that nature uses. They could occur in other natural materials with remarkable properties—perhaps in spider silk, which is tough, elastic, resilient, and one of the strongest materials known. "It's hard to see these metals," he says. "They appear in tiny concentrations and a single molecule at a time. But I think metal coordination complexes are much more prevalent in nature's materials than we are currently aware of." And coordination complexes are just one among many tricks that nature has developed over millions of years to help organisms deal with challenging environmental conditions.

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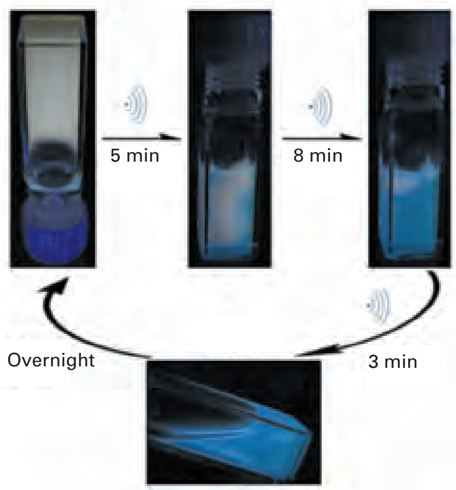
By Nancy W. Stauffer, MITEI

Response of white-light-emitting gel to high-frequency shaking

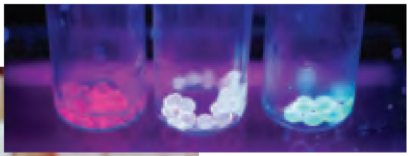


As one test of stimulus response, the researchers immerse samples of their white-light-emitting gel in an ultrasonic bath. Within a few minutes, the samples begin to change from gels to fluids as the complexes holding the polymer together break down. As shown above, the remaining gel emits white light, while the fluid shines blue—the color emitted by the now-unbound ligands. At 16 minutes, the sample is entirely blue liquid. Left overnight, the complexes reassemble, and the gel re-forms, emitting its characteristic white light.

This research was sponsored by the MIT Energy Initiative (MITEI) Seed Fund Program and by MIT Sea Grant via the Doherty Professorship in Ocean Utilization. Student researcher Caroline Liu '18 received support from the Energy Undergraduate Research Opportunities Program through MITEI with funding from Lockheed Martin, a Sustaining Member of MITEI. Further information can be found in:

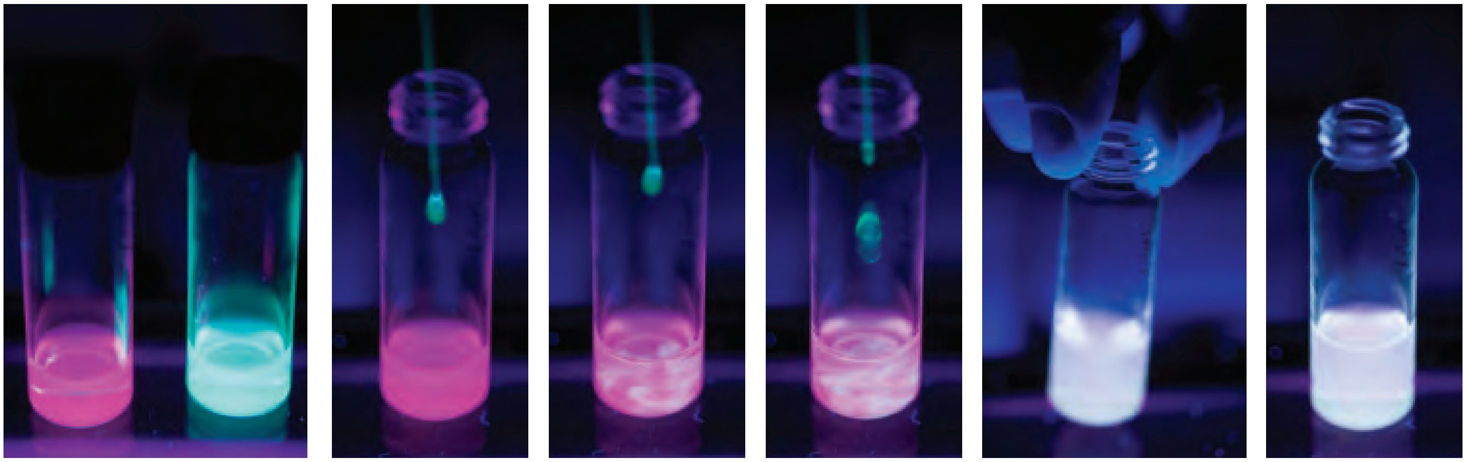
P. Chen and N. Holten-Andersen. "Multistimuli-responsive white luminescent fluids using hybrid lanthanide metal-coordinate complex probes." *Advanced Optical Materials*, vol. 3, issue 8, pp. 1041–1046, August 2015.

P. Chen, Q. Li, S. Grindy, and N. Holten-Andersen. "White-light-emitting lanthanide metallogels with tunable luminescence and reversible stimuli-responsive properties." *Journal of the American Chemical Society*, vol. 137, pp. 11590–11593, 2015.

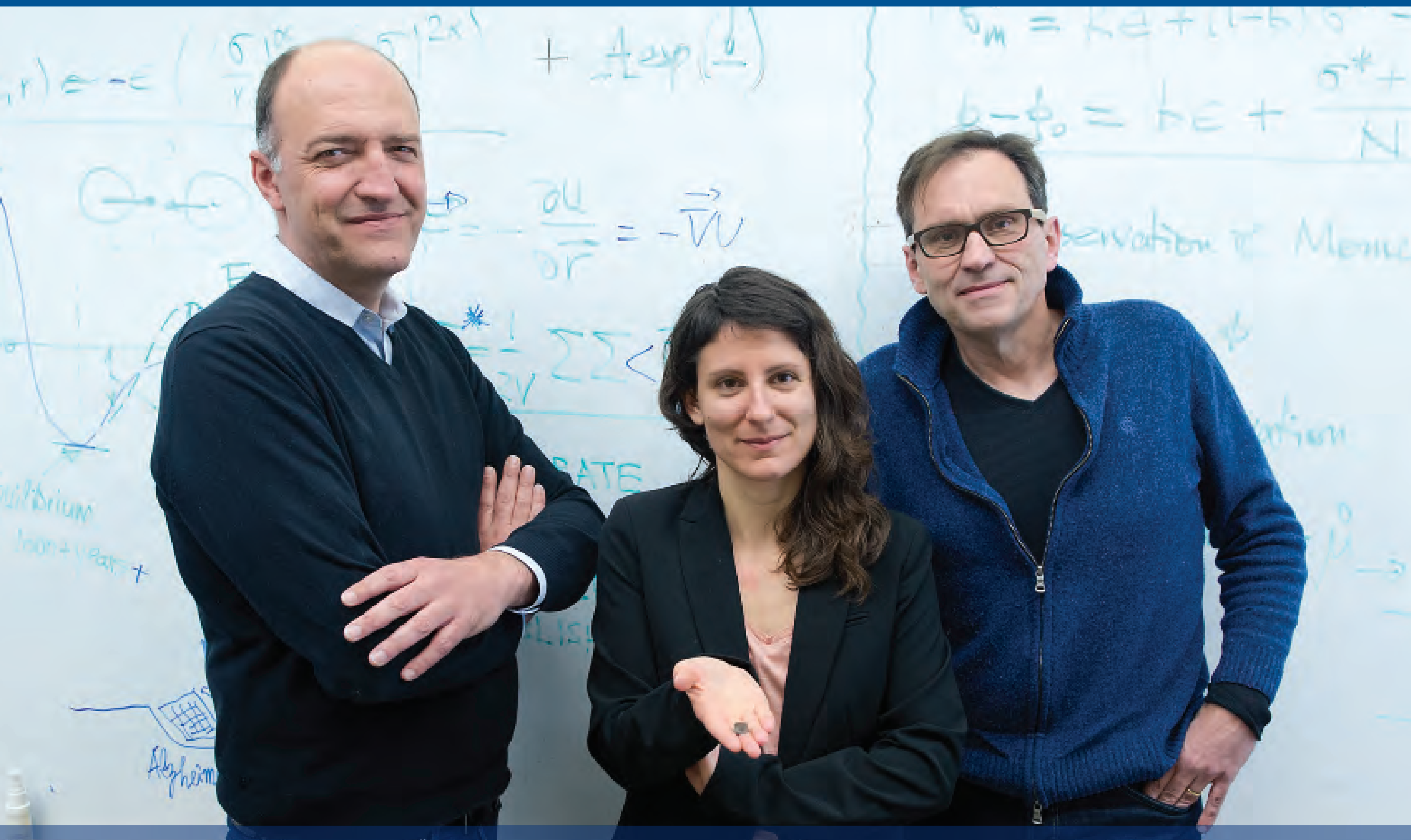


Photos: Stuart Darsch

In the lab, Caroline Liu '18 (left) and Rebecca Gallivan '17 combine alginic acid, a polymer, with a lanthanide metal ion and terpyridine to create spherical beads that fluoresce. Aided by stirring, the alginic acid causes the gels to form as individual millimeter-sized beads—a regular shape well-suited to optical and mechanical analysis.



Above: Postdoc Pangkuan Chen mixes together liquids made from terpyridine and europium—the red sample—and terpyridine and terbium—the green sample. As he drips the green liquid into the red, white swirls gradually appear until—with a little shaking—the red sample is entirely white. With collaborators from mechanical engineering, the researchers are investigating the use of these light-emitting liquids as sensors for measuring variations in pressure and other parameters in flowing fluids.



Designing climate-friendly concrete — from the nanoscale up

Left to right: Roland Pellenq of civil and environmental engineering (CEE), Katerina Ioannidou of the MIT Energy Initiative, and Franz-Josef Ulm of CEE have developed a detailed understanding of the nanoscale forces at work as cement hardens—a critical step toward developing stronger, longer-lasting, less carbon-intensive concrete for "greener" construction in the future.

This research was supported in part by Schlumberger, a Sustaining Member of the MIT Energy Initiative, and the Concrete Sustainability Hub at MIT. See page 20 for other sponsors and participants as well as a list of publications.

Photo: Stuart Darsch

An MIT-led team has defined the nanoscale forces that control how particles pack together during the formation of cement "paste," the material that holds together concrete and causes that ubiquitous construction material to be a major source of greenhouse gas emissions. By controlling those forces, the researchers will now be able to modify the microstructure of the hardened cement paste, reducing pores and other sources of weakness to make concrete stronger, stiffer, more fracture-resistant, and longer-lasting. Results from the researchers' simulations explain experimental measurements that have confused observers for decades, and they may guide the way to other improvements, such as adding polymers to fill the pores and recycling waste concrete into a binder material, reducing the need to make new cement.

Photo: Stuart Darsch

To validate their model of particle packing during cement hydrate formation, the researchers perform laboratory experiments on cement samples prepared with different ratios of water to cement powder to achieve carefully controlled packing fractions. Nanoindentation tests measure stiffness and hardness, and small-angle neutron scattering tests determine the distribution of particles and pores within the sample.

Each year, the world produces 2.3 cubic yards of concrete for every person on earth, in the process generating more than 10% of all industrial carbon dioxide (CO_2) emissions. New construction and repairs to existing infrastructure currently require vast amounts of concrete, and consumption is expected to escalate dramatically in the future. "To shelter all the people moving into cities in the next 30 years, we'll have to build the equivalent of several hundred New York cities," says Roland Pellenq, senior research scientist in civil and environmental engineering (CEE) and research director at France's National Center for Scientific Research (CNRS). "There's no material up to that task but concrete."

Recognizing the critical need for concrete, Pellenq and his colleague Franz-Josef Ulm, professor of CEE and director of the MIT Concrete Sustainability Hub (CSHub), have been working to reduce its environmental footprint. Their goal: to find ways to do more with less. "If we can make concrete stronger, we'll need to use less of it in our structures," says Ulm. "And if we can make it more durable, it'll last longer before it needs to be replaced."

Surprisingly, while concrete has been a critical building material for 2,000 years, improvements have largely come from trial and error rather than rigorous research. As a result, the factors controlling how it forms and performs have remained poorly understood. "People always deemed what they saw under a microscope as being coincidence or evidence of the special nature of concrete," says Ulm, who with Pellenq co-directs the joint MIT-CNRS laboratory called MultiScale Material Science for Energy and Environment, hosted at MIT by the MIT Energy Initiative (MITEI). "They didn't go to the very small scale to see what holds it together—and without that knowledge, you can't modify it."

Cement: the key to better concrete

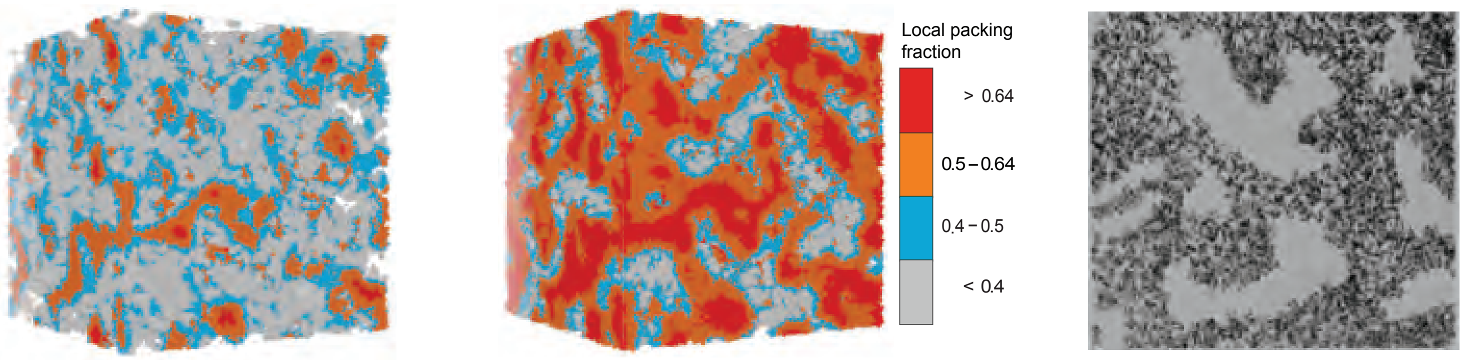
The problems with concrete—both environmental and structural—are linked to the substance that serves as its glue, namely, cement. Concrete is made by mixing together gravel, sand, water, and cement. The last two ingredients combine to make cement hydrate, the binder in the hardened concrete. But making the dry cement powder requires cooking limestone (typically with clay) at temperatures of 1,500°C for long enough to drive off the carbon in it. Between the high temperatures and the limestone decarbonization, the process of making cement powder for concrete is by itself responsible for almost 6% of all CO_2 emissions from industry worldwide. Structural problems can also be traced to the cement: When finished concrete cracks and crumbles, the failure inevitably begins within the cement hydrate that's supposed to hold it together—and replacing that crumbling concrete will require making new cement and putting more CO_2 into the atmosphere.

To improve concrete, then, the researchers had to address the cement hydrate—and they had to start with the basics: defining its fundamental structure through atomic-level analysis. In 2009, Pellenq, Ulm, and an international group of researchers associated with CSHub published the first description of cement hydrate's 3-dimensional molecular structure. Subsequently, they determined a new formula that yields cement hydrate particles in which the atoms occur in a specific configuration—a "sweet spot"—that increases particle strength by 50%.

However, that nanoscale understanding doesn't translate directly into macroscale characteristics. The strength and other key properties of cement hydrate actually depend on its structure at the "mesoscale"—specifically, on how nanoparticles have packed together over hundred-nanometer distances as the binder material forms.

When dry cement powder dissolves in water, room-temperature chemical reactions occur, and nanoparticles of cement hydrate precipitate out. If the particles don't pack tightly, the hardened cement will contain voids that are tens of nanometers in diameter—big enough to allow aggressive materials

Structure of hardened cement hydrate



The left and center diagrams show the structure of cement hydrate as determined by the researchers' model, which calculates the positions of particles based on particle-to-particle forces. Each simulation box is about 600 nanometers wide. The packing fraction (the fraction of the box occupied by particles) is assumed to be 0.35 in the left diagram and 0.52 in the center one. Open pores, indicated by the white areas, are more prevalent at the lower packing fraction. The right-hand diagram is a sketch of cement hydrate published by T.C. Powers in 1958.

such as road salt to seep in. In addition, the individual cement hydrate particles continue to move around over time—at a tiny scale—and that movement can cause aging, cracking, and other types of degradation and failure.

To understand the packing process, the researchers needed to define the precise physics that drives the formation of the cement hydrate microstructure—and that meant they had to understand the physical forces at work among the particles. Every particle in the system exerts forces on every other particle, and depending on how close together they are, the forces either pull them together or push them apart. The particles seek an organization that minimizes energy over length scales of many particles. But reaching that equilibrium state takes a long time. When the Romans made concrete 2,000 years ago, they used a binder that took many months to harden, so the particles in it had time to redistribute so as to relax the forces between them. But construction time is money, so today's binder has been optimized to harden in a few hours. As a result, the concrete is solid long before the cement hydrate particles have relaxed, and when they do, the concrete sometimes shrinks and cracks. So while the Roman Colosseum and Pantheon are still standing, concrete that's made today can fail in just a few years.

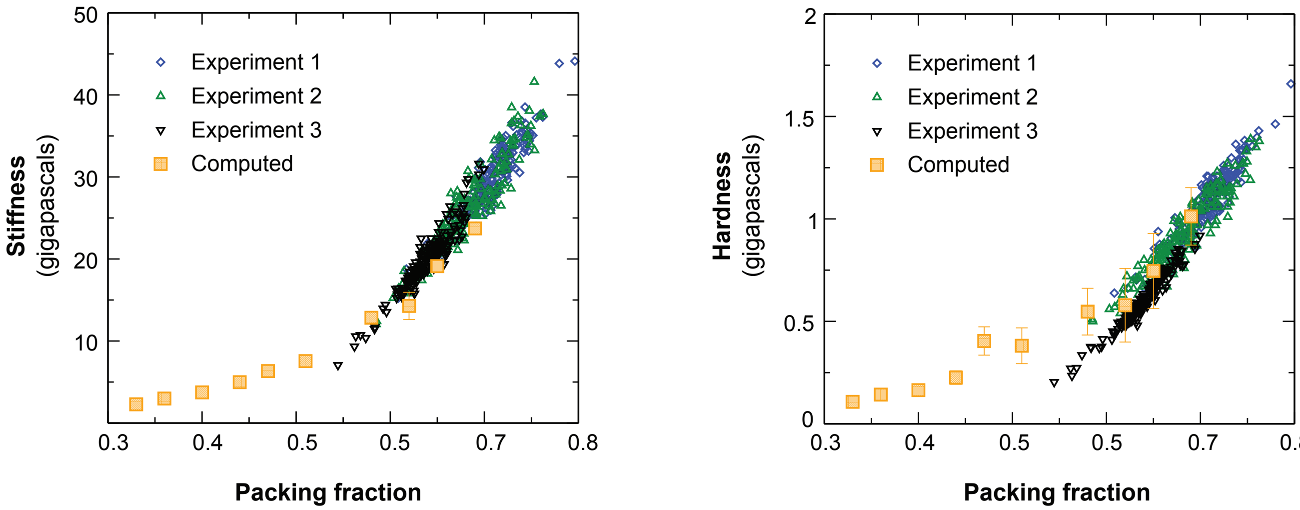
The research challenge

Laboratory investigation of a process that can take place over decades isn't practical, so the researchers turned to computer simulations. "Thanks to statistical physics and computational methods, we're able to simulate this system moving toward the equilibrium state in a couple of hours," says Ulm.

Based on their understanding of interactions among atoms within a particle, the researchers—led by MITEI postdoc Katerina Ioannidou—defined the forces that control how particles space out relative to one another as cement hydrate forms. The result is an algorithm that mimics the precipitation process, particle by particle. By constantly tracking the forces among the particles already present, the algorithm calculates the most likely position for each new one—a position that will move the system toward equilibrium. It thus adds more and more particles of varying sizes until the space is filled and the precipitation process stops.

Results from sample analyses appear in the first two diagrams in the figure on this page. The width of each simulation box is just under 600 nanometers—about a tenth the diameter of a human hair. The two analyses assume different packing fractions, that is, the total fraction of the simulation box occupied by particles. The packing fraction is 0.35 in the left-hand diagram and 0.52 in the center diagram. At the lower fraction, far more of the volume is made up of open pores, indicated by the white regions.

Measured and calculated cement hydrate stiffness and hardness



These figures show stiffness and hardness of cement hydrate at various packing fractions as measured by nanoindentation in three laboratory samples (small symbols) and calculated in a simulated sample generated by the researchers' model (yellow squares). The simulation results match the experimental data well. The computed results extend down to packing fractions that produce material too soft to be tested experimentally.

The third diagram in the figure on page 18 is a sketch of the cement hydrate structure proposed in pioneering work by T.C. Powers in 1958. The similarity to the center figure is striking. The MIT results thus support Powers' idea that the formation of mesoscale pores can be attributed to the use of excessive water during hydration—that is, more water than needed to dissolve and precipitate the cement hydrate. "Those pores are the fingerprint of the water you put into the mix in the first place," says Pellenq. "Add too much water, and at the end you'll have a cement paste that is too porous, and it will degrade faster over time."

To validate their model, the researchers performed experimental tests and parallel theoretical analyses to determine the stiffness and hardness (or strength) of cement hydrate samples. The laboratory measurements were taken using a technique called nanoindentation, which involves pushing a hard tip into a sample to determine the relationship between the applied load and the volume of deformed material beneath the indenter.

The figures on this page show results from small-scale nanoindentation tests on three laboratory samples (small symbols) and from computations of those properties in a "sample" generated by the simulation (yellow squares). The figure on the left shows results for stiffness, the figure on the right results for hardness. In both cases, the X-axis indicates the packing fraction. The results from the simulations match the experimental results well. (The researchers note that at lower packing fractions, the material is too soggy to test experimentally—but the simulation can do the calculation anyway.)

In another test, the team investigated experimental measurements of cement hydrate that have mystified researchers for decades. A standard way to determine the structure of a material is using small-angle neutron scattering (SANS). Send a beam of neutrons into a sample, and how they bounce back conveys information about the distribution of particles and pores and other features on length scales of a few hundred nanometers.

SANS had been used on hardened cement paste for several decades, but the measurements always exhibited a regular pattern that experts in the field couldn't explain. Some talked about fractal structures, while others proposed that concrete is simply unique.

To investigate, the researchers compared SANS analyses of laboratory samples with corresponding scattering data calculated using their model. The experimental and theoretical results showed excellent agreement, once again validating their technique.
In addition, the simulation elucidated the source of the past confusion:
The unexplained patterns are caused by the rough edges at the boundary between the pores and the solid

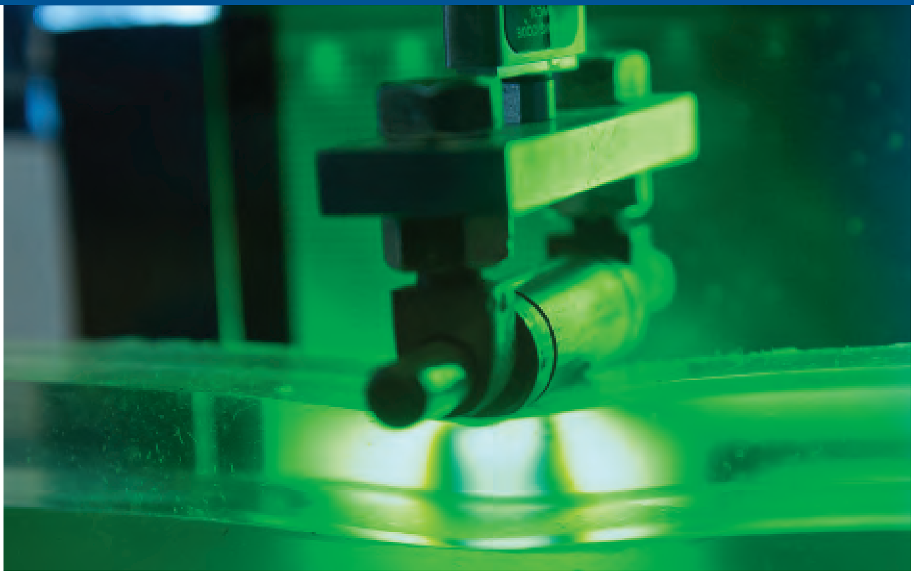


Photo: Stuart Darsch

In this novel CSHub experimental setup, a half-inch tire of rigid steel rolls along a polymer pavement, providing a detailed look at the interaction between the wheel and the pavement structure. Tests show that the maximum pavement deflection is just behind the path of travel; in effect, the wheel is constantly rolling uphill. Making road surfaces stiffer—for example, by adding a concrete layer—would mitigate that effect, decreasing wasted fuel and associated emissions.

regions. "All of a sudden we could explain this signature, this mystery, but on a physics basis in a bottom-up fashion," says Ulm. "That was a really big step."

New capabilities, new studies

"We now know that the microtexture of cement paste isn't a given but is a consequence of an interplay of physical forces," says Ulm. "And since we know those forces, we can modify them to control the microtexture and produce concrete with the characteristics we want." The approach opens up a new field involving the design of cement-based materials from the bottom up to create a suite of products tailored to specific applications.

The CSHub researchers are now exploring ways to apply their new techniques to all steps in the life cycle of concrete. For example, a promising beginning-of-life approach may be to add another ingredient—perhaps a polymer—to alter the particle-particle interactions and serve as filler for the pore spaces that now form in cement hydrate. The result would be a stronger, more durable concrete for construction and also a high-density, low-porosity cement that would perform well in a variety of applications. For instance, at today's oil and natural gas wells, cement sheaths are generally placed around drilling pipes to keep gas from escaping. "A molecule of methane is 500 times smaller than the pores in today's cement, so filling those voids would help seal the gas in," says Pellenq.

The ability to control the material's microtexture could have other, less-expected impacts. For example, novel CSHub work has demonstrated that the fuel efficiency of vehicles is significantly affected by the interaction between tires and pavement. Simulations and experiments in the lab-scale setup shown in the image above suggest that making concrete surfaces stiffer could reduce vehicle fuel consumption by as much as 3% nationwide, saving energy and reducing emissions.

Perhaps most striking is a concept for recycling spent concrete. Today, methods of recycling concrete generally involve cutting it up and using it in place of gravel in new concrete. But that approach doesn't reduce the need to manufacture more cement. The researchers' idea is to reproduce the cohesive forces they've identified in cement hydrate. "If the microtexture is just a consequence of the physical forces between nanometer-sized particles, then we should be able to grind old concrete into fine particles and compress them so that the same force field develops," says Ulm. "We can make new binder without needing any new cement—a true recycling concept for concrete!"

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By Nancy W. Stauffer, MITEI

This research was supported by Schlumberger; France's National Center for Scientific Research (through its Laboratory of Excellence Interdisciplinary Center on MultiScale Materials for Energy and Environment); and the Concrete Sustainability Hub at MIT (cshub.mit.edu). Schlumberger is a Sustaining Member of the MIT Energy Initiative. The research team also included other investigators at MIT; the University of California at Los Angeles; Newcastle University in the United Kingdom; and Sorbonne University, Aix-Marseille University, and the National Center for Scientific Research in France. Further information can be found in:

K. Ioannidou, K.J. Krakowiak, M. Bauchy, C.G. Hoover, E. Masoero, S. Yip, F-J. Ulm, P. Levitz, R.J-M. Pellenq, and E. Del Gado. "Mesoscale texture of cement hydrates." *Proceedings of the National Academy of Sciences*, vol. 113, no. 8, pp. 2029–2034, 2016.

R.J-M. Pellenq, A. Kushima, R. Shahsavari, K.J. Van Vliet, M.J. Buehler, S. Yip, and F-J. Ulm. "A realistic molecular model of cement hydrates." *Proceedings of the National Academy of Sciences*, vol. 106, no. 38, pp. 16102–16107, 2009.

M.J.A. Qomi, K.J. Krakowiak, M. Bauchy, K.L. Stewart, R. Shahsavari, D. Jagannathan, D.B. Brommer, A. Baronnet, M.J. Buehler, S.Yip, F.-J. Ulm, K.J. Van Vliet, and R.J-M. Pellenq. "Combinatorial molecular optimization of cement hydrates." *Nature Communications*, vol. 5, doi:10.1038/ncomms5960, 2014.

Regulating particulate pollution

Novel analysis yields new insights

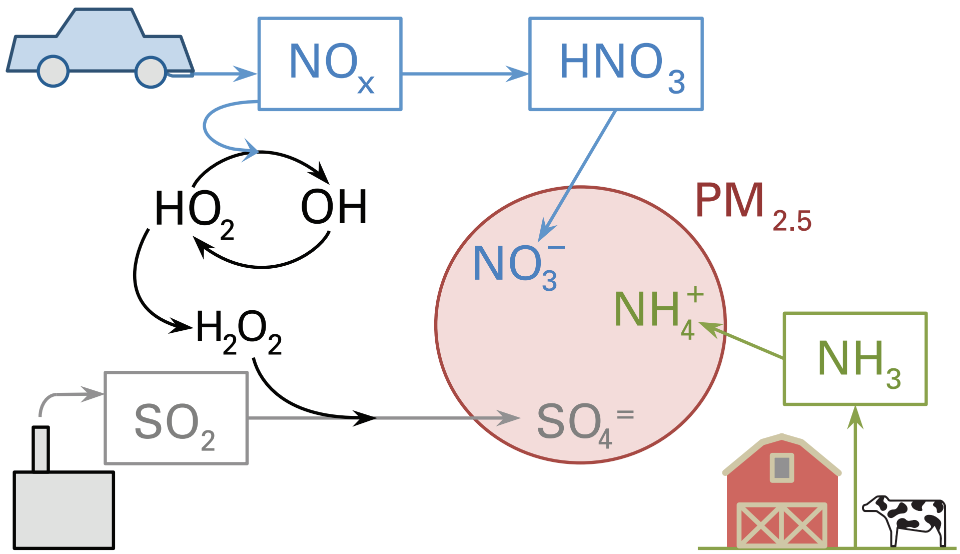
Left to right: Jareth Holt, Susan Solomon, and Noelle Selin of earth, atmospheric and planetary sciences have developed new insights into how energy-related emissions form fine airborne particles that damage human health, and they have demonstrated a new way to design emissions-control measures specially tailored to reduce particulate pollution in a specific location.

This research was supported by the MIT Energy Initiative Seed Fund Program. See page 24 for more information on funding and a publication resulting from this research.

Photo: Justin Knight

An MIT analysis of how best to reduce fine particulate matter in the atmosphere has brought some surprising results. Due to past regulations, levels of key emissions that form those harmful particles are now lower than they were a decade ago, causing some experts to suggest that cutting them further might have little effect. Not true, concludes the MIT study. Using an atmospheric model, the researchers found that new policies to restrict the same emissions would be even more effective now than they were in the past. Further analysis elucidated the chemical processes—some unexpected—that explain their findings. Their results demonstrate the importance of tailoring air pollution policies to specific situations and of addressing a variety of emissions in a coordinated way.

Formation of fine particulate matter from atmospheric emissions



This sketch shows the three major emissions that form inorganic fine airborne particulate matter: nitrogen oxides (NO_x) largely from vehicles, sulfur dioxide (SO_2) from power plants and industrial facilities, and ammonia (NH_3) from agricultural activities. Sunlight and chemical reactions in the atmosphere convert the emissions to new chemical species that can combine to form tiny particles known as $PM_{2.5}$.

One of the most pervasive and worrisome of today's air pollutants is particulate matter known as $PM_{2.5}$. Less than 2.5 microns in diameter, these tiny particles are too small to see, but they can lodge deep within the lungs, causing health problems—including asthma and heart disease—and premature death. Many of these particles are the result of chemical reactions within water droplets among three types of emissions: nitrogen oxides (NO_x) primarily from vehicles, sulfur dioxide (SO_2) from power plants and industrial facilities, and ammonia (NH_3) from agricultural activities (see the diagram on this page). The mix of multiple emissions and the chemistry involved make regulating this type of pollution tricky: Reducing a given emission by 5% won't necessarily reduce $PM_{2.5}$ formation by 5%. Nevertheless, past regulations limiting NO_x and SO_2 emissions—along with economic trends and increased use of natural gas—have reduced $PM_{2.5}$ concentrations over the past decade or so.

Even so, problems persist in some regions, so more policy action is needed if damage to human health is to be reduced. But how best to achieve further cuts in $PM_{2.5}$ hasn't been clear, according to Noelle Selin, the Esther and Harold E. Edgerton Career Development Associate Professor in MIT's Institute for Data, Systems, and Society and the Department of Earth, Atmospheric and Planetary Sciences (EAPS). The reason? Background concentrations of NO_x and SO_2 are now far lower than they were, and that change could profoundly affect the chemistry by which emissions form $PM_{2.5}$.

As a result, some experts have suggested that further cuts in NO_x and SO_2 could have diminishing returns. Indeed, several years ago, Selin and her EAPS colleague Susan Solomon, the Ellen Swallow Richards Professor of Atmospheric Chemistry and Climate Science, wondered whether the dramatic changes in NO_x and SO_2 concentrations in the last decade had changed the background chemistry such that decreasing SO_2 emissions might actually now increase formation of $PM_{2.5}$ because of how the emitted chemicals interact as they form particles.

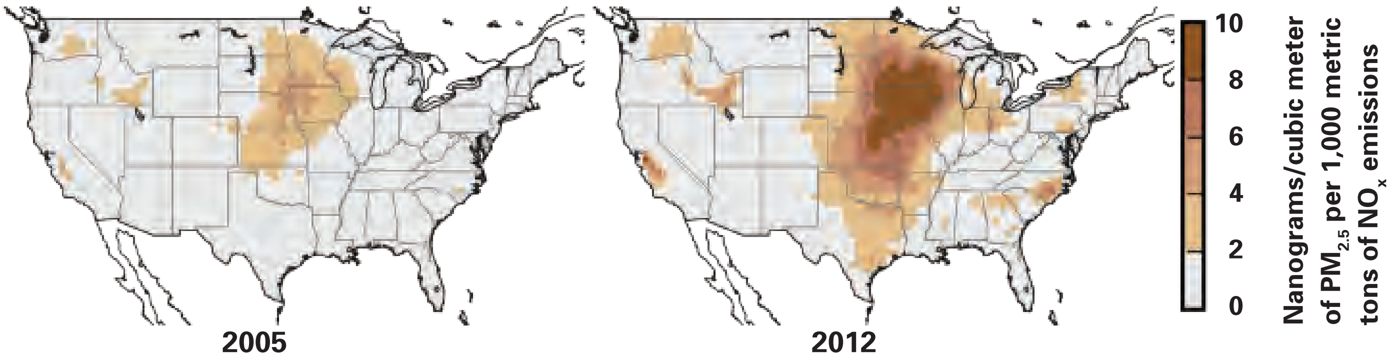
Clearly, making sound regulations for particulate pollution is now more difficult than ever. "For policymaking, we'd like to know what the effectiveness of cutting one unit of a given emission would be," says Selin. "But for every unit of NO_x emitted, you might get a different amount of $PM_{2.5}$ forming depending on background conditions." Understanding the chemistry of $PM_{2.5}$ formation is thus critical to designing policies that will "give us the most bang for our buck," notes Selin.

Over the past three years, Selin, Solomon, and EAPS graduate student Jareth Holt have used complex models of chemical reactions in the atmosphere to examine that chemistry and determine how $PM_{2.5}$ responds to changes in emissions levels, taking into account ambient conditions and chemistries. The analysis provides new insights into the processes by which $PM_{2.5}$ forms, including unexpected changes in what controls the outcome when background conditions vary.

The MIT analysis

In their study, the MIT researchers focused on 2005 and 2012—years with markedly different background chemistries: Between 2005 and 2012, emissions of NO_x dropped by 42% and SO_2 by 62%, while ammonia remained about constant. They calculated "sensitivities"—how much less (or more) $PM_{2.5}$ forms for a one-unit decrease (or increase) in emissions—for each of the three emissions in 2005 and 2012 all across the United States. And to capture the effects of temperature and humidity, they performed calculations for both winter and summer of each year.

Sensitivities of $PM_{2.5}$ to NO_x in winter of 2005 and 2012



These maps show sensitivities of $PM_{2.5}$ concentrations to emissions of NO_x at locations across the United States in winter of 2005 (left) and 2012. The darker the color, the greater the concentration of $PM_{2.5}$ formed for every 1,000 metric tons of emitted NO_x. In general, sensitivities are higher in 2012 than in 2005. Therefore, reducing NO_x emissions now would bring an even larger reduction in $PM_{2.5}$ than it brought in the past.

They based the 2005 calculations on emissions levels from the US Environmental Protection Agency's National Emissions Inventory. Geographically resolved emissions inventories weren't yet available for 2012, but the nationwide percentage change in each of the three emissions was known. So using that percentage, the researchers adjusted the 2005 data to generate 2012 values for emissions levels across the country, thereby obtaining values for both high-emissions (2005) and low-emissions (2012) scenarios.

To simulate $PM_{2.5}$ formation, the researchers used GEOS-Chem, a global chemical transport model that can track the atmospheric chemistry and 3-dimensional transport of pollutants. The following example demonstrates how they calculated the sensitivities of interest. To determine the sensitivity of $PM_{2.5}$ formation to NO_x emissions at a given time, they needed to see how a small change in those emissions would change the amount of $PM_{2.5}$ formed. So for winter of 2005, they set appropriate ambient conditions and ran two simulations, one starting with emissions 10% higher and the other 10% lower than the EPA data for that year. Comparing the results of the two simulations gave them their sensitivity value for winter of 2005, that is, the effect of a small change in emissions at that time. To test the impact of lower background concentrations of NO_x, they then used the same procedure to calculate a sensitivity value based on their emissions data for winter of 2012.

Unexpected findings

The researchers performed the same analysis to find the sensitivities of each of the three pollutants—NO_x, SO_2, and ammonia—using their 2005 and 2012 data and assuming winter and summer ambient conditions. They found that sensitivities differ significantly in some cases—not only by year but also by season and by location within the United States. But in general, for both NO_x and SO_2, the findings run counter to expectations: While many experts would have expected sensitivities to be lower when background concentrations are lower, in many cases the calculated sensitivities are higher, meaning that more $PM_{2.5}$ is formed for every unit of NO_x and SO_2 emitted into the atmosphere.

As an example, the maps above show results for wintertime sensitivities of $PM_{2.5}$ formation to NO_x emissions in 2005 (left) and 2012. Each point on the map shows the change in $PM_{2.5}$ at that location that results from a change in NO_x emissions of 1,000 metric tons. The darker the color, the greater the response to the emissions change. A comparison of the two maps shows that the sensitivity is generally higher in 2012 than in 2005, especially in the cold, humid areas of the northern Midwest. Indeed, in those regions, the sensitivity is twice as high in 2012 as in 2005, so far more $PM_{2.5}$ is formed per unit NO_x emitted in 2012 than in 2005.

Sensitivities of $PM_{2.5}$ formation to SO_2 are likewise greater in 2012 than in 2005—both year-round and across most of the United States. One result stands out: Sensitivity to SO_2 is up to 80% larger in 2012 than in 2005 in the eastern United States in the summer. In contrast, sensitivities to ammonia emissions are some 40% lower in 2012 than in 2005, year-round and across the United States.

The results provide important guidance for policymaking: If more $PM_{2.5}$ forms for each unit of NO_x and of SO_2 emitted now than in 2005, then the potential benefits of policies restricting those emissions have not shrunk since 2005 but rather increased in much of the country—for NO_x, especially in the most polluted areas. "Because NO_x levels have changed enough, you're in a situation now where if you reduced NO_x you could improve air quality significantly in the Midwest," says Solomon.

Understanding why

Further analysis of the $PM_{2.5}$ chemistry yielded explanations for those unexpected findings. How much of the airborne emissions enters an atmospheric particle depends on the availability and solubility of the three types of emitted chemicals and also on the need to maintain a neutral electrical balance within the particle. As the emissions pass through the atmosphere, they interact with light, water, and other chemical species, and—as shown in the figure on page 22—they ultimately are converted to an electrically charged form: NO_x becomes nitrate (NO_3^-), SO_2 becomes sulfate (SO_4^{2-}), and ammonia becomes ammonium (NH_4^+). The ammonium is the only positively charged ion; the nitrate and sulfate are both negative. Those components combine in the form of ammonium nitrate or ammonium sulfate in the particle such that there is no net charge. (The reactions are sensitive to temperature and relative humidity.)

That charge balance helps explain why the calculated wintertime sensitivity of $PM_{2.5}$ formation to NO_x emissions in some regions—in particular, the northern Midwest—is higher rather than lower in 2012. In 2005, there was an excess of nitrogen, so additional NO_x wouldn't yield more ammonium nitrate in particles. The NO_x would become nitrate in the atmosphere, but it wouldn't form ammonium nitrate because there wouldn't be ammonia available to combine with it and neutralize its negative charge. Given abundant nitrogen, the availability of ammonia limits $PM_{2.5}$ formation.

But when nitrogen is no longer plentiful, it becomes the limiting factor in the formation of ammonium nitrate in particles. "So when NO_x emissions dropped, we went from having an excess of nitrate [in the atmosphere] to having not enough nitrate to neutralize all the available ammonia," explains Selin. "In our model, winter conditions in the northern Midwest crossed that [chemical] threshold between 2005 and 2012. The 'chemical regime' changed, and suddenly every additional nitrate really matters because it will combine with ammonia to form more $PM_{2.5}$. So this suggests that cutting NO_x emissions now might result in even more benefit than it did in 2005."

The fate of SO_2 was also a surprise. The researchers had hypothesized that if sulfur emissions were removed but nitrogen emissions were still present, nitrate would simply replace the sulfate in the particles. Indeed, ammonium nitrate might form even more readily than ammonium sulfate does, and $PM_{2.5}$ formation could increase.

But according to the analysis, that process isn't the dominant chemical mechanism at work in 2012. The lower concentration of NO_x in the atmosphere in 2012 is accompanied by a higher concentration of a key oxidizing compound that converts SO_2 to sulfate. That conversion process occurs more quickly, so there's more sulfate present in the atmosphere to combine with ammonia and produce $PM_{2.5}$.

"So we found that what's driving the change isn't the chemistry of the particle—as we had expected—but rather the chemistry in the gases in the atmosphere," says Selin. "And the result is that reducing the amount of SO_2 in the atmosphere will reduce $PM_{2.5}$ formation even more in 2012 than it did in 2005."

Taken together, the findings of the study demonstrate the importance of understanding the processes that lead to $PM_{2.5}$ formation before taking policy action. Moreover, given the major role played by interactions among the emissions, the researchers recommend considering a coordinated, multi-pollutant approach to regulation that may involve a range of emission sources, stakeholders, and government agencies.

Perhaps the most important outcome of their study, notes Solomon, is the demonstration of a new way to analyze the $PM_{2.5}$ problem in any year and location. "Applying it to other places would be pretty exciting," she says. "For example, Beijing and New Delhi have terrible pollution problems. Where are they going to get the best leverage on improving their air quality?" Answering that question is the first step in designing a cost-effective, efficient approach to reducing particulate pollution and the threat it poses to human health and well-being.

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By Nancy W. Stauffer, MITEI

This research was supported by the MIT Energy Initiative Seed Fund Program. Follow-on research is being funded by the US Environmental Protection Agency. Further information can be found in:

J. Holt, N.E. Selin, and S. Solomon. "Changes in inorganic fine particulate matter sensitivities to precursors due to large-scale US emissions reductions." *Environmental Science & Technology*, vol. 49, pp. 4834–4841, 2015.

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

The MIT Energy Initiative (MITEI) has announced nine awards totaling $1.3 million under its annual Seed Fund Program. Winning teams across campus will use the grants—in amounts of up to $150,000 each—to support early-stage innovative research across the energy spectrum.

Over the past nine years, the MITEI Seed Fund Program has supported 151 energy-focused research projects including the latest round, amounting to a total of $19.9 million in funding. Grant awardees include well-established faculty and new professors just beginning to define their research paths at MIT. The competition encourages entrants to collaborate in novel ways to explore energy ideas.

"MITEI's Seed Fund awards provide fertile ground for innovative and collaborative research efforts aimed at key global energy and climate solutions," says MITEI Director Robert C. Armstrong, the Chevron Professor of Chemical Engineering. "The early-stage projects that our members are supporting through the Seed Fund Program this year have immense potential, and I have no doubt they'll join the ranks of past years' winners in successfully tackling some of our most difficult energy questions."

The nine projects were selected out of a record pool of 81 proposals representing 23 departments, labs, and centers. Four out of the nine projects involve collaborations of two or more principal investigators, and three collaborations span multiple departments. Topics addressed range from synthetic fuel production to energy storage to energy cybersecurity.

One of the winners is a design for metal-oxide surfaces to enable fast oxygen exchange in fuel cells. The project—a collaboration between Bilge Yildiz, associate professor of nuclear science and engineering, and Ahmed Ghoniem, the Ronald C. Crane ('72) Professor of Mechanical Engineering—seeks to significantly improve the performance of perovskite oxides that function in extreme environments. Yildiz says, "The MITEI Seed Fund Program is a critical enabler for faculty to initiate novel research directions and form new multidisciplinary collaborations with colleagues at MIT." The goal of her team's proposal, she says, is "to improve materials not only for solid oxide fuel cells and electrolyzers, which I study in my own laboratory, but also for gas conversion and thermochemical reactors to produce clean fuels, which are Ahmed Ghoniem's area of expertise."

In another winning project, Yogesh Surendranath, assistant professor of chemistry, and T. Alan Hatton, the Ralph Landau Professor of Chemical Engineering, are collaborating on a project aiming to cycle carbon dioxide (CO_2) emissions back into chemical fuel. Surendranath says that he and Hatton are "eager to work together to address the dual challenges of carbon dioxide capture and conversion to valuable fuels—a key component of a low-carbon energy future."

Another awarded Seed Fund project, to be conducted by Stuart Madnick, the J.N. Maguire Professor of Information Technologies in the MIT Sloan School of Management and professor of engineering systems in the School of Engineering, will test a new method of cybersecurity risk reduction for energy systems based on applying concepts from industrial safety and systems thinking, called the Cybersafety Analysis Approach. The need for such a method is motivated by the intensified security risks presented by today's increasingly complex and dynamic energy systems. Madnick plans to initially experiment with this method in action using the MIT Cogeneration Plant as a test case.

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

A full list of the winning projects and teams follows.

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By Francesca McCaffrey, MITEI

Recipients of MITEI Seed Fund grants, spring 2016

Advanced algorithms for carbon capture and sequestration monitoring

Michael Fehler
Earth, Atmospheric and Planetary Sciences
Laurent Demanet
Mathematics
Aimé Fournier
Earth, Atmospheric and Planetary Sciences

Aluminum polymer battery for automobile propulsion

Donald Sadoway
Materials Science and Engineering

Combined electrochemical concentration and upgrading of carbon dioxide

Yogesh Surendranath
Chemistry
T. Alan Hatton
Chemical Engineering

Cost-optimizing solar power systems for water desalination
Amos Winter
Mechanical Engineering
Tonio Buonassisi
Mechanical Engineering
Ian Marius Peters
Mechanical Engineering

Cybersafety analysis of energy systems
Stuart Madnick
MIT Sloan School of Management

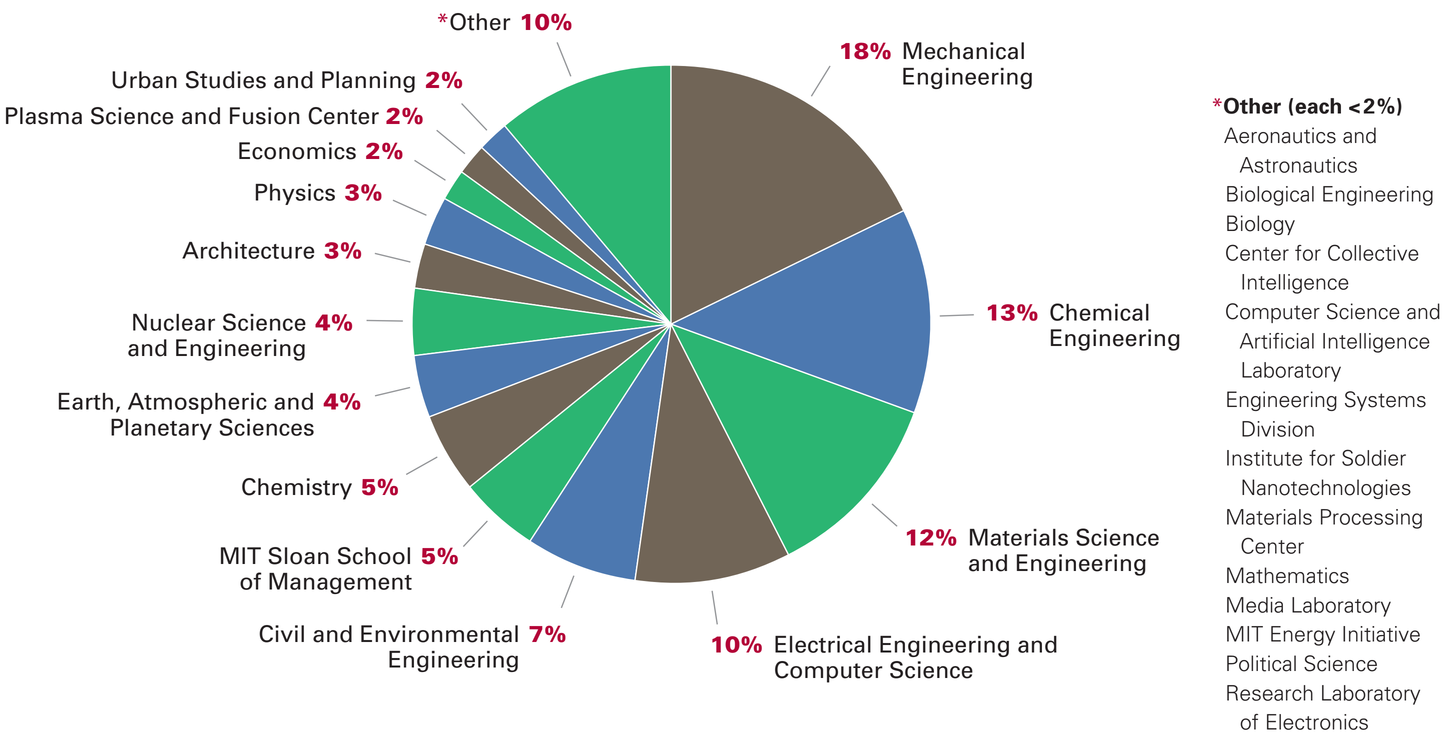
Design of metal-oxide surfaces for fast oxygen exchange in fuel cells, synthetic fuel production, and separation membranes
Bilge Yildiz
Nuclear Science and Engineering
Ahmed Ghoniem
Mechanical Engineering

Efficient ensemble-based closed-loop oil reservoir management using hyper-reduced-order models
John Williams
Civil and Environmental Engineering

Engineering bifunctional catalysts for CO_2-Fischer Tropsch
Yuriy Roman
Chemical Engineering

Understanding the impact of electric vehicle charging on the power grid: An urban mobility perspective
Marta Gonzalez
Civil and Environmental Engineering

Campus-wide distribution of Seed Fund participation



The 151 projects supported by the MITEI Seed Fund Program over the past nine years have involved 225 faculty and senior researchers from 27 departments, labs, and centers in all five of MIT's schools. This pie chart shows the distribution of projects based on the affiliations of those participants. Of the winning proposals, 61 involved between two and five principal investigators, demonstrating the Seed Fund Program's effectiveness in fostering creative collaborations among researchers throughout the Institute.

Air quality sensors: Understanding emissions in the world's most polluted cities

Glimpses of blue sky are becoming a rare sight in Delhi, India's capital, particularly in wintertime, when a thick white haze smothers the city. David Hagan, an MIT PhD candidate studying atmospheric chemistry and a Fellow in the MIT Tata Center for Technology and Design, says that the city's air quality is now quantifiably among the worst in the world.

"Beijing has bad episodes, but Delhi is worse because of the meteorology," says Hagan. "It's hot, it's humid, and in the winter an inversion layer settles in. Delhi is a perfect reactor of anthropogenic and biogenic particulates."

Meanwhile, a lack of specific data has frustrated scientists and governments hoping to understand the complex environments of megacities in India and China, where air quality is inextricably linked to energy systems. Emissions in megacities like Delhi can be traced to a wide variety of sources, including automobiles, fossil fuel-driven power plants, and open burning of biomass for warmth and cooking, each producing different kinds of particles.

Hagan and his advisor, Associate Professor Jesse Kroll of civil and environmental engineering, saw this complexity as motivation to design a compact, low-cost air quality sensor that they hope will be deployed in dense networks across cities like Delhi, logging accurate, real-time data on the chemistry of the air.

"Air quality monitoring is often discussed as an either-or situation," says Kroll. "One can have expensive, regulatory-grade monitors or else distributed, low-cost sensors. But in reality it's a continuum, with a tradeoff between cost, size, and power on one hand, and accuracy, precision, and sensitivity on the other. We're somewhere in the middle of the continuum, with enough accuracy and precision to provide quantitative measurements."

Photos: Shriya Parekh, MIT Tata Center

David Hagan, a Tata Fellow and PhD candidate in civil and environmental engineering, is designing and building low-cost sensors that could be deployed in dense networks to monitor air pollution. Here, Hagan makes some last-minute tweaks to his prototype in a hotel room in New Delhi, India.

"If we can generate a better data set," Hagan adds, "it could lead to a sustainable public good."

The production of $PM_{2.5}$ (particulate matter less than 2.5 microns across) is a particular area of concern for epidemiologists. These fine particulates are largely generated by fuel combustion, and when they're inhaled, they can have dire health effects, including asthma, lung disease, and heart attack. In fact, a recent study by the Chittaranjan National Cancer Institute estimated that half of Delhi's schoolchildren have suffered irreversible lung damage.

"In Manhattan the highest level of $PM_{2.5}$ you'll see is about 12 micrograms per cubic meter," Hagan says. "Delhi can be anywhere from 150 to 1,000 micrograms per cubic meter, so the levels are dozens of times higher. However, there is no safe level of $PM_{2.5}$. We all have a long way to go to make it better."

Kroll and Hagan already have several prototypes on the ground in India, reporting data to a remote server every 30 seconds. Two units are located at Nehru Place in south Delhi, and four are near Connaught Place in central Delhi, co-located with a regulatory-grade sensor for calibration. Two are in the city of Pune, near Mumbai, and one is mobile—Hagan can frequently be seen taking it on rickshaw rides around Delhi.

A regulatory-grade sensor, of which there are roughly 20 in Delhi, costs between \$50,000 and \$100,000. Kroll and Hagan's sensor costs "on the order of \$1,000" per unit, says Hagan, and offers comparable performance, measuring six types of gases (O_3, NO, NO_2, SO_2, CO, and volatile organic compounds) and 16 size groups, or "bins," of particles, ranging from coarse to fine. The lower cost makes it feasible for these sensors to be deployed in large volumes, creating an opportunity to map pollutant distribution at greater levels of detail.

There are several low-cost and do-it-yourself devices on the market already, but the sensitivity of Hagan's design, including its ability to measure particles as small as 380 nanometers across, sets it apart.

"Most low-cost sensors only measure one size bin of particulate—coarse," he says. "I'm very interested in both the atmospheric chemistry and the user experience, which is why my sensor is different. There hasn't been a low-cost sensor made with a good mix of quality components and a well-engineered interface."

Kroll adds: "We're interested in measurements with reasonably good spatial coverage, but that are also directly comparable to those from regulatory-grade monitors and that provide insight into the chemical changes that pollutants undergo in the atmosphere."

Part of the learning process for Kroll and Hagan has been understanding how the sensors will respond to a diverse set of environmental circumstances.

They, along with other MIT researchers, have subjected different generations of sensors to the seasonal extremes of the Boston area, where two small grids are up and running—one on the MIT campus and the other in Dorchester—and to the highly variable conditions around the Hawaiian volcano Kilauea.

Now, with a refined prototype, they're beginning to see how the intense heat and dirty air of Delhi will affect the sensor's performance. One of the Nehru Place sensors became so clogged with black grime that air could no longer pass through, and, ironically, it began to record low pollutant numbers.

PhD candidate David Hagan frequently takes his sensor on rides around Delhi in one of the ubiquitous auto-rickshaws that fill the Indian capital's streets. Rickshaw drivers and passengers are exposed to some of the highest levels of air pollution in the world.

Transparency is vital to the success of the project, Hagan says. "It's important to be honest about what the sensor is measuring and what its limitations are." He adds, "The next generation will be much better," citing a robust filtration system to prevent clogging and a smaller, more energy-efficient design.

Hardware is just one part of the equation. Hagan also wrote the algorithms that interpret the sensors' raw data. He envisions a number of different possible applications for the data in both the public and private sectors. Governments and academic researchers could use it to identify emissions sources and create mitigation strategies, while factories and office buildings could integrate the sensors into their HVAC systems for indoor air quality monitoring. Entrepreneurs might purchase access and use the data in commercial products, such as in-home monitoring systems or smartphone apps that show people real-time information on the air they're breathing.

For millions of Delhi residents who live with the effects of air pollution every day, solutions can't come soon enough.

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By Ben Miller, MIT Tata Center for Technology and Design

This research was supported by the MIT Tata Center for Technology and Design (tatacenter.mit.edu). More details can be found at tatacenter.mit.edu/portfolio/air-pollution-sensors. To read about an MIT analysis of $PM_{2.5}$ formation and regulatory strategies for controlling it, please turn to page 21 of this issue.

John Fernandez: Growing grassroots for sustainability on campus and abroad

John Fernandez '85 is not interested in overleaping boundaries so much as erasing them. The MIT professor, who was recently named director of the Environmental Solutions Initiative (ESI), started out as a child who loved math and art, and saw no reason to keep them separate.

"What brought me to MIT was my love of math. But I had always loved to draw, too, and I found sketching and the arts super interesting."

The "happy medium," as Fernandez calls it, for a student like him was architecture and design—the subject he ended up studying, and later teaching, at MIT.

"I have always been most excited by creating an environment where there are no boundaries between disciplines," he says. "In architecture, the most important boundary to dismiss is that boundary between design and technology or science. For me there is no boundary there. It's all the same thing."

Architecture is also what brought Fernandez to the topic of sustainability. The period when he was studying architecture in school coincided with the rise of the green building movement. The United States Green Building Council had just been formed—the organization that would soon introduce the voluntary LEED (Leadership in Energy and Environmental Design) certification process, the most widely used third-party verification system for sustainable building in the world.

Today, this interest in sustainability and architecture has grown from a focus on buildings into an interest in the cities in which they're housed. Fernandez studies urban resource flows, also known as "urban metabolism." Since starting the

Photo: Jose Mandojana, courtesy of MIT Resource Development Communications

John Fernandez '85, professor of building technology in the Department of Architecture and director of the MIT Environmental Solutions Initiative.

Urban Metabolism Group at MIT a decade ago, Fernandez has conducted research in several cities across the globe, including Lima, Manila, Los Angeles, New York, Lisbon, and Boston.

This research on sustainability played a large part in Fernandez's selection in October 2015 as director of ESI, succeeding Susan Solomon, the Ellen Swallow Richards Professor in the Department of Earth, Atmospheric and Planetary Sciences, who served as the initiative's founding director.

ESI's focus is environmental and social sustainability at all scales, from campuswide to worldwide. In the MIT News announcement of the new appointment, Solomon emphasized Fernandez's international research on urban sustainability as a major asset to ESI but explained that he also brings much more to the initiative. Fernandez, she said, "has a deep understanding of MIT's strengths across a very diverse suite of environmental challenges, and he brings a clear commitment to excellence and breadth."

This breadth becomes clear when Fernandez describes his vision for ESI. "There is enormous potential on campus to greatly expand in many different ways MIT's engagement with the environment, both locally and regionally, but also to extend MIT's role as a critical global player."

According to Fernandez, "research, education, and convening" are the pillars in ESI's next phase as an organization. He's looking forward to working with the MIT Energy Initiative, Office of Sustainability, Climate CoLab, Joint Program on the Science and Policy of Global Change, and others on campus engaged in solving challenges at the intersection of energy, environment, and climate change. Fernandez knows that participating in "strong, deep, and sustained conversations" will continue to propel MIT forward as a leader in these areas.

On the research front, a key ESI activity is providing seed funding for highly multidisciplinary projects that can be difficult to fund through traditional channels. In fall 2015, ESI awarded nine seed grants for research focusing on topics including sustainable consumption in cities, safe mining on land and at sea, and mitigating global climate change. The initiative expects to launch another round of seed grants in fall 2016.

In terms of education, says Fernandez, "We want to expand the undergraduate and graduate students' exposure to environmental topics as part of their education, as part of the offerings that are available for their courses and their individual research." ESI is now designing an environment and sustainability minor for undergraduates, in consultation with faculty and students across the Institute.

In Fernandez's view, MIT students are central to all ESI efforts. Part of the importance of focusing on students, he says, lies in engaging them to catalyze change. "We want to create a pathway from learning and research to action," he says. "Many of the most promising modes of action are student-driven."

In Fernandez's own research on urban metabolism, the action that stems from the data is also important. Fernandez and his fellow researchers are trying to "establish a typology, or classification, of urban resource consumption." In Fernandez's words, "The idea is that all cities are different, but we wondered whether you could group cities in clusters depending on their urban resource consumption." To bring this about, Fernandez and his team ran a statistical study and developed a global urban resource consumption profile. This profile, in turn, informed a computational model that enables city leaders to visualize their cities' resource needs and utilize materials and energy in the most efficient, sustainable way possible.

Research on this model is part of what has made Fernandez's travel destinations over the past decade so free-ranging: He aims to understand, and help others to understand, resource consumption on a global scale. The timescales he thinks in are similarly large. "One thought experiment we run is to imagine what pre-fossil-fuel-era cities' resource intensity was," he says. "If we want to have a post-fossil-fuel future, we can also look to the past for clues as to what that looks like."

There is no one answer. Fernandez is quick to point out that development needs vary greatly between what he refers to as "the global north and global south." This means that the ideal definition of urban sustainability varies, too. "In the north, stand-out cities are those that have begun to shift their existing infrastructure toward decarbonization and deep resource efficiency, including better water management and waste management systems," he says. "In the developing global south, model cities are those that are leapfrogging 20th century urban models to take advantage of renewable energies and decentralized and modular technologies and systems."

On top of this, Fernandez says, it's important to remember that the most important measure of a city's sustainability is how it treats its inhabitants. "Development and sustainability must be accomplished in a humane way," he says. "The most resource-efficient cities on the planet—the ones that run themselves with the least amount of resources—are also the least humane cities because they essentially underserve their populations. We need to couple sustainable development with lifting people to humane living standards."

On campus, director of ESI isn't Fernandez's only new position. He was recently made head of Baker House, meaning that he acts as a faculty presence within that slice of the student community, albeit "one who is never going to grade you." Fernandez and his family live in an apartment attached to the dorm, and he holds weekly events with the students. "Being head of house means you're someone students can bounce ideas off of and have an intellectual relationship with, but the evaluation piece goes away. That's really nice, because that cuts through the anxiety and the stress."

Being head of Baker also gives Fernandez a chance to partner with interested students on small-scale sustainability projects. One example, he says, is a form of dorm-scale indoor farming. The incentive, he says, is not just to have herbs and vegetables at the ready for cooking, but also "for the mental health benefits of having plants around."

The personal growth of students is important to Fernandez for several reasons. What he finds most exciting about teaching, he says, is "the full cycle. Seeing students going from the classroom out into the world within just a couple years, practicing in their fields and in many cases becoming champions of a better world—that's the most rewarding part of teaching."

By Francesca McCaffrey, MITEI

New electives augment undergraduate energy curriculum

Photo: Justin Knight

Jean-François Hamel, a research engineer in chemical engineering and instructor for 10.28 Chemical-Biological Engineering Laboratory (left), shows senior Juan Jaramillo the real-time results of bioreactor fermentation in the process of creating muconic acid, an essential ingredient in the manufacture of products including resins, food additives, and pharmaceuticals.

The first several classes in a wave of new electives for the Energy Studies Minor arrived in fall 2015, updating and expanding content for the undergraduate curriculum in energy science, technology, and policy. The S.D. Bechtel, Jr. Foundation provided funding for what will eventually be five new classes and new energy components for four existing classes.

These new additions are in large part a response to mounting undergraduate student demand for course-based exposure to energy applications in the private and public sectors as well as hands-on experience in energy technologies and for an energy education that addresses urgent, real-world challenges.

Jessica Torres, a senior majoring in chemical-biological engineering, says she is seeking ways "to help society come up with cleaner alternatives for producing things." Another senior, Juan Jaramillo, a chemical engineering major, says, "[I'm] driven to learn more about energy because it's an increasingly important topic in the industries I'm pursuing."

Cooking up cleaner compounds

Jaramillo and Torres were classmates in the energy module added last fall to 10.28 Chemical-Biological Engineering Laboratory, a core chemical engineering class taught since 2003 by Jean-François Hamel, a research engineer in chemical engineering.

"Students want to be ready to solve the urgent problems of the environmental impacts of traditional energy sources," says Hamel. "With this in mind, I try to offer innovative, state-of-the-art technology, communication, and software tools, and we teach them how to use these tools for solving real-world problems."

To meet student interest in bringing energy into the chemical engineering curriculum, Hamel worked to supplement the existing biopharmaceutical-oriented lab projects of 10.28 with a substantive energy project. He found an enthusiastic partner in the National Renewable Energy Laboratory (NREL), a government research entity exploring biologically derived alternatives to petrochemical-based manufacturing compounds.

For 10.28's energy module, NREL provided not only microbial strains but also a real-world research problem: optimizing bioprocessing methods for creating muconic acid, a substrate used when manufacturing resins, bioplastics, food additives, and pharmaceuticals. "Bioprocessing is the key word for 10.28," says Hamel, "and the theme of the course is to teach fundamental principles and elements of this field through different experiments."

Muconic acid is normally derived from oil, but it can also be produced by fermenting lignin, a biological waste left over from cellulosic ethanol production. Using NREL's genetically engineered bacterium, *Pseudomonas putida,* 10.28 students set out "to grow cells, achieve the right levels of product formation, and create value from an energy waste product," says Hamel.

For the nine students in 10.28 engaged in the energy module (more than one-third of the class), there was an extra dimension of excitement: They were conducting direct real-world research for NREL, which had not yet turned to these specific muconic acid experiments. "It is rare for undergraduates to get this kind of opportunity," notes Hamel.

"We had to…design the experiment, figure out what and how to test, and then report results," says Torres. "It was the first time I'd done that in a class." Adds Jaramillo, "I really liked that I was working in a cutting-edge lab, Photos: Justin Knight

Chemical engineering seniors Jessica Torres (left) and Ruifan Pei work on assembling a bioreactor that uses the genetically engineered bacterium *Pseudomonas putida* to ferment lignin, a plant waste from cellulosic ethanol, in the process of creating muconic acid.

learning to use bench-top bioreactors to help address an energy-related problem in an environmentally friendly fashion."

Students also had unusual access to sophisticated software, OSIsoft (courtesy of the OSIsoft company), which monitored their fermentation experiments in real time. "Using the bioreactors and software, which you can't usually find in a college classroom, was one of the most meaningful aspects of 10.28," says Jaramillo. "What I learned will be helpful in any industry I end up in."

Students also benefited from another aspect of the class: formally communicating their research results. 10.28 is one of chemical engineering's communication-intensive courses, and Hamel provided an opportunity that was simultaneously challenging and rewarding by inviting industry colleagues to observe the class for student presentations.

"I wanted to show industry what my students could do and also give students the benefit of having industry experts engage them and share their experience," says Hamel. These experts included representatives from Thermo Fisher Scientific, Inc., which lent the class a $100,000 mass spectrometer.

"I made it clear to students that high-quality presentations would prove very useful in learning how to interview for internships and jobs, as well as in their careers in general," Hamel says.

As a senior interested in an energy career, Torres made the most of her opportunity. "I felt like I knew a lot about the subject, and it was so good talking to industry professionals and hearing them say we did great job." Eager to leverage the skills and knowledge she gained from 10.28, Torres decided to apply for an internship directly related to bioprocessing. "I got so much out of the class and really became passionate about coming up with cleaner ways of approaching energy and making things."

"Several students were so fascinated that they have asked to stay with the energy bioprocessing research after the course," says Hamel. One of them was Jaramillo, who began work in Hamel's lab on reducing the level of ethanol in wine using yeast as a fermenting agent in bioprocessors. "I will let people know about my experience in the class, which definitely helped me grow as a scientist and professional," says Jaramillo.

Hamel has extended the NREL research to the spring version of the lab class, 10.26, with two projects from NREL, and he plans to include energy experiments in the classes going forward. He envisions his lab courses as potential additions to the core Energy Studies Minor classes. "I believe the energy module we've included opens up the class to deeper discussions," he says. "We're thinking more about the planet and climate change, and finding solutions."

Ethics and energy

Students in search of an elective devoted exclusively to deep discussion of energy and ethics last fall did not have far to look. That's when Lucas Stanczyk, assistant professor in political science, introduced 17.051 The Ethics of Energy Policy.

Developed in partnership with Nathan Lee SM '14, a former researcher with the MIT Energy Initiative, the class arose to meet a need: Climate change raises "very big policy problems that face us with important ethical dimensions," says Stanczyk. And according to Lee, "Nowhere in the MIT curriculum was there an opportunity for students to address these questions directly."

The class 17.051 attracted interest from schools and departments across MIT: 26 students enrolled, which "is pretty big for…first-time classes at MIT," says Stanczyk. Through a combination of lectures, seminar-style discussions, and essays, students tackled a range of topics, deploying Stanczyk's method of first identifying the fundamental ethical assumptions underlying a certain policy assessment framework, then drawing attention to potential questions or problems with the approach.

"We had lively discussions about a bunch of issues," says Stanczyk. For instance, the class debated what might be reasonable international standards for reducing greenhouse gas emissions: Should we take into account emissions since the beginning of the industrial age? Should developing nations be asked to make cuts on a par with rich countries, even if this comes at the cost of their ability to provide better lives to hundreds of millions of poor people?

According to Stanczyk, conversation became especially heated when the class considered whether individuals have a strong moral duty to reduce carbon by changing their own life habits. Students strongly defended passionately held positions.

"Many students came to class caring very deeply about some of these topics," says Stanczyk. But after carefully reasoned arguments, "they began to appreciate the complexity of questions, realizing they needed to rethink or even abandon some of their original background assumptions."

The class posed challenges for Stanczyk himself. "I had to gain new competencies such as learning the regulatory approaches of the Environmental Protection Agency and other administrative agencies." For his next pass at 17.051, Stanczyk must have command of the latest political, international, and technical developments in climate and energy policy. "There's new science demonstrating faster melt rates in Antarctica than previously thought, and [there's] the possibility that political parties might backtrack on international agreements," he says.

Stanczyk looks forward to teaching 17.051 again. "It was remarkable and rewarding working with students who on the one hand care deeply about energy policy issues and on the other hand are really in a position to understand and do something serious…about these issues in the course of their careers," says Stanczyk.

Left to right: Linda Jing '17, Seraphina Kim '16, Yoonjeong Kim '16, and Jacqueline Kuo '16 discuss their final group project for 15.S42, titled "GreenMIT: Using Collective Intelligence for Change at MIT," with guest Steven Lanou, deputy director, Office of Sustainability, and Joshua Lehman, class teaching assistant and graduate student at the MIT Sloan School of Management. The project involved spurring cross-campus interaction on ways of addressing climate change.

Enabling sustainable buildings

"If we're going to get where we need to go in climate, we need to engage young people at an early stage in their education," says Harvey Michaels, lecturer and member of the research faculty in energy strategy at the MIT Sloan School of Management. He developed 15.S42 Energy Management for a Sustainable Future as a way of introducing undergraduates to what he calls the "ecosystem" of building energy management, which he believes can make a dramatic impact on energy use and climate change.

Michaels has launched his own energy efficiency and smart grid startups and has supported MIT graduates in spawning their own energy management businesses. "[The MIT graduates] told me they would have benefited as undergraduates from a course focused on current practice and emerging opportunities in the field," he says. Having had to turn away undergraduates from his graduate-level energy management courses at MIT Sloan, Michaels says he "heard the need."

With 15.S42, he set out to create a foundational class for undergraduates touching on all dimensions of the demand side of energy in the built environment, including technology, services, analytics, and policy applied to improving efficiency.

In designing and teaching the class, Michaels recruited a group of complementary talents, including MIT Sloan management professors John Sterman and Thomas Malone (principal investigator of the Climate CoLab); Leon Glicksman, professor of building technology and mechanical engineering; and Sanjay Sarma, professor of mechanical engineering, vice president for Open Learning, and director of the Office of Digital Learning. Michaels also gained vital assistance from graduate students, including class teaching assistant Joshua Lehman of MIT Sloan, who was co-president of the MIT Energy Club in the 2015–2016 academic year.

Photo: Joshua Lehman G

At an outdoor session in November 2015, special guest Ben Bixby, director of energy products at Nest Labs, addresses the 15.S42 class while instructor Harvey Michaels looks on.

"I was really excited to hear about the course," says Lehman. "I'd felt for a long time that people were too focused on supply-side solutions to reducing the carbon intensity of our economy, like solar and wind power." For Lehman, who majored in environmental science at Brown University, energy demand management is at least as important. "Getting students interested in the demand side seems a powerful way to build awareness of this other path to sustainability."

The class last fall rolled out in stages: a "boot camp" that provided primers on such topics as building energy management technologies and innovations, grid economics, and energy markets; visits from experts and leaders in the energy management field; and research leading to group projects and presentations.

"It's such a big part of our lives, but before this class I didn't know anything about the grid, how utility companies worked, or how people got their energy," says senior Jacqueline Kuo of mechanical engineering. Kuo was one of 15 students from a range of majors who enrolled in 15.S42—her first energy class. "I got a really good overview of where our energy comes from."

Student encounters with energy management professionals took place both at MIT and on field trips to such companies as Boston's EnerNOC, which makes software to help commercial end-users save on energy in their buildings. As Michaels intended, the burden of learning during these interactions fell on the students. "Someone from Google/Nest came to class with a big presentation on their smart thermostat technology and business, and I said, 'Don't lecture,'" he recalls. "Students do the research and have to interview you."

The class took advantage of current events to focus on policy. One assignment asked students to write a letter to MIT President L. Rafael Reif (not intended for delivery) in response to the Institute's just-released climate action plan. "We had a lot of discussions in reaction to what was happening at MIT and in the climate change talks in Paris," says Kuo. "We learned a lot from each other, and the class felt really relevant."

For final projects, Michaels drove home the real-world applications of energy management. Students could choose either to devise an energy management-based policy for limiting worldwide temperature increases to 2°C or to propose strategies for improving energy use on campus by applying such techniques as new building technologies, retrofits, behavior tools, building analytics, and GIS data maps of the school's carbon footprint.

Students presented their plans to representatives from MIT's Department of Facilities and Office of Sustainability, and from KGS Buildings, a firm with MIT roots that is responsible for analyzing school energy usage.

"I wanted to give undergraduates some understanding and a level of excitement about energy management," says Michaels, who would like to situate a future version of 15.S42 in the Energy Studies Minor or in a potential environment and sustainability minor. "Some students want to work in this field after graduation, and I hope my class gave them ideas for improving the field once they're in it."

15.S42 has already proved a valuable stepping-stone for Kuo, who landed a job during January's Independent Activities Period with an engineering firm. "It was great because I had just taken a class on buildings and energy, and then I was applying all these tools for using energy more efficiently as a climate engineering intern," she says. "More classes like this should happen at MIT."

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By Leda Zimmerman, MITEI correspondent

For more details about the development of 17.051 The Ethics of Energy Policy, see the Spring 2014 issue of *Energy Futures* or go to energy.mit.edu/energyfuturesspring16. The MIT Energy Initiative (MITEI) created and administers the interdisciplinary Energy Studies Minor for undergraduates. The faculty-led Energy Minor Oversight Committee of MITEI's Energy Education Task Force provides institutional leadership for the development and support of the energy studies curriculum.

Energy Studies Minor alumni: Where are they now?

Photo: David Sella

Jacqueline Han SB ’14, Political Science

Jacqueline Han came to MIT expecting to study engineering, but she soon realized that majoring in political science and minoring in energy studies would best further her interest in going into energy policy. She now works for Bain & Company in Dallas, Texas, where she uses her expertise in energy markets to inform her work in private equity.

What role does your background in energy studies play in your current job?

I’m an assistant consultant at Bain & Company in the private equity group. We cover a whole range of topics—everything from market sizing and competitive positioning to operating models and supply chain optimization. I am heavily focused on the oil and gas practice, so some of my energy background comes into play there. In addition, the analytical and critical thinking I gained from my studies at MIT has been very helpful.

How do political science and energy studies go together? Do you use skills from both courses of study in your current job?

Content-wise, they don’t go together. However, in political science I learned a lot about good research practices and how to frame questions—skills I use on a daily basis. Going into college, I was really interested in the energy field in general, especially in renewables, and I wanted to get some perspective on oil and gas as well. The breadth of the Energy Studies Minor really helped solidify that interest, and it’s still directing me to new places where I can continue to focus on energy. My background helps support the technical side of things, too, so I can really understand the mechanics of the industry.

How does your work in consulting prepare you for a potential move into the energy industry?

Someday I’d like to move into the renewables space, now that I have some perspective on oil and gas, but I haven’t decided where specifically. I think my work in consulting would be particularly useful there because there’s been a lot of growth in renewables recently, and with that comes a lot of new and big questions. The way I’ve learned to think in consulting will help me navigate those questions, distill the relevant information, and translate it into tangible impacts.

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By Elizabeth Boxer, MITEI

Photo courtesy of Christian Welch

Christian Welch SB ’13, Mechanical and Ocean Engineering; SM ’15, Mechanical Engineering

As an undergraduate researcher at MIT, Christian Welch became involved in designing, fabricating, and programming navigation systems and other components for autonomous underwater vehicles—an interest he also pursued in summer internships at Chevron (a Sustaining Member of the MIT Energy Initiative). Welch is now working on his PhD at the MIT/Woods Hole Oceanographic Institution Joint Program, where he studies applied ocean sciences and engineering.

What’s the focus of your current research?

After a certain amount of time, offshore structures used in the oil and gas industry have to be taken down because of loss of production or damage or decay. The current practice for removing them uses both remotely operated vehicles (ROVs) and divers. The ROVs are expensive and aren’t ideal for seeing underwater, though, and it’s a very risky, even life-threatening, job for divers. That's why I'm working on replacing divers and ROVs with completely autonomous technology. We have to teach the robots how to maneuver around the environment as well as the ROVs do and to touch and manipulate their environment as well as the divers do. If we can achieve that, we can take the ROVs and divers out of the equation.

Are there other areas of autonomous technology that are of interest to you?

I think that the world is moving toward simplifying processes or making them a little more predictable using autonomy. I'm not 100% sure if I want to stay in the applied ocean sciences field, but at the very least working in this field has taught me how to do robotics in some of the most unforgiving environments. Another growing field is autonomous cars. There's huge potential for reducing fuel emissions by mitigating traffic and for saving lives by reducing the likelihood of accidents.

What's the most important role played by MIT's Energy Studies Minor?

The energy minor really gives students the tools to use their technical background to address climate issues. It also does a great job of showing students how [the climate challenge] is more than just a technical problem—it's a social and an economics problem, and everyone can do something about it. The curriculum does an amazing job of bridging the gap between academia and what's going on in the world.

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By Elizabeth Boxer, MITEI

Photo: Justin Knight

Jenny Hu SB '14, Management

As a new MIT undergraduate, Jenny Hu was involved in research to develop a novel way to generate electricity using fuel-coated carbon nanotubes. But she also developed a keen interest in economics. To combine her interests, she declared a major in management science with a concentration in operations research and a minor in energy studies. Since graduating, she has worked in home automation R&D and solar financing, and most recently joined the solution design team at Advanced Microgrid Solutions in San Francisco.

Some of your early work in clean energy was as an intern at Clean Power Finance. What did you learn there?

Clean Power Finance was using innovative financing structures to drive the mass-market adoption of solar. I realized that third-party financing, securitization, and other kinds of financial engineering were key to driving the adoption of many technologies, so I became interested in how to use finance to advance clean energy.

Can you tell us about the interplay between your energy knowledge and business background in your career?

It's my opinion that energy—more than many other technology-oriented fields—consists of an even mix of law, finance, and technology. As such, you can't really do one in isolation from the other. In just the few years that I've been in cleantech, I've had the chance to see the entire industry move and opportunities emerge from changes in the interplay of law, finance, and technology. So a lot of the cutting-edge work done in cleantech today is at the intersections of those fields.

What should students know about pursuing a career in clean energy?

Cleantech today is a very small field. Everybody is here because they want to help move the market toward clean energy. I find that to be incredibly inspiring, so I make a point to keep in touch with the folks I've met in energy through the years. Energy is an old industry, but it's now undergoing the most change it has seen in almost a century. So we need the best and the brightest to add as much new knowledge as possible to this industry. And for that, I turn to the community at the MIT Energy Initiative and the energy minor.

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By Sofia Cardamone, MITEI

Photo: Siobhan Duncan

Jacob Jurewicz SB '14, Nuclear Science and Engineering, and Physics; SM '15 Nuclear Science and Engineering

When Jacob "Jake" Jurewicz came to MIT, he planned to study nuclear fusion. But he soon broadened his focus to include not only developing and improving nuclear technology—fission as well as fusion—but also examining the social and political issues that can present barriers to the expanded use of nuclear energy. Since graduating from MIT, Jurewicz has been working as a senior analyst at Exelon in Chicago, where he enjoys keeping one foot in industry and finance, and the other in research and academia, thereby staying abreast of cutting-edge technologies with the potential to have a dramatic effect on the energy industry.

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

I work in corporate strategy, looking at US utilities, major trends in the US energy space, and particularly emerging and nontraditional participants. Our team is responsible for synthesizing Exelon's vision for the energy system of the future. Most of what I do is related to looking at how various technologies are affecting and disrupting industry. I frequently leverage a great deal of my engineering knowledge of various energy technologies that I researched during my time at MIT. One day I am assessing a novel nuclear fusion concept and the next I am evaluating how a lower-cost battery may impact electricity markets.

What did the Energy Studies Minor teach you?

The breadth of topics that the energy minor addressed—in classes like Sustainable Energy, Energy Economics, and Energy Decisions, Markets, and Policies—complemented the technical learning in my engineering courses. The minor taught me a lot of the basics—about economics, market design, policy, and regulation—and it gave me perspective on how to create the greatest change in the system. The minor taught me to take a step back and look at the industry as it is now, applying those basics in order to be more effective, rather than just taking the most radical approach.

What would you tell students about pursuing a career in your field?

Don't be afraid to take a nontraditional path, and don't listen to anyone who immediately tries to write off a particular idea. Take in everything you learn and use everything you know from the classes you've taken and the experts you've talked to—and then go do what you feel is right.

NOTE: In early 2016, Jurewicz helped set up a research agreement that made Exelon one of the first members of the MIT Energy Initiative's new Low-Carbon Energy Centers *(see page 3).*

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By Sofia Cardamone, MITEI

Porous materials workshop in France focuses on nuclear industry

Fourteen MIT students joined an international group of 70 in Marseille, France, in January 2016 for a weeklong workshop on multiscale porous materials and their applications in the nuclear power industry.

Offered for the first time as an official MIT class during MIT's Independent Activities Period, the Marseille Winterschool provided training in all facets of these materials, ranging from advanced microscopy and spectroscopy techniques to nanomechanical testing of stiffness, strength, and fracture properties.

"This program offers MIT students a rich introduction to the use of complex porous materials that are everywhere in everyday life—in soils, cement, and [other components] critical to virtually all industrial energy processes," says Roland Pellenq, senior research scientist in MIT's Department of Civil and Environmental Engineering (CEE) and one of the co-organizers of the Winterschool.

Marseille Winterschool was founded four years ago to give graduate students and postdocs around the world the chance to learn about porous materials at multiple scales—from nanometer to micron—in applications from the lab up to energy resource management. Each year, the program has focused on the impact of such materials within a different domain, including global warming, infrastructure, and gas shale operations.

"The theme this year is porous materials around the nuclear energy cycle," says CEE Professor Franz-Josef Ulm, one of the instructors for the class (another MIT instructor was CEE Professor John R. Williams). "Porous materials are absolutely critical for the nuclear cycle, from shielding [radiation] up to the ultimate safe storage of these materials."

A highlight of the week was a trip to ITER, a multibillion-dollar experimental fusion reactor that is under construction in France thanks to a collaboration of 35 nations. "Fusion is an exciting prospect for the future of energy; the physics behind it is amazing, but I didn't know much about it," says Gerald Wang, a third-year graduate student in mechanical engineering who attended Winterschool. "I was really impressed by the herculean engineering task they are undertaking and felt very lucky to have been on site to see these things."

Students toured the facility and had a seminar with ITER's director-general, Bernard Bigot. "It was an inspiration to hear what he had to say about the role ITER will play in the future of energy," says physics major Alexander Andriatis '18, one of just two MIT undergraduates to participate in Winterschool. "It was really amazing to be able to see this cutting-edge research and multibillion-dollar investment from countries from around the world."

Organized by MIT and CNRS (the French National Center for Scientific Research), Winterschool featured lectures by experts from MIT, Georgetown University, Aix-Marseille University, and the University of Paris. "I was very impressed with the enthusiasm and participation of the MIT students during the series of lectures, and I think everyone got a lot out of the very dense Winterschool program," Pellenq says.

Winterschool was founded with the support of CNRS, Aix-Marseille University (through the AMIDEX Foundation), and France's national science foundation, the Agence Nationale de la Recherche (through its Laboratory of Excellence Interdisciplinary Center on MultiScale Materials for Energy and Environment).

Photo: Franz-Josef Ulm, MIT

ITER Director-General Bernard Bigot gives students a tour of ITER, a multibillion-dollar experimental fusion reactor project in France, during the Marseille Winterschool held in January 2016. Fourteen MIT students attended Winterschool, a weeklong workshop on multiscale porous materials that this year focused on nuclear applications.

MIT's participation was supported by funding from the MIT Energy Initiative and MIT-France, which together supplied fellowships for seven of the 14 students. The MIT students came from CEE, chemical engineering, mechanical engineering, nuclear science and engineering, physics, and materials science and engineering.

To build on this success, Ulm says he hopes to expand Winterschool in the future. "We are in discussions with different partners to create an education infrastructure for training the next generation of researchers working on porous materials as [these materials] become more and more important in fields from batteries to oil and gas to geothermal applications," he says. "This would be a fantastic enrichment of MITEI's educational outreach, for MIT students and far beyond MIT's boundary."

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By Kathryn M. O'Neill, MITEI correspondent

MIT at the Paris climate conference

Photo: Emily Dahl, MITEI

Outside Le Bourget, the COP21 venue in Paris, nations' flags wrap around columns representing global participation.

In late 2015, MIT faculty, staff, and students attended the United Nations Climate Change Conference (COP21) in Paris, participating as observers of the climate negotiations and hosting several programs to discuss MIT research and activities geared toward mitigating climate change and increasing public engagement on climate issues. During and after the conference, the MIT Energy Initiative (MITEI) shared news and insights related to COP21 from MIT community members (see mitei.mit.edu/news/cop21). Emily Dahl, MITEI's communications director, filed several stories during the event, which we've reprinted below. The photos on page 44 highlight other activities, with a link to full articles for further details.

MIT at COP21: Sharing climate research and strategies in Paris

This article was originally published on December 11, 2015.

"The world needs an aggressive but pragmatic transition from our current energy mix to a zero-carbon future," said MIT Vice President for Research Maria Zuber on a panel during the United Nations Climate Change Conference (COP21) talks in Paris on December 11, 2015. "It's going to take industry, government, and academia working together to invent our way forward, and to provide policy incentives to adopt promising technologies."

This sentiment has rung true throughout COP21, as members of the MIT community have held events to share climate and energy research with members of the public and the media from around the world, launch new international partnerships and initiatives for climate solutions, and discuss pathways toward a global low-carbon energy future.

Exploring China's role in climate talks and global energy future

On December 4, MIT Sloan School of Management Professor Emeritus Henry Jacoby and Assistant Professor Valerie Karplus and their collaborator, Professor Xiliang Zhang of Tsinghua University and the MIT-Tsinghua China Energy and Climate Project, gave a talk at the MIT Club of France in the historic France-Amériques building. Addressing an audience of COP21 attendees, MIT alumni, current students, and others, they discussed how China's actions coming out of COP21 could help shape the future global energy system.

In a brief history of international climate negotiations, Jacoby described the shift from developed nations' attempts to control greenhouse gas emissions to the current "pledge and review" process that is more inclusive of developing nations and takes their sustainable development needs into account.

Citing the 185 countries that have pledged Intended Nationally Determined Contributions (INDCs) for COP21, Jacoby said, "There's been real progress in spreading around the notion that everybody has some responsibility for this."

Zhang, who introduced himself as the father of an MIT student, gave an overview of China's energy and climate policy to help provide policy context for China's COP21 pledge.

He reviewed policy mechanisms that have been helping China decrease energy intensity, including the legally binding targets for energy intensity that have been introduced for China's major cities, industries, and companies, with monitoring for accountability and consequences if targets are not met. "This policy has been largely contributing to the energy intensity declining for the past eight years," he said, noting that the provincial targets have been largely fulfilled and adding, "We can see increased decoupling of economic growth and energy consumption."

Karplus followed up by exploring the implications of China's climate policies for its energy system and for air quality improvement—including its announced nationwide carbon trading regime. She and Associate Professor Noelle Selin of MIT's Institute for Data, Systems, and Society (IDSS), both faculty affiliates of the MIT Joint Program on the Science and Policy of Global Change, together with their research teams have developed a model that connects a model of China's provincial energy economy with an air chemistry model

Photos: Emily Dahl, MITEI

MIT Sloan School of Management Assistant Professor Valerie Karplus discusses implications of China's climate and energy policies at an MIT Club of France event during COP21 in Paris. Karplus is also affiliated with the MIT Joint Program on the Science and Policy of Global Change.

to look at how changes in energy policy translate into changes in projected emissions and air quality impacts, and examine impacts on morbidity, mortality, and the economy. This analysis can also be used in other developing and emerging markets that are experiencing tension between environmental and developmental goals.

"China needs a carbon price to ensure that actions to curb air pollution are consistent with climate mitigation goals," said Karplus. "It has a unique opportunity to address climate change and air quality at the same time."

In its joint climate agreement with the United States, China has promised to increase its non-fossil fuel share of primary energy to 20% by 2030 and has also pledged to reduce carbon intensity by 60%-65% by 2030 relative to 2005 levels. It has also made significant reforestation commitments.

Karplus added, "One new dynamic in Paris is the cooperation between China and the United States, built on the joint announcement of each country's climate pledges in November 2014. Nobody is pointing fingers anymore, saying the other should act first. The focus has shifted to vital issues such as finalizing contributions, financing energy system transformation, and reviewing progress."

To broaden the reach of the MIT-Tsinghua partnership's model, Karplus's team is building an interactive website that will allow people to explore China's regional energy systems.

Event organizer Stephanie Ng '01, head of innovation and director of cultural affairs for the MIT Club of France, said, "I am reminded of an inspiring conversation I shared with [MIT] President Reif: We discussed how, at MIT, students come from across the globe, and what unites us is our common mission to solve the world's greatest challenges. Nowhere is this more evident than here at COP21, where faculty and alumni have come to the City of Light to illuminate us on climate mitigation goals and share a vision of the future of global energy."

Calling for international collaboration

At COP21, others from MIT have also been underscoring the importance of rapid decarbonization of energy systems. In a packed press conference on December 3, alongside other leading climate scientists, MIT Professor Kerry Emanuel of earth, atmospheric and planetary sciences challenged world leaders to fully decarbonize the world economy by employing all available sustainable energy sources, including renewable energy and nuclear energy.

Emanuel and fellow scientists James Hansen of the Columbia University Earth Institute, Tom Wigley of the University of Adelaide and the National Center for Atmospheric Research, and Ken Caldeira of the Carnegie Institution for Science outlined how only a combined strategy employing all major sustainable energy options can prevent the worst impacts of climate change by 2100.

In an open letter in *The Guardian* that ran on the same day, they argued: "Nuclear power, particularly next-generation nuclear power with a closed fuel cycle (where spent fuel is reprocessed), is uniquely scalable and environmentally advantageous."

At the launch of a new MIT Climate CoLab partnership with the UN secretary-general at COP21 to strengthen vulnerable nations' resilience to climate change, MIT Sloan Professor and CoLab Director Thomas Malone spoke about the importance of broadly engaging people on numerous solutions. "No matter the outcome of the international climate negotiations, it is clear that, now more than ever before, we need the ideas and contributions of as many people as possible to address climate change," he said.

Laur Fisher, project manager at the Climate CoLab, also presented at several events, including the Innovation Climate Accelerator's Breakthrough Night during COP21, which showcased global projects that actively contribute to the realization of a post-carbon world. The CoLab also launched a partnership with Taiwan's Environmental Protection Administration to help the region solicit ideas from the public to work on climate change issues that impact Taiwan.

One of the engaging, interactive side events of COP21 was the "World

Climate" role-play led by Professor John Sterman of MIT Sloan and the nonprofit Climate Interactive in which people from around the world took on roles as climate negotiators to experience the challenges of reaching strong, inclusive international agreements that limit temperature and sea level rise.

The panel on which Maria Zuber spoke was another event drawing on global perspectives. It was hosted by Delta Group, with an audience including European, Chinese, and Taiwanese industry and government. Following Zuber's overview of the MIT Plan for Action on Climate Change, she and fellow panelists discussed the need to invest more resources globally in increasing energy efficiency across sectors, from the manufacturing industry to the built environment and power electronics.

Robert Stoner, MIT Energy Initiative deputy director and MIT Tata Center for Technology and Design director, attended the Global Landscapes Forum during COP21. The forum featured economist and MIT alumna Ngozi Okonjo-Iweala PhD '81, who has held positions including managing director of the World Bank and Nigerian minister of finance. Her message resonated with Stoner, who said, "Ngozi was characteristically clear-eyed as she emphasized the importance of massive investment in land restoration and water protection, combined with a sincere and effective response by governments to manage and enforce laws and regulations to help developing nations reduce their contribution to greenhouse emissions while protecting the livelihoods of their forest-dependent populations."

Meanwhile, Assistant Professor Jessika E. Trancik of IDSS shared her research with the White House, US Department

Left to right: MIT Sloan School of Management Professor Emeritus Henry Jacoby, Professor Xiliang Zhang of Tsinghua University and the MIT-Tsinghua China Energy and Climate Project, and MIT Sloan Assistant Professor Valerie Karplus discuss China's energy policies at an MIT Club of France event during COP21 in Paris in December 2015.

of Energy, and others—leading up to and during COP21—on how nations' INDCs could increase renewable energy adoption and drive down future deployment costs in a mutually reinforcing cycle. Policymakers referenced her work to show how making early, significant investments to reduce greenhouse gas emissions could make future mitigation efforts less costly.

Students and recent alumni witnessing history in the making

During the second week of COP21, MIT PhD candidates Michael Roy Davidson of IDSS and Jessica Gordon of urban studies and planning, undergraduate student Joseff Kolman, and Ellen Czaika PhD '15 were among those who participated as observers. In addition to watching the main negotiations, they have had the opportunity to attend other special events, including a briefing with US Environmental Protection Agency Administrator Gina McCarthy.

Czaika, who earned her PhD in September from IDSS, has been sharing her experience of COP21 through webinars with Noelle Selin's class, which has been studying and blogging about the climate talks. Czaika said she is "impressed by all of the work that has gone into this event: preparation on substantive issues, establishing procedural guidelines, facilitation and logistics, educational sessions, demonstrations, and communication."

Davidson, a graduate student researcher with the MIT-Tsinghua China Energy and Climate Project, has found the talks highly relevant to his work. "One of the key outcomes of Paris which we see increasing convergence on is to set up a regular review mechanism to encourage countries like the US and China to ratchet up their ambition further to meet long-term climate stabilization goals," he said.

Kolman has also found the experience exciting and rewarding: "It's been interesting being in the middle of this busy little village of activity, with hundreds of observers from all corners of the world—each waiting to see what the negotiations yield," he said. "It is clear that leaders here recognize the enormous threat of climate change, and the general consensus is that we'll be moving forward from Le Bourget with an agreement. Now the question remains of how ambitious it will be."

On December 12, at the conclusion of COP21, 196 parties signed a historic agreement to combat climate change.

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By Emily Dahl, MITEI

Climate negotiation role-play in Paris feels like the real thing

This article was originally published on December 7, 2015.

As delegates work to cut global greenhouse gas emissions at the United Nations Climate Change Conference (COP21) talks in Paris, a vibrant hub of activity next door in the conference's "Climate Generations" area attracts people from around the world. Environmental and energy non-governmental organizations and agencies engage visitors in their work through visualizations and demonstrations, while numerous conference sessions range in topics from ocean sustainability to green growth in Africa.

In one of the conference rooms on Friday, December 4, 2015, United Nations Secretary-General Ban Ki-Moon instructs delegates on how to begin their climate negotiations. Only the secretary-general isn't himself today: He is being played by Professor John Sterman of the MIT Sloan School of Management. And the "delegates" are actually visitors to COP21, some here on behalf of organizations, others as interested citizens. All have gathered to play "World Climate," a live-action role-playing simulation developed by Sterman and MIT alumnus Andrew Jones of the not-for-profit Climate Interactive. World Climate helps policymakers, business leaders, and citizens understand first-hand the complexities of the climate and global negotiations—and what's needed to limit anthropogenic climate change.

The World Climate Project was launched in August 2015 at the White House and has since been used in more than 45 countries, from Argentina to Zimbabwe—with more than 10,000 participants to date. The simulation held here at the Paris climate talks brings diverse perspectives together. "The participants came from a wide range of countries and ethnicities, and about half were women, which was great to see," Sterman says.

Sterman and Jones, with MIT researcher and Climate Interactive Program Director Travis Franck, University of Massachusetts Professor Juliette Rooney-Varga, and Climate Interactive's Ellie Johnston begin the role-play for the large group that has assembled. Sterman asks, "Who here is from the European Union?" Hands go up. "Great! Today, you represent China. Now, who here is from China? Today, you are the United States." Taking roles completely different from their own backgrounds helps some participants experience challenges they might not otherwise consider. Others such as Thango, a young woman from South Africa well-versed in the issues facing her country and continent, play more familiar roles. She joins the group representing developing nations. For Thango, it's an opportunity to share with fellow delegates the struggle of such nations to develop sustainably even as they stand to suffer the most from climate change.

Discussions quickly become heated, with delegates taking their new national identities seriously. At the end of the first round of negotiations, a representative of each delegation addresses the plenary assembly. In their roles as national leaders—Barack Obama of the United States, Vladimir Putin of Russia, Narendra Modi of India, François Hollande of France, and Xi Jinping of China—participants explain their emissions pledges and financial commitment or demands.

Sterman and Franck then plug the delegates' pledges into the C-ROADS climate policy simulation developed by Sterman and Climate Interactive. C-ROADS is a peer-reviewed model that matches the dynamics of the models used by the Intergovernmental Panel on Climate Change, but runs in about one second on an ordinary laptop. The model and materials to facilitate the entire "World Challenge" exercise are freely available through Climate Interactive's website, climateinteractive.org.

As Sterman enters the pledges, the delegates see global emissions flatten, but when the last pledge is recorded, the model shows that the world will still warm by 3.5°C (6.3°F) by 2100, leading to ocean acidification and other harms, including about a meter of sea-level rise. Sterman and the team drape the participants with a billowing cloth to show how many parts of the world will be inundated despite the emissions reductions they have pledged.

"The first round's pledges produced results extremely close to the initial pledges here in Paris—nowhere near enough to curb climate change," Sterman says. "When the delegates in the workshop saw this, some were shocked, because they thought their pledges would get the job done."

Sterman and his team give the participants another chance to reach stronger agreements. Raymond Song, a high school student from China representing

Photo courtesy of Climate Interactive

Chinese high school student Raymond Song (right) represents the United States in the World Climate role-play, addressing delegates as President Obama. Overseeing the negotiations is UN Secretary-General Ban Ki-Moon, played by MIT Sloan School of Management Professor John Sterman (left, background).

Photo: Emily Dahl, MITEI

Thango of South Africa (foreground right), representing developing nations in the World Climate role-play, negotiates for financial and technological aid from developed nations. She discusses the climate issues developing nations face with her fellow delegates.

the United States in the game, channels President Obama with an impassioned plea for the other developed nations to step up—and pledges that the United States will do more. Intense negotiations ensue, with India agreeing to emissions cuts in exchange for financial assistance from developed nations and China pledging future emissions cuts, leading to a much more promising outcome.

"The model provides people with immediate feedback on the consequences of their proposals," Sterman says. "They saw how much their countries will suffer without deeper emissions cuts, and that motivated them to reach a much better agreement," limiting warming to just about 2°C (3.6°F), the limit the nations of the world have declared must not be exceeded.

The passionate dialogue generated by the mock-debate is an example of why MIT representatives are here in Paris: to help make climate issues more accessible and understandable; to convey the monumental importance of taking strong collective action to combat global climate change; and to share climate research with scientific peers and journalists.

For participants in the World Climate role-play, the simulation has been an eye-opening experience: "I really liked the game. It made me understand how negotiations work, [and] the importance of talking about the impact of climate change on [people's] lives," says Thango. She plans to use the game to educate girls she works with in South Africa on how countries can use the negotiations to collectively meet global emissions reductions goals.

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By Emily Dahl, MITEI

Fostering a community of climate engagement at MIT

Photo: Susan Young

Photo: MITEI Office of Communications.

Joseff Kolman
An MIT Undergrad at the Paris Climate Talks

Joseff Kolman, a senior majoring in both physics and political science, joined a group of graduate students and MIT faculty attending COP21 as observers. Sponsored by MITEI donors who support education initiatives, the trip allowed Kolman to envision a potential career in sustainability and environmental policy. Kolman's previous experience participating in the MITEI Energy Undergraduate Research Opportunities Program and serving on the MITEI Energy Education Task Force provided a solid background for his experience at the climate negotiations.

Fred Krupp
The Paris Agreement and the Race of Our Lives

At the MITEI Spring Colloquium on March 28, 2016, Environmental Defense Fund President Fred Krupp highlighted the importance of moving forward in terms of policy and governance following the Paris Agreement. Krupp reviewed three major topics that the global community must address: climate progress in the United States, climate progress in China, and how to conduct an across-the-board examination of climate policy. He highlighted the importance of ensuring that policies are fair and equitable for people in developing nations.

Photo: Dimonika Bray, MIT

Photo: Dimonika Bray, MIT

History in the Making:
The Outcome of the Paris Climate Change Negotiations

Left to right: Moderator Susan Solomon of earth, atmospheric and planetary sciences joined panelists Noelle Eckley Selin and Jessika Trancik of the Institute for Data, Systems, and Society and Henry Jacoby of the MIT Sloan School of Management in exploring the implications of the landmark Paris Agreement at an event on December 17, 2015, drawing on their related areas of research. Solomon noted that the structure of the negotiations, where each nation brought its own greenhouse gas emissions reduction commitments to the table, was a major factor in the successful outcome in Paris.

Janos Pasztor
Getting the World to Turn Down the Heat

At a weeklong series of talks at MIT in February 2016, MIT alumnus Janos Pasztor, senior advisor to the UN secretary-general on climate change, discussed the history, status, and possible future of international climate change negotiations. He highlighted the "tectonic changes" resulting from the strong presence and deep engagement of the private sector in the Paris climate negotiations.

For links to full articles, please go to energy.mit.edu/energyfuturesspring16.

Energy Secretary Ernest Moniz touts great opportunities in energy

In his first official return to the MIT campus since taking the job of US Secretary of Energy in 2013, former MIT physics professor and founding director of the MIT Energy Initiative Ernest J. Moniz spoke to the annual, student-run MIT Energy Conference on Friday, March 4, 2016, saying that the prospects for new jobs in energy-related fields are booming—and include roles for virtually every academic discipline.

The annual event, which is the largest student-run energy conference in the nation and is now in its 11th year, brings together leaders in energy technology, business, and policy from around the nation and the world. Moniz, who under federal guidelines was recused from involvement in any MIT activities for his first two years, said he was now taking advantage of the "brief window" between that recusal period and the end of President Obama's term of office—and thus, presumably, his own term as well.

Moniz said that last fall's climate conference in Paris "was, in my view, enormously successful." He said that among the outcomes of that international conference, at which virtually every nation on Earth vowed to take measures toward a low-carbon future, "an important point to make is that innovation was placed at the heart of the climate change response."

That central role for innovation was far from just talk, he stressed. The International Energy Agency calculated that the commitments reached in Paris will lead to about $1 trillion a year being invested in various nations' efforts to pursue low-carbon technology. "It's really a big deal!" he said.

Photo: Bryce Vickmark

US Secretary of Energy Ernest Moniz, founding director of the MIT Energy Initiative (MITEI), right, and Robert Armstrong, MITEI director, at the MIT Energy Conference in March 2016. In a keynote address, Moniz called innovation "the essence of America's strength."

Doubling of R&D

In addition, the 20 countries that already spend the lion's share of all worldwide energy research and development money—representing some 80% to 85% of the global total—agreed to take part in a new "Mission Innovation" initiative, which includes a commitment to double their annual research and development expenditures in this area. The number of countries that opted to join in this agreement, Moniz said, "far exceeded our expectations."

Innovation, Moniz said, is "the essence of America's strength." In addition to the plan for doubling national investments in energy research, he said, there will also be a parallel effort, spearheaded by a group of 28 wealthy individuals from 10 countries, including Bill Gates, to form a group called the Breakthrough Energy Coalition, which will invest additional billions of dollars on energy research. The group aims "to increase the investment pipeline in these countries in a way that will maximize risk tolerance"—something that is necessary to bring about significant advances, but which traditional investors, whether private or governmental, tend to be wary of.

In fact, the track record for the Department of Energy's research investments has been very good, Moniz said. Since the Advanced Research Projects Agency–Energy (ARPA–E) program to fund early-stage energy research was started, he said, after five years of investment, about 200 projects have been funded, and about a quarter of those have gone on to raise a total of about $250 million in private funding. Yet it's still not enough, he said. Last year, of the applications submitted for that program only 2% were funded, meaning that "we are still leaving a lot of innovations on the table." The new Mission Innovation initiative, he said, hopes to help address that.

Creating new jobs

In addition to helping to address global climate change, these new energy investments will also create significant numbers of new jobs, both nationally and globally, he said. For example, the solar industry alone has created some 200,000 full-time jobs in the United States, and many more part-time jobs. "That is a big industry!" he said.

And the energy-related employment opportunities go well beyond just the obvious jobs in engineering and basic science research. There are also great opportunities for students interested in policy and analysis, he said. This is "a new way of doing business, based on really deep and fundamental analysis," and there are great needs for people trained in economics, public policy, and a variety of other fields.

"We need innovations in science, innovations in technology, innovations in policy, innovations in business models," Moniz said. Because all these roles are so important and interconnected, he said, when he and Robert Armstrong, who succeeded him as director of the MIT Energy Initiative (MITEI), were setting up that program, he said "we made sure that every school and every discipline was engaged" in the process. "That multidisciplinary approach has been so critical" to the program's success, he said.

And in that vein, one of the first things he did when he assumed his present office, he explained, was to establish a new Office of Energy Policy and Systems Analysis, headed by Melanie Kenderdine, who had been MITEI's executive director. That office now has 75 people, "quite a few" of them from MIT, he said.

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Excerpted from an article by David L. Chandler, MIT News Office

To read this full article and more about the Energy Conference, please go to energy.mit.edu/energyfuturesspring16.

MITEI energizes visitors at MIT Open House

On Saturday, April 23, 2016, MIT opened its doors to the entire community for an Open House as part of ongoing celebrations honoring the 100th anniversary of the Institute's move from Boston to Cambridge. The MIT Energy Initiative (MITEI) was represented in force, welcoming curious visitors to the world of energy science. In the pavilion next to Walker Memorial, MITEI staff, students, and researchers gathered to offer information about the Initiative's mission for a low-carbon future and to demonstrate the science underlying the energy research done at MITEI every day. Visitors conducted thermoelectric experiments, observed the inner chemical workings of fuel cell cars, looked at the potential for solar panels on their roofs and in their communities, and more.

Photos: Francesca McCaffrey, MITEI

Graduate student Michael Campion of materials science and engineering explains the science behind wind turbines and thermoelectric devices to onlookers. Lucky participants received thermoelectric devices to take home.

Graduate student Michael Campion guides a young participant experimenting with the effects of wind speed on turbine rotation.

MIT student Lilly Chin '16 of electrical engineering and computer science demonstrates the energy of cookie-baking, showing how just a few changes to ingredients can affect consistency and baking time.

Events of note

Photo: Sofia Cardamone, MITEI

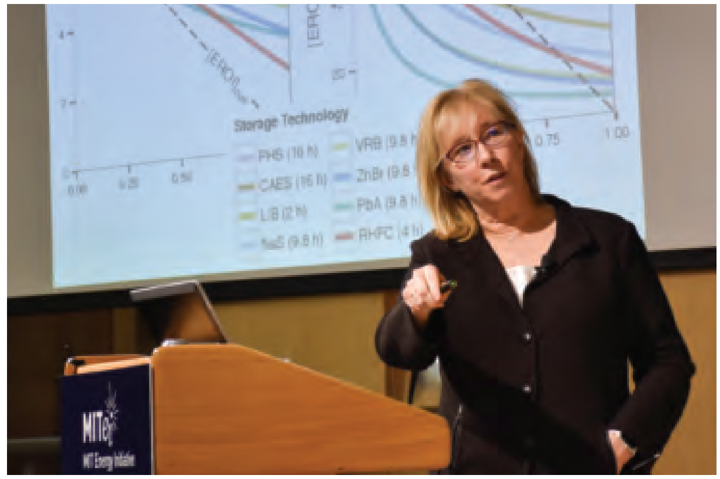

Photo: Shriya Parekh, MIT Tata Center

William Magwood
Looking Forward: The Next Future of Nuclear Energy

At a seminar on March 14, 2016, William Magwood, director-general of the Organisation for Economic Co-operation and Development's Nuclear Energy Agency, discussed the state of global nuclear power today and in the future. He called for a global agenda to foster nuclear energy R&D to accelerate the development of safer, more economic reactors. The MIT Energy Initiative (MITEI) and the Department of Nuclear Science and Engineering co-hosted the event.

Sally Benson
Decision-Making for a Low-Carbon Future

Stanford University's Sally Benson, co-director of the Precourt Institute for Energy and director of the Global Climate and Energy Project, spoke at a MITEI-hosted IHS Seminar on February 9, 2016. She emphasized the importance of using systemwide analyses of energy challenges to make sound decisions for a low-carbon future—rather than focusing solely on issues of cost, which fail to take into account many elements of a new technology's true price, including co-benefits, short-term supply excesses and deficits, and un-priced externalities.

Photo: MITEI Office of Communications

Photo: MITEI Office of Communications

Energy Efficiency and Renewable Energy Day

On March 17, 2016, MITEI hosted the US Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy for a full-day MIT community event dedicated to the future of low-carbon energy. DOE leaders and MIT faculty discussed current research to accelerate scientific breakthroughs in clean energy fields, and an MIT student-hosted panel on careers in energy policy and research featured Institute alumni who currently work at DOE. Above, left to right: Michael Birk SM '16, Statoil-MIT Energy Fellow and research associate for MITEI's Utility of the Future study; David Danielson PhD '07, DOE assistant secretary for energy efficiency and renewable energy; Joyce Yang PhD '06, former DOE lab impact director; Johanna Wolfson PhD '13, DOE energy efficiency and renewable energy tech-to-market director; Brian Walker PhD '11, DOE Clean Energy Manufacturing Initiative senior fellow; and Linda Cheung, MBA candidate at the MIT Sloan School of Management.

MIT at IHS Energy's CERAWeek

On February 22, 2016, MIT researchers gathered at IHS CERAWeek, one of the world's largest energy conferences. At the plenary session, MIT faculty shared their research into potentially game-changing technologies and described MITEI's new Low-Carbon Energy Centers. Kristala Jones Prather of chemical engineering (center) discussed advancements in synthetic biology such as new kinds of biofuels, and Yogesh Surendranath of chemistry (left) spoke about the potential to use carbon dioxide as a fuel and what it means for the future of energy cycling. Yet-Ming Chiang of materials science and engineering discussed developments in energy storage technologies.

For links to full articles, please go to energy.mit.edu/energyfuturesspring16.

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 151 seed grant projects across the campus as well as fellowships for more than 350 graduate students and postdoctoral fellows in 20 MIT departments and divisions.

MITEI FOUNDING MEMBERS

MITEI SUSTAINING MEMBERS

MITEI Associate Members

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

MITEI ASSOCIATE MEMBERS

MITEI Affiliates

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

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Members as of April 2016

MITEI member news

National energy provider Exelon has joined MITEI as a member, with plans to focus its research support through MITEI's Low-Carbon Energy Centers to advance key enabling technologies crucial to addressing climate change.

"Engagement with industry to accelerate deployment of clean energy technologies is a crucial component of MIT's Plan for Climate Action, a driving force behind the development of the Low-Carbon Energy Centers, and an important strategy for academia and governments to pursue to meet the objectives of the Paris climate agreement," said MITEI Director Robert Armstrong in the February announcement of the collaboration. "By joining the MIT Energy Initiative to support research through the centers, Exelon demonstrates a strong commitment to advancing the affordability, scalability, and rapid deployment of low- and zero-carbon energy technologies."

MITEI—in collaboration with IIT-Comillas—has launched a project with energy and utility company AVANGRID, which holds the US operations of parent company Iberdrola, to create a model that could support New York's Reforming the Energy Vision plan by simulating how distributed resources might impact the power system. The model seeks to identify the scale at which distributed generation—from sources including solar photovoltaics, battery storage, and combined heat and power—becomes beneficial to the grid while taking into account potential impacts on electricity prices, grid reliability, and the environment.

The project is part of MITEI's Utility of the Future study, through which MITEI, IIT-Comillas, and a consortium of leading international companies are analyzing emerging issues in the electric power sector.

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MIT at the Paris climate summit

At the 2015 climate talks in Paris, also known as COP21, MIT faculty, students, staff, and alumni observed negotiations and hosted several side events. Among those participating were (left to right) MIT researcher and Climate Interactive Director Travis Franck; PhD candidate Michael Davidson; MIT Center for Collective Intelligence/Climate CoLab Director Thomas Malone; MIT Climate CoLab Project Manager Laur Fisher; alumna Ellen Czaika; undergraduate Joseff Kolman (funded by the MIT Energy Initiative); and PhD candidate Jessica Gordon. For more on MIT's wide range of COP21-related activities, turn to page 39 or visit mitei.mit.edu/news/cop21. On page 6, learn about an MIT analysis that informed the COP21 negotiations, and on page 3, read about MITEI's eight new Low-Carbon Energy Centers, which will speed the development and deployment of energy technologies crucial to addressing climate change. Photo: Emily Dahl, MITEI