Energy Futures

MIT ENERGY INITIATIVE MASSACHUSETTS INSTITUTE OF TECHNOLOGY AUTUMN 2018

New Energy @ MIT podcast launches

The global energy landscape continues to change as new technology and research enter the playing field, and it can be hard to keep up. To bridge that gap, the MIT Energy Initiative (MITEI) began a new podcast series this fall, offering fresh perspectives from inside MIT on some of the world's most pressing energy issues.

The series starts with MITEI's Director of Research Francis O'Sullivan speaking with John Deutch, MIT Institute Professor and former CIA director, and Arun Majumdar, the Jay Precourt Professor at Stanford University and former director of the Advanced Research Projects Agency-Energy at the US Department of Energy, about policies and technologies that could advance negative carbon emissions at the gigatonne scale as part of the US and global portfolio of climate solutions.

In another episode, Jacopo Buongiorno and John Parsons, study co-chairs, and doctoral student Karen Dawson discuss MIT's new nuclear energy study and the mix of technologies that may shape our low-carbon future. Listen to their accounts of behind-the-scenes details and surprises from over the course of the study. Read more about their findings on page 4.

MITEI researchers Jesse Jenkins and Nestor Sepulveda also came by the show to talk about their new paper on the firm low-carbon energy resources that could be critical to decarbonizing our electricity system. To read more about their findings, see page 25.

More episodes are in the pipeline as we continue sharing the story of Energy @ MIT. Listeners can find these episodes and subscribe at **energy.mit.edu/podcast**, Google Play, iTunes, SoundCloud, or wherever you get your podcasts by searching "MIT Energy."

On the cover

In early September, the MIT Energy Initiative released *The Future of Nuclear Energy in a Carbon-Constrained World*, a comprehensive report based on more than two years of research by a multidisciplinary team of investigators. The team's findings suggest that new policy models, cost-cutting technologies, and standardization could help nuclear energy play a vital role in climate solutions. Read more on page 4.

Energy Futures is published twice yearly by the MIT Energy Initiative. It reports on research results and energy-related activities across the Institute. To subscribe, please visit **energy.mit.edu/subscribe**.

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MIT Energy Initiative
The MIT Energy Initiative is MIT's hub for energy research, education, and outreach. Our mission is to create low- and no-carbon solutions that will efficiently meet global energy needs while minimizing environmental impacts and mitigating climate change.

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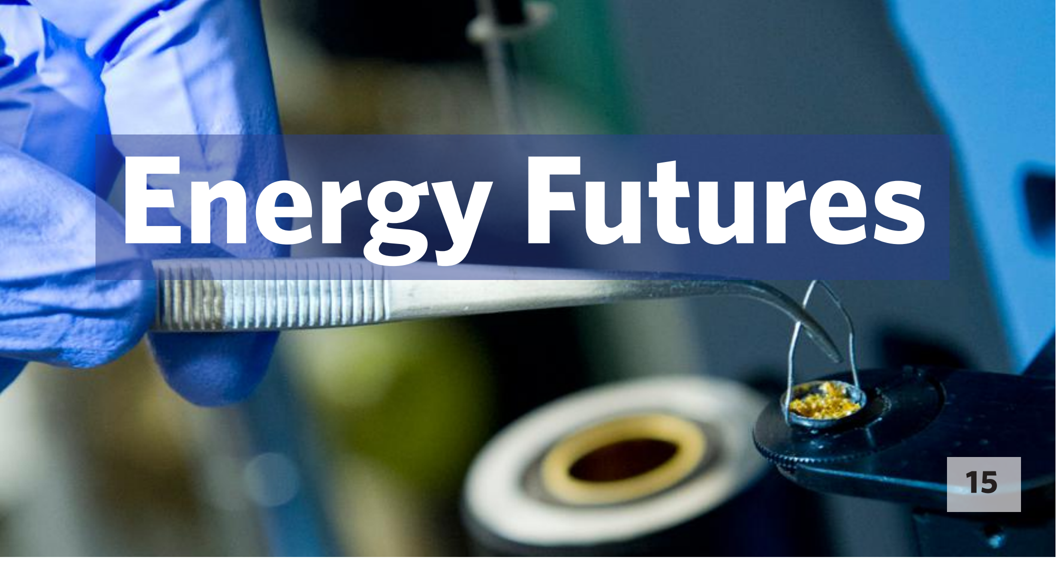


Energy Futures

Autumn 2018

MIT Energy Initiative

Massachusetts Institute of Technology

A letter from the director

Dear friends,

In September, the MIT Energy Initiative (MITEI) issued the eighth of our "Future of..." reports, *The Future of Nuclear Energy in a Carbon-Constrained World*, with key findings and recommendations presented at events in the United States, Europe, and Asia. These comprehensive, multidisciplinary reports are intended to help guide researchers, policymakers, and industry by highlighting specific energy technologies that could contribute to ever-increasing energy demand in a carbon-constrained world.

This study emphasizes the importance of incorporating nuclear energy into the mix of low-carbon energy technologies and analyzes why the growth in nuclear energy capacity has stalled and how that trend can be reversed. Study co-chair MIT Professor Jacopo Buongiorno says, "Our analysis demonstrates that realizing nuclear energy's potential is essential to achieving a deeply decarbonized energy future in many regions of the world." To learn more about the study and its release, see our special reports on pages 4 and 6.

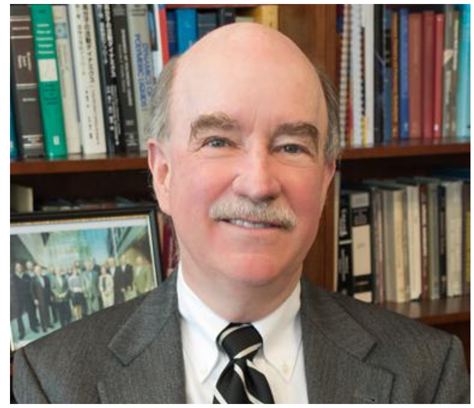
In this issue of *Energy Futures*, you will also read about an analysis that provides guidelines for cost-effective and reliable ways to build a zero-carbon electricity grid (page 25) and a novel technology designed to provide drinking water by capturing water droplets from industrial cooling towers (page 23).

You'll learn about innovations that fine-tune existing technologies, materials, and processes to achieve greater efficiency, sustainability, speed, and control. MIT investigators have developed a new method for rapid 3D printing of complex objects, along with a process for printing with renewable cellulosic feedstocks instead of plastics (page 9). Other researchers have demonstrated a new concept for thermal energy storage that uses conventional "phase-change" materials but defers the release of stored heat until it's needed (page 15). Another team has gained new insights into how plants control the amount of sunlight they use to produce nutrients—information that could one day lead to increased yields of biomass for fuel and crops for food (page 19).

Earlier this fall, I joined former US Secretary of State George P. Shultz and colleagues in Washington, DC, for the MIT-Stanford Energy Game Changers Symposium to reinforce the value of fundamental research in energy. This meeting underscored the importance of energy research with two main topics: how we can change the future of the electric power sector and how we will provide energy for industry of the future. The symposium highlighted game-changing technologies for generating and storing energy and also for lowering the greenhouse gas footprint of the industrial sector going forward. The project examples that participants shared also illustrated advances that can be made when academia, government, and industry work together.

MITEI just wrapped up this year's Annual Research Conference, where we explored the energy-intelligence nexus through a special collaboration with the MIT Quest for Intelligence, a new initiative that focuses on advancing the science and engineering of both human and machine intelligence. Together, we considered ways in which artificial intelligence and machine learning can help us realize a low-carbon energy future (page 38).

At the conference, undergraduate students presented posters about their summer research to our academic and industry participants. These presentations demonstrated what they learned not only in their research but also in newly designed professional-development workshops meant to build critical skills not found in the lab or classroom (page 33).


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

In other education news, we welcomed a new cohort of graduate students and postdocs into our Society of Energy Fellows (page 30) and introduced a crop of incoming undergraduates to the energy opportunities at MIT through our Freshman Pre-Orientation Program (page 36).

Many people throughout the Institute are working to develop and advance low- and no-carbon energy technologies, examine transition pathways for different parts of the energy sector, inform policy discussions about transforming the energy system, and educate the next generation of energy innovators. But there is still much more to be done. Please read on to learn more about our efforts and, as always, be in touch with any feedback and thoughts.

Warm regards,

Robert C Armstrong

Professor Robert C. Armstrong
MITEI Director
November 2018

MIT Energy Initiative announces new class of membership geared toward energy startups

The MIT Energy Initiative (MITEI) has created a new class of membership aimed at easing the way for energy startups. All startups face challenges early on, but those in the energy field, with their need for specialized talent and capital-intensive equipment and facilities, confront a particularly daunting challenge. This new model brings the specific needs of energy startups to the forefront while building on the well-established MITEI membership model, which provides access to research experts and facilities in the form of sponsored research, as well as a built-in network of companies across the energy sector.

"By creating a new MITEI membership category specifically designed for energy startup companies, we have created a path for engagement between startups and MITEI's other members," says MITEI Director Robert Armstrong. "These more established members will share knowledge of the energy sector, thereby helping to accelerate commercialization of new technologies to improve our global energy systems. Speeding such deployment is central to what MIT had in mind when embarking on its Plan for Action on Climate Change."

This spring, MITEI announced Cambridge-based fusion startup Commonwealth Fusion Systems (CFS) as its inaugural Startup Member. CFS is collaborating with MITEI through an initial three-year member agreement as part of its goal of making magnetic fusion power a reality.

The new membership category enables startup companies like CFS to more easily engage with the MIT ecosystem, which includes labs, scientists, engineers, and students, offering access to the tools and talent that they need to succeed in scaling up their energy technology. CFS, for example, will access MIT's deep expertise in fusion and magnet research through its program of sponsored research. With this membership model, MITEI hopes to enable promising energy startups to overcome research and development hurdles and successfully commercialize technologies that could change the face of the energy sector for the better.

"Our goal is to open our doors to new entrants to our innovation ecosystem who bring with them new perspectives and ideas. We need to reach into the classroom and lab earlier in the game to identify the most promising ideas—and the inventors and founders behind them," says Louis Carranza, MITEI associate director, who will manage the program and lead recruitment. "The startup membership is a platform where promising discoveries can be nurtured to the point where they can become investable. We help companies reach that stage by facilitating sponsored research aimed at clearing specific technology hurdles."

For instance, CFS plans to carry out rapid, staged research in fusion energy generation using high-temperature superconductors that have recently become commercially available. The company will fund complementary fusion research at MIT, as researchers from MIT's Plasma Science and Fusion Center design and build a powerful experimental fusion device called SPARC (Soonest/Smallest Privately-Funded Affordable Robust Compact). This experiment, building on work made possible by decades of federal funding for basic research, will be a critical step in a project whose goal is the design of the world's first commercial power-producing fusion plants.

"The collaboration inherent in this new model enables the startup researchers to work side-by-side in the MIT labs as visiting scientists, contributing to the work. This puts the best people and perspectives together from all sides all the time," says Bob Mumgaard, CFS CEO. "This dynamic mix of people and perspectives connects startups to the deep talent and infrastructure of MIT while also fostering a fertile culture of experimentation."

Francesca McCaffrey, MITEI

NOTE

To learn more about our new Startup Member category, please contact MITEI Associate Director Louis Carranza at carranza@mit.edu or 617-324-7029. Information about other MITEI membership opportunities is online at energy.mit.edu/membership.

New report examines the future of nuclear energy in a carbon-constrained world

Francesca McCaffrey, MITEI

How can the world achieve the deep carbon emissions reductions that are necessary to slow or reverse the impacts of climate change? The authors of a new MIT study say that unless nuclear energy is meaningfully incorporated into the global mix of low-carbon energy technologies, the challenge of climate change will be much more difficult and costly to solve. For nuclear energy to take its place as a major low-carbon energy source, however, issues of cost and policy need to be addressed.

In *The Future of Nuclear Energy in a Carbon-Constrained World*, released by MITEI on September 3, 2018, the authors analyze the reasons for the current global stall of nuclear energy capacity—which currently accounts for only 5% of global primary energy production—and discuss measures that could be taken to arrest and reverse that trend.

The study group, led by MIT researchers in collaboration with colleagues from the Idaho National Laboratory and the University of Wisconsin at Madison, presented its findings and recommendations at events in London, Paris, and Brussels during the week of September 3, followed by events on September 25 in Washington, DC, and on October 9 in Tokyo. MIT graduate and undergraduate students and postdocs, as well as faculty from Harvard University and members of various think tanks, also contributed to the study as members of the research team.

"Our analysis demonstrates that realizing nuclear energy's potential is essential to achieving a deeply decarbonized energy future in many regions of the world," says study co-chair Jacopo Buongiorno, the TEPCO Professor and associate department head of the Department of Nuclear Science and Engineering at MIT. He adds, "Incorporating new policy and business models, as well as innovations in construction that may make deployment of cost-effective nuclear power plants more affordable, could enable nuclear energy to help meet the growing global demand for energy generation while decreasing emissions to address climate change."

The study team notes that the electricity sector in particular is a prime candidate for deep decarbonization. Global electricity consumption is on track to grow 45% by 2040, and the team's analysis shows that the exclusion of nuclear from low-carbon scenarios could cause the average cost of electricity to escalate dramatically.

"Understanding the opportunities and challenges facing the nuclear energy industry requires a comprehensive analysis of technical, commercial, and policy dimensions," says Robert C. Armstrong, director of MITEI and the Chevron Professor of Chemical Engineering. "Over the past two years,

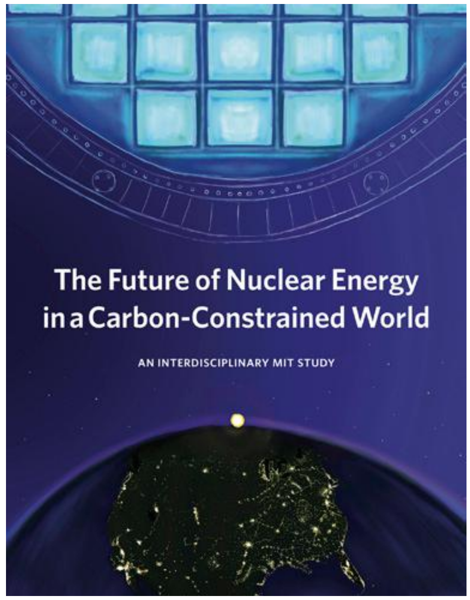
Above *The Future of Nuclear Energy in a Carbon-Constrained World* study co-chair Jacopo Buongiorno presents findings from the report at an event in Washington, DC. Photo: Diana Bowen this team has examined each issue, and the resulting report contains guidance policymakers and industry leaders may find valuable as they evaluate options for the future."

The report discusses recommendations for nuclear plant construction, current and future reactor technologies, business models and policies, and reactor safety regulation and licensing. The researchers find that changes in reactor construction are needed to usher in an era of safer, more cost-effective reactors; these changes include proven construction management practices that can keep nuclear projects on time and on budget.

"A shift towards serial manufacturing of standardized plants, including more aggressive use of fabrication in factories and shipyards, can be a viable cost-reduction strategy in countries where the productivity of the traditional construction sector is low," says MIT Visiting Research Scientist David Petti, study executive director and laboratory fellow at the Idaho National Laboratory. "Future projects should also incorporate reactor designs with inherent and passive safety features."

These safety features could include core materials with high chemical and physical stability and engineered safety systems that require limited or no emergency AC power and minimal external intervention. Features like these can reduce the probability of severe accidents occurring and mitigate offsite consequences in the event of an incident. Such designs can also ease the licensing of new plants and accelerate their global deployment.

"The role of government will be critical if we are to take advantage of the economic opportunity and low-carbon potential that nuclear has to offer," says John Parsons, study co-chair and senior lecturer at the MIT Sloan School of Management. "If this future is to be realized, government officials must create new decarbonization policies that put all low-carbon energy technologies (e.g., renewables, nuclear,



fossil fuels with carbon capture) on an equal footing, while also exploring options that spur private investment in nuclear advancement."

The study lays out detailed options for government support of nuclear. For example, the authors recommend that policymakers should avoid premature closures of existing plants, which undermine efforts to reduce emissions and increase the cost of achieving emission-reduction targets. One way to avoid these closures is the implementation of zero-emissions credits—payments made to electricity producers where electricity is generated without greenhouse gas emissions—which the researchers note are currently in place in New York, Illinois, and New Jersey.

Another suggestion from the study is that the government support development and demonstration of new nuclear technologies through the use of four "levers": funding to share regulatory licensing costs; funding to share research and development costs; funding for the achievement of specific technical milestones; and funding for production credits to reward successful demonstration of new designs.

The study includes an examination of the current nuclear regulatory climate, both in the United States and internationally. While the authors note that significant social, political, and cultural differences may exist among many of the countries in the nuclear energy community, they say that the fundamental basis for assessing the safety of nuclear reactor programs is fairly uniform and should be reflected in a series of basic aligned regulatory principles. They recommend regulatory requirements for advanced reactors be coordinated and aligned internationally to enable international deployment of commercial reactor designs and to standardize and ensure a high level of safety worldwide.

The study concludes with an emphasis on the urgent need for both cost-cutting advancements and forward-thinking policymaking to make the future of nuclear energy a reality.

The Future of Nuclear Energy in a Carbon-Constrained World is the eighth in the "Future of…" series of studies that are intended to serve as guides to researchers, policymakers, and industry. Each report explores the role of technologies that might contribute at scale in meeting rapidly growing global energy demand in a carbon-constrained world. Nuclear power was the subject of the first of these interdisciplinary studies, with the 2003 *Future of Nuclear Power* report (an update was published in 2009). The series has also included a study on the future of the nuclear fuel cycle. Other reports in the series have focused on carbon dioxide sequestration, natural gas, the electric grid, and solar power. These comprehensive reports are written by multidisciplinary teams of researchers. The research is informed by a distinguished external advisory committee.

NOTE

For more information and an online version of *The Future of Nuclear Energy in a Carbon-Constrained World*, visit bit.ly/future-of-nuclear.

Student researchers lend their voices and ideas to Future of Nuclear study

Francesca McCaffrey and Emily Dahl, MITEI

In late September 2018, researchers shared findings and recommendations from the new interdisciplinary MIT study, *The Future of Nuclear Energy in a Carbon-Constrained World*, at a series of events and meetings in Washington, DC. On September 25 and 26, study participants from MIT and other institutions involved in the report spoke with a variety of energy stakeholders and discussed nuclear energy's potential to help address climate change—and how industry and government could solve issues of cost and policy currently limiting that potential. For four of the graduate students from the research team who participated in the events, the DC visits held additional significance, as they saw their years of work on the study come to fruition.

Karen Dawson, a doctoral candidate in nuclear science and engineering, said, "I found it valuable to participate in the panel and meetings on the Hill because it felt like I was moving from the minor leagues to the major leagues." She added, "It was also really fulfilling to see industry experts discussing my work. It demonstrated the impact of my contributions to the study."

The lead researchers on the study repeatedly underscored the value of the students' work as well. Addressing an audience of approximately 150 people at the American Association for the Advancement of Science, study co-chair Jacopo Buongiorno began by acknowledging the efforts of the study team, composed of MIT and non-MIT researchers and advisors. Buongiorno, the TEPCO Professor and associate head of the Department of Nuclear Science and Engineering, cited the contributions of the graduate students at the event and other students who worked on the report as being a vital part of the team effort.

Another study co-chair, Michael Corradini, echoed Buongiorno's remarks, crediting the students as being "extremely important in doing these analyses." Corradini, an emeritus professor of engineering physics at the University of Wisconsin at Madison, told the audience, "When you get to the tough questions, we'll pass it on to them."

In addition to taking audience questions on their areas of expertise within the study, the students answered one from event moderator Professor Robert C. Armstrong, director of the MIT Energy Initiative (MITEI). He asked what had surprised them as they were working on the study.

Amy Umaretiya, a master's student in the Technology and Policy Program at the MIT Institute for Data, Systems, and Society, worked with study co-chair John Parsons, a senior lecturer at the MIT Sloan School of Management, to examine policy issues. She said that learning that some public policies didn't incorporate

Above *The Future of Nuclear Energy* study panelists. Front row (from left): Robert C. Armstrong, Karen Dawson, and Amy Umaretiya. Back row (from left): Patrick Champlin, Michael Corradini, Jacopo Buongiorno, Patrick White, David Petti, and John Parsons. Photo: Diana Bowen nuclear energy as a low-carbon solution came as a surprise. "The fact that clean energy standards are actually focused only on renewable energy as opposed to [a wider portfolio of] clean energy was a big shock for me," she said.

Audience members also wanted to know why students had chosen to study nuclear science and engineering, and not "something 'sexier' like battery storage, smart grids, or next-generation solar."

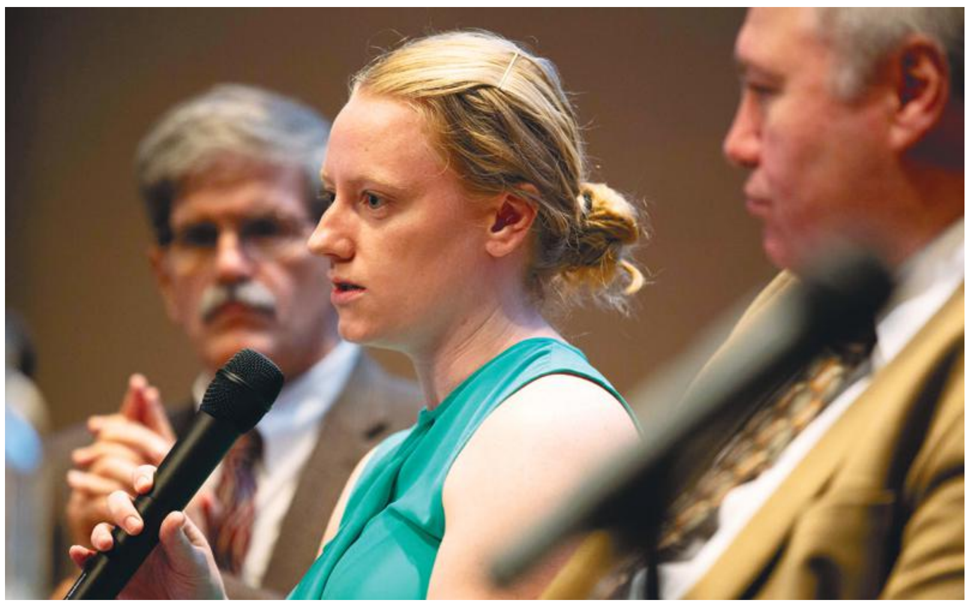
"My interest in nuclear science and engineering really comes down to the amount of energy that's released when you split an atom apart," said doctoral candidate Patrick White. "We're talking 40 to 50 million times more energy per reaction if you look at the fission of a uranium atom versus the combustion of a carbon atom."

He said he began to wonder, "What kind of opportunities do you have when you take that kind of energy and apply it in places where solar and wind might not be appropriate—or even to help complement other technologies?"

Dawson added, "I was amazed that there was this technology that was viable on the grid already and had zero carbon emissions, and nobody really seemed to be talking about it as a solution, at least when I was an undergrad."

She said, "After a couple of years at MIT, I believed in nuclear being a strong part of the future energy system, and then I got interested in what the obstacles were to its development. That's what brought me to this study."

Dawson, Umaretiya, White, and nuclear science and engineering master's student Patrick Champlin also participated in meetings at the US Department of Energy, at the Center for Strategic and International Studies, on Capitol Hill with legislators and staff members (arranged by the MIT Washington

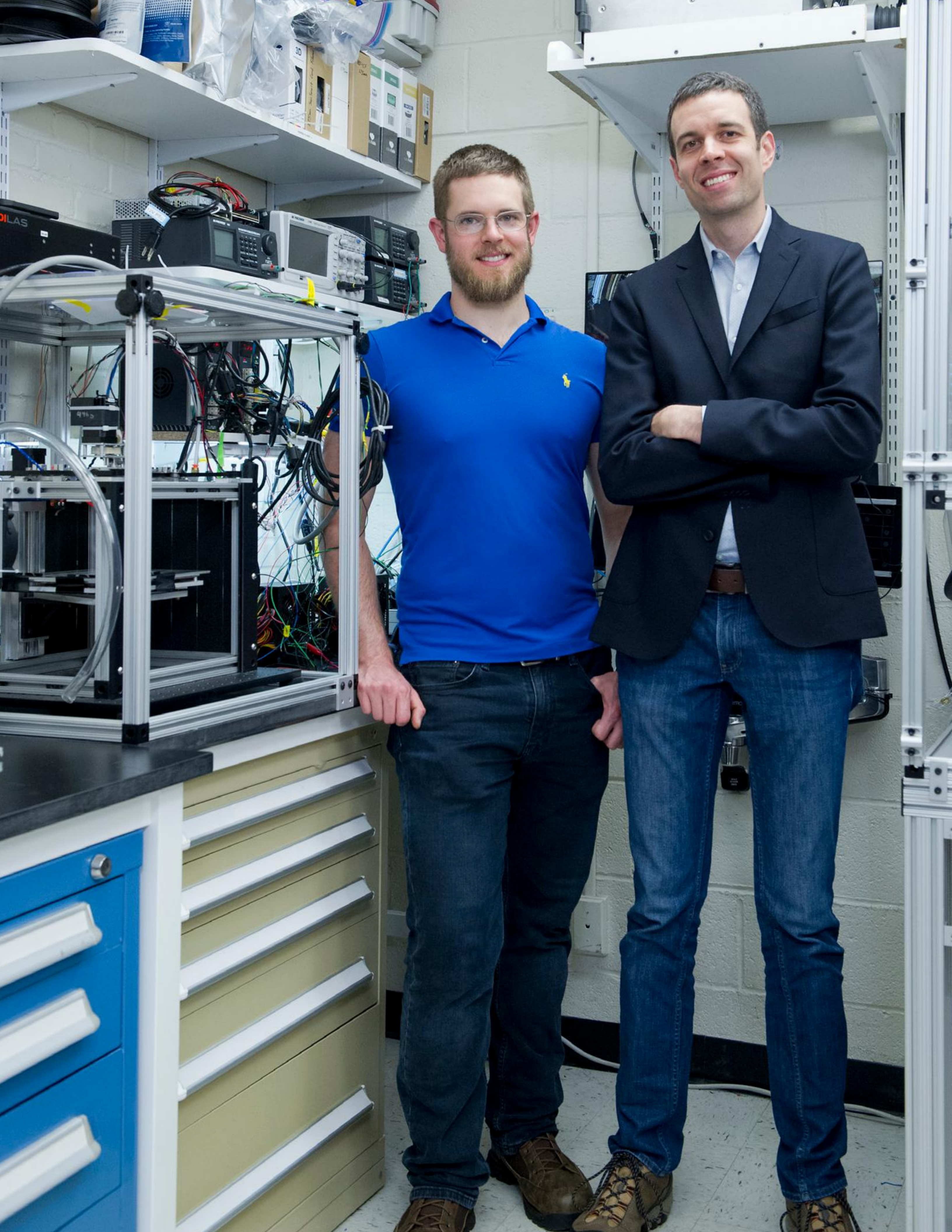


Student researchers respond to questions from the audience. Top photo: Amy Umaretiya, master's student, Technology and Policy Program at the MIT Institute for Data, Systems, and Society. Bottom photo: Karen Dawson, doctoral candidate, nuclear science and engineering. Photos: Diana Bowen

Office), and at a dinner hosted by the Alumni Club of DC.

About these meetings in DC, White said, "It's so important that we're able communicate our report findings to policymakers. It was a really different experience to explain my research to a member of Congress instead of my advisor, but if we want to make our work matter, it's a conversation we need to learn to have."

MITEI, which published the study, sponsored Dawson's, Umaretiya's, and White's travel for the DC events. MIT's International Policy Laboratory also provided support for outreach on the study. Other students who worked on the study included undergraduate students Rasheed Auguste, Ze (Jenny) Dong, and Ka-Yen Yau; doctoral candidate Lucas Rush; and PhD candidate Nestor Sepulveda, all of nuclear science and engineering.



Accelerating 3D printing

Faster fabrication, renewable materials

Nancy W. Stauffer, MITEI

IN BRIEF

Recent work from an MIT lab may help 3D printing fulfill its long-standing promise to transform manufacturing by enabling the rapid design and production of customized and complex objects. Key to 3D printing is a printhead that deposits successive layers of material onto a surface until the final three-dimensional object is complete. The researchers have designed a novel printhead that can melt and extrude material with unprecedented speed. The system can create a complex handheld object in a few minutes rather than the hour required by a typical desktop 3D printer. The researchers have also demonstrated a room-temperature process for 3D printing with cellulose—a renewable, biodegradable alternative to the plastics now generally used. To show the chemical flexibility of cellulose, they've mixed in an antimicrobial dye and printed a pair of bacteria-resistant surgical tweezers.

Imagine a world in which objects could be fabricated in minutes and customized to the task at hand. An inventor with an idea for a new product could develop a prototype for testing while on a coffee break. A company could mass-produce parts and products—even complex ones—without being tied down to part-specific tooling and machines that can't be moved. A surgeon could get a bespoke replacement knee for a patient without leaving the operating theater. And a repair person could identify a faulty part and fabricate a new one on site—no need to go to a warehouse to get something out of inventory.

Facing page Doctoral student Adam Stevens SM '15 (left), Associate Professor A. John Hart, and their colleagues have designed a 3D printer that can deposit material 10 times faster than today's desktop models can. The team has also developed a novel process for 3D printing using a widely available natural polymer: cellulose. Photos: Stuart Darsch

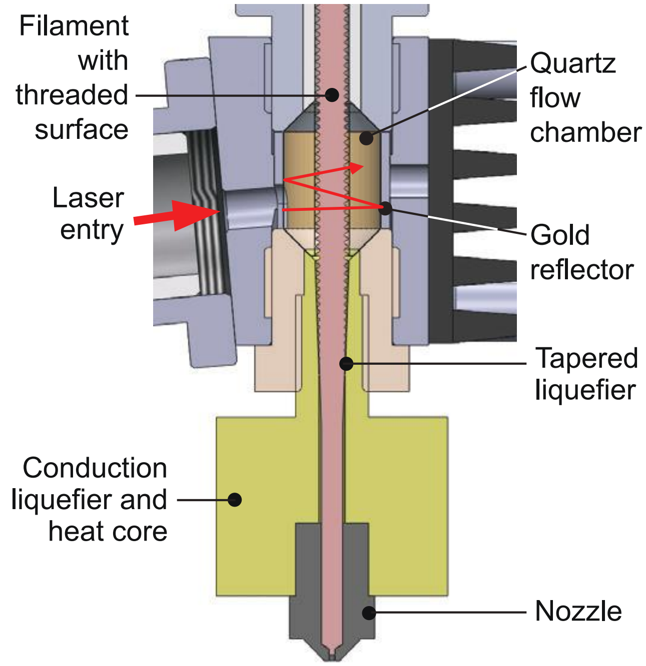
Above In one test, the researchers used their printer and a conventional plastics-based feedstock to create this helical bevel gear—a special challenge because of its complex shape. Printing the gear took just 10 minutes, and the finished product was strong, robust, and composed of highly uniform layers.

Such a future could be made possible by 3D printing, says A. John Hart, an associate professor of mechanical engineering and director of the Laboratory for Manufacturing and Productivity and the Mechanosynthesis Group at MIT. "3D printing compels us to rethink how we develop, produce, and service products."

A common method of 3D printing—extrusion—starts with a polymer rod, or filament. The filament is heated, melted, and forced through a nozzle in a printhead. The printhead moves across a horizontal surface (the print bed) in a prescribed pattern, depositing one layer of polymer at a time. On each pass over the print bed, instructions tell the printhead exactly where material should and shouldn't be extruded so that, in the end, the layers stack up to form the desired, freestanding 3D object. "So rather than starting with a solid block and grinding material away, in 3D printing—also called additive manufacturing—you start with nothing and build up your object one layer at a time," explains Hart.

Engineers have used 3D printing as a tool for rapid prototyping since its invention some three decades ago, but in recent years its use has expanded. Hart credits that expansion to better 3D printers but also to the widespread adoption of computer-aided design, or CAD, and emerging software tools for 3D shape optimization. Today's designers can use CAD software to create a virtual 3D model of their targeted product, and in the process they generate a digitized description of it. That description can feed into software that develops the instructions for controlling the path of the 3D printer. As a result, designers no longer have to confine themselves to structures that can be made by machining or molding. "For instance, you can make an airplane seat with a complex internal structure that makes it light and saves fuel in flight," notes Hart.

3D printing has made great strides, but it's still a long way from what Hart envisions. Two recent advances out of his lab may



Cutaway model of the novel MIT printhead In the "fast fused filament fabrication" (Fast FFF) printhead, the threaded filament enters from the top and is pulled along by a rotating nut that has matching internal threads for maximum contact. It passes into a quartz chamber covered by gold foil. There, a laser beam enters from the side and is reflected through the core of the filament to preheat it. The filament then passes into a hot metal block, where it melts before being extruded out of the nozzle.

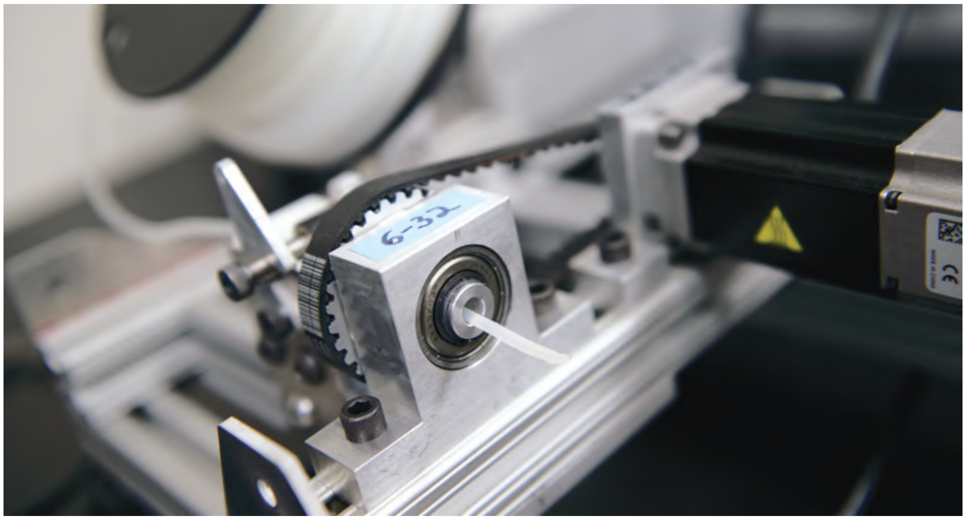
help accelerate the adoption of 3D printing: a machine that can print handheld objects far faster than today's desktop 3D printers can, and a process for using cellulose as an inexpensive, biorenewable replacement for the usual plastics.

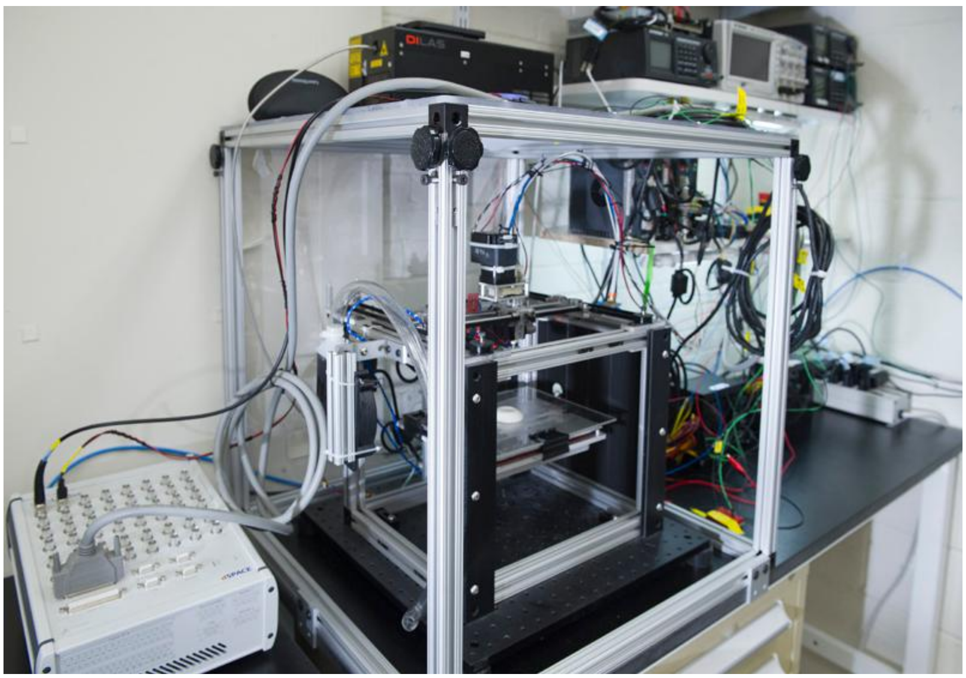
Sources of the slowdown

To find out what slows down current 3D printers, Hart, Jamison Go SM '15, now a mechanical engineer at Desktop Metal, and Adam Stevens SM '15, now a doctoral student in Hart's lab, examined several commercial, extrusion-based desktop models and concluded that their so-called volumetric building rates were limited by three factors: how much force the printhead could apply as it pushed the material through the nozzle; how quickly it could transfer heat to the material to get it to melt and flow; and how fast the printer could move the printhead.

Based on those findings, they designed a machine with special features that address all three limitations. In their novel design, a filament with a threaded surface goes into the top of the printhead between two rollers that keep it from twisting. It then enters the center of a rotating nut, which is turned by a motor-run belt and has internal threads that mesh with the external threads on the filament. As the nut turns, it pushes the filament down into a quartz chamber surrounded by gold foil (see the figure above). There, a laser enters from the side and is reflected by the gold foil several times, each time passing through the center of the filament to preheat it. The softened filament then enters a hot metal block, which heats it further (by conduction) to a temperature above its melting point. As it descends, the molten material is further heated and narrowed and finally extruded through a nozzle onto the print bed.

That design overcomes the limits on force and heating that slow current 3D printers. In a standard printer, the filament is





The top photo shows a filament passing through a device that presses into its surface the threads that keep it from slipping as it enters the novel 3D printer—shown in the bottom photo—at high force and feed rate. Photos: Stuart Darsch

pushed by two small, rotating wheels. Add more force to speed things up, and the wheels lose traction and the filament stops moving. That's not a problem with the new design. Matching the threads on the filament and the nut ensures maximum contact between the two. As a result, the system can transfer a high force to the filament without losing its grip. The standard printer also relies on thermal conduction between the moving filament and a heated block, and that process takes time. At a higher feed rate, the core may not completely melt, with two impacts: Pushing the material through the nozzle will be harder, and the extruded material may not adhere well to the previously deposited layer. Preheating the filament with a laser ensures that the filament is thoroughly melted by the time it reaches the nozzle.

Tests showed that their novel printhead can deliver at least two and a half times more force to the filament than standard desktop models can, and it can achieve an extrusion rate that's 14 times greater.

Given such a high extrusion rate, the researchers needed to find a way to move the printhead fast enough to keep up. They designed a mechanism with a metal overhead suspension gantry that's shaped like an "H" and has a continuous belt that travels around pulleys powered by two motors mounted on the stationary frame. The printhead sits atop a stage that's connected to the belt and is carried quickly and smoothly through the prescribed positions within each plane.

To test the new gantry, the researchers subjected it to a battery of tests. In one, they commanded it to execute a continuous back-and-forth motion between two positions at various speeds and checked the consistency of where it ended up. Based on those challenges, the researchers concluded that the gantry was sufficiently fast and accurate to do the job.

Fabricating test objects

To demonstrate their system, the team printed a series of test objects, including those shown on page 12. Printing a pair of eyeglass frames took 3.6 minutes, a small spiral cup just over 6 minutes, and a helical bevel gear (a circular gear with angled teeth) about 10 minutes. Microscopic examination of the objects confirmed that the individual deposited layers were highly uniform at 0.2 mm thick, and tests of their mechanical properties confirmed that they were strong and robust.

The complex shape of the bevel gear made it a particularly good test subject. The interior surface is tapered such that the open space is wider at the bottom than the top. The researchers have produced even more complex shapes with greater interior openings, and the machine successfully created the thin, solid legs that are initially needed to provide support and are removed after the piece solidifies.

To better evaluate their printer, the researchers used it and several commercial desktop models to print the same

Using the new MIT system and a plastics-based feedstock, the researchers printed a series of test objects, including those shown above. Mechanical testing confirmed that the objects were strong and robust, and microscopic examination showed that the deposited layers were highly uniform. Printing the helical bevel gear (top left) took longest at 10 minutes—a reflection of its complex shape. The "dogbone" in the foreground is a standard shape used to test tensile strength, that is, how much stress an object can withstand while being stretched before it breaks.
Photo: Stuart Darsch

object—a triangular prism 20 mm tall. For a comparable resolution (based on nozzle diameter and layer height), their printer achieved an average volumetric build rate up to 10 times higher than the desktop models. It even did three times better than an industrial-scale system that has a significantly larger printhead and motion system, and costs over $100,000.

The researchers have been identifying and tackling issues introduced by the high-speed deposition conditions. For example, at high build rates, they found that their layers didn't adhere well and the shapes sometimes became distorted. Directing a controlled flow of cooling air onto newly deposited material solved those problems. They also determined that they should be able to improve the coupling between the laser and the filament, getting even more efficient heating. The team is also improving the system's accuracy by coordinating the extrusion rate and printhead speed, and implementing new control algorithms for the printer.

The researchers aren't ready to estimate the potential cost of their printer. Their prototype system costs about $15,000, two-thirds of which comes from the laser and motors. Thus, it's unlikely to replace today's personal desktop systems. But it should be cost-competitive with state-of-the-art professional systems while offering decreased operating costs from faster output.

Cellulosic feedstocks

Another critical component of Hart's vision for 3D printing is the ability to process materials that are abundant and environmentally friendly. Hart and Sebastian Pattinson, a postdoctoral fellow in mechanical engineering who is now a lecturer at the University of Cambridge, United Kingdom, demonstrated a technique using the world's most abundant natural polymer: cellulose. Cellulose offers many advantages over current plastics-based feedstocks: It's inexpensive, biorenewable, biodegradable, mechanically robust, and chemically versatile. In addition, it's widely used in pharmaceuticals, packaging, clothing, and a variety of other products, many of which could be customized using 3D printing.

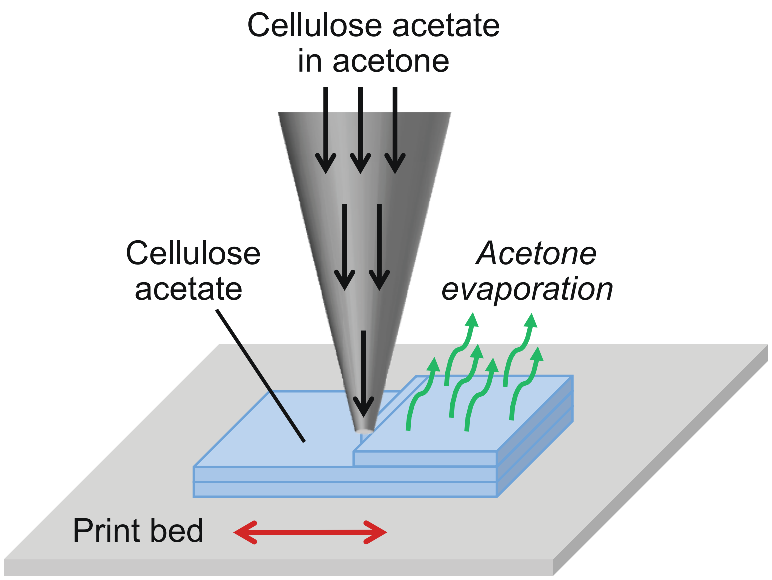
Past efforts to 3D print cellulose have largely been unsuccessful. The problem is that the abundant hydrogen bonding between the cellulose molecules—the thing that makes it strong in plants—makes it not conducive to 3D printing. Heat up cellulose, and it decomposes before it becomes sufficiently flowable to extrude from the nozzle of a printhead.

To solve that problem, Hart and Pattinson worked with cellulose acetate, a chemically treated form of cellulose that has fewer hydrogen bonds. The figure on page 13 shows the process. They first dissolve the cellulose acetate in an acetone solvent to form a viscous feedstock, which flows easily through the printer nozzle at room temperature. As the mixture spreads across the print bed, the acetone solvent rapidly evaporates, leaving behind the cellulose acetate. Immersing the finished cellulose acetate object in sodium hydroxide removes the acetate and restores the cellulose with its full network of hydrogen bonds.

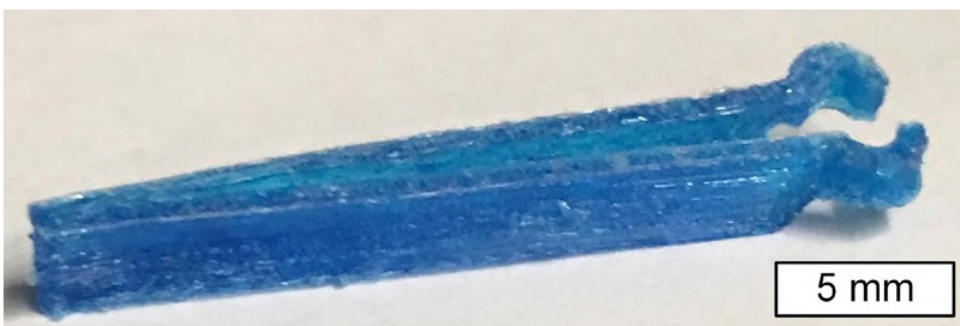
Using that procedure, the researchers printed complex objects out of their cellulosic materials, and the mechanical properties of the parts were good. Indeed, after the sodium hydroxide treatment, their strength and stiffness—measured in any direction—were superior to those of parts made out of commonly used 3D printing materials.

Hart also notes that cellulose provides chemical versatility. "You can modify cellulose in different ways, for example, to increase its mechanical properties or to add color," he says.

One option the researchers explored was adding antimicrobial properties. They printed a series of disks, some from plain cellulose acetate and some with an antimicrobial dye added, and deposited a



Process for 3D printing of cellulose Cellulose acetate dissolved in acetone is fed through the nozzle of the printhead onto the print bed below. The acetone quickly evaporates, leaving layers of cellulose acetate. The printed object is subsequently immersed in sodium hydroxide to remove the acetate, leaving a finished product of pure cellulose.



Microbe-resistant surgical tweezers To show the chemical versatility of using cellulose, the researchers added antimicrobial dye to their starting material and printed the surgical tweezers shown above. Tests showed that objects made with the added antimicrobial dye suppressed the growth of added *E. coli* bacteria after 20 hours' exposure to fluorescent light similar to that used in many medical settings. Photo courtesy of the researchers

solution containing *E. coli* bacteria on each one. They then left some of the disks in the dark and exposed others to light from a fluorescent bulb like those used in laboratories and hospitals. Analysis of the bacteria surviving after 20 hours showed that the disks made with dye and exposed to the light had 95% fewer bacteria than the others. As a sample product, they printed the surgical tweezers shown in the photo above—an instrument that could be highly valuable in any surgical setting where ensuring sterility might be an issue.

Hart thinks that the opportunities offered by their cellulose printing process could be of commercial interest. It uses a commodity product that's widely available and less expensive than the typical extrusion filament material. It takes place at room temperature, so there's no need for a costly heat source such as the laser used in the novel printhead described earlier. And as long as the acetone is captured and recycled, the process is environmentally friendly.

One more ingredient

Hart hopes that these and other developments coming out of his lab will help advance 3D printing. But there's another critical element that's needed: a workforce knowledgeable in both the technical and business aspects of additive manufacturing.

To that end, he teaches a graduate-level MIT class in additive manufacturing (additivemanufacturing.mit.edu), which is proving highly popular; and in 2018, he launched an online professional course via MIT xPRO that enrolled nearly 1,200 people during its first run. He also offers a five-day, on-campus MIT Short Program that has attracted worldwide participants who want to learn about using additive manufacturing in their design and manufacturing operations. He is now leading MIT's new Center for Additive and Digital Advanced Production Technologies (adapt.mit.edu), and plans are in the works for symposia at which its members will share their knowledge, ideas, and experiences. The enthusiastic response to these offerings suggests that Hart's vision of 3D printing and digitized design and production may at last be on its way to becoming a reality.

NOTES

This research was supported in part by Lockheed Martin Corporation. Sebastian Pattinson was supported by a National Science Foundation Science, Engineering, and Education for Sustainability postdoctoral fellowship.
Further information can be found in:

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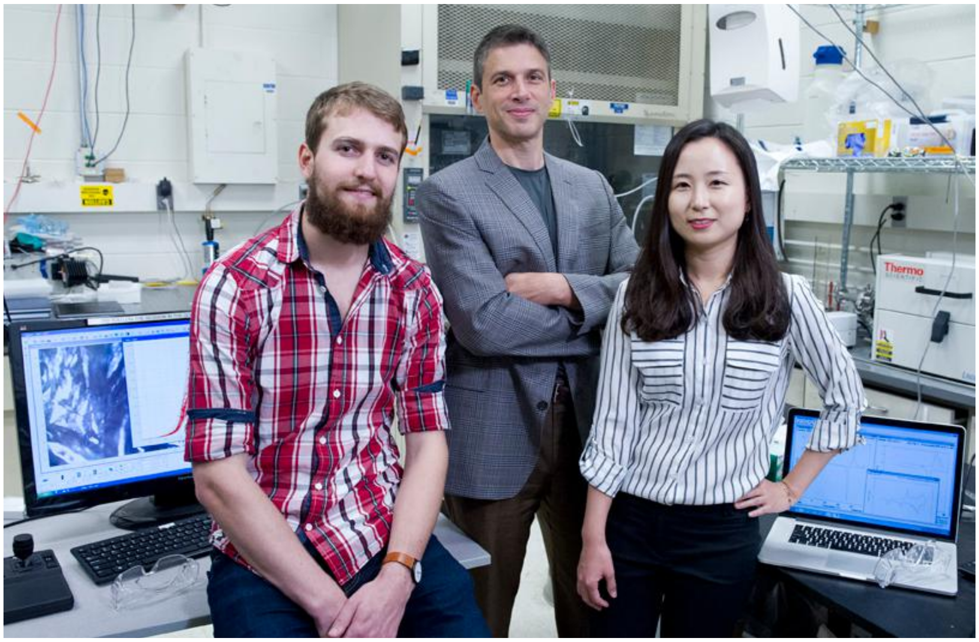


Saving heat until you need it

A new concept for thermal energy storage

Nancy W. Stauffer, MITEI

IN BRIEF

MIT researchers have demonstrated a new way to store unused heat from car engines, industrial machinery, and even sunshine until it's needed. Central to their system is a "phase-change" material that absorbs lots of heat as it melts and releases it as it resolidifies. Once melted and activated by ultraviolet light, the material stores the absorbed heat until a beam of visible light triggers solidification and heat release. Key to that control are added molecules that respond to light by changing shape—from one that impedes solidification to a different one that permits it. In a proof-of-concept experiment, the researchers kept a sample mixture in liquid form down to room temperature—fully 10°C below where it should have solidified—and then, after 10 hours, used a light beam to trigger solidification and release the stored thermal energy.

More than half of all the energy used to power mechanical, chemical, and other processes is expelled into the environment as heat. Power plants, car engines, and industrial processes, for example, produce vast amounts of heat but use a relatively small fraction of it to actually do work. And while sunlight delivers abundant radiant energy, today's photovoltaic devices convert only a fraction of it into electricity. The rest is either reflected or absorbed and converted into heat that goes unused.

The challenge is finding a way to store all that thermal energy until we want to

Facing page Using this instrument, the researchers shine a laser on their photoswitching molecules and then perform photoluminescence and Raman spectroscopy studies to gather information on the molecules' electronic structure and chemical bonding. Photos: Stuart Darsch

Above From left: Graduate student Cédric Viry, Professor Jeffrey Grossman, and postdoc Grace Han, with their collaborators, are using specially designed "photoswitching" molecules to control the release of heat from materials used to store thermal energy in devices ranging from solar concentrators and solar cookers to heated seats in vehicles.

use it. Jeffrey Grossman, the Morton and Claire Goulder and Family Professor in Environmental Systems and professor of materials science and engineering, has been working on that problem for more than a decade.

A good way to store thermal energy is by using a phase-change material (PCM) such as wax. Heat up a solid piece of wax, and it'll gradually get warmer—until it begins to melt. As it transitions from the solid to the liquid phase, it will continue to absorb heat, but its temperature will remain essentially constant. Once it's fully melted, its temperature will again start to rise as more heat is added. Then comes the benefit. As the liquid wax cools, it will solidify, and as it does, it will release all that stored phase-change heat—also called latent heat.

PCMs are now used in applications such as solar concentrators, building heating systems, and solar cookers for remote regions. But there's a problem: While PCMs can give off abundant heat, there's no way to control exactly when they do it. The timing depends on the temperature of the air around them. "You can charge a battery, and it'll store the electricity until you want to use it, say, in your cell phone or electric car," says Grossman. "But people have to heat up their solar cooker when the sun's out, and by the time they want to make dinner, it may well have given off all its stored heat to the cool evening air."

PCMs have thus proved a highly successful means of storing thermal energy, but getting it back out in a useful way has remained a challenge. "What we needed was a trigger that would give us control over the timing of the heat release," says Grossman.

Molecules that can trigger

A few years ago, Grossman began to wonder whether he might already have the trigger he needed. In related work, his group had been studying the storage of energy in special molecules known as photoswitches. Shine a certain wavelength of light on a photoswitch, and its shape will change. The same atoms are present, but their orientation relative to one another shifts. Moreover, they'll stay in that shifted configuration until they're exposed to another wavelength of light. Then they'll snap back to their original shape, in the process releasing thermal energy.

Grossman's group has made good progress on designing photoswitches for storing energy, but the molecules have a key limitation: They can be switched into their energy-storing configuration only by light. As a result, they can't be "charged" using waste heat from cars and machines and sunshine.

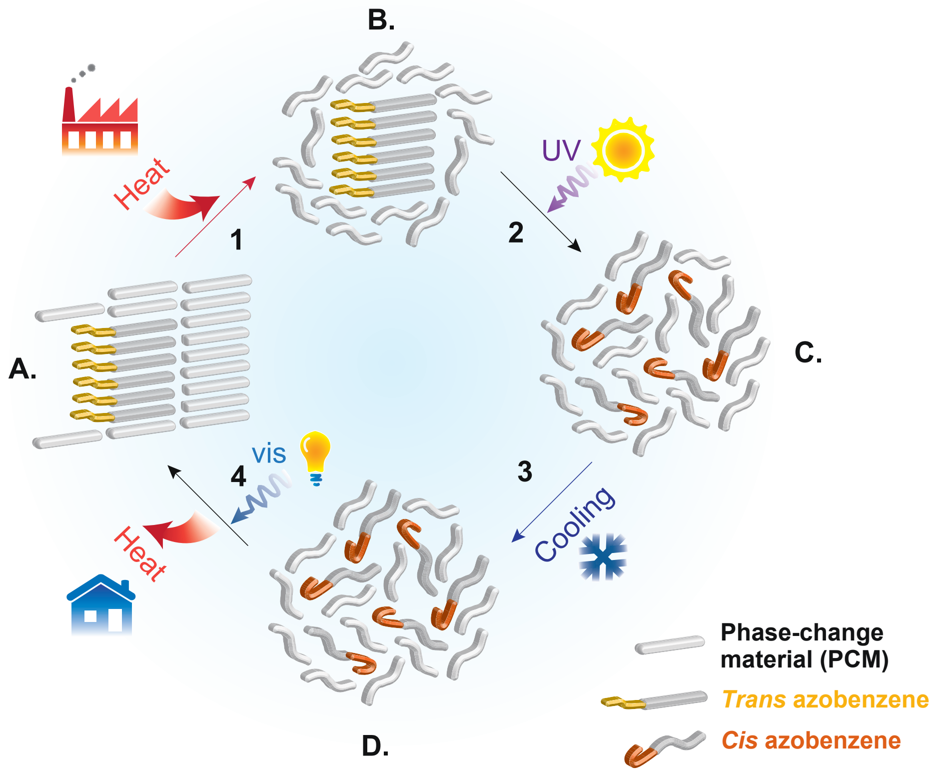
So Grossman and former postdocs Grace Han and Huashan Li of materials science and engineering began examining the possibility of using a photoswitch in a new way—as a trigger for controlling the release of energy from a phase-change material. "We could tailor its chemistry so that it matches the phase-change material really well when it's in one form, but when we switch it, it doesn't match anymore," explains Grossman. If mixed with a melted PCM in the mismatched form, the photoswitch would keep it from becoming a solid—even below its normal solidification temperature. Shining a different wavelength of light could change the photoswitch back to its matching structure. The PCM would then solidify, releasing its stored latent heat.

Proof-of-concept tests

To explore the viability of that approach, the researchers used a conventional PCM called tridecanoic acid and prepared a special variation of the photoswitch molecule azobenzene, which consists of two linked rings of atoms that can be in different positions with respect to one another. In the "*trans*" form of the molecule, the rings are flat—its naturally occurring ground state. In its "*cis*" form, one of the benzene rings is tilted at 56° relative to the other one. It switches from one shape to the other in response to light. Shine ultraviolet (UV) light on the flat version, and it'll twist; shine visible light on the twisted version, and it'll flatten out.

The figure on page 17 shows what Grossman calls the thermal energy storage and release cycle and illustrates the role played by the azobenzene photoswitch as a low-concentration "dopant" (a material added to alter the properties of a substance). When the PCM-azobenzene mixture, or composite, is solid with the azobenzene in its *trans* form, the two constituents pack together tightly, as shown in drawing A. When heated, the composite absorbs thermal energy, and the PCM melts (drawing B). Zapping it with UV light changes the azobenzene dopant from *trans* to *cis*, indicated by the hooked ends in drawing C. When that mixture cools, the *cis* azobenzene prevents solidification of the PCM, so the latent heat remains stored (drawing D). Illumination with visible light switches the azobenzene back to its *trans* form. The mixture can now solidify (drawing A), in the process releasing its stored latent heat.

A series of tests showed that their system worked well. Shining an ultraviolet lamp (at a wavelength of 365 nanonometers, or nm) on the liquid mixture changed most of the starting *trans* azobenzene molecules to their *cis* form. Once it was charged, the mixture didn't solidify even at room temperature—fully 10°C below where it would have without the charged photoswitches in the mix. Illuminating the liquid with visible light (450 nm) for 30 seconds activated solidification and release of the stored latent heat. Moreover, essentially all of the latent heat came out; little or none of it had been lost to leakage. "With the added switches, the thermal energy is locked in," says Grossman. "As a result, there may be less need for the heavy insulation that's used to keep heat from leaking out of conventional PCMs."



The thermal energy storage and release cycle In a solidified sample (structure A), crystals of the PCM and the azobenzene photoswitch in its *trans* form pack together tightly. The cycle proceeds as follows. Step 1—Heat the solid composite above the melting point of the PCM. It becomes a mixture of molten PCM and crystals of the azobenzene dopant, which has a higher melting point (structure B). Step 2—Shine ultraviolet (UV) light onto the mixture (and keep heating it so it stays melted), and the azobenzene dopant switches from *trans* to *cis* (the form with the twisted ends) and disperses into the liquid PCM (structure C). Step 3—Cool the composite to a temperature below its solidification point. The *cis* azobenzene dopants keep the PCM molecules from aligning, so the mixture can't solidify; it remains in its liquid form (structure D). Step 4—Shine visible light onto the mixture so that the *cis* azobenzene dopant changes back to its *trans* form. The PCM molecules and the *trans* dopant can now stack tightly, so the composite immediately solidifies (structure A), releasing its latent heat.

When the researchers didn't shine the visible light on their mixture, they found that it remained a liquid at temperatures below its original solidification point for 10 hours. The mixture then gradually began to solidify, giving off its stored heat.

To demonstrate the durability and repeatability of the system, the researchers switched it back and forth—between charging and discharging—100 times over more than 50 hours. During the initial discharging step, the crystallinity of the PCM changed slightly from the starting material, but after that, its structure remained unchanged.

Other tests confirmed the importance of carefully selecting or designing a photoswitch that interacts effectively with a specific PCM. Again, the photoswitch must mix well with the liquid PCM to form the composite and must change—when activated by light—between two distinct structures that blend with or interfere with the packing of the selected PCM. The researchers also found that optimizing the concentration of the photoswitch in the PCM is critical. When it's too low, it won't interfere with solidification. When it's too high, the ultraviolet light may not penetrate the mixture completely, and the dopant molecules may react with one another, clumping together rather than distributing well and preventing PCM packing.

Basics of a practical device

Grossman stresses that the work thus far is a proof of principle. "There's a lot of work to do to make applications based on this concept," he says. But the researchers envision the following type of device.

The mixture would be held in a container with windows that could be covered to control light intake. A heat exchanger would deliver thermal energy from the sun or another source to the PCM composite, and a separate LED or gas-discharge lamp would simultaneously send UV light in through the uncovered windows to charge the azobenzene dopant. The windows would then be covered to enable thermal storage, even as the mixture dropped to room temperature. When heat release is desired, the windows would be uncovered, and the liquid composite would be exposed to ambient light or to blue LED light for a faster response. The windows would be made of common borosilicate glass, which would transmit over 90% of the relevant UV and visible light, and a stirrer inside the container would help to keep the azobenzene molecules from sticking together.

Films, beads, and different materials

Grossman's group is continuing work to apply and improve the thermal storage concept. For example, they're examining its possible use as a novel system for de-icing—a topic of ongoing interest to Grossman, who notes that today's electric cars consume so much battery power for de-icing and heating that their driving range can drop by 30% during cold weather. A far better approach would be to store thermal energy in a thin, transparent film and trigger a blast of heat when it's needed to melt that troublesome layer of ice.

"With that in mind, we wanted to see if we could make thin films of our material over larger areas and have it exhibit the

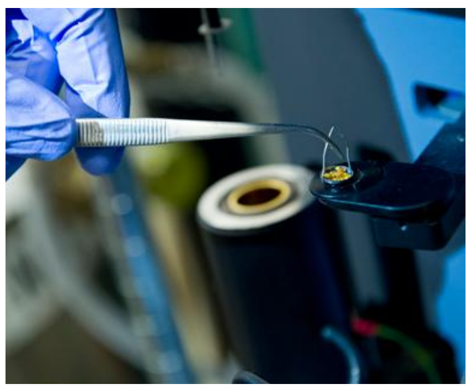
Charging and discharging films of a PCM composite The researchers used their approach to solidify sections of a PCM composite film sandwiched between two glass slides. First they heated the film to 43°C and exposed it to UV light to charge the photoswitch dopants (first photo). As the sample cooled to 36°C, they covered most of it with a black mask (second photo) and shone visible light selectively on the uncovered areas—the orange letters—causing the dopants there to revert to their *trans* form. With the mask removed (third photo), a light-colored pattern in the film shows that the PCM composite solidified only in the uncovered areas. (Scale bar is 10 mm.) Photos courtesy of the researchers

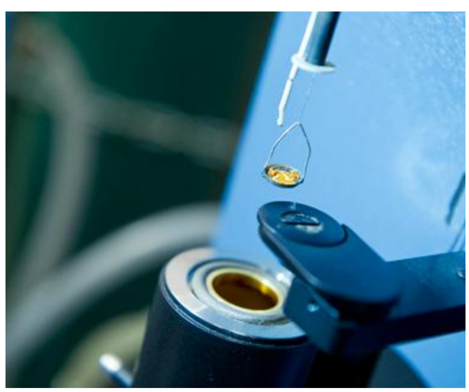
same behaviors we saw in our lab samples," Grossman says. They deposited their liquid PCM composite on a sheet of glass, put another sheet on top, and sealed it up. They found that they could charge up the mixture with UV light and then discharge it later with visible light, getting the stored phase-change energy back out as heat. Moreover, they could do it selectively so that part of the film solidified and the rest remained liquid (see the photos above).

Other work focuses on designing a solar cooker that can store heat after the sun sets—for longer than the 10 minutes typical of today's best models, which still rely on conventional PCMs for storage. A PCM composite could do better, except for one drawback: As it goes from solid to liquid, it also changes in volume—potentially enough to damage the container.

To prevent that behavior, Cédric Viry, a graduate student in materials science and engineering and a fellow in the Tata Center for Technology and Design, is working to encapsulate the composite inside tiny beads with shells made of silica or calcium carbonate. The confined composite will go through the necessary phase changes, but the strong shell will limit the massive volume change that occurs in an unconfined mixture. The encapsulated beads could be suspended in other liquids, and better methods of delivering light into the materials might be possible. "Once we get the micro-encapsulation to work, there will be many more applications," says Grossman.

Finally, the researchers are extending their concept to different materials and temperature ranges. "We've figured out some interesting and important technical aspects of how the system works, in particular, how the PCMs and photoswitches interact at the molecular level," says Grossman.





In this thermogravimetric analyzer, the researchers measure properties of their PCM composites such as thermal stability, thermal degradation point, and moisture content. Here, a sample (the yellow powder) is placed on a platinum pan (top photo) and then lowered into a furnace (bottom photo), where measurements will be taken as temperatures rise from 25°C to 800°C. Photos: Stuart Darsch

That fundamental understanding has already enabled them to develop systems using PCMs with different molecular structures—notably, with chains rather than rings of atoms—along with photoswitches optimized for each one. In the future, Grossman believes they should be able to develop systems that can store more thermal energy and can operate at a variety of temperature ranges, including the low temperatures of interest for biomedical and electronic applications.

NOTES

This research was supported by the Tata Center for Technology and Design at the MIT Energy Initiative (MITEI). Grace Han was a Tata Fellow at MIT and is now an assistant professor of chemistry at Brandeis University. At Brandeis, she and her new group are extending her MIT work by investigating the phase change of diverse molecular switches and metal complexes for energy and optoelectronic applications. Huashan Li is now on the faculty of the Department of Nuclear Engineering and Technology at Sun Yat-Sen University, Guangzhou, China. Other participants in the research were Eugene Cho PhD '17 and Joshua Deru, a visiting undergraduate student from the University of Oxford, United Kingdom. Early work on photoswitches at MIT was supported in part by the MITEI Seed Fund Program. Further information can be found in:

G.G.D. Han, H. Li, and J.C. Grossman. "Optically-controlled long-term storage and release of thermal energy in phase-change materials." *Nature Communications*, vol. 8, article no. 1446, 2017. Online: doi.org/10.1038/s41467-017-01608-y.

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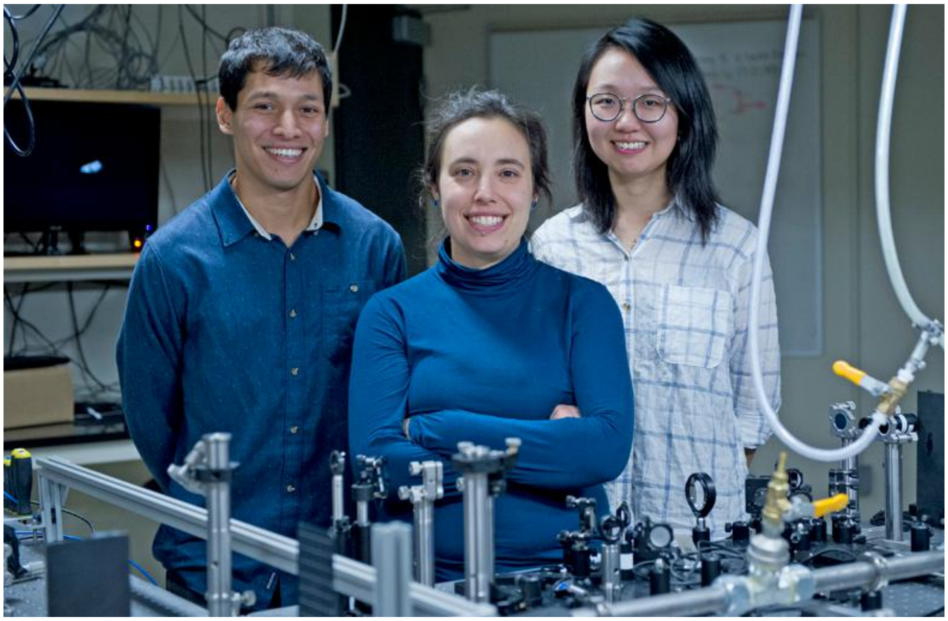


Understanding how plants use sunlight

Possible pathway to more biomass and crops

Nancy W. Stauffer, MITEI

IN BRIEF

Plants protect themselves from intense sunlight by rejecting much of it as heat—sometimes far more than needed to prevent damage. Engineering plants to be less cautious could significantly increase yields of biomass for fuel and crops for food. But exactly how the photoprotection system turns on and off has remained unclear. MIT researchers have now gathered new insights into the protein that controls the switch. They zapped individual copies of that protein with a laser and used a highly sensitive microscope to measure the fluorescence emitted by each protein in response. Based on those tests, they concluded that there are two distinct mechanisms by which the dissipation of heat begins. One is a split-second response to a sudden increase in sunlight, say, after a cloud passes by, while the other activates over minutes to hours as light gradually changes during sunrise or sunset. In both cases, the response is triggered by a specific change in the protein's structure.

Plants rely on the energy in sunlight to produce the nutrients they need. But sometimes they absorb more energy than they can use, and that excess can damage critical proteins. To protect themselves, they convert the excess energy into heat and send it back out. Under some conditions, they may reject as much as 70% of all the solar energy they absorb.

"If plants didn't waste so much of the sun's energy unnecessarily, they could be producing more biomass," says Gabriela S. Schlau-Cohen, the Cabot Career Development Assistant Professor of Chemistry. Indeed, scientists estimate that algae could grow as much as

Above Professor Gabriela S. Schlau-Cohen (center) and graduate students Raymundo Moya (left) and Wei Jia Chen worked with collaborators at the University of Verona, Italy, to develop a new understanding of the mechanisms by which plants reject excess energy they absorb from sunlight so it doesn't harm key proteins. The insights gained could one day lead to critically needed increases in yields of biomass and crops. Photo: Stuart Darsch

30% more material for use as biofuel. More importantly, the world could increase crop yields—a change needed to prevent the significant shortfall between agricultural output and demand for food expected by 2050.

The challenge has been to figure out exactly how the photoprotection system in plants works at the molecular level—in the first 250 picoseconds of the photosynthesis process. (A picosecond is a trillionth of a second.) "If we could understand how absorbed energy is converted to heat, we might be able to rewire that process to optimize the overall production of biomass and crops," says Schlau-Cohen. "We could control that switch to make plants less hesitant to shut off the protection. They could still be protected to some extent, and even if a few individuals died, there'd be an increase in the productivity of the remaining population."

First steps of photosynthesis

Critical to the first steps of photosynthesis are proteins called light-harvesting complexes, or LHCs. When sunlight strikes a leaf, each photon (particle of light) delivers energy that "excites" an LHC. That excitation passes from one LHC to another until it reaches a so-called reaction center, where it drives chemical reactions that split water into oxygen gas, which is released, and positively charged particles called protons, which remain. The protons activate the production of an enzyme that drives the formation of energy-rich carbohydrates needed to fuel the plant's metabolism.

But in bright sunlight, protons may form more quickly than the enzyme can use them, and the accumulating protons signal that excess energy is being absorbed and may damage critical components of the plant's molecular machinery. So some plants have a special type of LHC—called a light-harvesting complex stress-related, or LHCSR—whose job is to intervene. If proton buildup indicates that too much sunlight is being harvested, the LHCSR flips the switch, and some of the energy is dissipated as heat.

It's a highly effective form of sunscreen for plants—but the LHCSR is reluctant to switch off that "quenching" setting. When the sun is shining brightly, the LHCSR has quenching turned on. When a passing cloud or flock of birds blocks the sun, it could switch it off and soak up all the available sunlight. But instead, the LHCSR leaves it on—just in case the sun suddenly comes back. As a result, plants reject a lot of energy that they could be using to build more plant material.

An evolutionary success

Much research has focused on the quenching mechanism that regulates the flow of energy within a leaf to prevent damage. Optimized by 3.5 billion years of evolution, its capabilities are impressive. It can deal with wildly varying energy inputs: In a single day, the sun's intensity can increase and decrease by a factor of 100 or even 1,000. And it can react to changes that occur slowly over time—say, at sunrise—and in just seconds, for example, due to a passing cloud.

Researchers agree that one key to quenching is a pigment within the LHCSR—called a carotenoid—that can take two forms: violaxanthin (Vio) and zeaxanthin (Zea). They've observed that LHCSR samples are dominated by Vio molecules under low-light conditions and Zea molecules under high-light conditions. Conversion from Vio to Zea would change various electronic properties of the carotenoids, which could explain the activation of quenching. However, it doesn't happen quickly enough to respond to a passing cloud. That type of fast change could be a direct response to the buildup of protons, which causes a difference in pH from one region of the LHCSR to another.

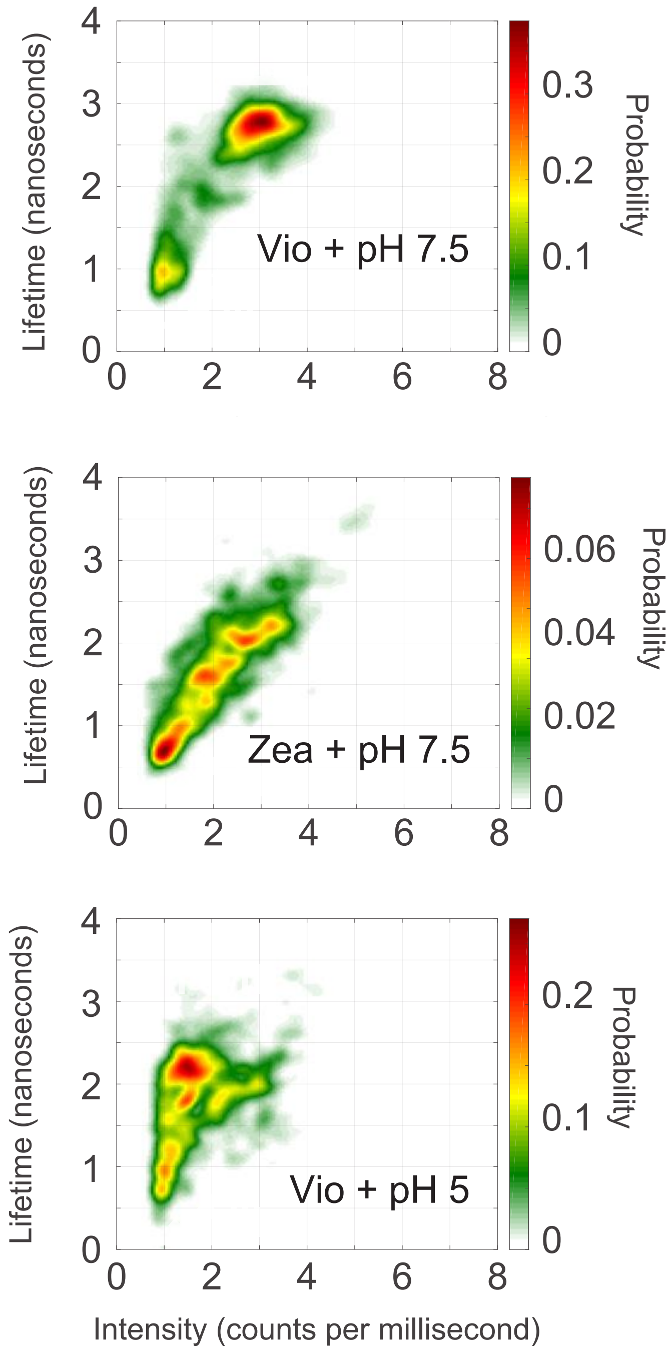
Clarifying those photoprotection mechanisms experimentally has proved difficult. Examining the behavior of samples containing thousands of proteins doesn't provide insights into the molecular-level behavior because various quenching mechanisms occur simultaneously and on different time scales—and in some cases, so quickly that they're difficult or impossible to observe experimentally.

Testing the behavior of proteins, one at a time

Schlau-Cohen and her MIT colleagues, postdoc Toru Kondo and graduate student Wei Jia Chen, both of chemistry, decided to take another tack. Focusing on the LHCSR found in green algae and moss, they examined what was different about the way that stress-related proteins rich in Vio and those rich in Zea respond to light—and they did it one protein at a time.

According to Schlau-Cohen, their approach was made possible by the work of her collaborator Roberto Bassi and his colleagues Alberta Pinnola and Luca Dall'Osto at the University of Verona, Italy. In earlier research, they had figured out how to purify the individual proteins known to play key roles in quenching. They thus were able to provide samples of individual LHCSRs, some enriched with Vio carotenoids and some with Zea carotenoids.

To test the response to light exposure, Schlau-Cohen's team uses a laser to shine picosecond light pulses onto a single LHCSR. Using a highly sensitive microscope, they can then detect the fluorescence emitted in response. If the LHCSR is in quench-on mode, it will turn much of the incoming energy into heat and expel it. Little or no energy will be left to be reemitted as fluorescence. But if the LHCSR is in quench-off mode, all of the incoming light will come out as fluorescence. "So we're not measuring the quenching directly," says Schlau-Cohen. "We're using decreases in fluorescence as a signature of quenching. As the fluorescence goes down, the quenching goes up."



Top and middle figures: Fluorescence behavior of Vio-enriched and Zea-enriched LHCSR proteins These figures show probability distributions of fluorescence intensity and lifetime from experiments with hundreds of individual LHCSR proteins enriched with either Vio carotenoids (top) or Zea carotenoids (middle). The most likely intensity-lifetime combinations are highlighted in red, less likely in yellow, and least likely in green. The Vio distribution shows the response when quenching is off. The Zea results show the impact of having quenching switched on: The population moves to a much lower intensity and a much shorter lifetime.

Bottom figure: Fluorescence response to pH changes This figure shows the response of Vio-enriched proteins when subjected to a lower pH, that is, an increase in proton concentration replicating conditions in bright sunlight. Compared to the results with Vio in pH 7.5 (the top figure), the intensity is much lower, and the lifetime is slightly shorter. The significantly reduced intensity indicates that quenching is turned on. But the shift in lifetime is less dramatic than with Zea, suggesting that conversion to Zea and the lowering of pH turn quenching on by two different mechanisms.

Using that technique, the MIT researchers examined the two proposed quenching mechanisms: the conversion of Vio to Zea and a direct response to a high proton concentration.

To address the first mechanism, they characterized the response of the Vio-rich and Zea-rich LHCSRs to the pulsed laser light using two measures: the intensity of the fluorescence (based on how many photons they detect in one millisecond) and its lifetime (based on the arrival time of the individual photons).

Using the measured intensities and lifetimes of responses from hundreds of individual LHCSR proteins, they generated the probability distributions shown in the figures on this page. In each case, the red region shows the most likely outcome based on results from all the single-molecule tests. Outcomes in the yellow region are less likely, and those in the green region are least likely.

The top figure shows the likelihood of intensity-lifetime combinations in the Vio samples, representing the behavior of the quench-off response. Moving to the Zea results in the middle figure, the population shifts to a shorter lifetime and also to a much lower-intensity state—an outcome consistent with Zea being the quench-on state.

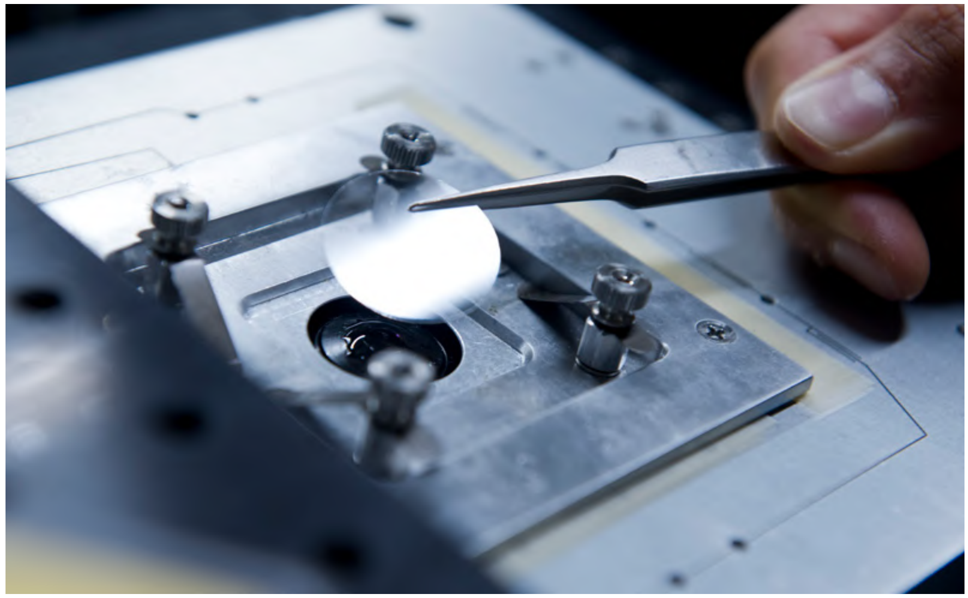
To explore the impact of proton concentration, the researchers changed the pH of their system. The results just described came from individual proteins suspended in a solution with a pH of 7.5. In parallel tests, the researchers suspended the proteins in an acidic solution of pH 5, thus in the presence of abundant protons, replicating conditions that would prevail under bright sunlight.

The bottom figure shows results from the Vio samples. Shifting from pH 7.5 to pH 5 brings a significant decrease in intensity, as it did with the Zea samples, so quenching is now on. But it brings only a slightly shorter lifetime, not the significantly shorter lifetime observed with Zea.

The dramatic decrease in intensity with the Vio-to-Zea conversion and the lowered pH suggests that both are quenching behaviors. But the different impact on lifetime suggests that the quenching mechanisms are different. "Because the most likely outcome—the red region—moves in different directions, we know that two distinct quenching processes are involved," says Schlau-Cohen.

Their investigation brought one more interesting observation. The intensity-lifetime results for Vio and Zea in the two pH environments are consistent when they're taken at time intervals spanning seconds or even minutes in a given sample. According to Schlau-Cohen, the only explanation for such stability is that the responses are due to differing structures, or conformations, of the protein. "It was known that both pH and the switch of the carotenoid from violaxanthin to zeaxanthin played a role in quenching," she says. "But what we saw was that there are two different conformational switches at work."

Based on their results, Schlau-Cohen proposes that the LHCSR can have three distinct conformations. When sunlight is dim, it assumes a conformation that allows all available energy to come in. If bright sunlight suddenly returns, protons quickly build up and reach a critical concentration at which point the LHCSR switches to a quenching-on conformation—probably a more rigid structure that permits energy to be rejected by some mechanism not yet fully understood. And when light increases slowly, the protons accumulate over time, activating an enzyme that in turn accumulates, in the process causing a carotenoid in the LHCSR to change from Vio to Zea—a change in both composition and structure. "So the former quenching mechanism works in a few seconds, while the latter works over time scales of minutes to hours," says Schlau-Cohen. Together, those conformational options explain the remarkable control system that enables plants to regulate energy uptake from a source that's constantly changing.


This specially designed microscope is capable of detecting fluorescence from single LHCSR proteins attached to a glass coverslip. Photo: Stuart Darsch

Exploring what comes next

Schlau-Cohen is now turning her attention to the next important step in photosynthesis—the rapid transfer of energy through the network of LHCs to the reaction center. The structure of individual LHCs has a major impact on how quickly excitation energy can jump from one protein to the next. Some investigators are therefore exploring how the LHC structure may be affected by interactions between the protein and the lipid membrane in which it's suspended.

However, their experiments typically involve sample proteins mixed with detergent, and while detergent is similar to natural lipids in some ways, its impact on proteins can be very different, says Schlau-Cohen. She and her colleagues have therefore developed a new system that suspends single proteins in lipids more like those found in natural membranes. Already, tests using ultrafast spectroscopy on those samples has shown that one key energy-transfer step occurs 30% faster than measured in detergents. Those results support the value of the new technique in exploring photosynthesis and demonstrate the importance of using "near-native" lipid environments in such studies.

NOTES

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New system recovers fresh water from power plants; prototype installed on MIT's Central Utility Plant

A new system devised by MIT engineers could provide a low-cost source of drinking water for parched cities around the world while also cutting power plant operating costs.

About 39% of all the fresh water withdrawn from rivers, lakes, and reservoirs in the US is earmarked for the cooling needs of electric power plants that use fossil fuels or nuclear power, and much of that water ends up floating away in clouds of vapor. But the new MIT system could potentially save a substantial fraction of that lost water—and could even become a significant source of clean, safe drinking water for coastal cities where seawater is used to cool local power plants.

The principle behind the new concept is deceptively simple: When air that's rich in fog is zapped with a beam of electrically charged particles, known as ions, water droplets become electrically charged and thus can be drawn toward a mesh of wires, similar to a window screen, placed in their path. The droplets then collect on that mesh, drain down into a collecting pan, and can be reused in the power plant or sent to a city's water supply system.

The system, which is the basis for a startup company called Infinite Cooling that won MIT's $100K Entrepreneurship Competition in May 2018, is described in a paper published on June 8, in the journal *Science Advances*. The paper is co-authored by Maher Damak PhD '18, now a fellow in the Tata Center for Technology and Design, and Associate Professor of Mechanical Engineering Kripa Varanasi SM '02, PhD '04. Damak and Varanasi are among the co-founders of the startup, and their research is supported in part by the Tata Center.

On the Central Utility Plant roof in front of the newly installed water-capture system (from left): Derek Warnick, COO, Infinite Cooling; Karim Khalil PhD '18; Maher Damak PhD '18; Professor Kripa Varanasi of mechanical engineering; Patrick Karalekas, plant engineer, and Jodi Cooksey, safety engineer, Central Utilities Plant; and Erich Ryan, intern, Infinite Cooling. Photo: Kelley Travers, MITEI

Varanasi's vision was to develop highly efficient water recovery systems by capturing water droplets from both natural fog and plumes of industrial cooling towers. The project began as part of Damak's doctoral thesis, which aimed to improve the efficiency of fog-harvesting systems that are used in many water-scarce coastal regions as a source of potable water. Those systems, which generally consist of some kind of plastic or metal mesh hung vertically in the path of fogbanks that regularly roll in from the sea, are extremely inefficient, capturing only about 1% to 3% of the water droplets that pass through them. Varanasi and Damak wondered if there was a way to make the mesh catch more of the droplets—and found a very simple and effective way of doing so.

The reason for the inefficiency of existing systems became apparent in the team's detailed lab experiments: The problem is in the aerodynamics of the system. As a stream of air passes an obstacle, such as the wires in these mesh fog-catching screens, the airflow naturally deviates around the obstacle, much as air flowing around an airplane wing separates into streams that pass above and below the wing structure. These deviating airstreams carry droplets that were heading toward the wire off to the side, unless they were headed bang-on toward the wire's center.

The result is that the fraction of droplets captured is far lower than the fraction of the collection area occupied by the wires, because droplets are being swept aside from wires that lie in front of them. Just making the wires bigger or the spaces in the mesh smaller tends to be counterproductive because it hampers the overall airflow, resulting in a net decrease in collection.

But when the incoming fog gets zapped first with an ion beam, the opposite effect happens. Not only do all of the droplets that are in the path of the wires land on them, even droplets that were aiming for the holes in the mesh get pulled toward the wires. This system can thus capture a much larger fraction of the droplets passing through. As such, it could dramatically improve the efficiency of fog-catching systems, and at a surprisingly low cost. The equipment is simple, and the amount of power required is minimal.

Next, the team focused on capturing water from the plumes of power plant cooling towers. There, the stream of water vapor is much more concentrated than any naturally occurring fog, and that makes the system even more efficient. And since capturing evaporated water is in itself a distillation process, the water captured is pure, even if the cooling water is salty or contaminated. At this point, Karim Khalil, another graduate student from Varanasi's lab, joined the team.

"It's distilled water, which is of higher quality, that's now just wasted," says Varanasi. "That's what we're trying to capture." The water could be piped to a city's drinking water system, or used in processes that require pure water, such as in a power plant's boilers, as opposed to being used in its cooling system where water quality doesn't matter much.

A typical 600-megawatt power plant, Varanasi says, could capture 150 million gallons of water a year, representing a value of millions of dollars. This represents about 20% to 30% of the water lost from cooling towers. With further refinements, the system may be able to capture even more of the output, he says.

What's more, since power plants are already in place along many arid coastlines, and many of them are cooled with seawater, this provides a very simple way to provide water desalination services at a tiny fraction of the cost of building a standalone desalination plant. Damak and Varanasi estimate that the installation cost of such a conversion would be about one-third that of building a new desalination plant, and its operating costs would be about 1/50. The payback time for installing such a system would be about two years, Varanasi says, and it would have essentially no environmental footprint, adding nothing to that of the original plant.

During the installation, the dome was transported from the build site, lifted by crane, and lowered onto the top of one of the Central Utility Plant cooling towers. Photos: Kelley Travers, MITEI

"This can be a great solution to address the global water crisis," Varanasi says. "It could offset the need for about 70% of new desalination plant installations in the next decade."

In a series of dramatic proof-of-concept experiments, Damak, Khalil, and Varanasi demonstrated the concept by building a small lab version of a stack emitting a plume of water droplets, similar to those seen on actual power plant cooling towers, and placed their ion beam and mesh screen on it. In video of the experiment, a thick plume of fog droplets is seen rising from the device—and almost instantly disappears as soon as the system is switched on.

During summer 2018, the team built a full-scale test version of their system, and on October 18, they installed it on the cooling tower of MIT's Central Utility Plant, a natural-gas cogeneration power plant that provides most of the campus' electricity, heating, and cooling (see photos at left). Planned tests of the setup include trying different variations of the mesh and its supporting structure, Damak says.

That should provide the needed evidence to enable power plant operators, who tend to be conservative in their technology choices, to adopt the system. Because power plants have decades-long operating lifetimes, their operators tend to be "very risk-averse" and want to know "has this been done somewhere else?" Varanasi says. The campus power plant tests will not only "de-risk" the technology, but will also help the MIT campus improve its water footprint, he says. "This can have a high impact on water use on campus."

David L. Chandler, MIT News

Adapted with permission from MIT News (news.mit.edu). Read more about Infinite Cooling at www.infinite-cooling.com.

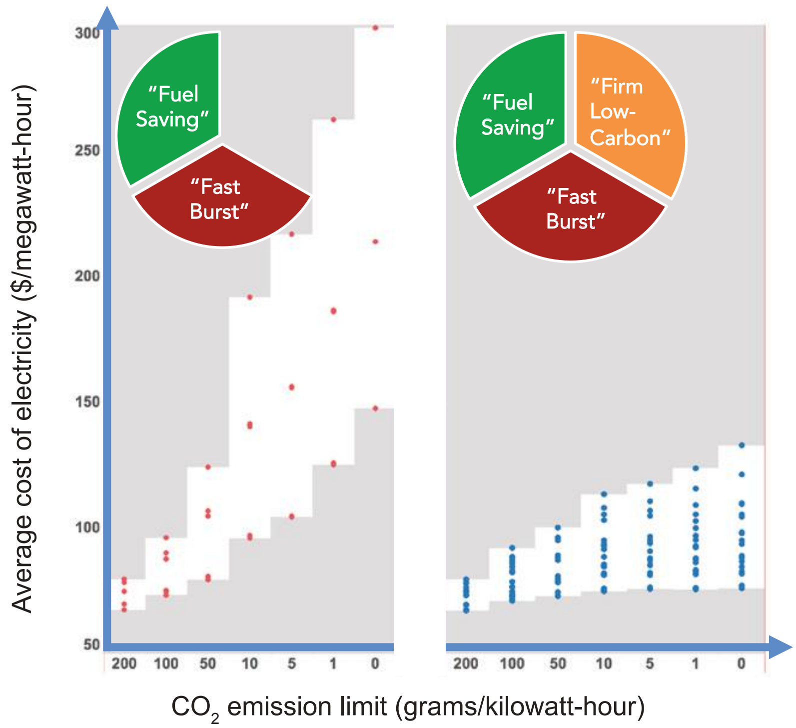
Carbon-free electricity: Reducing cost and risk by combining fuel-saving, flexible, and firm sources

In major legislation passed at the end of August, California committed to creating a 100% carbon-free electricity grid—once again leading other nations, states, and cities in setting aggressive policies for slashing greenhouse gas emissions. Now, a study by MIT researchers provides guidelines for cost-effective and reliable ways to build such a zero-carbon electricity system.

The best way to tackle emissions from electricity, the study finds, is to use the most inclusive mix of low-carbon electricity sources.

Costs have declined rapidly for wind power, solar power, and energy storage batteries in recent years, leading some researchers, politicians, and advocates to suggest that these sources alone can power a carbon-free grid. But the new study finds that across a wide range of scenarios and locations, pairing these sources with steady carbon-free resources that can be counted on to meet demand in all seasons and over long periods—such as nuclear, geothermal, bioenergy, and natural gas with carbon capture—is a less costly and lower-risk route to a carbon-free grid.

The new findings are described in a paper published on September 6, 2018, in the journal *Joule*, by MIT doctoral student Nestor Sepulveda, Jesse Jenkins PhD '18, Fernando de Sisternes PhD '14, and Professor of Nuclear Science and Engineering and Associate Provost Richard Lester.



These charts compare the expected costs of electricity under a wide variety of scenarios in a New England-like system. In all cases, the costs of electricity are projected to be significantly lower, as shown on the vertical axis, if a wider range of carbon-free supply options are included (chart at right) than with a more limited set of choices (chart at left), especially in the later years as carbon emissions get closer to zero, as shown on the horizontal axis. The plotted data points represent the results of many different simulations using different assumptions.

The need for cost-effectiveness

"In this paper, we're looking for robust strategies to get us to a zero-carbon electricity supply, which is the linchpin in overall efforts to mitigate climate change risk across the economy," Jenkins says. To achieve that, "we need not only to get to zero emissions in the electricity sector, but we also have to do so at a low enough cost that electricity is an attractive substitute for oil, natural gas, and coal in the transportation, heat, and industrial sectors, where decarbonization is typically even more challenging than in electricity."

Sepulveda also emphasizes the importance of cost-effective paths to carbon-free electricity, adding that in today's world, "we have so many problems, and climate change is a very complex and important one, but not the only one. So every extra dollar we spend addressing climate change is also another dollar we can't use to tackle other pressing societal problems, such as eliminating poverty or disease." Thus, it's important for research not only to identify technically achievable options to decarbonize electricity, but also to find ways to achieve carbon reductions at the most reasonable possible cost.

To evaluate the costs of different strategies for deep decarbonization of electricity generation, the team looked at nearly 1,000 different scenarios involving different assumptions about the availability and cost of low-carbon technologies, geographical variations in the availability of renewable resources, and different policies on their use.

Regarding the policies, the team compared two different approaches. The "restrictive" approach permitted only the use of solar and wind generation plus battery storage, augmented by measures to reduce and shift the timing of demand for electricity, as well as long-distance transmission lines to help smooth out local and regional variations. The "inclusive" approach used all of those technologies but also permitted the option of using continual carbon-free sources, such as nuclear power, bioenergy, and natural gas with a system for capturing and storing carbon emissions. Under every case the team studied, the broader mix of sources was found to be more affordable.

The cost savings of the more inclusive approach relative to the more restricted case were substantial. Including continual, or "firm," low-carbon resources in a zero-carbon resource mix lowered costs anywhere from 10% to as much as 62%, across the many scenarios analyzed. That's important to know, the authors stress, because in many cases existing and proposed regulations and economic incentives favor, or even mandate, a more restricted range of energy resources.

"The results of this research challenge what has become conventional wisdom on both sides of the climate change debate," Lester says. "Contrary to fears that effective climate mitigation efforts will be cripplingly expensive, our work shows that even deep decarbonization of the electric power sector is achievable at relatively modest additional cost. But contrary to beliefs that carbon-free electricity can be generated easily and cheaply with wind, solar energy, and storage batteries alone, our analysis makes clear that the societal cost of achieving deep decarbonization that way will likely be far more expensive than is necessary."

A new taxonomy for electricity sources

In looking at options for new power generation in different scenarios, the team found that the traditional way of describing different types of power sources in the electrical industry—"baseload," "load following," and "peaking" resources—is outdated and no longer useful, given the way new resources are being used.

Rather, they suggest, it's more appropriate to think of power sources in three new categories: "fuel-saving" resources, which include solar, wind, and run-of-the-river (that is, without reservoirs) hydropower; "fast-burst" resources, providing rapid but short-duration responses to fluctuations in electricity demand and supply, including battery storage and technologies and pricing strategies to enhance the responsiveness of demand; and "firm" resources, such as nuclear, hydro with large reservoirs, biogas, and geothermal.

"Because we can't know with certainty the future cost and availability of many of these resources," Sepulveda notes, "the cases studied covered a wide range of possibilities, in order to make the overall conclusions of the study robust across that range of uncertainties."

Range of scenarios

The group used a range of projections, made by agencies such as the National Renewable Energy Laboratory, as to the expected costs of different power sources over the coming decades, including costs similar to today's and anticipated cost reductions as new or improved systems are developed and brought online. For each technology, the researchers chose a projected mid-range cost, along with a low-end and high-end cost estimate, and then studied many combinations of these possible future costs.

Under every scenario, cases that were restricted to using fuel-saving and fast-burst technologies had a higher overall cost of electricity than cases using firm low-carbon sources as well, "even with the most optimistic set of assumptions about future cost reductions," Sepulveda says.

That's true, Jenkins adds, "even when we assume, for example, that nuclear remains as expensive as it is today, and wind and solar and batteries get much cheaper."

The authors also found that across all of the wind-solar-batteries-only cases, the cost of electricity rises rapidly as systems move toward zero emissions, but when firm power sources are also available, electricity costs increase much more gradually as emissions decline to zero.

"If we decide to pursue decarbonization primarily with wind, solar, and batteries," Jenkins says, "we are effectively 'going all in' and betting the planet on achieving very low costs for all of these resources" as well as the ability to build out continental-scale high-voltage transmission lines and to induce much more flexible electricity demand.

In contrast, "an electricity system that uses firm low-carbon resources together with solar, wind, and storage can achieve zero emissions with only modest increases in cost even under pessimistic assumptions about how cheap these carbon-free resources become or our ability to unlock flexible demand or expand the grid," says Jenkins. This shows how the addition of firm low-carbon resources "is an effective hedging strategy that reduces both the cost and risk" for fully decarbonizing power systems, he says.

Even though a fully carbon-free electricity supply is years away in most regions, it is important to do this analysis today, Sepulveda says, because decisions made now about power plant construction, research investments, or climate policies have impacts that can last for decades.

"If we don't start now" in developing and deploying the widest range of carbon-free alternatives, he says, "that could substantially reduce the likelihood of getting to zero emissions."

The research received support from the MIT Energy Initiative, the Martin Family Trust, and the Chilean Navy.

David L. Chandler, MIT News

US Department of Energy funds MIT Center for Enhanced Nanofluidic Transport

A new MIT research center is among the recipients of the most recent round of $100 million in funding for 42 Energy Frontier Research Centers (EFRCs) announced by the US Department of Energy (DOE) on June 29, 2018. The centers are a core component of DOE's funding for basic energy science research.

Michael Strano, the Carbon P. Dubbs Professor of Chemical Engineering, leads the new EFRC being established at MIT. The Center for Enhanced Nanofluidic Transport (CENT) will focus on the nanoscale study of energy to achieve energy efficiency in separation and chemical purification processes as well as in the synthesis of new materials.

Strano says, "The Center for Enhanced Nanofluidic Transport presents an important opportunity to significantly expand our available tools to study, image, and understand fluidic transport through the smallest of conduits. The potential benefits to water purification, high-efficiency separation, and energy-saving processes are exciting."

Nanopores—small, nanometer-scale pathways or openings in materials—exist in many forms across a wide range of materials. But those less than approximately 10 nanometers in diameter have only recently been available for careful study in single pore platforms. "What we have learned, as a community, so far from such single-digit pores has been surprising," says Strano.

An example of a research study area is the unusual behavior sometimes exhibited by ions that migrate or flow across single-digit nanopores, such as correlated motion, or complete rejection based on subtle differences in size, charge density, or hydration. Understanding these phenomena

MIT Professor Michael Strano is leading the latest MIT Energy Frontier Research Center announced by the Department of Energy. Photo: Webb Chappell

promises new desalination and chemical separation technologies that can be very energy-efficient.

Research in the Strano lab focuses on understanding nanometer-scale phenomena through mathematics and chemistry in order to develop new technologies for health, energy, food production, and materials science.

DOE created the EFRCs in 2009 to support basic science research at universities, national laboratories, nonprofit organizations, and private firms across the nation. The goal of the program is to accelerate foundational research toward meeting critical energy challenges. This latest cohort of 42 EFRCs includes nine renewed centers and 22 new ones. Another 11 existing centers were awarded two-year extensions to support the completion of research still in progress.

"America's continued energy security and global competitiveness will depend vitally on a sustained effort in science and discovery," said US Secretary of Energy Rick Perry in a DOE press release. "By mobilizing the talents of our nation's top scientists and forging them into powerful, proactive teams, the EFRC program will help ensure America's leadership in the development of critical energy technologies and innovations."

The new center joins two previously named MIT EFRCs: the Center for Excitonics, directed by Marc A. Baldo, professor of electrical engineering and a principal investigator in the Research Laboratory for Electronics, and the Solid-State Solar-Thermal Energy Conversion Center, directed by Gang Chen, the Carl Richard Soderberg Professor of Power Engineering and director of the Pappalardo Micro and Nano Engineering Laboratories.

Francesca McCaffrey, MITEI

Christoph Reinhart: Applying physics to the design of energy-efficient buildings

Developing a perfectly energy-efficient building is relatively easy to do—if you don't give the building's occupants any control over their environment. Since nobody wants that kind of building, Professor Christoph Reinhart has focused his career on finding ways to make buildings more energy-efficient while keeping user needs in mind.

"At this point in designing buildings, the biggest uncertainty comes from user behavior," says Reinhart, who heads the Sustainable Design Lab in MIT's Department of Architecture. "Once you understand heat flow, it's a very exact science to see how much heat to add or take from a space."

Trained in physics, Reinhart made the move to architecture because he wanted to apply the scientific concepts he'd learned to make buildings more comfortable and energy-efficient. Today, he is internationally known for his work in "daylighting" (the use of natural light to illuminate building interiors) and urban-level environmental building performance analysis. The design tools that emerged from his lab are used by architects and urban planners in more than 90 countries.

The Sustainable Design Lab's work has also produced two spinoff companies—Mapdwell, which provides individualized cost-benefit analyses for installing solar panels; and Solemma, which provides environmental analysis tools such as DIVA-for-Rhino, a highly optimized daylighting and energy modeling software component. (Reinhart is a co-founder and strategic development advisor at Mapdwell, and he is CEO of Solemma.)

Through it all, physics has remained a central underpinning. "Everything our lab develops is based on physics first," says Reinhart, who earned master's degrees in

Christoph Reinhart, professor in the Building Technology Program of the Department of Architecture and head of the MIT Sustainable Design Lab. Photos: Kelley Travers, MITEI

physics from Albert Ludwigs Universität in Freiburg, Germany, and Simon Fraser University in Vancouver, Canada.

Informing design

A lifelong environmentalist, Reinhart says he was inspired to study architecture in part by the work of the Fraunhofer Institute for Solar Energy Systems, which built a completely self-sufficient solar house in Freiburg in the early 1990s.

While finishing his master's thesis, Reinhart says, he also read an article that suggested that features such as color can be more important than performance to architects choosing a solar system—an idea that drove him to find ways to empower architects to consider aesthetics and the environmental performance of their designs at the same time. He began this effort by investigating daylighting at the Technical University of Karlsruhe, Germany.

Light is incredibly important from a design standpoint—architects talk of "painting with light"—but there are also significant technical challenges involved in lighting, Reinhart notes, such as how to manage heat and glare.

"You need good sky models and you need good rendering tools to model the light. You also need computer science to make it faster—but that's just the basics," Reinhart says, noting that the next step is to consider how people perceive and use natural light. "This really nuanced way of thinking is what makes daylighting so fun and interesting."

For example, designers typically render buildings with all the blinds open. If they learn that people will keep the blinds down 90% of the time with a given design, they are likely to rethink it, Reinhart says—because "nobody wants that."

The daylighting analysis software developed by Reinhart's team in 1998 provides just this kind of information. Known as DAYSIM, it is now used all over the world to model annual daylight availability in and around buildings.

Reinhart has also published a textbook on daylighting, *Daylighting Handbook I: Fundamentals and Designing with the Sun* (2014). A second volume, *Daylighting Handbook II: Daylight Simulations and Dynamic Facades*, was released in late October 2018.

"Daylighting was really my first way into architecture," Reinhart says, noting that he thinks it's wonderful that the field combines "rock solid science" like sky modeling with more subjective questions related to the users' experience, such as: "When is sunlight a liability?" and "When does it add visual interest?"

Teaching and advising

After earning his doctorate in architecture from Technical University in 2001, Reinhart taught briefly at McGill University in Canada before being named an associate professor of architecture at

Harvard University's Graduate School of Design. In 2009, the student forum there named him faculty member of the year.

In 2012, he joined the faculty at MIT, where he typically supervises seven or eight graduate students, including about three working on their PhDs. Often, he also has students working in his lab through the Undergraduate Research Opportunities Program. Several majoring in computer science have proved particularly helpful, he says. "It's amazing what MIT students can implement."

Reinhart is also an instructor, of course, notably teaching 4.401/4.464 Environmental Technologies in Buildings, which focuses on how to assess the energy efficiency of buildings. "There's nothing more fun—especially at an institution like MIT—than to teach these concepts," he says.

The MIT Energy Initiative (MITEI) is now working to make that subject available online via MITx, and the class is expected to be part of a planned graduate certificate in energy, according to Antje Danielson, MITEI's director of education.

City-scale modeling

Meanwhile, Reinhart has scaled his own research up to modeling energy use at the city level. In 2016, he and colleagues unveiled an energy model for Boston that estimates the gas and electricity demands of every building in the city—and his team has since assessed other urban areas.

This work has underscored for him how significant user behavior is to calculating energy use. "For an individual building you can get a sense of the user behavior, but if you want to model a whole city, that problem explodes on you," Reinhart says, noting that his team uses statistical methods such as Bayesian calibration to determine likely behaviors.

Essentially, they collect data on energy use and train the computer to recognize

Professor Reinhart (left) and graduate student Hellen Rose Anyango Awino of architecture discuss a class assignment on measuring thermal comfort.

different scenarios—such as the energy used by different numbers of people and appliances. "We throw 800 user behaviors at a sample of buildings, and since we know how much energy these buildings actually use, we only keep those behavioral patterns that give us the right energy use," Reinhart says, explaining that repeating the process produces a curve that indicates the buildings' most likely uses. "We don't know exactly where people are, but at the urban level, we get it right."

Determining how energy is being used at this broad scale provides critical information for addressing the needs of the energy system as a whole, Reinhart says. That's why Reinhart is currently working with Exelon Corporation, a major national energy provider, to assess energy use in Chicago. "We can say, let's foster these kinds of upgrades and pretty much guarantee that this is how the energy load throughout a neighborhood or for particular substations will change—which is just what utilities want to know," he says.

Food, energy, water nexus

Recently, Reinhart has also begun investigating ways to make food production more energy-efficient and sustainable. His lab is developing a software component that can estimate food yields, associated use of energy and water, and the carbon emissions that result for different types of urban farms.

For example, hydroponic container farming—a system of growing food without soil inside something like a shipping container—is now being promoted by companies in some cities, including Boston. This system typically uses more electricity than conventional farming does, but that energy use can be more than offset by the reduced need for transportation, Reinhart says. Already, Reinhart's team has shown that rooftop and container farming on available land in Lisbon, Portugal, could theoretically meet the city's total vegetable demand.

This work exploring the nexus between food, energy, and water is just the next level of complexity for Reinhart in a career dedicated to moving the needle on sustainability. Fortunately, he's not alone in his work; he has sent a host of young academics out into the world to work on similar concerns.

Former graduate students now work at universities including Cornell, Harvard, Syracuse, and the University of Toronto, and Reinhart continues to collaborate with them on projects. It's like having a growing family, says Reinhart, a father of two. "Students never leave. It's like kids."

Kathryn M. O'Neill, MITEI correspondent

Energy Fellows, 2018–2019

The Society of Energy Fellows at MIT welcomed 25 new members in fall 2018. The Energy Fellows network now totals more than 430 graduate students and postdoctoral fellows and spans 20 MIT departments and divisions and all five MIT schools. Fellows include incoming graduate students and graduate student researchers, teaching fellows, and postdoctoral associates. This year's fellowships are made possible through the generous support of seven MITEI Member companies.

Bosch

Eric Fadel
Materials Science and Engineering

Commonwealth Fusion Systems

Erica Salazar
Nuclear Science and Engineering
Assignment in Plasma Science and Fusion Center

Eni S.p.A.

Alfonso Carrillo, PhD
Materials Science and Engineering

William Howland
Chemistry

Soyoung Kim
Chemistry

Bora Ozaltun
Institute for Data, Systems, and Society

Caroline Sorensen
Mechanical Engineering
Assignment in Plasma Science and Fusion Center

Mohammed Mahdi Tavakoli, PhD
Electrical Engineering and Computer Science

Sohum Pawar
Institute for Data, Systems, and Society

ExxonMobil

Samiya Alkhairy, PhD
Earth, Atmospheric, and Planetary Sciences

Mindy Bishop
Health Sciences and Technology

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

Xin He, PhD
Chemistry

Onyu Jung
Chemistry

Omer Karaduman
Economics

Jaclyn Rose Lunger
Materials Science and Engineering

Jayson Lynch
Electrical Engineering and Computer Science
Assignment in Computer Science and Artificial Intelligence Laboratory

GE

Laureen Meroueh
Mechanical Engineering

Shell

Dixia Fan
Mechanical Engineering

Wei Kong
Mechanical Engineering

Ellen Lalk
Earth, Atmospheric, and Planetary Sciences

Dai Lin
Sloan School of Management

Alex Wallar
Electrical Engineering and Computer Science
Assignment in Computer Science and Artificial Intelligence Laboratory

Total

Zhe Liu, PhD
Mechanical Engineering

Shijing Sun, PhD
Mechanical Engineering

Fellows as of September 20, 2018
Photo: Eric Haynes

Grad student Prosper Nyovanie: Powering off-grid communities with scalable solar electric systems

During high school, Prosper Nyovanie '13 had to alter his daily and nightly schedules to accommodate the frequent power outages that swept cities across Zimbabwe.

"[Power] would go almost every day—it was almost predictable," Nyovanie recalls. "I'd come back from school at 5 p.m., have dinner, then just go to sleep because the electricity wouldn't be there. And then I'd wake up at 2 a.m. and start studying…because by then you'd usually have electricity."

At the time, Nyovanie knew he wanted to study engineering, and upon coming to MIT as an undergraduate, he majored in mechanical engineering. He discovered a new area of interest, however, when he took 15.031J Energy Decisions, Markets, and Policies, which introduced him to questions of how energy is produced, distributed, and consumed. He went on to minor in energy studies.

Now as a graduate student and fellow in MIT's Leaders for Global Operations (LGO) program, Nyovanie is on a mission to learn the management skills and engineering knowledge he needs to power off-grid communities around the world through his startup, Voya Sol (www.voya-sol.com). The company develops solar electric systems that can be scaled to users' needs.

Graduate student Prosper Nyovanie is working to ensure reliable energy for communities worldwide. Photo: Ian MacLellan

Determination and quick thinking

Nyovanie was originally drawn to MIT for its learning-by-doing engineering focus. "I thought engineering was a great way to take all these cool scientific discoveries and technologies and apply them to global problems," he says. "One of the things that excited me a lot about MIT was the hands-on approach to solving problems. I was super excited about UROP [the Undergraduate Research Opportunities Program]. That program made MIT stick out from all the other universities."

As a mechanical engineering major, Nyovanie took part in a UROP for 2.5 years in the Laboratory for Manufacturing and Productivity with Professor Martin Culpepper. But his experience in 15.031J made him realize his interests were broader than just research and included the intersection of technology and business.

"One big thing that I liked about the class was that it introduced this other complexity that I hadn't paid that much attention to before, because when you're in the engineering side, you're really focused on making technology, using science to come up with awesome inventions," Nyovanie says. "But there are considerations that you need to think about when you're implementing [such inventions]. You need to think about markets, how policies are structured."

The class inspired Nyovanie to become a fellow in the LGO program, where he will earn an MBA from the MIT Sloan School of Management and a master's in mechanical engineering. He is also a fellow of the Legatum Center for Development and Entrepreneurship at MIT.

When Nyovanie prepared for his fellowship interview while at home in Zimbabwe, he faced another electricity interruption: A transformer blew and would take time to repair, leaving him without power before his interview.

"I had to act quickly," Nyovanie says. "I went and bought a petrol generator just for the interview.…The generator provided power for my laptop and for the WiFi." He recalls being surrounded by multiple solar lanterns that provided enough light for the video interview.

While Nyovanie's determination in high school and quick thinking before graduate school enabled him to work around power supply issues, he realizes that luxury doesn't extend to all those facing similar situations.

"I had enough money to actually go buy a petrol generator. Some of these communities in off-grid areas don't have the resources they need to be able to get power," Nyovanie says.

Scaling perspectives

Before co-founding Voya Sol with Stanford University graduate student Caroline Jo, Nyovanie worked at SunEdison, a renewable energy company, for three years. During most of that time, Nyovanie worked as a process engineer and analyst through the Renewable Energy Leadership Development Rotational Program. As part of the program, Nyovanie rotated between different roles at the company around the world.

During his last rotation, Nyovanie worked as a project engineer and oversaw the development of rural minigrids in Tanzania. "That's where I got firsthand exposure to working with people who don't have access to electricity and working to develop a solution for them," Nyovanie says. When SunEdison went bankrupt, Nyovanie wanted to stay involved in developing electricity solutions for off-grid communities. So, he stayed in talks with rural electricity providers in Zimbabwe, Kenya, and Nigeria before eventually founding Voya Sol with Jo.

Voya Sol develops scalable solar home systems that are different from existing solar home system technologies. "A lot of them are fixed," Nyovanie says. "So if you buy one, and need an additional light, then you have to go buy another whole new system….The scalable system would take away some of that risk and allow the customer to build their own system so that they buy a system that fits their budget." By giving users the opportunity to scale up or scale down their wattage to meet their energy needs, Nyovanie hopes that the solar electric systems will help power off-grid communities across the world.

Nyovanie and his co-founder are currently both full-time graduate students in dual degree programs. But to them, graduate school didn't necessarily mean an interruption to their company's operations; it meant new opportunities for learning, mentorship, and team-building. Over this past spring break, Nyovanie and Jo traveled to Zimbabwe to perform prototype testing for their solar electric system, and they plan to conduct a second trip soon.

"We're looking into ways we can aggregate people's energy demands," Nyovanie says. "Interconnected systems can bring in additional savings for customers." In the future, Nyovanie hopes to expand the distribution of scalable solar electric systems through Voya Sol to off-grid communities worldwide. Voya Sol's ultimate vision is to enable off-grid communities to build their own electricity grids, by allowing individual customers to not only scale their own systems, but also interconnect their systems with their neighbors'. "In other words, Voya Sol's goal is to enable a completely build-your-own, bottom-up electricity grid," Nyovanie says.

Supportive communities

During his time as a graduate student at MIT, Nyovanie has found friendship and support among his fellow students.

"The best thing about being at MIT is that people are working on all these cool, different things that they're passionate about," Nyovanie says. "I think there's a lot of clarity that you can get just by going outside of your circle and talking to people."

Back home in Zimbabwe, Nyovanie's family cheers him on.

"Even though [my parents] never went to college, they were very supportive and encouraged me to push myself, to do better, and to do well in school, and to apply to the best programs that I could find," Nyovanie says.

Fatima Husain, MIT News

"You don't learn this in class": Undergraduate researchers build professional skills

MIT Energy Initiative (MITEI) Director of Education Antje Danielson loves summer. It's not just the weather or the lighter traffic around campus. It's the UROPs. Undergraduate research, she says, isn't just one of the "best-known and best-loved" features of the undergraduate experience at MIT. It's also "one of the most important ways we help students prepare to put MIT's *mens et manus* motto into practice." Common enough to be a verb as well as a noun, MIT's Undergraduate Research Opportunity Program (UROP) gives students the opportunity to do advanced work alongside professors and graduate students. And, she says, summer research is especially valuable because it lets students focus on one project with limited interruption.

Professor Amy Glasmeier (left) and Taimor Williams '21 discuss his research project on cascading failures in critical infrastructure systems. Everything from grid design to energy policy to human factors and design influences these types of system failures, and the data surrounding them are immense and complex. Photo: Kelley Travers, MITEI

With MITEI, summer UROP students get an additional layer of experience. "The MITEI UROP is special because we encourage contact between industry sponsors and students, and because we help bridge disciplines to prepare the next generation of energy innovators and leaders no matter what their eventual career path," Danielson says. "We also add extra programming that provides students the experience of professional life outside the lab."

In the lab

Amy Glasmeier is no stranger to having UROPs in her lab. "I've learned that as a principal investigator [PI] it's critical to have a good match between the lab's needs and the student's needs," says Glasmeier, a professor of economic geography and regional planning at MIT. After all, she says, undergraduate researchers aren't just assistants or technicians. They require additional engagement with faculty and graduate students before their work can contribute to a larger research project.

For example, she says, students who are mostly familiar with clearly delineated problem sets and calculations might struggle with nonstandard, unstructured data or project instruction. Her 2018 summer student, mechanical engineering major Taimor Williams '21, quickly vaulted over that obstacle. "Taimor has the intellectual flexibility and adaptability this project needs. I was able to just give him a big stack of reading on grid design, energy policy, data structures, and physics, to put it all in context," says Glasmeier. That's important, she believes, because "you need the context of multiple scientific disciplines as well as social sciences and humanities to make the work relevant."

Williams is characteristically modest about the amount of work he did to get started, saying only that "it was a lot of information, but manageable." With an understanding of the literature in hand, Williams moved on to organizing qualitative descriptions of past electric system failures into data sets that can be analyzed programmatically. The ultimate goal is to identify patterns of system behavior that can be used to predict and prevent future outages.

Professional development

Over the past two years, MITEI Undergraduate Academic Coordinator Rachel Shulman has designed and built a program that brings students together across disciplinary boundaries and prepares them to be colleagues as well as researchers. This year, she had 25 participants. MITEI funded 19 of them, including four who came from Wellesley College. The students had supervisors representing 10 departments across campus.

A key part of their UROP experience was participating in MITEI's professional development workshops, which are designed to provide support and guidance to make an undergraduate's contributions

Professor Julia Ortony (left) and Cynthia Lo ’18 of materials science and engineering review chromatographs of a newly synthesized fluorescent molecule under ultraviolet light. Lo is studying these small organic compounds for their potential use as photoswitchable molecular nanomaterials. Photos: Kelley Travers, MITEI

Veronica Ripper ’20, an electrical engineering and computer science major, outlines her research for an informal presentation to peers during a workshop on scientific poster preparation. Ripper works with MITEI Director of Research Francis O’Sullivan on applying machine learning to unconventional oil and gas exploration and production software.

more valuable. Together, the workshops build critical skills not taught in the lab or the classroom, such as library research, scientific and policy communication, professional networking and career planning, and poster design.

“Being a researcher isn’t just doing the lab work,” Shulman says. “That’s why we do these professional skills workshops and why we make sure all the students can communicate their research to different kinds of audiences.” In all fields, but especially in energy, it’s important to be able to reach across disciplines to build professional relationships; chemists and engineers and software developers and economists all need to be able to work together. And of course, she adds, “they’ll need to bring these ideas out of the lab as well, and explain them to general audiences.”

Students echo her statement: “You don’t learn this in class,” says Luke Hartnett ’20, a mechanical engineering major. Working on biomass gasification with Principal Research Engineer Leslie Bromberg of the Plasma Science and Fusion Center and Research Scientist Emmanuel Kasseris of mechanical engineering was his first taste of professional lab work. “Seeing my PI and the postdocs bouncing ideas off each other is just incredibly exciting. I feel like I’m getting a much better feel for what it’s like to work in the field in real life,” he says. At the same time, he’s also taken to heart advice to prepare a general-audience explanation of the work. “If I’m doing something really important,” he says, “I want to be able to tell everybody about it, not just my lab-mates.”

Alpha Yacob Arsano, a graduate student in architecture, says the workshops help students contribute more, and more quickly. She’s supervising Wellesley College computer science major Chloe Blazey ’19 in the development of software to evaluate thermal comfort and performance of energy-efficient buildings for different climates. Blazey’s work as a computer science student was largely focused on abstract problem sets, so she needed research skills to rapidly gain a broad understanding of architecture and sustainable design. “Chloe has already been using the lessons from the library session,” Arsano says, “and after just a couple of weeks she’s really helping to accelerate the work we’re doing.”

Blazey agrees that having a guide to the MIT library’s specialized academic research tools helped her adjust to working in architecture. It has also changed the way she sees her course of study. “I used to just think about computer science careers as being programming jobs,” she says. “It’s really opened my eyes to see the real-world applications of the theory I’ve been working on and how many different places my major can take me.”

Presenting the research

The culmination of the summer UROP experience is a presentation at the poster session at the MITEI Annual Research Conference in the fall. Shulman says that MITEI puts the UROPs alongside graduate students, research scientists, and professors to “really experience what it’s like to present their work in a professional context.”

Shulman brought in Writing and Communication Center Lecturer Thalia Rubio to help the students prepare. In several meetings over the summer, she gave them a crash course in the research poster, a scientific communication format that most students don’t get to practice. “They’re very familiar with term papers and lectures,” says Rubio. “They’ve done presentations. But a poster session uses different skills they don’t get much chance to exercise: design, very concise writing, and a presentation style that’s much more of a conversation than a lecture.”

Poster sessions are a key way for researchers to share work in progress and gain exposure to different perspectives on their work before they prepare it for publication. She has students practice creating posters and presentations for made-up topics like whether chewing gum improves mental concentration. Then, they get questions they aren't prepared for: How do you know your measurement of concentration was a good one? What has previous research shown? Did you try different flavors of gum? What about organic versus conventional gum?

Obviously, says Rubio, it's not about gum. It's about how to handle questions that you haven't considered.

"You're going to get a question you aren't prepared to answer, so be prepared to ask for their contact information and get back to them later," she tells the students. She encourages them to learn from their oversights as well, noting that the feedback from a poster session can be incorporated into future research.

Bringing students together

Shulman has designed the student programming to reflect the inherent interdisciplinary nature of energy research. "We're aiming for cross-pollination," she says. "That's one reason we don't limit professional development work to students we fund or supervise."

Professor of Building Technology and Mechanical Engineering Leon Glicksman agrees. He enjoys being able to see students tackle real-world problems and encourages them to focus on the issues that lie between different academic disciplines. "MITEI doesn't have a single lab location, and although it doesn't sound like it, that's actually an advantage," he says. "It prevents us from being cordoned off from other departments, initiatives, labs, and research centers. I like to tell students that energy is a great career for everyone, because the need to generate, distribute, and conserve energy isn't going anywhere, and energy problems need people with lots of different skills and backgrounds to solve them."

For example, Jose Soto Rivera '20, an electrical engineering and computer science major, is working with MITEI Deputy Director for Science and Technology Robert Stoner on a project about grid resilience in Puerto Rico. Without the workshops from the MITEI summer UROP, he might not have met Williams, whose work on infrastructure resilience in general may inform future grid designs. Neither of them would have met mechanical engineering students Cole Legg '20, who's modeling waste-to-energy systems under Professor Ahmed Ghoniem of mechanical engineering, or Hartnett and Jimmy Tran '21, who are working on biomass gasification.

Their collaboration so far has been limited to speculative conversations over lunch; after all, they still have to finish their current research projects. But it's possible that sometime in the future you might hear about a groundbreaking project that supplies hard-to-serve areas with reliable, low-carbon energy by combining smart grids, waste-to-energy systems, and biomass gasification—undertaken by students who met as UROPs in 2018.

The important thing for professors and investigators to remember, Glasmeier says, is that "a UROP is a gift." Whether funding comes from MITEI, the MIT UROP office, or the lab itself, "having a UROP means having the ability to really watch someone develop as a researcher and as a person."

Aaron Weber, MITEI

Bottom photo, from left: MIT graduate student Alpha Yacob Arsano, Wellesley College undergrad Chloe Blazey '19, and Christoph Reinhart, principal investigator and professor of architecture, pose with a weather station they use to gather data that will help them develop software for evaluating the performance of energy-efficient buildings in different climates. Top photo: Blazey (left) and Arsano adjust the data-collection hardware.

Jimmy Tran '21 practices his research poster presentation during a workshop session on scientific communication. Tran is working with Leslie Bromberg of the Plasma Science and Fusion Center and Emmanuel Kasseris of mechanical engineering to remove tar from biomass-generated gases. The engine they're developing could make biomass gasification a clean and reliable source of energy for isolated or rural areas, especially in developing countries.

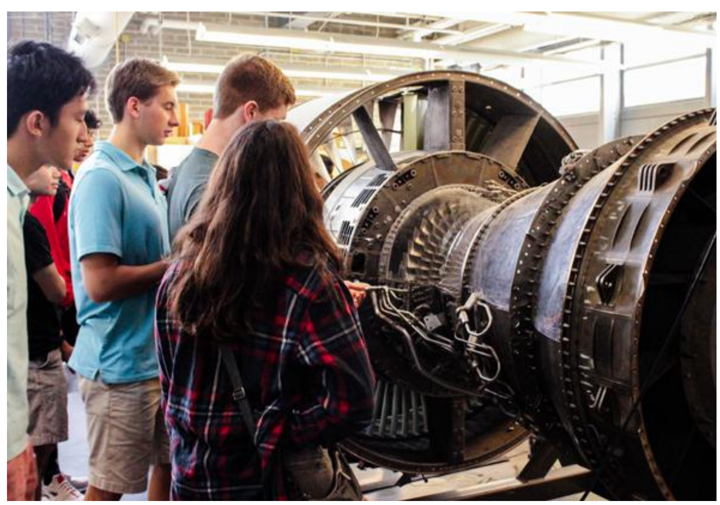
MITEI welcomes Class of 2022 to campus

Every year, MITEI hosts the Discover Energy Freshman Pre-Orientation Program (DE FPOP), a weeklong event where students are able to bond and explore their shared interest in energy through a series of fun, energy-related field trips and activities. At left, students prepare for a tour of the Massachusetts Clean Energy Center's Wind Technology Testing Center (WTTC). Photo: Ryan M. Sander '20, MIT

DE FPOP student Moises Trejo tests the flexibility of a wind turbine blade at the WTTC. Photo: Corey Watanabe, MITEI

DE FPOP students explore cutting-edge energy technology through an interactive touch screen at the Fraunhofer Center for Sustainable Energy Systems. Photo: Corey Watanabe, MITEI

Working in Professor Steven Leeb's mechanical engineering lab, DE FPOP students Ana Fiallo (left) and Emily Yuan (second from right) construct mini electric motors with assistance from counselors Jimmy Tran '21 (second from left) and Ryan M. Sander '20. Photo: Corey Watanabe, MITEI



DE FPOP students examine an airplane jet engine before exploring the MIT Wright Brothers Wind Tunnel. Photo: Corey Watanabe, MITEI

Education updates

Energy Education Task Force, 2018–2019

William Green
Chemical Engineering

Bradford Hager, co-chair
Earth, Atmospheric, and Planetary Sciences

David Hsu
Urban Studies and Planning

Robert Jaffe
Physics

Ruben Juanes
Civil and Environmental Engineering

Christopher Knittel
Management

Steven Leeb
Electrical Engineering and Computer Science

Rajeev Ram, co-chair
Electrical Engineering and Computer Science

Yang Shao-Horn
Mechanical Engineering

Yogesh Surendranath
Chemistry

Konstantin Turitsyn
Mechanical Engineering

Energy Studies Minor graduates, 2018

Meredith Barr
Chemical–Biological Engineering

Nathaniel Johnson
Mechanical Engineering

Michael Dornu Kitcher
Materials Science and Engineering

Michelle Lauer
Computer Science and Engineering

Emily Penn
Chemical Engineering

3 Questions: Howard J. Herzog discusses the state of carbon capture

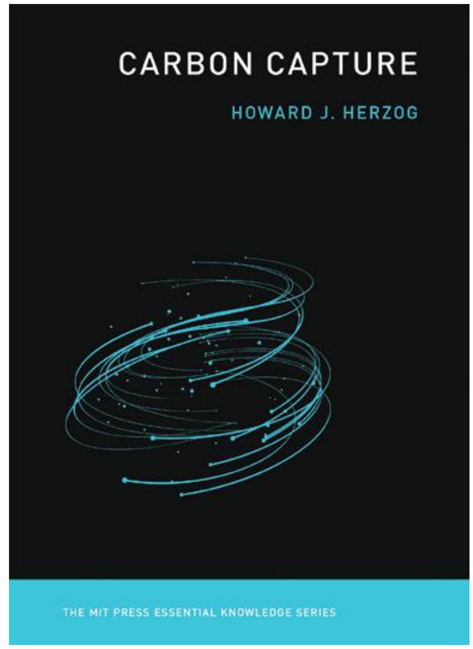
Howard J. Herzog is a senior research engineer at the MIT Energy Initiative. In September, he published Carbon Capture, *a new addition to the MIT Press Essential Knowledge book series. In this interview, he discusses the current landscape of carbon capture research.*

If you were to explain carbon capture in a few sentences, what would you say? What do people need to know?

Carbon capture is a way to keep CO_2 out of the atmosphere. Most climate change mitigation options would take something that produces CO_2 and replace it with something that performs the same service but doesn't emit CO_2—such as using renewables instead of fossil fuels to produce electricity. Carbon capture permits fossil fuel use, but it captures the emissions rather than allowing them to enter the atmosphere. You're producing energy in a similar way but with fewer emissions. That's important because over 80% of our energy is generated using fossil fuels, which produce CO_2.

Why is it important to include carbon capture as part of the low-carbon energy portfolio?

Based on my years of experience and the research, I think it's going to be extremely difficult, if not impossible, to hit current climate goals without using carbon capture to some degree. Carbon capture technology exists today, but there are many ideas out there about how to improve it, and you only need a couple of those ideas to go to fruition to have a dramatic impact. I write in the book about a couple of technologies that look very promising.



What types of policy changes could enable more implementation of carbon capture?

I always think the best policy is putting a price on carbon and letting the markets decide. As I said in the book, there's some bias against carbon capture, so if the politicians want to start mandating technologies, carbon capture may not fare so well in that process. But I think if you let the market decide, it will find the best uses for carbon capture, and you'll see it being pretty effective. I'm absolutely convinced that it can compete as long as there's a fair playing field.

Hannah Bernstein, MITEI

NOTE

Please go to bit.ly/herzog-book for more information about the new book, *Carbon Capture*, published by the MIT Press.

Climate change, "tough tech" startups, and the future of energy intelligence: Q&A with Robert C. Armstrong

MITEI's 2018 Annual Research Conference brought together energy researchers, policymakers, and industry members who are working on the cutting-edge technologies and business models for the transition to a low-carbon future. Panels covered a range of topics from the latest developments in the fight against climate change to innovations for creating a better environment for energy startups to thrive. A special segment of the conference, presented in collaboration with MIT's recently launched Quest for Intelligence, focused on the role of artificial intelligence and machine learning in the energy sector. Below, MITEI Director Robert C. Armstrong discusses highlights from the conference and visions for the future of energy innovations to meet global energy demand while addressing climate change.

Q Entrepreneurship and energy startups were a big theme of this year's conference. How is the MIT innovation ecosystem working to make it easier for "tough tech" startups like those in energy, which require more capital and different kinds of resources than typical startups?

A MIT realizes the value of proximity. In Kendall Square and in the Greater Boston area, we have a rich innovation ecosystem, from the Institute itself, paired with industry and federal government support for fundamental and applied research, to the startup incubators right down the street, like Greentown Labs. Most recently, MIT started The Engine, which offers a new way to fund and nurture startups in the tough tech area. All of these spaces help startups find their footing and grow. It's more than just the physical space, too. It's networking with other startups and sharing of ideas and laboratory facilities.

A good example of a startup that needs a different kind of nurturing is Commonwealth Fusion Systems (CFS), a recent MIT spinout that aims to develop affordable, practical fusion power. Fusion is an area in which a startup generally needs a lot more capital than is typical. It's not an area for typical venture capital investment. MITEI, though, brought CFS in contact with energy companies that had the interest and the resources to engage in this area of the energy transition. Connections like these are an integral part of MITEI's new startup membership model, which brings the unique needs of energy startups to the forefront.

Many of these startups also need access to very specialized equipment, facilities, and infrastructure. The MIT ecosystem, with our specialized lab space that you won't find in a typical startup garage, can help with that—including the new MIT.nano building, which is being outfitted with cutting-edge equipment that will be available for both MIT and non-MIT entities to use. At MIT, we also have access to highly talented and skilled human capital, which for tough tech startups can be substantial: It's not three people in a garage; it can be 30 people, each with a specific skill set.

Q Some of the conference focused on advances and opportunities in materials design and application. What role does the study and development of new and advanced materials play in the energy space?

A Materials needs in the energy industry are extremely diverse. From nanomaterials to metal alloys, materials are going to play a role in everything from energy production and conversion to transmission, distribution, and end use.

The challenges facing the materials industry are broad, though. One example is the issue of materials lifetimes. How do they degrade? Which properties are most affected as they degrade? How can performance lifetimes be extended? The degradation of every material is different, so there's not going to be one breakthrough that tells you how to stop degradation of every material in your business, wish as you might.

The energy space is also rich with instances where there's a need for the discovery and creation of new materials. With batteries, for example, we need new materials and new chemistries, depending on the application of the battery, that allow you to store energy very cheaply. These materials also need to withstand the cycling of the batteries, the rate of charge and discharge, and allow them to retain performance over many cycles at a price point that makes them affordable for deployment with intermittent renewables like solar or wind.

In the nuclear area, as well, we're working on designing materials that are better at withstanding corrosion, which can guarantee the safety and reliability of nuclear plants for much longer lifetimes.

Q Research discussed at the conference ranged from more efficient 3D printing to the use of carbon nanotube electrodes in water desalination. How do all of these technological advances play into the larger framework of combatting climate change?

A Just before the conference convened, the Intergovernmental Panel on Climate Change (IPCC) special report was released, which shows that when it comes to climate change, adverse impacts are happening faster than we thought.

MIT Energy Initiative Director Robert C. Armstrong welcomes attendees to MITEI's Annual Research Conference and describes upcoming panels on topics including climate stabilization, energy startups, and the critical role that artificial intelligence and machine learning can play in developing technology for a low-carbon energy future. Photo: Eric Haynes

The changes in our world, in storm intensity and sea level rise and so much else, that we thought would come with a 2°C rise in global temperatures may now happen at 1.5 degrees. With this in mind, we need to lower our estimates for the temperature rise that we think is feasible to live with.

That's different than saying we know how to get there, though. It is challenging to think about 2°C, and it's even more challenging to think about 1.5°C. A lot of our discussion focused on how we might do that, with tools like negative emissions technologies, paired with a carbon price. Somewhere down the road we will almost certainly find we've exceeded 1.5 degrees, so how do we get back to where we need to be?

It's really important to develop a common understanding of what the problem is and what its dimensions are. At this conference, we examined the range of technologies and sectors in the economy that need to be addressed to mitigate climate change. Energy is the big one, but not the only one. Within energy, the electric power system has received the most attention, and we looked in depth at the rapid changes occurring there. We discussed how to not only develop low-carbon energy technology but also to get it out of the lab and scale it up. Our industrial collaborators are essential here. In addition, the innovation ecosystem centered at MIT, with all of its promising energy startups, can and is playing an increasing role in mitigating greenhouse gas emissions from all parts of the energy sector. The transportation sector also presents significant opportunities, which we'll be examining in our forthcoming *Mobility of the Future* report.

Q The theme of this year's Annual Research Conference was "Energy Intelligence." What role will artificial intelligence play in realizing the low-carbon energy future?

A There are many points of connection and crossover between energy and artificial intelligence. The newly founded Quest for Intelligence at MIT is a very exciting example where MIT is bringing together researchers from multiple disciplines across all of MIT's five schools. At its core, the Quest is looking at the essence of human and machine intelligence. But it's also looking to connect this high-level study of intelligence to other disciplines that can benefit from the crossover.

One example is intelligence in robotics. Today's drones are capable of a new level of speed and dexterity that has important implications in the energy industry. Nimble drones could change the way infrastructure surveys are done and could also be used for monitoring. Monitoring for natural gas leaks, for example, is important in ensuring that you recover all possible carbon-reduction benefits from coal-to-gas switching. In the transportation sector, this kind of technology could allow us to create the next generation of energy-efficient autonomous vehicles, for example, designing cars that can drive in close proximity to one another to reduce air drag.

MITEI researchers are also tying artificial intelligence into their domain-specific energy research through the use of machine learning. Machine learning can be used to identify patterns of degradation in advanced materials and can even be used to quickly screen thousands of journal articles for the best recipes for manufacturing new materials at commercial scale. That kind of innovation is going to grow rapidly in coming years, which will only serve to enrich the research projects coming out of MITEI. Part of the Energy Initiative's mission is to bring faculty members and researchers together who have complementary skills. As faculty from the Quest begin collaborating with faculty focusing on energy in new ways, they'll be able to accomplish things together that none of them could do alone, opening up new doors to a low-carbon energy future.

Francesca McCaffrey, MITEI

MIT Energy Initiative Members

MITEI Founding and Sustaining Members

MITEI's Founding and Sustaining Members support "flagship" energy research programs and projects at MIT to advance energy technologies to benefit their businesses and society. They also provide seed funding for early-stage innovative research projects and support named Energy Fellows at MIT. To date, members have made possible 170 seed grant projects across the campus as well as fellowships for more than 430 graduate students and postdoctoral fellows in 20 MIT departments and divisions.

MITEI Founding Members

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MITEI Startup Members

MITEI has created a new class of membership for energy startups, designed to help them clear technology hurdles and advance toward commercialization by accessing the talent and facilities at MIT.

COMMONWEALTH FUSION SYSTEMS

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.

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

Asociación Nacional de Empresas Generadoras (ANDEG)
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Bill Brown, Jr. '77
David L. desJardins '83
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Patrik Edsparr PhD '94
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S. Jones Fitzgibbons SM '73 and Michael Fitzgibbons SM '73
A. Thomas Guertin PhD '60
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William W. Vanderson '99, MNG '00 and Christina L. Gehrke '99
David Wang '00, MNG '00
William Wojeski '71 and Karen Leider '72
William A. Wynot '44

Members as of October 1, 2018

MITEI member news

INALUM becomes a MITEI member
Indonesia's state-owned holding company PT Indonesia Asahan Aluminium (Persero), also known as INALUM, has joined MITEI as a member company to support research that advances development of low-carbon energy technologies and explore ways to reduce the company's carbon footprint through MITEI's Low-Carbon Energy Center for Materials in Energy and Extreme Environments. Above: Lihong (Wendy) Duan, manager of MITEI's Asia Pacific energy partnerships, and Budi Gunadi Sadikin, CEO of INALUM, celebrate the new collaboration. Among INALUM's research interests with MITEI are developing more environmentally sustainable processes for mining, refining, and smelting metals; investigating high-performance materials for energy storage; and exploring rare earth metal applications such as magnets for use in electric vehicles and wind power. Read more online at bit.ly/inalum-member. Photo courtesy of INALUM

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Undergraduate students contribute to MIT research across campus

Above: Wellesley College student Chloe Blazey '19 (left) and her supervisor, MIT graduate student Alpha Yacob Arsano, examine a weather station where they're gathering data to support development of software for actionable climate data visualization online that will help architects evaluate thermal comfort and low-energy building strategies for different climates—a project led by Professor Christoph Reinhart of architecture.

Blazey was one of 25 students who took part in MITEI's Undergraduate Research Opportunities Program (UROP) during summer 2018. The UROP students became integral members of MIT teams in 10 departments across campus and contributed to research on topics ranging from biomass gasification and waste-to-energy conversion to infrastructure resilience and chromophores for advanced photovoltaics. In addition, they participated in MITEI workshops in which they learned critical skills such as scientific and policy communication, professional networking and career planning, library research, and poster design. For more details and photos, see page 33.

Photo: Kelley Travers, MITEI