Energy Futures

MIT ENERGY INITIATIVE   MASSACHUSETTS INSTITUTE OF TECHNOLOGY   SPRING 2019

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MIT Professors Fikile Brushett, Elsa Olivetti, and Yogesh Surendranath discuss building the next generation of materials for future energy systems.

The human environmental nexus
Frances Beinecke, past president of the Natural Resources Defense Council, discusses the US climate trajectory, the need for national leadership, and how to make an impact on climate change. (See article on page 32.)

Solar energy
Professor Vladimir Bulović, director of MIT.nano and co-director of the MITEI Solar Low-Carbon Energy Center, talks about what's coming in solar and what MIT.nano is doing to change how startups launch from MIT. (See article on page 36.)

…and more.

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On the cover
Professor Stuart Madnick (left), graduate student Shaharyar Khan (right), and Professor James L. Kirtley Jr. (not pictured) have developed a technique for identifying vulnerabilities to cyberattack in complex energy systems such as power plants. In case studies, they found numerous vulnerabilities stemming not only from equipment but also from operator behavior, management decisions, and more. See page 3. Photo: Stuart Darsch

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

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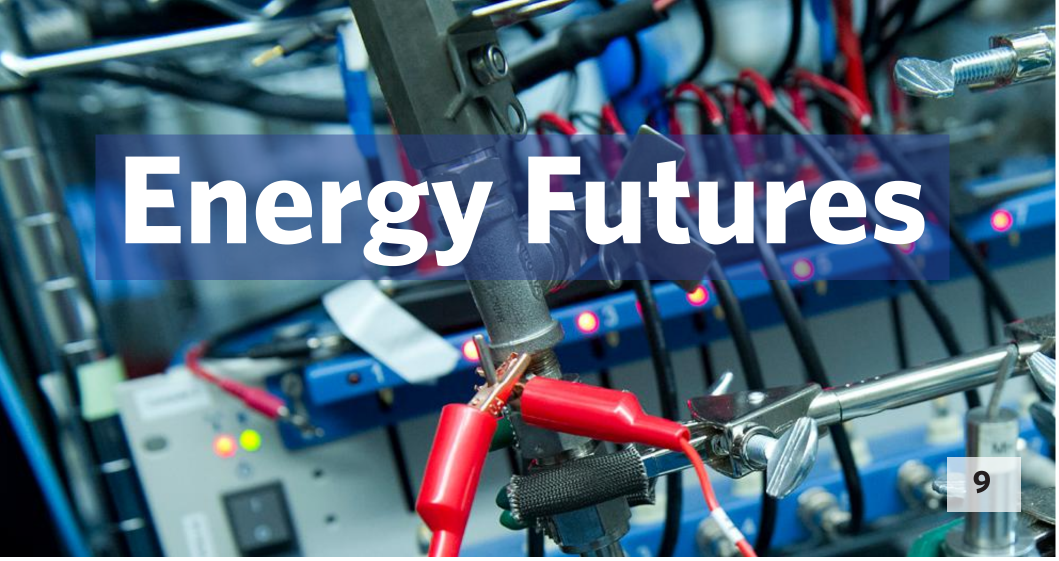

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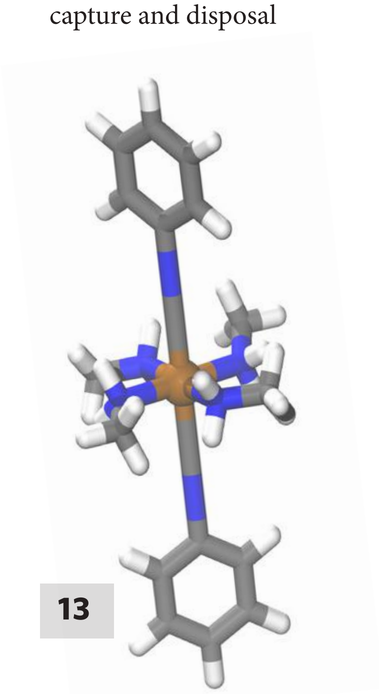
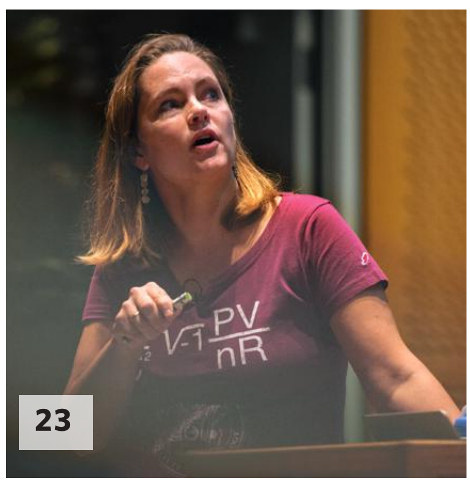




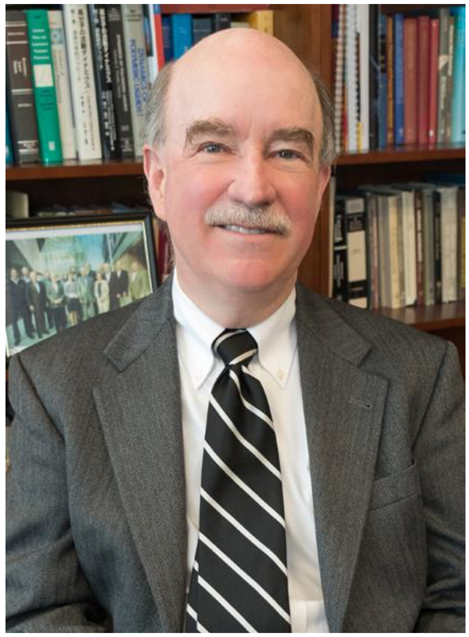
A letter from the director

Dear friends,

With the launch of the Quest for Intelligence and the Schwarzman College of Computing, MIT is making an Institute-wide response to the increasing importance of artificial intelligence and computing in the future of education, research, and industry. At the MIT Energy Initiative (MITEI), we are already exploring how these technologies can be used to reshape the energy sector and accelerate the low-carbon energy transition.

The potential energy applications for artificial intelligence are wide-ranging—from the ability to accelerate the discovery of new materials to the development of better battery management systems to the implementation of new demand-side opportunities to improve power system operations. In this issue of *Energy Futures*, you will read about how machine learning can dramatically reduce the time required to evaluate new transition metal compounds for their potential as novel sensors or switches or as improved catalysts for industrially important processes (page 13).

Artificial intelligence also figures into our Mobility of the Future study, which examines autonomous vehicles and their potential future impacts on urban mobility and the global personal transportation system. The study, anticipated for publication in fall 2019, explores many different areas of mobility—an important and dynamic component of the energy sector. To build on this foundation, MITEI is developing a new Low-Carbon Energy Center, the Mobility Systems Center, to help guide sustainable and efficient global mobility growth by developing, maintaining, and applying state-of-the-art tools for mobility research. Center researchers and industry members have identified topics of interest, including mobility evolution in high-growth countries, freight ground transportation, clean fuels and propulsion systems, and potential disruptors of mobility systems.



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

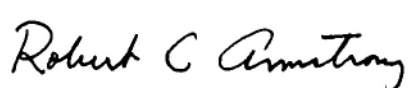
In this issue, you will also read about a new methodology that can help protect power plants and other critical energy infrastructure from cyberattack (page 3). Other advances covered in this issue focus on simultaneously capturing CO_2 in power plant exhaust and preparing it for safe disposal (page 9), turning waste brine from desalination plants into useful chemicals (page 19), and observing hydrogen's effects on metals to help in the design of safer hydrogen storage tanks (page 21). On the policy front, investigators have demonstrated new analytical tools that countries can use to develop practical emissions-reduction strategies to meet their Paris Agreement commitments (page 17).

To help train the global network of professionals needed to realize a low-carbon energy future, the MITEI education team has been busy launching a new series of online energy courses based on interdisciplinary MIT graduate classes currently taught on campus (page 27). The first four courses will focus on electric power systems design and management.

One highlight of on-campus student activities was a design-thinking workshop that MITEI co-hosted during MIT's Independent Activities Period in January to creatively explore pathways toward a net-zero carbon future for the Massachusetts island community of Martha's Vineyard (page 30). We hope the work on Martha's Vineyard can inspire action and serve as a model for other communities working toward carbon neutrality.

With the diverse nature of our global energy system landscape, there are still many technology, business, and policy innovations yet to explore—and I am excited that we continue to expand research frontiers here at MIT. I invite you to be in touch with any thoughts or feedback and hope you enjoy this issue of *Energy Futures*.

Warm regards,



Professor Robert C. Armstrong
MITEI Director
April 2019

Protecting our energy infrastructure

New analysis targets cybersafety

Nancy W. Stauffer, MITEI

IN BRIEF

Using a new, holistic approach called cybersafety, an MIT team has shown that today's energy systems are rife with vulnerabilities to cyberattack—often the result of increased complexity due to high interconnectivity between devices and greater use of software to control system operation. The methodology examines a spectrum of factors that influence system operation, from physical design to operator behavior to organizational and managerial actions, and then determines how interactions among those factors can affect system safety. The resulting analysis can point to specific steps a company can take to strengthen the cybersecurity of its facilities. In the past decade, cyberattacks on physical systems have demonstrated that traditional IT security measures are largely impotent in protecting critical infrastructure from advanced cyber adversaries. The researchers therefore stress the urgent need to identify and mitigate cyber vulnerabilities, as future cyberattacks could cause unimaginable disruptions such as interrupting the flow of fuels or shutting down the US electric grid.

Almost every day, news headlines announce another security breach and the theft of credit card numbers and other personal information. While having one's credit card number stolen can be alarming, a far more significant yet less recognized concern is the security of physical infrastructure, including energy systems.

"With a credit card theft, you might have to pay $50 and get a new credit card," says Stuart Madnick, the John Norris Maguire Professor of Information Technologies at the MIT Sloan School of Management, a professor of engineering systems at the MIT School of Engineering, and founding director of the Cybersecurity

Above Using their "cybersafety" methodology, Professor Stuart Madnick (left), graduate student Shaharyar Khan (right), and Professor James L. Kirtley Jr. (not pictured) identified several cyber vulnerabilities in a small power plant, including a system that poses a risk because it relies on software rather than mechanical safety devices to keep turbines from spinning out of control. Photo: Stuart Darsch at MIT Sloan consortium. "But with infrastructure attacks, real physical damage can occur, and recovery can take weeks or months." Madnick and his colleagues are now releasing methods and analytical tools they've developed that organizations can use to examine their facilities for vulnerabilities to cyberattack—including those that may arise from organizational, managerial, or employee actions.

A few examples of attacks since the advent of cyber-physical infrastructures demonstrate the seriousness of the threat. In 2008, an alleged cyberattack blew up an oil pipeline in Turkey, shutting it down for three weeks; in 2009, the malicious Stuxnet computer worm destroyed hundreds of Iranian centrifuges, disrupting that country's nuclear fuel enrichment program; and in 2015, an attack brought down a section of the Ukrainian power grid—for just six hours, but substations on the grid had to be operated manually for months.

According to Madnick, for adversaries to mount a successful attack, they must have the capability, the opportunity, and the motivation to do so. In the incidents just cited, all three factors aligned, and attackers effectively crippled major physical systems.

"The good news is that, at least in the United States, we haven't really experienced that yet," says Madnick. But he believes that "it's only motivation that's lacking." Given sufficient motivation, attackers anywhere in the world could, for example, bring down some or all of the nation's interconnected power grid or stop the flow of natural gas through the country's 2.4 million miles of pipeline. And while emergency facilities and fuel supplies may keep things running for a few days, it's likely to take far longer than that to repair systems that attackers have damaged or blown up.

"Those are massive impacts that would affect our day-to-day lives," says Madnick. "And it's not on most people's radar. But just hoping that it won't happen is not exactly a safe way to go about life." He firmly believes that "the worst is yet to come."

The challenge for industry

Ensuring the cybersecurity of energy systems is a growing challenge. Why? Today's industrial facilities rely extensively on software for plant control rather than on traditional electro-mechanical devices. In some cases, even functions critical for ensuring safety are almost entirely implemented in software. In a typical industrial facility, dozens of programmable computing systems distributed throughout the plant provide local control of processes—for example, maintaining the water level in a boiler at a certain setpoint. Those devices all interact with a higher-level "supervisory" system that enables operators to control the local systems and overall plant operation, either on site or remotely. In most facilities, such programmable computing systems do not require any authentication for settings to be altered. Given this setup, a cyberattacker who gains access to the software in either the local or the supervisory system can cause damage or disrupt service.

The traditional approach used to protect critical control systems is to "air gap" them, that is, separate them from the public internet so that intruders can't reach them. But in today's world of high connectivity, an air gap no longer guarantees security. For example, companies commonly hire independent contractors or vendors to maintain and monitor specialized equipment in their facilities. To perform those tasks, the contractor or vendor needs access to real-time operational data—information that's generally transmitted over the internet. In addition, legitimate business functions such as transferring files and updating software often require the use of USB flash drives, which can inadvertently jeopardize the integrity of the air gap, leaving a plant vulnerable to cyberattack.

Looking for vulnerabilities

Companies actively work to tighten up their security—but typically only *after* some incident has occurred. "So we tend to be looking through the rear-view mirror," says Madnick. He stresses the need to identify and mitigate the vulnerabilities of a system before a problem arises.

The traditional method of identifying cyber vulnerabilities is to create an inventory of all of a system's components, examine each one to identify any vulnerabilities, mitigate those vulnerabilities, and then aggregate the results to secure the overall system. But that approach relies on two key simplifying assumptions, says Shaharyar Khan, a fellow of the MIT System Design and Management program. It assumes that events always run in a single, linear direction, so one event causes another event, which causes another event, and so on, without feedback loops or interactions to complicate the sequence. And it assumes that understanding the behavior of each component in isolation is sufficient to predict the behavior of the overall system.

Those assumptions don't hold for complex systems—and modern control systems in energy facilities are extremely complex, software-intensive, and made up of highly coupled components that interact in many ways. As a result, says Khan, "the overall system exhibits behaviors that the individual components do not"—a property known in systems theory as emergence. "We consider safety and security to be emergent properties of systems," says Khan. The challenge is therefore to control the emergent behavior of the system by defining new constraints, a task that requires understanding how all the interacting factors at work—from people to equipment to external regulations and more—ultimately impact system safety.

To develop an analytical tool up to that challenge, Madnick, Khan, and James L. Kirtley Jr., a professor of

Overview of cybersafety analysis

This figure summarizes the steps an analyst takes in performing a cybersafety analysis.

Step 1: Define the purpose of the analysis by identifying unacceptable losses for the system as well as high-level system conditions that could be exploited to result in those worst possible outcomes.

Step 2: Develop a model of the hierarchy of controllers and their interactions that together enforce safety and security constraints on system operation. (Controllers include human operators, automated systems, management, and even government and regulatory entities.)

Step 3: Identify control actions that could be unsafe and lead to system disruption or damage.

Step 4: Hypothesize how the controllers could interact to issue unsafe commands, given the malicious actions of an attacker. The analyst can now identify new requirements that would prevent the worst possible outcomes named in Step 1.

electrical engineering, turned first to a methodology called System Theoretic Accident Model and Process (STAMP), which was developed more than 15 years ago by MIT Professor Nancy Leveson of aeronautics and astronautics. With that work as a foundation, they created "cybersafety," an analytical method specifically tailored to analyze the cybersecurity of complex industrial control systems (see the diagram above).

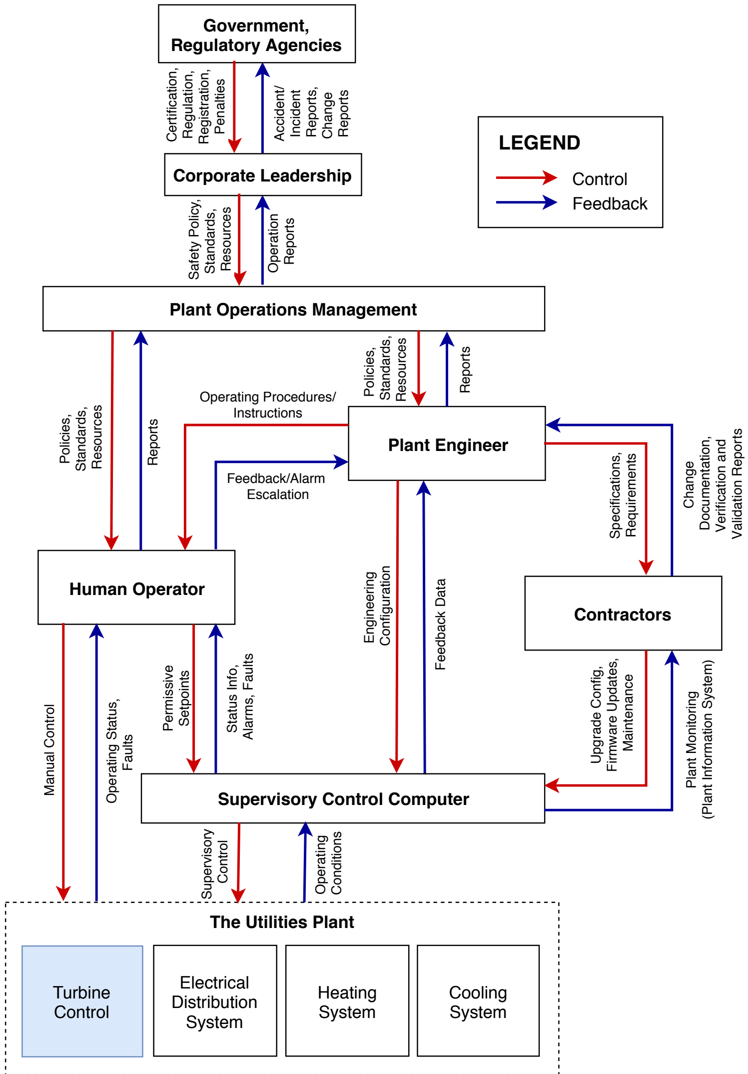
To apply the cybersafety procedure to a facility, an analyst begins by answering the following questions to define the task at hand.

- What is the main purpose of the system being analyzed, that is, what do you need to protect? Answering that question may sound straightforward, but Madnick notes, "Surprisingly, when we ask companies what their 'crown jewels' are, they often have trouble identifying them."
- Given that main purpose, what's the worst thing that could happen to the system? Defining the main purpose and the worst possible losses is key to understanding the goal of the analysis and the best allocation of resources for mitigation.
- What are key hazards that could lead to that loss? As a simple example, having wet stairs in a facility is a hazard; having someone fall down the stairs and break an ankle is a loss.
- Who or what controls that hazard? In the above example, the first step is to determine who or what controls the state of the stairs. The next step is to ask, who or what controls that controller? And then, who or what controls *that* controller? Answering that question recursively and mapping the feedback loops among the various controllers yields a hierarchical control structure responsible for maintaining the state of the stairs in an acceptable condition. The diagram on page 6 shows a hierarchical control structure for the primary functions delivered by a small-scale industrial plant, illustrating the complexity of the factors and feedbacks involved.

Given the full control structure, the next step is to ask: What control actions might be taken by a controller that would be unsafe given the state of the system? For example, if an attacker corrupts feedback from a key sensor, a controller will not know the actual state of the system and therefore may take an incorrect action or may take the correct actions at the wrong time or in the wrong order—any of which would lead to damage.

Based on the now-deeper understanding of the system, the analyst next hypothesizes a series of loss scenarios stemming from unsafe control actions and examines how the various controllers might interact to issue an unsafe command. "At each level of the analysis, we try to identify constraints on the process being controlled that, if violated, would result in the system moving into an unsafe state," says Khan. For example, one constraint could dictate that the steam pressure inside a boiler must not exceed a certain upper bound—a limit needed to prevent the boiler from bursting due to over-pressure.

"By continually refining those constraints as we progress through the analysis, we are able to define new requirements that will ensure the safety and security of the overall system," he says. "Then we can identify practical steps for enforcing adherence to those constraints through system design, processes and procedures, or social controls such as company culture, regulatory requirements, or insurance incentives."



High-level hierarchical control diagram This illustration is a high-level diagram of the interplay among various actors in controlling a gas turbine in a typical power plant. Blue lines show information that each actor, or controller, receives in feedback. Red lines indicate actions that the controller can take in response to the received information.

Case studies

To demonstrate the capabilities of cybersafety analysis, Khan selected a 20-megawatt gas turbine power plant—a small facility that has all the elements of a full-scale power plant on the grid. In one analysis, he examined the control system for the gas turbine, focusing in particular on how the software controlling the fuel-control valve could be altered to cause system-level losses.

Performing the cybersafety analysis revealed that attacks targeting software could produce several turbine-related loss scenarios, including fires or explosions, catastrophic equipment failure, and ultimately the inability to generate power.

For example, in one scenario, the attacker disables the turbine's digital protection system and alters the logic in the software that controls the fuel-control valve to keep the valve open when it should be closed, stopping fuel from flowing into the turbine. If the turbine is then suddenly disconnected from the grid, it will begin to spin faster than its design limit and will break apart, damaging nearby equipment and harming workers in the area.

The cybersafety analysis uncovered the source of that vulnerability: An updated version of the control system had eliminated a backup mechanical bolt assembly that ensured turbine "overspeed" protection. Instead, overspeed protection was implemented entirely in software.

That change made sense from a business perspective. A mechanical device requires regular maintenance and testing, and those tests can subject the turbine to such extreme stresses that it sometimes fails. However, given the importance of cybersecurity, the researchers say it might be wise to bring back the mechanical bolt as a standalone safety device—or at least to consider standalone electronic overspeed protection schemes as a final line of defense.

Another case study focused on systems used to deliver chilled water and air conditioning to the buildings being served. Once again, the cybersafety analysis revealed multiple loss scenarios; and in this case, most had one cause in common: the use of variable frequency drives (VFDs) to adjust the speed of motors that drive water pumps and compressors—a practice that significantly increases the flexibility of operation and energy efficiency.

Like all motors, the motor driving this chiller's compressor has certain critical speeds at which mechanical resonance occurs, causing excessive vibration. VFDs are typically programmed to skip over those critical speeds during motor startup. But some VFDs are programmable over the network, which means that an attacker can query a VFD for the critical speed of the attached motor and then command it to drive the motor at that dangerous speed, permanently damaging the motor and the equipment connected to it.

"This is a simple kind of an attack; it doesn't require a lot of sophistication," says Khan. "But it could be launched and could cause catastrophic damage." He cites earlier work performed by Matthew Angle '07, MEng '11, PhD '16, in collaboration with Madnick and Kirtley. As part of a 2017 study of cyberattacks on industrial control systems, Angle built a lab-scale motor test kit equipped with a complete VFD with computer code familiar to the researchers. By simply altering a few key lines of computer code, they caused capacitors in the VFD to explode, sending smoke billowing out into the courtyard behind their MIT lab (photo at right). In an industrial setting with full-sized VFDs, a similar cyberattack could cause significant structural damage and potentially harm personnel.

Given such possibilities, the research team recommends that companies carefully consider the "functionality" of the equipment in their systems. Many times, plant personnel are not even aware of the capabilities that their equipment offers. For example, they may not realize that a VFD driving a motor in their plant can be made to operate in reverse direction by a small change in the computer code controlling it—a clear cyber vulnerability. Removing that vulnerability would require using a VFD with less functionality. "Good engineering to remove such vulnerabilities can sometimes be mistakenly characterized as a move backwards, but it may be necessary to improve a plant's security posture," says Khan. A full cybersafety analysis of a system will not only highlight such issues but also guide the strategic placement of analog sensors and other redundant feedback loops that will increase the resiliency of system operation.

Addressing the challenge

Throughout their cybersecurity research, Khan, Madnick, and their colleagues have found that vulnerabilities can often be traced to human behavior as well as management decisions. In one case, a company had included the default passcode for its equipment in the operator's manual, which was publicly available on the internet. Other cases

In 2017, MIT researchers demonstrated a cyber vulnerability in a variable frequency drive (VFD) used to control the speed of a motor. For the demonstration, they used a lab-scale motor-development kit that had all the components found in a typical VFD. By altering a few lines in the VFD-control software, they caused a small-scale explosion that sent smoke billowing out into a nearby MIT courtyard, as shown above. Addressing the identified vulnerability is critical, as VFDs are ubiquitous in energy systems ranging from gas pipelines and oil wells to refineries and power plants. Photo: Matthew Angle, MIT

involved operators plugging USB drives and personal laptops directly into the plant network, thereby breaching the air gap and even introducing malware into the plant control system. In one case, an overnight worker downloaded movies onto a plant computer using a USB stick.

But more often such infractions were part of desperate attempts to get a currently shut-down plant back up and running. "In the grand scheme of priorities, I understand that focusing on getting the plant running again is part of the culture," says Madnick. "Unfortunately, the things people do in order to keep their plant running sometimes put the plant at an even greater risk."

Fostering a new culture and mindset about cybersecurity requires a serious commitment from every level of the management chain, the researchers say. Mitigation strategies are likely to require some combination of reengineering the control system, buying new equipment, and making changes in processes and procedures, which might incur extra costs. Given what's at stake, the researchers argue that management must not only approve such investments but also instill a sense of urgency in their organizations to identify vulnerabilities and eliminate or mitigate them.

Based on their studies, the researchers conclude that it's impossible to guarantee that an industrial control system will never have its network defenses breached. "Therefore, the system must be designed so that it's resilient against the effects of an attack," says Khan. "Cybersafety analysis is a powerful method because it generates a whole set of requirements—not just technical but also organizational, logistical, and procedural—that can improve the resilience of any complex energy system against a cyberattack."

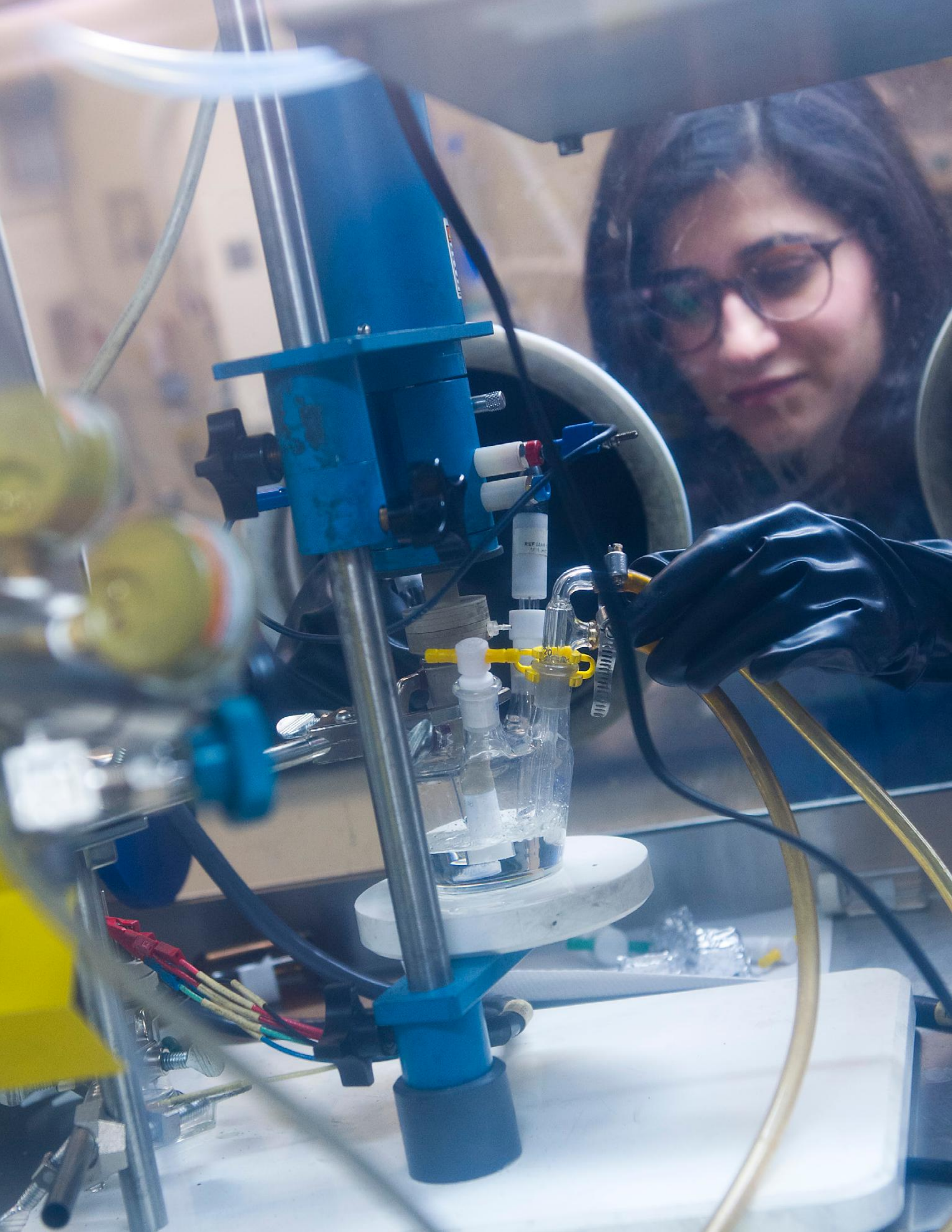
NOTES

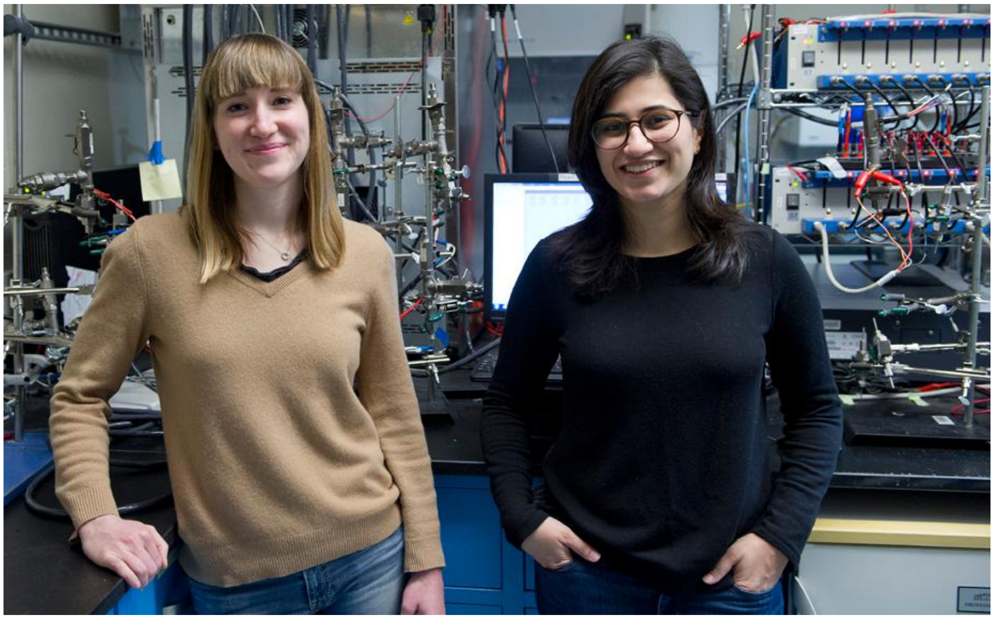
This research was supported by the US Department of Energy, the MIT Energy Initiative Seed Fund Program, and members of the Cybersecurity at MIT Sloan consortium.
More information and the latest publications can be found at cams.mit.edu. See also the following papers:

M.G. Angle, S. Madnick, and J.L. Kirtley Jr. *Identifying and Anticipating Cyber Attacks that could cause Physical Damage to Industrial Control Systems*. Working Paper CISL#2017-14, August 2017, revised May 1, 2019. Online: bit.ly/madnick-cyber-attacks.

S. Khan, S. Madnick, and A. Moulton. *Cybersafety Analysis of Industrial Control System for Gas Turbines*. Working Paper CISL#2018-12, October 2018, revised April 28, 2019. Online: bit.ly/madnick-turbine-analysis.

A. Nourian and S. Madnick. "A systems theoretic approach to the security threats in cyber physical systems applied to Stuxnet." *IEEE Transactions on Dependable and Secure Computing*, vol. 15, issue 1, 2018. Online: doi.org/10.1109/TDSC.2015.2509994.





Removing CO_2 from power plant exhaust

Combining capture and disposal

Nancy W. Stauffer, MITEI

IN BRIEF

Some power plants use materials called sorbents to remove carbon dioxide (CO_2) from their exhaust so it can be sequestered from the environment. But separating the CO_2 from the sorbent requires high temperatures and produces CO_2 gas that must be put into long-term storage—a prospect that raises safety and security concerns. In a proof-of-concept study, MIT researchers have demonstrated a battery-like system that uses the same CO_2-capturing sorbent in a specially designed electrolyte that drives electrochemical reactions with three benefits: They separate the CO_2 from the sorbent; they promote the discharge of electricity from the battery; and they incorporate the CO_2 into a solid that can serve as electrode material or be safely discarded. Their system—made of lithium and carbon electrodes plus the special electrolyte—achieves discharge voltages similar to those of other lithium-gas batteries under development. The researchers are now working to understand and optimize their lithium-based system and to see whether less-expensive, earth-abundant metals might work as well.

Reducing CO_2 emissions from power plants is widely considered an essential component of any climate change mitigation plan. Many research efforts focus on developing and deploying carbon capture and sequestration (CCS) systems to keep CO_2 emissions from power plants out of the atmosphere. But separating the captured CO_2 and converting it back into a gas that can be stored can consume up to 25% of a plant's power-generating capacity. In addition, the CO_2 gas is generally injected into underground geological formations for long-term storage—a disposal method whose safety and reliability remain unproven.

A better approach would be to convert the captured CO_2 into useful products

Facing page Graduate student Aliza Khurram prepares for experiments by pumping carbon dioxide through an electrochemical cell consisting of lithium and carbon electrodes plus a specially designed electrolyte. Photos: Stuart Darsch

Above Assistant Professor Betar Gallant (left) and graduate student Aliza Khurram are developing a novel battery that could both capture carbon dioxide in power plant exhaust and convert it to a solid ready for safe disposal.

such as value-added fuels or chemicals. To that end, attention has focused on electrochemical processes—in this case, a process in which chemical reactions release electrical energy, as in the discharge of a battery. The ideal medium in which to conduct electrochemical conversion of CO_2 would appear to be water. Water can provide the protons (positively charged particles) needed to make fuels such as methane. But running such "aqueous" (water-based) systems requires large energy inputs, and only a small fraction of the products formed are typically those of interest.

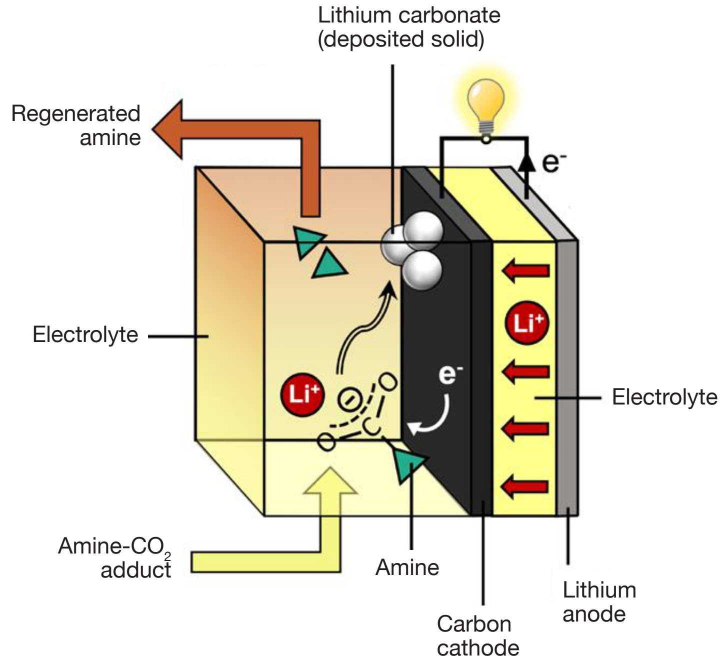
Betar Gallant, an assistant professor of mechanical engineering, and her group have therefore been focusing on non-aqueous (water-free) electrochemical reactions—in particular, those that occur inside lithium-CO_2 batteries.

Research into lithium-CO_2 batteries is in its very early stages, according to Gallant, but interest in them is growing because CO_2 is used up in the chemical reactions that occur on one of the electrodes as the battery is being discharged. However, CO_2 isn't very reactive. Researchers have tried to speed things up by using different electrolytes and electrode materials. Despite such efforts, the need to use expensive metal catalysts to elicit electrochemical activity has persisted.

Given the lack of progress, Gallant wanted to try something different. "We were interested in trying to bring a new chemistry to bear on the problem," she says. And enlisting the help of the sorbent molecules that so effectively capture CO_2 in CCS seemed like a promising way to go.

Rethinking amine

The sorbent molecule used in CCS is an amine, a derivative of ammonia. In CCS, exhaust is bubbled through an amine-containing solution, and the amine chemically binds the CO_2, removing it from the exhaust gases. The

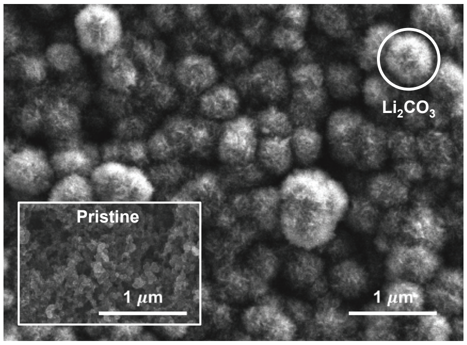


Process during discharge of the novel lithium-CO_2 battery The researchers' proposed battery consists of a lithium anode plus a carbon cathode that is surrounded by a special electrolyte that incorporates lithium ions (Li^+) and amine. When the battery is discharged, positively charged lithium ions move from the lithium anode through the electrolyte to the carbon cathode, while negatively charged electrons (e^-) travel through an external circuit, powering a device along the way. When power plant exhaust passes through the electrolyte, the amine chemically bonds with CO_2 molecules to form an adduct. Chemical reactions on the carbon cathode between the adduct, electrons, and lithium ions split the adduct apart, releasing the CO_2 in a new, highly reactive form and the amine in its unreacted state, ready to collect more CO_2. The CO_2 then reacts with the electrons and lithium ions to form solid spheres of lithium carbonate (Li_2CO_3) on the surface of the carbon cathode.

CO_2—now in liquid form—is then separated from the amine and converted back to a gas for disposal.

In CCS, those last steps require high temperatures, which are attained using some of the electrical output of the power plant. Gallant wondered whether her team could instead use electrochemical reactions to separate the CO_2 from the amine—and then continue the reaction to make a solid, CO_2-containing product. If so, the disposal process would be simpler than it is for gaseous CO_2. The CO_2 would be more densely packed, so it would take up less space; and it couldn't escape, so it would be safer. Better still, additional electrical energy could be extracted from the device as it discharges and forms the solid material. "The vision was to put a battery-like device into the power plant waste stream to sequester the captured CO_2 in a stable solid, while harvesting the energy released in the process," says Gallant.

Research on CCS technology has generated a good understanding of the carbon-capture process that takes place inside a CCS system. When CO_2 is added to an amine solution, molecules of the two species spontaneously combine to form an "adduct," a new chemical species in which the original molecules remain largely intact. In this case, the adduct forms when a carbon atom in a CO_2 molecule chemically bonds with a nitrogen atom in an amine molecule. As they combine, the CO_2 molecule is reconfigured: It changes from its original,



SEM image of carbon cathode after discharge This scanning electron microscope (SEM) image shows the cathode from the researchers' lithium-CO_2 system after discharge. Analysis of the spherical structures that coat the surface confirms that they are composed of Li_2CO_3. The inset shows an SEM image of the carbon cathode before discharge. The absence of the spheres confirms that they were formed by reactions during discharge.

highly stable, linear form to a "bent" shape with a negative charge—a highly reactive form that's ready for further reaction.

In her scheme, Gallant proposed using electrochemistry to break apart the CO_2-amine adduct—right at the carbon-nitrogen bond. Cleaving the adduct at that bond would separate the two pieces: the amine in its original, unreacted state, ready to capture more CO_2, and the bent, chemically reactive form of CO_2, which might then react with the electrons and positively charged lithium ions that flow during battery discharge (see the diagram on page 10). The outcome of that reaction could be the formation of lithium carbonate (Li_2CO_3), which would deposit on the carbon electrode.

At the same time, the reactions on the carbon electrode should promote the flow of electrons during battery discharge—even without a metal catalyst. "The discharge of the battery would occur spontaneously," Gallant says. "And we'd break the adduct in a way that allows us to renew our CO_2 absorber while taking CO_2 to a stable, solid form."

A process of discovery

In 2016, Gallant and doctoral student Aliza Khurram of mechanical engineering began to explore that idea.

Their first challenge was to develop a novel electrolyte. A lithium-CO_2 battery consists of two electrodes—an anode made of lithium and a cathode made of carbon—and an electrolyte, a solution that helps carry charged particles back and forth between the electrodes as the battery is charged and discharged. For their system, they needed an electrolyte made of amine plus captured CO_2 dissolved in a solvent—and it needed to promote chemical reactions on the carbon cathode as the battery discharged.

They started by testing possible solvents. They mixed their CO_2-absorbing amine with a series of solvents frequently used in batteries and then bubbled CO_2 through the resulting solution to see if CO_2 could be dissolved at high concentrations in this unconventional chemical environment. None of the amine-solvent solutions exhibited observable changes when the CO_2 was introduced, suggesting that they might all be viable solvent candidates.

However, for any electrochemical device to work, the electrolyte must be spiked with a salt to provide positively charged ions. Because it's a lithium battery, the researchers started by adding a lithium-based salt—and the experimental results changed dramatically. With most of the solvent candidates, adding the salt instantly caused the mixture either to form solid precipitates or to become highly viscous—outcomes that ruled them out as viable solvents. The sole exception was the solvent dimethyl sulfoxide, or DMSO. Even when the lithium salt was present, the DMSO could dissolve the amine and CO_2.

"We found that—fortuitously—the lithium-based salt was important in enabling the reaction to proceed," says Gallant. "There's something about the positively charged lithium ion that chemically coordinates with the amine-CO_2 adduct, and together those species make the electrochemically reactive species."

Exploring battery behavior during discharge

To examine the discharge behavior of their system, the researchers set up an electrochemical cell consisting of a lithium anode, a carbon cathode, and their special electrolyte—for simplicity, already loaded with CO_2. They then tracked discharge behavior at the carbon cathode.

As they had hoped, their special electrolyte actually promoted discharge reaction in the test cell. "With the amine incorporated into the DMSO-based electrolyte along with the lithium salt and the CO_2, we see very high capacities and significant discharge voltages—almost 3 volts," says Gallant. Based on those results, they concluded that their system functions as a lithium-CO_2 battery with capacities and discharge voltages competitive with those of state-of-the-art lithium-gas batteries.

The next step was to confirm that the reactions were indeed separating the amine from the CO_2 and further continuing the reaction to make CO_2-derived products. To find out, the researchers used a variety of tools to examine the products that formed on the carbon cathode.

In one test, they produced images of the post-reaction cathode surface using a scanning electron microscope (SEM). Immediately evident were spherical formations with a characteristic size of 500 nanometers, regularly distributed on the surface of the cathode (see the image on this page). According to Gallant, the observed spherical structure of the discharge product was similar to the shape of Li_2CO_3 observed in other lithium-based batteries. Those spheres were not evident in SEM images of the "pristine" carbon cathode taken before the reactions occurred (see the inset on the page 11 image).

Other analyses confirmed that the solid deposited on the cathode was Li_2CO_3. It included only CO_2-derived materials; no amine molecules or products derived from them were present. Taken together, those data provide strong evidence that the electrochemical reduction of the CO_2-loaded amine occurs through the selective cleavage of the carbon-nitrogen bond.

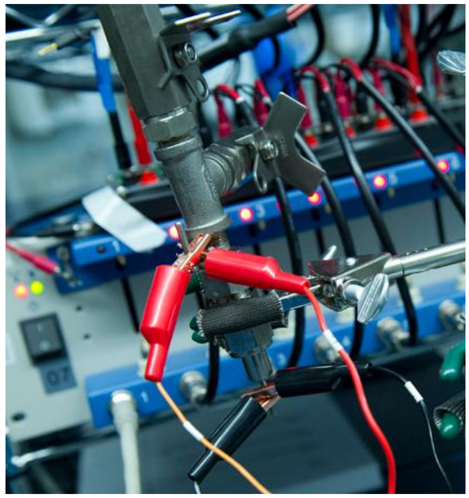
"The amine can be thought of as effectively switching on the reactivity of the CO_2," says Gallant. "That's exciting because the amine commonly used in CO_2 capture can then perform two critical functions. It can serve as the absorber, spontaneously retrieving CO_2 from combustion gases and incorporating it into the electrolyte solution. And it can activate the CO_2 for further reactions that wouldn't be possible if the amine were not there."

Future directions

Gallant stresses that the work to date represents just a proof-of-concept study. "There's a lot of fundamental science still to understand," she says, before the researchers can optimize their system.

She and her team are continuing to investigate the chemical reactions that take place in the electrolyte as well as the chemical makeup of the adduct that forms—the "reactant state" on which the subsequent electrochemistry is performed. They are also examining the detailed role of the salt composition.

In addition, there are practical concerns to consider as they think about device design. One persistent problem is that the solid deposit quickly clogs up the carbon cathode, so further chemical reactions can't occur. In one configuration they're investigating—a rechargeable battery design—the cathode is uncovered during each discharge-charge cycle. Reactions during discharge deposit the solid Li_2CO_3, and reactions during charging lift it off, putting the lithium ions and CO_2 back into the electrolyte, ready to react and generate more electricity. However, the captured CO_2 is then back in its original gaseous form in the electrolyte. Sealing the battery would lock that CO_2 inside, away from the atmosphere—but only so much CO_2 can be stored in a given battery, so the overall impact of using batteries to capture CO_2 emissions would be limited in this scenario.



The researchers use this setup to test the storage capacity and discharge voltage of their batteries. Photo: Stuart Darsch

The second configuration the researchers are investigating—a discharge-only setup—addresses that problem by never allowing the gaseous CO_2 to re-form. "We're mechanical engineers, so what we're really keen on doing is developing an industrial process where you can somehow mechanically or chemically harvest the solid as it forms," Gallant says. "Imagine if by mechanical vibration you could gently remove the solid from the cathode, keeping it clear for sustained reaction." Placed within an exhaust stream, such a system could continuously remove CO_2 emissions, generating electricity and perhaps producing valuable solid materials at the same time.

Gallant and her team are now working on both configurations of their system. "We don't know which is better for applications yet," she says. While she believes that practical lithium-CO_2 batteries are still years away, she's excited by the early results, which suggest that developing novel electrolytes to pre-activate CO_2 could lead to alternative CO_2 reaction pathways. And she and her group are already working on some.

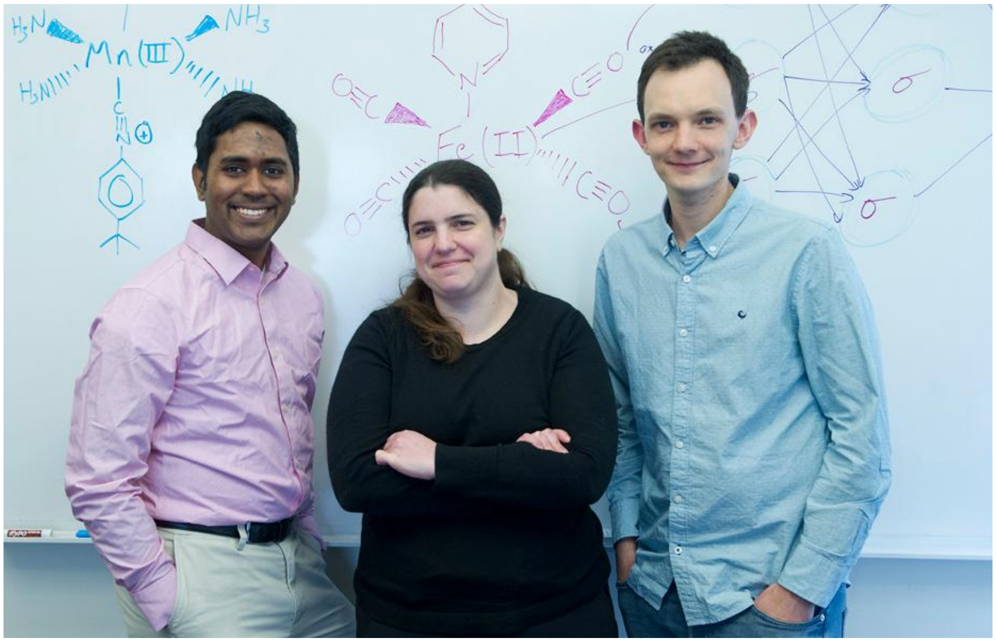
One goal is to replace the lithium with a metal that's less costly and more earth-abundant, such as sodium or calcium. With seed funding from the MIT Energy Initiative, the team has already begun looking at a system based on calcium, a material that's not yet well-developed for battery applications. If the calcium-CO_2 setup works as they predict, the solid that forms would be calcium carbonate—a type of rock now widely used in the construction industry.

In the meantime, Gallant and her colleagues are pleased that they have found what appears to be a new class of reactions for capturing and sequestering CO_2. "CO_2 conversion has been widely studied over many decades," she says, "so we're excited to think we may have found something that's different and provides us with a new window for exploring this topic."

NOTES

This research was supported by startup funding from the MIT Department of Mechanical Engineering. Mingfu He, a postdoc in mechanical engineering, also contributed to the research. Work on a calcium-based battery is being supported by the MIT Energy Initiative Seed Fund Program. Further information can be found in:

A. Khurram, M. He, and B.M. Gallant. "Tailoring the discharge reaction in Li-CO_2 batteries through incorporation of CO_2 capture chemistry." *Joule*, vol. 2, pp. 1–18, December 19, 2018. Online: doi.org/10.1016/j.joule.2018.09.002.



Above Assistant Professor Heather Kulik (center) and graduate student Jon Paul Janet (right) are using neural networks coupled with genetic algorithms to examine huge databases of transition metal compounds for potential use in practical devices. Using the same technique, graduate student Aditya Nandy (left) is designing better catalysts for methane conversion reactions. Photo: Stuart Darsch

Finding novel materials for practical devices

New machine learning technique can help

Nancy W. Stauffer, MITEI

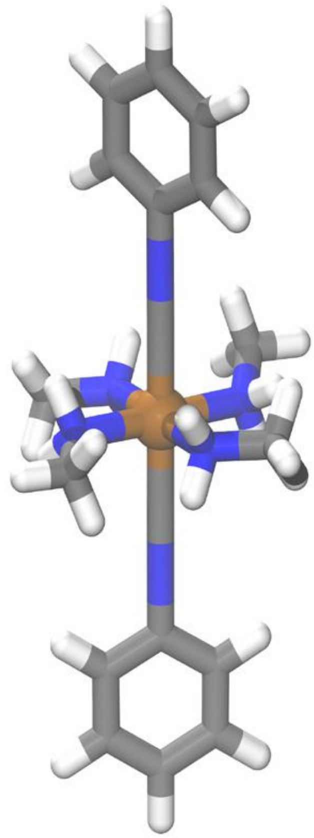
IN BRIEF

MIT researchers have demonstrated a way to rapidly evaluate new transition metal compounds to identify those that can perform specialized functions, for example, as sensors or switches or catalysts for fuel conversion. Using data on known materials, they first trained an artificial neural network to identify good candidates—an approach that's been used with success in organic chemistry but not previously in transition metal chemistry. They then coupled their trained network with a genetic algorithm that could score each compound, discarding those that are too different from the training data for the neural network to be accurate and too similar to be viewed as new options. Using this procedure, they examined a database of 5,600 possible compounds and identified three dozen promising candidates, some of which were totally unfamiliar to materials scientists. Performing the analysis took just minutes on a desktop computer rather than the years that would have been required using conventional techniques.

In recent years, machine learning has been proving a valuable tool for identifying new materials with properties optimized for specific applications. Working with large, well-defined data sets, computers learn to perform an analytical task to generate a correct answer and then use the same technique on an unknown data set.

While that approach has guided the development of valuable new materials, they've primarily been organic compounds, notes Heather Kulik PhD '09, an assistant professor of chemical engineering. Kulik focuses instead on inorganic compounds, in particular, those based on transition metals, a family of elements (including iron and copper) that have unique and useful properties. In those compounds—known as transition metal complexes—the metal atom occurs at the center with chemically bound arms, or ligands, made of carbon, hydrogen, nitrogen, or oxygen atoms radiating outward (see the drawing on this page).

Transition metal complexes already play important roles in areas ranging from energy storage to catalysis for manufacturing fine chemicals—for example, for pharmaceuticals. But Kulik thinks that machine learning could further expand their use. Indeed, her group has been working not only to apply machine learning to inorganics—a novel and challenging undertaking—but also to use the technique to explore new territory. "We were interested in understanding how far we could push our models to do discovery—to make predictions on compounds that haven't been seen before," says Kulik.



Sample transition metal complex
A transition metal complex consists of a central transition metal atom (shown above in orange) surrounded by an array of chemically bound organic molecules in structures known as ligands.

Sensors and computers

For the past four years, Kulik and Jon Paul Janet, a graduate student in chemical engineering, have been focusing on transition metal complexes with "spin"—a quantum mechanical property of electrons. Usually, electrons occur in pairs, one with spin up and the other with spin down, so they cancel each other out, and there's no net spin. But in a transition metal, electrons can be unpaired, and the resulting net spin is the property that makes inorganic complexes of interest, says Kulik. "Tailoring how unpaired the electrons are gives us a unique knob for tailoring properties."

A given complex has a preferred spin state. But add some energy—say, from light or heat—and it can flip to the other state. In the process, it can exhibit changes in macroscale properties such as size or color. When the energy needed to cause the flip—called the spin-splitting energy—is near zero, the complex is a good candidate for use as a sensor or perhaps as a fundamental component in a quantum computer.

Chemists know of many metal-ligand combinations with spin-splitting energies near zero, making them potential "spin-crossover" (SCO) complexes for such practical applications. But the full set of possibilities is vast. The spin-splitting energy of a transition metal complex is determined by what ligands are combined with a given metal, and there are almost endless ligands from which to choose. The challenge is to find novel combinations with the desired property to become SCOs—without resorting to millions of trial-and-error tests in a lab.

Translating molecules into numbers

The standard way to analyze the electronic structure of molecules is using a computational modeling method called density functional theory, or DFT. The results of a DFT calculation are fairly accurate—especially for organic systems—but performing a calculation for a single compound can take hours or even days. In contrast, a machine learning tool called an artificial neural network (ANN) can be trained to perform the same analysis and then do it in just seconds. As a result, ANNs are much more practical for looking for possible SCOs in the huge space of feasible complexes.

Because an ANN requires a numerical input to operate, the researchers' first challenge was to find a way to represent a given transition metal complex as a series of numbers, each describing a selected property. There are rules for defining representations for organic molecules, where the physical structure of a molecule tells a lot about its properties and behavior. But when the researchers followed those rules for transition metal complexes, it didn't work. "The metal-organic bond is very tricky to get right," says Kulik. "There are unique properties of the bonding that are more variable. There are many more ways the electrons can choose to form a bond." So the researchers needed to make up new rules for defining a representation that would be predictive in inorganic chemistry.

Using machine learning, they explored various ways of representing a transition metal complex for analyzing spin-splitting energy. The results were best when the representation gave the most emphasis to the properties of the metal center and the metal-ligand connection and less emphasis to the properties of ligands farther out. Interestingly, their studies showed that representations that gave more equal emphasis overall worked best when the goal was to predict other properties, such as the ligand-metal bond length or the tendency to accept electrons.

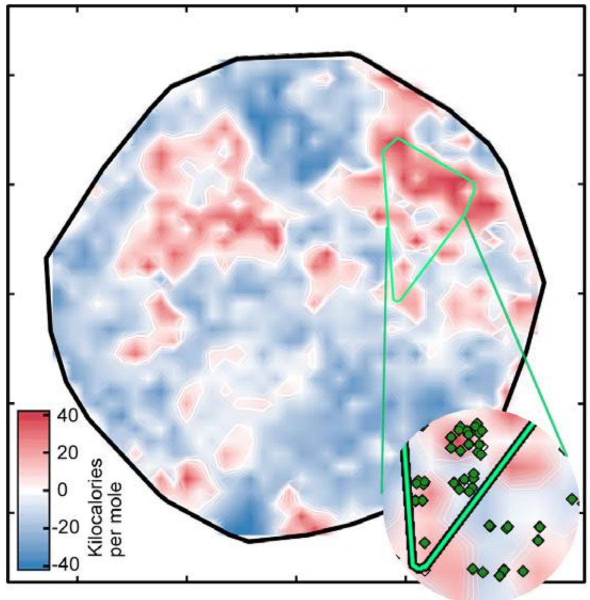
Testing the ANN

As a test of their approach, Kulik and Janet—assisted by Lydia Chan, a summer intern from Troy High School in Fullerton, California—defined a set of transition metal complexes based on four transition metals—chromium, manganese, iron, and cobalt—in two oxidation states with 16 ligands (each molecule can have up to two). By combining those building blocks, they created a "search space" of 5,600 complexes—some of them familiar and well-studied, and some of them totally unknown.

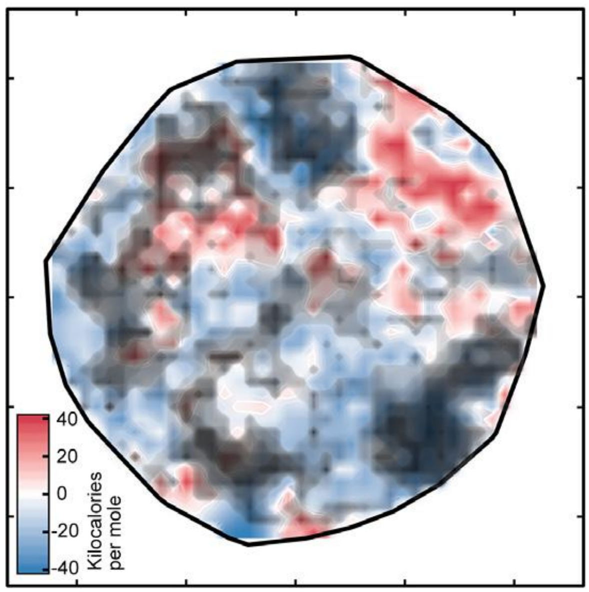
In previous work, the researchers had trained an ANN on thousands of compounds that were well-known in transition metal chemistry. To test the trained ANN's ability to explore a new chemical space to find compounds with the targeted properties, they tried applying it to the pool of 5,600 complexes, 113 of which it had seen in the previous study.

The result was the top plot on this page, which sorts the complexes onto a surface as determined by the ANN. The white regions indicate complexes with spin-splitting energies within 5 kilocalories per mole of zero, meaning that they are potentially good SCO candidates (see the key). The red and blue regions represent complexes with spin-splitting energies too large to be useful. The green diamonds that appear in the inset show complexes that have iron centers and similar ligands—in other words, related compounds whose spin-crossover energies should be similar. Their appearance in the same region of the plot is evidence of the good correspondence between the researchers' representation and key properties of the complex.

But there's one catch: Not all of the spin-splitting predictions are accurate. If a complex is very different from those on which the network was trained, the ANN analysis may not be reliable—a standard problem when applying machine learning models to discovery in materials science or chemistry, notes Kulik. Using an approach that looked successful in their previous work, the researchers compared the numeric representations for the training and test complexes and ruled out all the test complexes where the difference was too great. Those complexes are covered by the black clouds in the bottom figure on this page.



Results of ANN analysis of 5,600 transition metal complexes An analysis by the trained ANN of the full data set to identify potential spin-crossover complexes generated this plot in which complexes are colored based on their spin-splitting energy in kilocalories per mole (kcal/mol). In promising candidates, that energy is within 5 kcal/mol of zero. As the key shows, white areas are within that limit, while red and blue areas exceed it. The bright green diamonds in the inset are related complexes. Their appearance in the same region of the plot supports the accuracy of the proposed numerical representation of transition metal complexes for this analysis.



Eliminating unreliable results Results from an ANN analysis may not be reliable for molecules that are too different from those on which the ANN was trained. The black clouds shown here cover transition metal complexes in the data set whose numeric representations are too distant from those of the training complexes to be considered reliable.

Focusing on the best options

Performing the ANN analysis of all 5,600 complexes took just an hour. But in the real world, the number of complexes to be explored could be thousands of times larger—and any promising candidates would require a full DFT calculation. The researchers therefore needed a method of evaluating a big data set to identify any unacceptable candidates even before the ANN analysis. To that end, they developed a genetic algorithm—an approach inspired by natural selection—to score individual complexes and discard those deemed to be unfit.

To prescreen a data set, the genetic algorithm first randomly selects 20 samples from the full set of complexes. It then assigns a "fitness" score to each sample based on three measures. First, is its spin-crossover energy low enough for it to be a good SCO? To find out, the neural network evaluates each of the 20 complexes. Second, is the complex too far away from the training data? If so, the spin-crossover energy from the ANN may be inaccurate. And finally, is the complex too close to the training data? If so, the researchers have already run a DFT calculation on a similar molecule, so the candidate is not of interest in the quest for new options.

Based on its three-part evaluation of the first 20 candidates, the genetic algorithm throws out unfit options and saves the fittest for the next round. To ensure the diversity of the saved compounds, the algorithm calls for some of them to mutate a bit. One complex may be assigned a new, randomly selected ligand, or two promising complexes may swap ligands. After all, if a complex looks good, then something very similar could be even better—and the goal here is to find novel candidates. The genetic algorithm then adds some new, randomly chosen complexes to fill out the second group of 20 and performs its next analysis. By repeating this process a total of 21 times, it produces 21 generations of options. It thus proceeds through the search space, allowing the fittest candidates to survive and reproduce, and the unfit to die out.

Performing the 21-generation analysis on the full 5,600-complex data set required just over 5 minutes on a standard desktop computer, and it yielded 372 leads with a good combination of high diversity and acceptable confidence. The researchers then used DFT to examine 56 complexes randomly chosen from among those leads, and the results confirmed that two-thirds of them could be good SCOs.

While a success rate of two-thirds may not sound great, the researchers make two points. First, their definition of what might make a good SCO was very restrictive: For a complex to survive, its spin-splitting energy had to be extremely small. And second, given a space of 5,600 complexes and nothing to go on, how many DFT analyses would be required to find 37 leads? As Janet notes, "It doesn't matter how many we evaluated with the neural network because it's so cheap. It's the DFT calculations that take time."

Best of all, using their approach enabled the researchers to find some unconventional SCO candidates that wouldn't have been thought of based on what's been studied in the past. "There are rules that people have—heuristics in their heads—for how they would build a spin-crossover complex," says Kulik. "We showed that you can find unexpected combinations of metals and ligands that aren't normally studied but can be promising as spin-crossover candidates."

Sharing the new tools

To support the worldwide search for new materials, the researchers have incorporated the genetic algorithm and ANN into "molSimplify," the group's online, open-source software toolkit that anyone can download and use to build and simulate transition metal complexes. To help potential users, the site provides tutorials that demonstrate how to use key features of the open-source software codes. Development of molSimplify began with funding from the MIT Energy Initiative in 2014, and all the students in Kulik's group have contributed to it since then.

The researchers continue to improve their neural network for investigating potential SCOs and to post updated versions of molSimplify. Meanwhile, others in Kulik's lab are developing tools that can identify promising compounds for other applications. For example, one important area of focus is catalyst design. Graduate student Aditya Nandy of chemistry is focusing on finding a better catalyst for converting methane gas to an easier-to-handle liquid fuel such as methanol—a particularly challenging problem. "Now we have an outside molecule coming in, and our complex—the catalyst—has to act on that molecule to perform a chemical transformation that takes place in a whole series of steps," says Nandy. "Machine learning will be super-useful in figuring out the important design parameters for a transition metal complex that will make each step in that process energetically favorable."

NOTES

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J.P. Janet, L. Chan, and H.J. Kulik. "Accelerating chemical discovery with machine learning: Simulated evolution of spin-crossover complexes with an artificial neural network." *The Journal of Physical Chemistry Letters*, vol. 9, pp. 1064–1071, 2018. Online: doi.org/10.1021/acs.jpclett.8b00170.

J.P. Janet and H.J. Kulik. "Predicting electronic structure properties of transition metal complexes with neural networks." *Chemical Science*, vol. 8, pp. 5137–5157, 2017. Online: doi.org/10.1039/C7SC01247K.

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Technology and policy pathways to Paris Agreement emissions targets

Sergey Paltsev (center) speaks on a panel at the UN Climate Change Conference (COP24) in Katowice, Poland. Joining the conversation were (left to right): Matar Al Neyadi, United Arab Emirates undersecretary of energy; Claude Nahon, senior vice president of sustainable development at Électricité de France; George Heyman, British Columbia's climate minister; and Todd Muller, conservative opposition leader in New Zealand's parliament. Photo: Emily Dahl, MITEI

In early December 2018, amid dire warnings from the Intergovernmental Panel on Climate Change Special Report on Global Warming of 1.5°C and the National Climate Assessment about the pace of climate change and severity of its impacts, the 24th Conference of the Parties (COP24) to the United Nations Framework Convention on Climate Change convened in Katowice, Poland, with the goal of getting the world on track to keep global warming well below 2°C.

To that end, negotiators from the nearly 200 signatory nations in the 2015 Paris Agreement reported on their progress in meeting initial greenhouse gas emissions reduction targets, or Nationally Determined Contributions (NDCs), for 2025 to 2030, and they discussed pathways to achieving more ambitious NDCs.

In support of this global effort, a team of researchers at the MIT Joint Program on the Science and Policy of Global Change, the MIT Energy Initiative (MITEI), and the MIT Center for Energy and Environmental Policy Research (CEEPR) developed modeling tools to evaluate the climate progress and potential of two major world regions: Southeast Asia and Latin America.

The team analyzed gaps between current emission levels and NDC targets within each region, highlighted key challenges to compliance with those targets, and recommended cost-effective policy and technology solutions aimed at overcoming those challenges in consultation with General Electric and regional partners. The results appear in two "Pathways to Paris" reports released during the climate talks—one for the 10-member Association of Southeast Asian Nations (ASEAN), the other for selected countries in Latin America (LAM).

The researchers say they chose to study those two regions because they represent vastly different starting points on the road to emissions reduction and thus cover a wide range of technology and policy options for meeting or exceeding current NDCs.

"Whereas Southeast Asia relies heavily on fossil fuels, particularly coal, to produce energy, Latin America, which has embraced hydropower, is already on a far less carbon-intensive emissions path," says Sergey Paltsev, a deputy director at the Joint Program, senior research scientist at MITEI, and lead author of both reports. "These regions have not received as much attention as the largest emitting countries by most gap analysis studies, which tend to focus on the globe as a whole."

Paltsev presented key findings from the two reports to COP24 participants at the International Congress Centre in Katowice on December 10.

"Our reports help refine the overall picture of how countries in ASEAN and Latin America are doing in terms of progress toward NDC achievement, and how they get there," says CEEPR Deputy Director Michael Mehling, a co-author of both reports. "They also show pathways to achieve greater emissions reductions and/or reduce emissions at lower economic cost, both of which can help them understand the opportunities and implications of more ambitious NDCs."

While all economic sectors in both regions need to reduce emissions, the two reports focus on the power generation sector as it offers the least-cost opportunity to achieve the greatest emissions reductions through available technology and policy solutions.

Progress and next steps for ASEAN countries

The ASEAN report shows that, collectively, the 10 member countries have made good progress in reducing their greenhouse gas emissions but will need to implement additional steps to achieve the targets specified in their individual NDCs.

Under its Paris Agreement pledges in which no conditions (e.g., climate financing or technology transfers) apply, the ASEAN region is about 400 $MtCO_2e$ (megatons of carbon dioxide-equivalent emissions) short of its 2030 emissions target, and must therefore reduce emissions by 11% relative to its current trajectory. Under its conditional pledges, the emissions gap is about 900 $MtCO_2e$, indicating a need to reduce emissions by 24% by 2030.

The main challenge ASEAN countries face in achieving those goals is to lower emissions while expanding power generation to meet the growing energy demand—nearly a doubling of total primary energy consumption from 2015 to 2030—in their rapidly developing economies. To overcome this challenge and the emissions gaps described above, the ASEAN report recommends a shift to lower-carbon electricity generation and adoption of carbon-pricing policies.

Lower-carbon energy options include wind and solar generation along with a switch from coal to natural gas. Producing far less carbon emissions than coal, natural gas could also serve as a backup for intermittent renewables, thereby boosting their penetration in the market.

ASEAN countries could implement carbon pricing through carbon taxes or emissions trading systems, but such policies often face substantial political resistance. To build coalitions of support for ambitious climate policies and to create the domestic supply chains and know-how needed for robust markets in clean technology, the report calls for an initial focus on technology-specific policies such as renewable energy auctions and renewable portfolio standards.

Progress and next steps for Latin American countries

Due to government-driven initiatives to boost renewable electricity and natural gas, the countries covered by the LAM report—Argentina, Brazil, Chile, Colombia, Ecuador, Mexico, Panama, Peru, Uruguay, and Venezuela—have also made good progress toward their Paris Agreement goals.

Under its unconditional pledges, the region is only about 60 $MtCO_2e$ short of its collective 2030 emissions reduction target, and must cut emissions by 2% relative to its current trajectory to meet that target. Under its conditional pledges, the emissions gap is about 350 $MtCO_2e$, indicating a needed reduction of 10% by 2030.

Just as in the ASEAN region, energy demand in the LAM countries is projected to grow significantly; the LAM report projects an approximately 25% increase in total primary energy consumption from 2015 to 2030. A key challenge for some LAM countries in addressing that heightened demand is to develop stable regulatory and legal frameworks to further encourage private investment in clean energy projects.

The LAM report recommends similar technology and policy options for this region to those described above in the ASEAN report. For countries with more advanced administrative and technical capacities, the report calls for carbon pricing because it offers the greatest economic efficiency benefits.

Country-specific analyses

The two reports also show how the MIT team's tools and analysis can be applied at the country level.

The ASEAN report concludes that Indonesia and Vietnam may achieve their respective emissions-reduction goals at a manageable cost. If carbon pricing is applied on an economy-wide basis, the GDP cost in Indonesia and Vietnam is 0.03% and 0.008%, respectively, relative to GDP in a business-as-usual scenario in 2030.

The LAM report shows that Argentina and Colombia are on track to fulfill their unconditional emissions reduction pledges with existing plans to expand non-fossil electricity generation. To meet conditional pledges, the research team recommends adding an all-sectors emissions trading system once non-fossil electricity targets are met. Capping emissions at the level consistent with each nation's conditional pledge would result in carbon prices in Argentina and Colombia of, respectively, \$2.70 and \$2.90 per tCO_2e.

The authors of both reports have shared all input data and tools used to produce the results with the countries in both regions and plan to place these resources in the public domain in an open-source format. This approach makes it possible for additional countries to analyze their pathways to meeting or exceeding their energy, electrification, and emissions-reduction goals.

"We need more and more studies at the country level," says Paltsev. "We hope our analysis will help countries in other regions to improve their capability to assess their progress in meeting NDC targets and develop more effective technology and policy strategies to reduce their emissions."

This research was funded by GE and enhanced through collaboration with representatives of the ASEAN Centre for Energy and selected Latin American countries.

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

For more information, please see the following reports:

S. Paltsev, M. Mehling, N. Winchester, J. Morris, and K. Ledvina. *Pathways to Paris: ASEAN*. MIT Joint Program Special Report, 2018. To download, go to globalchange.mit.edu/publication/p2p-asean.

S. Paltsev, M. Mehling, N. Winchester, J. Morris, and K. Ledvina. *Pathways to Paris: Latin America*. MIT Joint Program Special Report, 2018. To download, go to globalchange.mit.edu/publication/p2p-lam.

Turning desalination waste into useful products

The rapidly growing desalination industry produces water for drinking and for agriculture in the world's arid coastal regions. But it leaves behind as a waste product a lot of highly concentrated brine, which is usually disposed of by dumping it back into the sea, a process that requires costly pumping systems and that must be managed carefully to prevent damage to marine ecosystems. Now, engineers at MIT say they have found a better way.

In a new study, they show that through a fairly simple process, the waste material can be converted into useful chemicals—including ones that can make the desalination process itself more efficient.

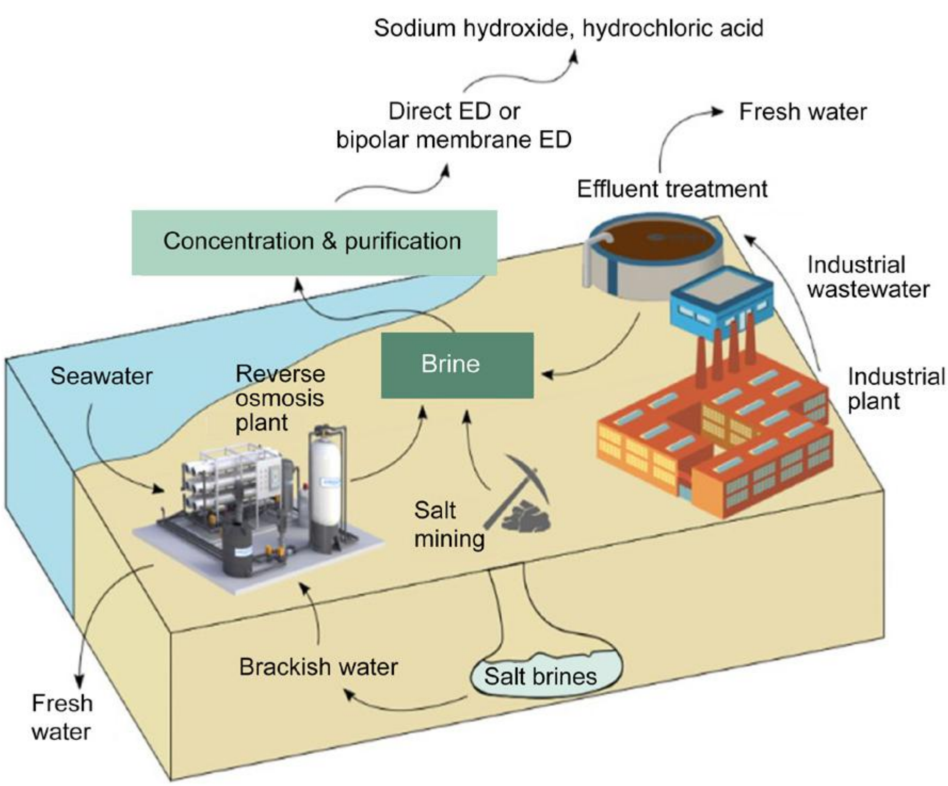
The approach can be used to produce sodium hydroxide, among other products. Otherwise known as caustic soda, sodium hydroxide can be used to pretreat seawater going into the desalination plant. This changes the acidity of the water, which helps to prevent fouling of the membranes used to filter out the salty water—a major cause of interruptions and failures in typical reverse osmosis desalination plants.

The concept was described on February 13, 2019, in the journal *Nature Catalysis* and in two earlier papers by MIT research scientist Amit Kumar, professor of mechanical engineering John H. Lienhard V, and several others. Lienhard is the Abdul Latif Jameel Professor of Water and Food and the director of the Abdul Latif Jameel Water and Food Systems Lab.

"The desalination industry itself uses quite a lot of it," Kumar says of sodium hydroxide. "They're buying it, spending money on it. So if you can make it *in situ* at the plant, that could be a big advantage." The amount needed in the plants themselves is far less than the total that could be produced from the brine, so there is also potential for it to be a salable product.

Sodium hydroxide is not the only product that can be made from the waste brine: Another important chemical used by desalination plants and many other industrial processes is hydrochloric acid, which can also easily be made on site from waste brine using established chemical processing methods. The chemical can be used for cleaning parts of the desalination plant but is also widely used in chemical production and as a source of hydrogen.

Currently, the world produces more than 100 billion liters (about 27 billion gallons) a day of water from desalination, which leaves a similar volume of concentrated brine. Much of that is pumped back out to sea, and current regulations require costly outfall systems to ensure adequate dilution of the salts. Converting the brine can thus be both economically and ecologically beneficial, especially as desalination continues to grow rapidly around the world. "Environmentally safe discharge of brine is manageable with current technology, but it's much better to recover resources from the brine and reduce the amount of brine released," Lienhard says.



This illustration depicts the potential of the suggested process. Brine, which could be obtained from the waste stream of reverse osmosis desalination plants, or from industrial plants or salt mining operations, can be processed by direct electrodialysis (ED) or bipolar membrane ED to yield useful chemicals such as sodium hydroxide or hydrochloric acid.

The method of converting the brine into useful products uses well-known and standard chemical processes, including initial nanofiltration to remove undesirable compounds, followed by one or more electrodialysis stages to produce the desired end product. While the processes being suggested are not new, the researchers have analyzed the potential for production of useful chemicals from brine and proposed a specific combination of products and chemical processes that could be turned into commercial operations to enhance the economic viability of the desalination process, while diminishing its environmental impact.

"This very concentrated brine has to be handled carefully to protect life in the ocean, and it's a resource waste, and it costs energy to pump it back out to sea," so turning it into a useful commodity is a win-win, Kumar says. And sodium hydroxide is such a ubiquitous chemical that "every lab at MIT has some," he says, so finding markets for it should not be difficult.

The researchers have discussed the concept with companies that may be interested in the next step of building a prototype plant to help work out the real-world economics of the process. "One big challenge is cost—both electricity cost and equipment cost," at this stage, Kumar says.

The team also continues to look at the possibility of extracting other, lower-concentration materials from the brine stream, he says, including various metals and other chemicals, which could make the brine processing an even more economically viable undertaking.

"One aspect that was mentioned…and strongly resonated with me was the proposal for such technologies to support more 'localized' or 'decentralized' production of these chemicals at the point-of-use," says Jurg Keller, a professor of water management at the University of Queensland in Australia, who was not involved in this work. "This could have some major energy and cost benefits, since the up-concentration and transport of these chemicals often adds more cost and even higher energy demand than the actual production of these at the concentrations that are typically used."

The research team also included MIT postdoc Katherine Phillips and undergraduate Janny Cai, and Uwe Schröder at the University of Braunschweig, in Germany. The work was supported by Cadagua, a subsidiary of Ferrovial, through the MIT Energy Initiative.

David L. Chandler, MIT News

 Further information can be found in:

F. Du, D.M. Warsinger, T.I. Urmi, G.P. Thiel, A. Kumar, and J.H. Lienhard V. "Sodium hydroxide production from seawater desalination brine: Process design and energy efficiency." *Environmental Science & Technology*, vol. 52, no. 10, pp. 5949–5958, 18 April 2018. Online: doi.org/10.1021/acs.est.8b01195.

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Observing hydrogen's effects in metal: Technique could lead to safer reactor vessels, hydrogen storage tanks

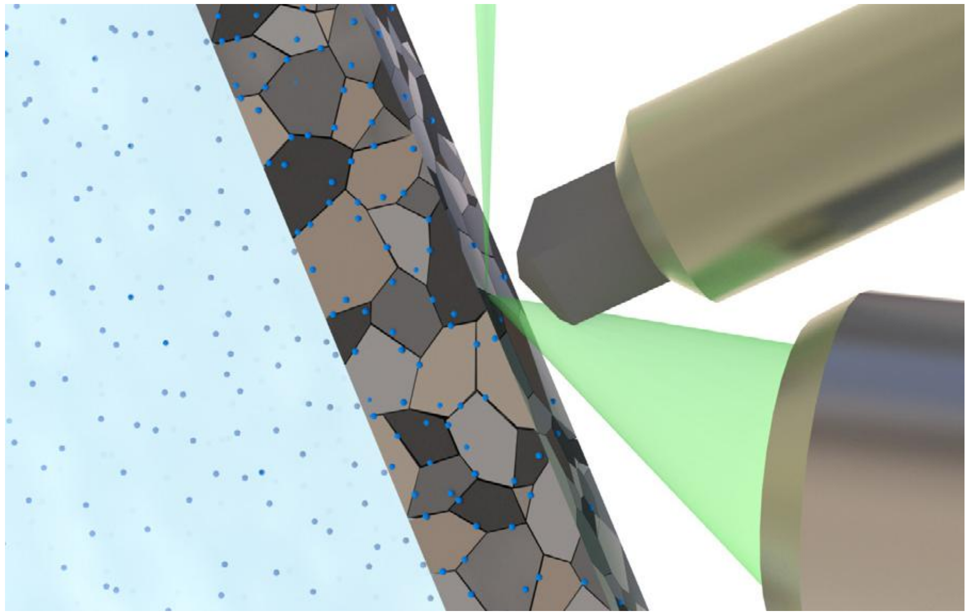
Hydrogen, the second-tiniest of all atoms, can penetrate right into the crystal structure of a solid metal.

That's good news for efforts to store hydrogen fuel safely within the metal itself, but it's bad news for structures such as the pressure vessels in nuclear plants, where hydrogen uptake eventually makes the vessel's metal walls more brittle, which can lead to failure. But this embrittlement process is difficult to observe because hydrogen atoms diffuse very fast, even inside the solid metal.

Now, researchers at MIT have figured out a way around that problem, creating a new technique that allows the observation of a metal surface during hydrogen penetration. Their findings are described in a paper in the *International Journal of Hydrogen Energy* by MIT postdoc Jinwoo Kim and Thomas B. King Assistant Professor of Metallurgy C. Cem Tasan.

"It's definitely a cool tool," says Chris San Marchi, a distinguished member of the technical staff at Sandia National Laboratories, who was not involved in this work. "This new imaging platform has the potential to address some interesting questions about hydrogen transport and trapping in materials, and potentially about the role of crystallography and microstructural constituents on the embrittlement process."

Hydrogen fuel is considered a potentially major tool for limiting global climate change because it is a high-energy fuel that could eventually be used in cars and planes. However, expensive and heavy high-pressure tanks are needed to contain it. Storing the fuel in the crystal lattice of the metal itself could be cheaper, lighter, and safer—but first the process of how hydrogen enters and leaves the metal must be better understood.



This illustration depicts the main elements of the system the team used. The multicolored slab at center is the metal layer being studied, the pale blue region at left is the electrolyte solution used as a source of hydrogen, the small blue dots are the hydrogen atoms, and the green beams at right are lasers probing the process. The large cylinder at right is a probe used to indent the metal to test its mechanical properties.

"Hydrogen can diffuse at relatively high rates in the metal, because it's so small," Tasan says. "If you take a metal and put it in a hydrogen-rich environment, it will uptake the hydrogen, and this causes hydrogen embrittlement," he says. That's because the hydrogen atoms tend to segregate in certain parts of the metal crystal lattice, weakening its chemical bonds.

The new way of observing the embrittlement process as it happens may help to reveal how the embrittlement gets triggered, and it may suggest ways of slowing the process—or of avoiding it by designing alloys that are less vulnerable to embrittlement.

Sandia's San Marchi says that "this method may play an important role—in coordination with other techniques and simulation—to illuminate the hydrogen-defect interactions that lead to hydrogen embrittlement. With more comprehensive understanding of the mechanisms of hydrogen embrittlement, materials and microstructures can be designed to improve their performance under extreme hydrogen environments."

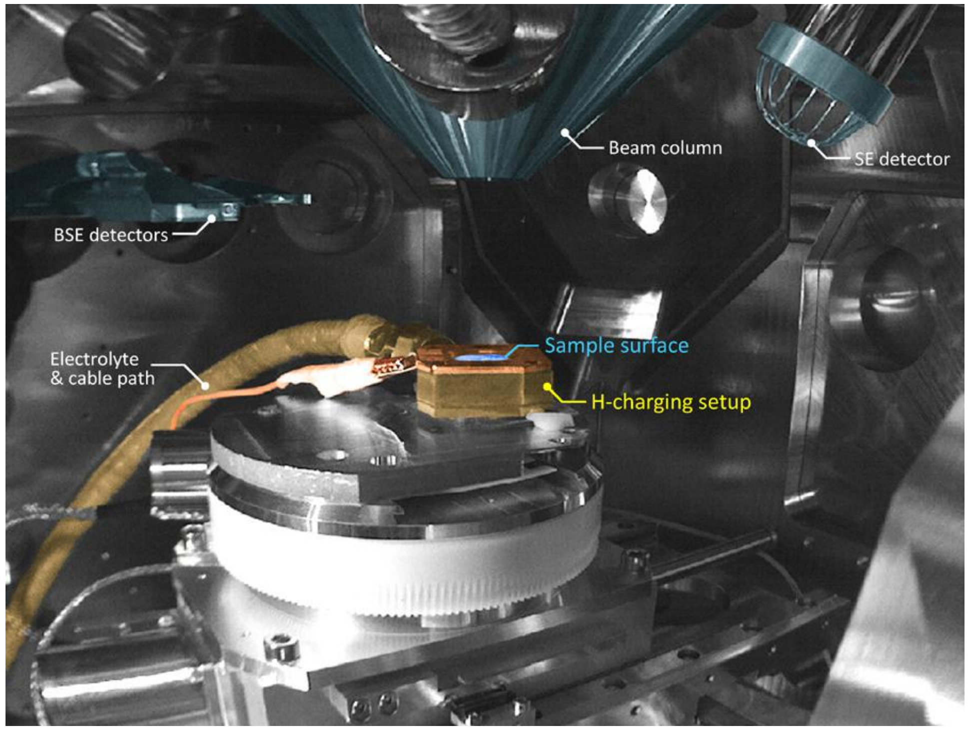
The key to the new monitoring process was devising a way of exposing metal surfaces to a hydrogen environment while inside the vacuum chamber of a scanning electron microscope (SEM). Because the SEM requires a vacuum for its operation, hydrogen gas cannot be charged into the metal inside the instrument, and if precharged, the gas diffuses out quickly. Instead, the researchers used a liquid electrolyte that could be contained in a well-sealed chamber, where it is exposed to the underside of a thin sheet of metal. The top of the metal is exposed to the SEM electron beam, which can then probe the structure of the metal and observe the effects of the hydrogen atoms migrating into it.

The hydrogen from the electrolyte "diffuses all the way through to the top" of the metal, where its effects can be seen, Tasan says. The basic design of this contained system could also be used in other kinds of vacuum-based instruments to detect other properties. "It's a unique setup—as far as we know, the only one in the world that can realize something like this," he says.

In their initial tests of three metals—two different kinds of stainless steel and a titanium alloy—the researchers have already made some new findings. For example, they observed the formation and growth process of a nanoscale hydride phase in the most commonly used titanium alloy, at room temperature and in real time.

Devising a leakproof system was crucial to making the process work. The electrolyte needed to charge the metal with hydrogen "is a bit dangerous for the microscope," Tasan says. "If the sample fails and the electrolyte is released into the microscope chamber," it could penetrate far into every nook and cranny of the device and be difficult to clean out. When the time came to carry out their first experiment in the specialized and expensive equipment, he says, "we were excited, but also really nervous. It was unlikely that failure was going to take place, but there's always that fear."

Kaneaki Tsuzaki, a distinguished professor of chemical engineering at Kyushu University in Japan, who was not involved in this research, says this "could be a key technique to solve how hydrogen affects dislocation motion. It is very challenging because an acid solution for hydrogen cathodic charging is circulating into an SEM chamber. It is one of the most dangerous measurements for the machine. If the circulation joints leak, a very expensive scanning electron microscope would be broken due to the acid solution. A very careful design and a very high-skill setup are necessary for making this measurement equipment."



This is the experimental scanning electron microscope setup used by the researchers to study the hydrogen-loading process.

Tsuzaki adds that "once it is accomplished, outputs by this method would be super. It has very high spatial resolution due to SEM; it gives *in situ* observations under a well-controlled hydrogen atmosphere." As a result, he says, he believes that Tasan and Kim "will obtain new findings of hydrogen-assisted dislocation motion by this new method, solve the mechanism of hydrogen-induced mechanical degradation, and develop new hydrogen-resistant materials."

The work was supported by Exelon through the MIT Energy Initiative's Low-Carbon Energy Center for Advanced Nuclear Energy Systems.

David L. Chandler, MIT News

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J. Kim and C.C. Tasan. "Microstructural and micro-mechanical characterization during hydrogen charging: An *in situ* scanning electron microscopy study." *International Journal of Hydrogen Energy*, vol. 44, issue 12, pp. 6333–6343, 1 March 2019. Online: doi.org/10.1016/j.ijhydene.2018.10.128.

Catherine Drennan: Catalyzing new approaches in research and education to meet the climate challenge

Catherine Drennan says nothing in her job thrills her more than the process of discovery. But Drennan, a professor of biology and chemistry, is not referring to her landmark research on protein structures that could play a major role in reducing the world's waste carbons.

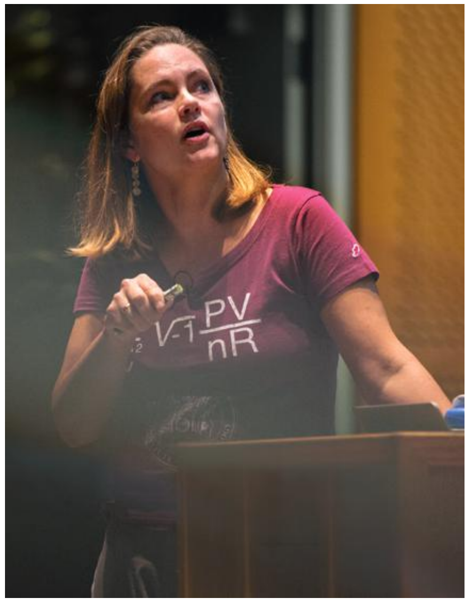
"Really the most exciting thing for me is watching my students ask good questions, problem-solve, and then do something spectacular with what they've learned," she says.

For Drennan, research and teaching are complementary passions, both flowing from a deep sense of "moral responsibility." Everyone, she says, "should do something, based on their skill set, to make some kind of contribution."

Drennan's own research portfolio attests to this sense of mission. Since her arrival at MIT 20 years ago, she has focused on characterizing and harnessing metal-containing enzymes that catalyze complex chemical reactions, including those that break down carbon compounds.

She got her start in the field as a graduate student at the University of Michigan, where she became captivated by vitamin B_{12}. This very large vitamin contains cobalt and is vital for amino acid metabolism, the proper formation of the spinal cord, and prevention of certain kinds of anemia. Bound to proteins in food, B_{12} is released during digestion.

"Back then, people were suggesting how B_{12}-dependent enzymatic reactions worked, and I wondered how they could be right if they didn't know what B_{12}-dependent enzymes looked like," she recalls. "I realized I needed to figure out how B_{12} is bound to protein to really understand what was going on."



Catherine Drennan, a professor of biology and chemistry, is shown here teaching 5.111 Chemical Principles. Photo: James Kegley

Drennan seized on X-ray crystallography as a way to visualize molecular structures. Using this technique, which involves bouncing X-ray beams off a crystallized sample of a protein of interest, she figured out how vitamin B_{12} is bound to a protein molecule.

"No one had previously been successful using this method to obtain a B_{12}-bound protein structure, which turned out to be gorgeous, with a protein fold surrounding a novel configuration of the cofactor," says Drennan.

Carbon-loving microbes show the way

These studies of B_{12} led directly to Drennan's one-carbon work. "Metallo-cofactors such as B_{12} are important not just medically, but in environmental processes," she says. "Many microbes that live on carbon monoxide, carbon dioxide, or methane—eating carbon waste or transforming carbon—use metal-containing enzymes in their metabolic pathways, and it seemed like a natural extension to investigate them."

Some of Drennan's earliest work in this area, dating from the early 2000s, revealed a cluster of iron, nickel, and sulfur atoms at the center of the enzyme carbon monoxide dehydrogenase (CODH). This so-called C-cluster serves hungry microbes, allowing them to "eat" carbon monoxide and carbon dioxide (CO_2).

Recent experiments by Drennan analyzing the structure of the C-cluster-containing enzyme CODH showed that in response to oxygen, it can change configurations, with sulfur, iron, and nickel atoms cartwheeling into different positions. Scientists looking for new avenues to reduce greenhouse gases took note of this discovery. CODH, suggested Drennan, might prove an effective tool for converting waste CO_2 into a less environmentally destructive compound, such as acetate, which might also be used for industrial purposes.

Drennan has also been investigating the biochemical pathways by which microbes break down hydrocarbon byproducts of crude oil production, such as toluene, an environmental pollutant.

"It's really hard chemistry, but we'd like to put together a family of enzymes to work on all kinds of hydrocarbons, which would give us a lot of potential for cleaning up a range of oil spills," she says.

The threat of climate change has increasingly galvanized Drennan's research, propelling her toward new targets. A 2017 study she co-authored in *Science* detailed a previously unknown enzyme pathway in ocean microbes that leads to the production of methane, a formidable greenhouse gas: "I'm worried the ocean will make a lot more methane as the world warms," she says.

Drennan hopes her work may soon help to reduce the planet's greenhouse gas burden. Commercial firms have begun using the enzyme pathways that she studies, in one instance employing a proprietary microbe to capture CO_2 produced during steel production—before it is released into the atmosphere—and convert it into ethanol.

"Reengineering microbes so that enzymes take not just a little but a lot of CO_2 out of the environment—this is an area I'm very excited about," says Drennan.

Creating a meaningful life in the sciences

At MIT, she has found an increasingly warm welcome for her efforts to address the climate challenge.

"There's been a shift in the past decade or so, with more students focused on research that allows us to fuel the planet without destroying it," she says.

In Drennan's lab, a postdoc, Mary Andorfer, and a sophomore, Phoebe Li, are currently working to inhibit an enzyme present in an oil-consuming microbe whose unfortunate residence in refinery pipes leads to erosion and spills. "They are really excited about this research from the environmental perspective and even made a video about their microorganism," says Drennan.

Drennan delights in this kind of enthusiasm for science. In high school, she thought chemistry was dry and dull, with no relevance to real-world problems. It wasn't until college that she "saw chemistry as cool."

The deeper she delved into the properties and processes of biological organisms, the more possibilities she found. X-ray crystallography offered a perfect platform for exploration. "Oh, what fun to tell the story about a three-dimensional structure—why it is interesting, what it does based on its form," says Drennan.

The elements that excite Drennan about research in structural biology—capturing stunning images, discerning connections among biological systems, and telling stories—come into play in her teaching. In 2006, she received a $1 million grant from the Howard Hughes Medical Institute (HHMI) for her educational initiatives that use inventive visual tools to engage undergraduates in chemistry and biology. She is both an HHMI investigator and an HHMI professor, recognition of her parallel accomplishments in research and teaching, as well as a 2015 MacVicar Faculty Fellow for her sustained contribution to the education of undergraduates at MIT.

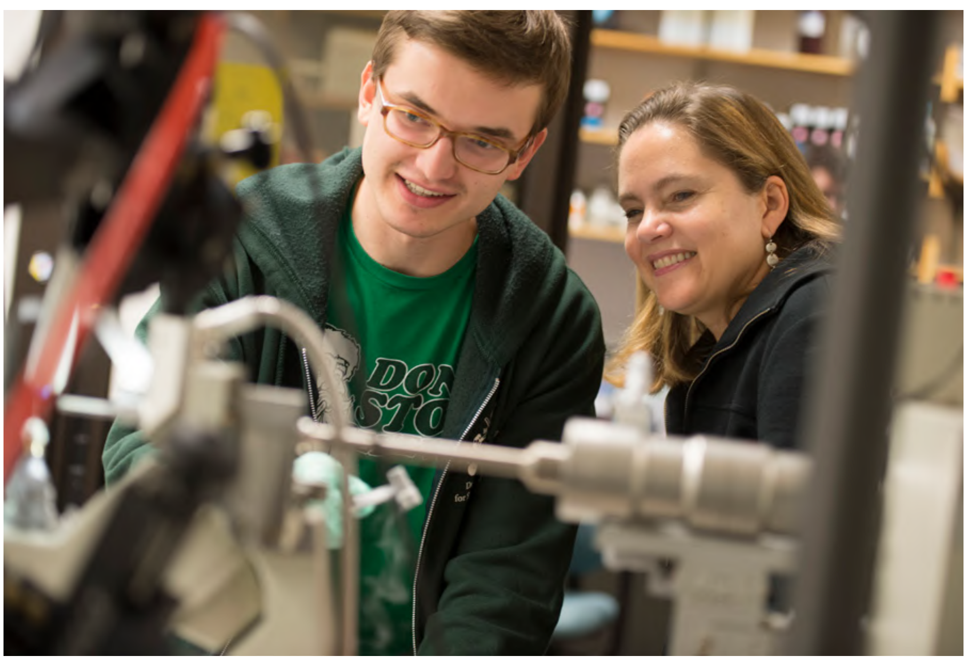
Drennan attempts to reach MIT students early. She taught introductory chemistry classes from 1999 to 2014, and in fall 2018 taught her first introductory biology class.

"I see a lot of undergraduates majoring in computer science, and I want to convince them of the value of these disciplines," she says. "I tell them they will need chemistry and biology fundamentals to solve important problems someday."

Drennan happily migrates among many disciplines, learning as she goes. It's a lesson she hopes her students will absorb. "I want them to visualize the world of science and show what they can do," she says. "Research takes you in different directions, and we need to bring the way we teach more in line with our research."

She has high expectations for her students. "They'll go out in the world as great teachers and researchers," Drennan says. "But it's most important that they be good human beings, taking care of other people, asking what they can do to make the world a better place."

Leda Zimmerman, MITEI correspondent



Professor Catherine Drennan (right) and former Undergraduate Research Opportunities Program (UROP) student Ben Bell '14 adjust a crystal for an X-ray diffraction experiment aimed at determining a structure of a metalloprotein at atomic resolution. Photo: James Kegley

Energy Ventures class proves successful launchpad for students, startups

They say the odds of starting a successful first business are about one in five, but the track record of 15.366 Energy Ventures suggests that taking this MIT Sloan School of Management class can significantly improve those odds.

Nearly a dozen companies have spun directly out of Energy Ventures, and alumni of the class have founded at least 25 more since the class began in 2007. Since about six teams of students work on ventures in the class each year, that's about a 40% rate of successful launch.

Why does it work? According to both instructors and students, it's because students learn by doing—with step-by-step guidance and a lot of advice and support from a broad range of experts, including top venture capitalists.

"They give you a structure for something that can seem very mysterious: how to start a company," says Teasha Feldman-Fitzthum '14, who used the class as a launchpad for EverVest, a business she co-founded to provide financial risk analyses for renewable energy projects. (Thanks to this work, Feldman-Fitzthum was named to *Forbes*' list of "30 under 30" for energy in 2016.)

"It was a safe place to develop ideas, test them, fail, and iterate. Energy Ventures was the ideal atmosphere to build a sustainable business model and find the right team," says Mike Reynolds MBA '14, Feldman-Fitzthum's co-founder. Today both Reynolds and Feldman-Fitzthum are directors at Ultra Capital, which acquired EverVest in 2016 and utilizes the EverVest technology to make investments in sustainable infrastructure projects.

Senior Lecturer Francis O'Sullivan (left) leads a discussion with an Energy Ventures team working on contactless steam generation technology for heating water in remote locations. The graduate students with him are, clockwise from left: Brian Gaudio, Robert Addy, Matt Severson (of Harvard Business School), Bidusha Poudyal, and Yoichiro Tsurimaki. Photo: Kelley Travers, MITEI

Framework for success

Francis O'Sullivan, former director of research at the MIT Energy Initiative, a senior lecturer at the MIT Sloan School of Management, and one of the instructors for the class, says 15.366 walks students through the startup process using the framework from *Disciplined Entrepreneurship: 24 Steps to a Successful Startup*, a book by Bill Aulet, the managing director of the Martin Trust Center for MIT Entrepreneurship.

"The things you really need to do to start a company are covered in the assignments," says Feldman-Fitzthum. Tasks range from producing an elevator pitch to developing a go-to-market strategy, drafting a business plan, and putting together a slide deck for potential investors.

"Through the semester, we step through the high-level elements [of starting a business] and contextualize them from an energy point of view," O'Sullivan says. The goal is to prepare students to take on all the multifaceted challenges of energy entrepreneurship. "It's partly about technology, but it's also about the business models and the regulation."

"This class is really special because it gives students a blank canvas to explore new technologies and learn how to make those technologies a reality in today's energy system," says Michael Kearney SM '11, a PhD student at Sloan who served as the teaching assistant for the one-term class this fall. "The secret sauce is to unite students across campus—and even outside, from places like Harvard—all of whom bring different perspectives to bear on the challenges facing energy systems today. That mix of people and ideas is conducive to creating really interesting business plans and scaling them to make a difference."

Novel technologies

Energy Ventures intentionally teams up students with expertise in such diverse areas as engineering, policy, and business

Andrew Wong '19 discusses the flow battery technology his team was considering for commercialization during 15.366 Energy Ventures last fall. Photo: Kelley Travers, MITEI

to determine the best path for commercialization of technologies drawn from labs at MIT and the surrounding area. "You have incredible students, you put them on teams and let them run," Kearney says.

This year, teams formed ventures based on a flow battery for energy storage, a system for low-cost electrolysis, a device that uses temperature swings to produce energy in a micro-generator, and more.

Elise Strobach, for example, took the class to commercialize a transparent silica aerogel she developed in the lab of Professor Evelyn Wang of mechanical engineering. Strobach hopes to turn the aerogel into an insulating material for affordable, energy-efficient windows.

"A lot of [the benefit of the class] is taking a very fledgling idea and turning it into something with real possibilities," says Strobach, who is pursuing a PhD in mechanical engineering. And, while it's not clear how her venture will fare, Strobach believes the class has put it on the right path. "In the end, we had confidence in what we needed to achieve and what kind of value we could bring."

Aaron Baskerville-Bridges, a graduate student in MIT Leaders in Global Operations, also sees a lot of promise for the project he worked on this year: a nanoporous silicon membrane that can be used for filtration. "When I heard the pitch, I could imagine a lot of markets for the technology. [The researchers] have been working on clean water initiatives, so in Energy Ventures we set out to see what other industries could benefit from this technology," he says.

Baskerville-Bridges' team identified a promising potential market in the oil industry, which currently adds a diluent to bitumen to enable the fuel to flow through pipes. The silicon membrane could be used like a nanoscale coffee filter to separate the diluent out passively at its final destination—supplanting today's more energy-intensive process. "If it works, that's a home run," Baskerville-Bridges says.

Access to experts

Students in 15.366 spend much of their class time moving the ventures forward, but they also get to hear from guest speakers and consult outside experts. "On three separate occasions, we were pitching to people from private equity or venture capital, and we got their honest feedback. I think that's a pretty cool opportunity in a low-risk environment to test your ideas with people who really know what it takes to be successful," Baskerville-Bridges says.

This year, speakers included Badar Khan, the president of National Grid Ventures; Carmichael Roberts, managing director of Breakthrough Energy Ventures; and Daniel Hullah, managing director of GE Ventures. "The network, the knowledge base, the expertise that you get and have access to is amazing," Strobach says.

Not surprisingly, given its high success rate, Energy Ventures is a very popular class. Students must apply with a resume, a statement of interest, and more—and not everyone is admitted. In fact, Feldman-Fitzthum almost didn't make it in. Most of the roughly 35 students accepted each year (out of about 100 applicants) are graduate students, and she applied as an undergraduate in 2013. Fortunately, the professor thought her work on a machine learning algorithm to predict wind patterns would make an interesting venture, so Feldman-Fitzthum was accepted.

During class, Feldman-Fitzthum teamed up with Reynolds, who had a finance background and found Feldman-Fitzthum's project inspiring. "I thought that if you can use her algorithm to predict the financial performance of a renewable energy project, you can make smarter investments," he says. "If you can make better investments, you can raise more capital, and in turn invest in more renewables. Teasha's technology was the spark that led us down that path."

Interestingly, while Feldman-Fitzthum and Reynolds initially thought they could build a business predicting wind patterns, they discovered—thanks in part to research done in class—that that would not be enough. "We learned quickly that we needed to build a more holistic financial modeling software product that would work across all infrastructure projects," she says.

Such missteps are easy to make, yet can prove fatal to a nascent enterprise. Energy Ventures provides the support necessary to help students navigate such common pitfalls. It's like entrepreneurship with training wheels. Still, the hard work and dedication are real—and so are the impressive results.

"My advice to people is to come in thinking you're not taking a class, you're working for a startup part-time," Baskerville-Bridges says. "That's the way to get the most out of it."

Kathryn M. O'Neill, MITEI correspondent

MITEI launches online energy classes to meet global needs

The MIT Energy Initiative (MITEI) is developing a new series of online energy classes designed to support MITEI's educational mission of finding and training people to solve the triple challenge of energy: producing more energy for more people, with fewer greenhouse gas emissions, within the short time frame available to avoid disastrous consequences for the planet.

Based on interdisciplinary MIT graduate classes in energy currently taught on campus, the first four classes—all MITx massive open online courses (MOOCs) slated to run on the edX platform—will hone in on the skills needed to be professionally successful in the area of electric power systems design and management.

This new pathway to energy education for a global audience will supplement MIT's OpenCourseWare (OCW), a free and open online collection of MIT class materials that does not include active instruction or individual feedback.

"Transitioning global energy systems to low-carbon energy solutions requires a global network of professionals trained to model, plan, and deploy relevant technologies within various geopolitical contexts," says Antje Danielson, MITEI's director of education. "To develop this future energy workforce, MITEI is building online courses that offer learners both an understanding of the future energy landscape and the skills necessary to actualize it."

The MITx courses will engage four critical aspects of future electricity systems: load and demand-side management; economics and regulation; production; and distribution and transmission. The first two classes, Professor Christoph Reinhart's 4.464 Environmental Technologies in Buildings and Professor Christopher Knittel's 15.038 Energy Economics and Policy, are projected to launch in late summer 2019 and spring 2020, respectively.

The new offerings join more than 35 energy-related courses currently covered by OCW. Fifteen of those courses were developed for the MIT Energy Studies Minor thanks to a course development grant received in 2009 from the S.D. Bechtel, Jr. Foundation. The materials for these classes have been used by millions of people.

Recently, MITEI received permission from the foundation to allocate the remainder of the initial course development grant to creating classes for MITx, MIT's vehicle for providing courses to edX, a platform that features MOOCs from many leading universities. This new content will enable thousands of students around the world to practice and apply their skills and actively pursue careers in the energy transition.

MITEI's dual-track approach to online education is intentional. "The learner experience is different in each one," says Curt Newton, director of OCW.

OCW is particularly suited to self-directed learning and to use by instructors in their classrooms. But OCW doesn't offer graded assignments, feedback from instructors or peers, or a credential. In contrast, learners get this feedback and interaction on edX, along with the option to earn a credential.

"If you're ready to devote a lot of time to the course, there's a lot to be gained by the support of instructors, colleagues, and other students," Newton says. But for a lot of other students, he says, a more "here's the stuff, do with it what you will" approach is appropriate. Self-directed students who want to study either more or less intensively, have less predictable schedules, or don't have the need for a credential benefit from the OCW model.

In the future, MITEI plans to develop additional MITx courses in clusters related to carbon capture, utilization, and storage, and other areas related to MITEI's Low-Carbon Energy Centers.

To get updates about upcoming online courses and other energy news, please subscribe to MITEI's newsletter at energy.mit.edu/subscribe.

MITEI Education Office

Hardworking undergraduates enrich MIT's energy ecosystem

Jessica Cohen '22

Jessica Cohen '22 is on a mission to help the planet and has been all her life. In elementary school, her goal was to help animals by becoming a marine biologist. In middle school, she investigated biodegradable plastics to combat pollution.

By the time she got to high school, she was developing new catalysts for carbon dioxide (CO_2) reduction with a professor at Yale—research that earned her fourth place in the chemistry category at the Intel International Science and Engineering Fair.

Now, Cohen is pursuing her passion at MIT. "MIT has a pretty hard focus on the environment, energy, and sustainability, so that helped my decision to come here," she says.

Cohen hit the ground running by signing up for the Discover Energy First-year Pre-Orientation Program (FPOP), a five-day introduction to the field of energy run by the MIT Energy Initiative (MITEI). "The Discover Energy FPOP was really amazing," she says. "They set up a lot of great opportunities for us to go to places and see renewable energy implementation in real life."

This winter, she got the chance to work in the lab of Karthish Manthiram, the Warren K. Lewis Career Development Professor in Chemical Engineering, through MIT's Undergraduate Research Opportunities Program (UROP). She's using electrochemical methods to perform olefin carbonylation, an example of which is converting CO_2 to acrylic acid. "It's taking a greenhouse gas, something harmful, and creating a valuable chemical for industry," she says.

Cohen isn't yet sure what her major will be, but she is hoping to complete an Energy Studies Minor. To that end, she is taking 8.21 Physics of Energy this spring—but Cohen's interest in energy extends beyond schoolwork. She also serves on the MIT Energy Club's Climate Action Team subcommittee and she's signed up for GRID Alternatives' Solar Spring Break, a MITEI-supported program that gives MIT students the chance to spend a week installing solar panels in underserved communities. "That should be exciting," Cohen says.

While Cohen is still deciding where she wants her education to take her, she's enjoying exploring all MIT has to offer. "I'm interested in learning more about solar or wind or more about biodegradable polymers or wastewater treatment. I think it's all interesting," she says. "All I know is, I want what I'm doing to be helping the environment."

Photo: Elaina Gemmati

Ryan Sander '20

There is a strong current of energy running through the MIT career of Ryan Sander '20. He has done two energy-related UROP research projects; he is planning to complete the Energy Studies Minor; and he is co-president of the Undergraduate Energy Club.

Sander has long been interested in renewable energy—especially solar power—but he actually credits the Discover Energy FPOP run by MITEI with launching his energy-intensive MIT trajectory.

"That's honestly what got me the most interested in energy at MIT," says Sander, who is double majoring in electrical engineering and computer science and in mathematical economics. "Discover Energy enabled me to meet some of my closest friends to this day and provided me with access to a myriad of resources that have critically shaped my academic and extracurricular experiences for the better at MIT."

In fact, an FPOP connection led Sander to his first UROP; he did titration testing of organic redox cells to support research into electrochemical CO_2 capture systems in the lab of T. Alan Hatton, the Ralph Landau Professor of Chemical Engineering. Later, Sander conducted a MITEI-sponsored UROP centered on mitigating the degradation of certain solar cells, working in the lab of Associate Professor Tonio Buonassisi of mechanical engineering.

Sander enjoyed FPOP so much that he returned as a program counselor in 2018. "My FPOPs in energy and the MITEI UROP have definitely piqued my interest in using engineering and science to solve big energy problems," he says.

FPOP also introduced Sander to the MIT Energy Club and the Undergraduate Energy Club, a subgroup of the larger club. While leading the latter club this year, Sander also served as director of the Tech Showcase, a key event within the MIT Energy Conference, the largest student-led energy conference in the country. Each spring the two-day conference draws about 600 people to MIT.

A recipient of scholarships from both the Institute of Electrical and Electronics Engineers and the US Department of Defense (DoD), Sander plans to begin his career at the DoD. In the meantime, however, he is working on energy efficiency in building design as a part-time co-op at Spacemaker AI.

Photo: Daniel Gonzales

Dana Dabbousi '19

Like many MIT undergraduates, Dana Dabbousi '19 has a lot of impressive accomplishments under her belt. But, at some level, her work can be symbolized by a simple bottle cap.

While participating this winter in the Young Future Energy Leaders program at Khalifia University in Abu Dhabi, United Arab Emirates, Dabbousi helped catalyze a project to get elementary school students to collect bottle caps for a hospital, which will use the plastic to 3D print artificial limbs.

The project is part entrepreneurship, part student organizing, and part environmental sustainability—all key elements of Dabbousi's MIT career.

Arriving with a scholarship from Saudi Aramco and majoring in chemical-biological engineering, Dabbousi hopes to help foster innovative solutions to the world's energy needs. "I'm really interested in sustainability," she says, noting that she plans to start her career working in the energy industry. "There are a lot of different ways to look at energy and how to fuel the world. I believe that everyone has the right to clean, affordable, and accessible energy."

In particular, the native of Saudi Arabia hopes to put her people skills to work for the Arab world's budding innovation ecosystem.

This task will require putting key stakeholders together, a job Dabbousi has already begun as president of MIT's Arab Student Association. Last year in that role, Dabbousi organized the MIT Arab Science and Technology (SciTech) Conference, which brought 200 leading scientists, engineers, business leaders, and entrepreneurs to MIT for a day of talks as well as an exhibition of startups from the Arab world.

That work, in turn, led to her organizing an Arab Energy Innovation Initiative at CERAWeek 2019, a major international energy conference—a task she undertook while planning this year's 2.5-day SciTech Conference.

"What I was hoping to do at all these events is spark conversations and create synergy that would benefit the ecosystem as a whole," she says.

Over the last four years, Dabbousi has participated in the Gordon-MIT Engineering Leadership Program, developed membranes for gas separation, optimized micro-bead assays for the detection of cancer in the lab of Associate Professor Hadley Sikes of chemical engineering, and worked for a startup that's producing lab-on-a-chip technology to detect food and water contamination.

But ultimately, Dabbousi says she sees herself bringing people together to solve problems—as in her bottle cap project. In particular, she hopes to support entrepreneurship as a route to prosperity for an educated Arab population with too few career opportunities. "That's what really drives me, helping people," she says.

Photo: Ebrahim Al Johani

Kathryn M. O'Neill, MITEI correspondent

EDUCATION

Students help to make island communities carbon-neutral

Small island communities across the globe are facing some of the earliest and most severe impacts of climate change. Many have started to turn away from traditional energy sources to reduce their own carbon footprints and inspire broader conversations on the urgent need for all communities to help mitigate climate change by dramatically reducing carbon dioxide emissions.

Participants in a Martha's Vineyard net-zero carbon design thinking workshop included MIT Energy Initiative staff; representatives from Martha's Vineyard, Shell, and Viessmann; and students from MIT, Harvard University, and Tufts University. Photos: Maud Bocquillod

Recently, the Massachusetts island community of Martha's Vineyard engaged with MIT students to discuss pathways toward a net-zero carbon future. Getting to net-zero carbon emissions entails transitioning to low- or no-carbon energy generation, employing energy efficiency measures, offsetting emissions by purchasing carbon credits, and other measures.

Prompted by the Vineyard Sustainable Energy Committee, Martha's Vineyard is looking to achieve net-zero carbon by 2030. Even with its relatively small carbon footprint, the Vineyard could serve as a model for other island communities.

To meet this challenge, Martha's Vineyard is collaborating with the MIT Energy Initiative (MITEI) to develop a multifaceted action plan. As a first step, MITEI hosted a net-zero carbon design thinking workshop during Independent Activities Period in January. The week-long program offered participants a chance to creatively explore clean energy options through a process known as the design thinking model. The workshop was co-sponsored with Shell, a Founding Member of MITEI.

Design thinking is a uniquely collaborative process where groups are constantly engaged in out-of-the-box thought exercises and activities such as fast-paced brainstorming and rapid prototyping sessions. While still relatively new, the concept has proven itself time and time again as an effective problem-solving tool.

For senior and chemical engineering major Allison Shepard, the design thinking process has changed how she thinks about everything. "Design thinking really brings creativity and hands-on, quick thinking to the forefront and makes things happen," she says.

During the workshop, graduate and undergraduate students from MIT, Harvard University, and Tufts University worked in three cross-institutional groups that each tackled a separate energy-related issue on Martha's Vineyard. One group addressed transportation, another focused on agriculture, and the third looked at the issue of the economic stability of year-round Martha's Vineyard residents. With the help of design thinking experts from Viessmann, a German manufacturer of heating, industrial, and refrigeration systems, the students say they experienced a continuous state of creative flow that produced innovative results.

At the beginning of the week, students were introduced to the conditions on Martha's Vineyard and to the basics of design thinking. As the workshop progressed, the group explored more complex topics that presented new opportunities and challenges.

Through brainstorming sessions involving hundreds of sticky notes, Lego prototypes, and numerous cups of coffee, each team devised a unique remedy for carbon reduction on the island. At the end of the week, each group presented its solutions to Martha's Vineyard residents and stakeholders.

Antje Danielson, MITEI's director of education, led the effort, assisted by Aisling O'Grady, a MITEI project coordinator. They engaged a series of experts, Martha's Vineyard stakeholders, and industry leaders to help

MIT senior Allison Shepard and representatives from the German manufacturing company Viessmann brainstorm energy solutions for Martha's Vineyard using the design thinking model.

Technology and Policy Program master's students Annette Brocks (left) and Nelson Lee (right) engage in a rapid prototyping exercise with Tufts master's student Alexis Washburn (center) and other participants in the design thinking workshop.

teach and work with the students. The workshop was also connected to National Science Foundation-funded research that Danielson performs on model-based reasoning, which is closely related to design thinking.

Rob Hannemann ScD '75 was the main point of contact on the island and initially proposed the idea of a collaboration between MITEI and Martha's Vineyard. "My goal in working with the Institute was to tap MITEI's expertise," he says. He believes that this collaboration is mutually beneficial as it not only helps Martha's Vineyard work toward its goal of net-zero carbon, but also provides MIT with "a conceptual test bed" where researchers can study the effects of clean energy technologies on a micro scale.

In the workshop, Danielson introduced students to the process of design thinking to see how group dynamics were affected in collaborative environments.

"Every grad student starts off wanting to change the world," she says. "But how do they get from, 'I want to change the world' to 'This is a project that I can do in a year for my master's degree'?"

Danielson believes that the distinctly cooperative nature of the design thinking model and other methods can play key roles in helping students gain a more comprehensive understanding of their respective fields and develop actionable plans. She says she is excited to see where the ideas generated in the workshop may go.

"Many communities in the US have now set timelines for going to net-zero carbon—not an easy task. The collaboration with Martha's Vineyard allows us to train our students in this area," she says. "By working on a real example, they can practice using new tools and apply their skills in a safe but meaningful way."

This workshop was supported by the National Science Foundation and Shell.

Turner Jackson, MITEI
Aaron Weber contributed to this article.

Frances Beinecke discusses how collective action can advance US climate policies

Frances Beinecke, former president of the Natural Resources Defense Council, spoke at the MIT Energy Initiative's annual fall colloquium, addressing topics ranging from the recent climate report by the Intergovernmental Panel on Climate Change (IPCC), to how to create better climate policy, to visions for the future energy transformation.

Former Natural Resources Defense Council President Frances Beinecke (left) and MITEI Director Robert C. Armstrong discuss the transition to a low-carbon energy future and the gains already achieved by the power and transportation sectors. Photo: Kelley Travers, MITEI

As she began her talk following an introduction by MITEI Director Robert C. Armstrong, a rainbow across Boston's skyline was visible out the window. She quipped that the beauty of nature was exactly why she was here—and then she got down to business.

"An unprecedented acceleration of actions is necessary between now and 2030. That is 12 years from now. That is very, very soon," Beinecke said.

Much of her lecture centered on climate policy, including steps taken by former President Barack Obama. Beinecke said she vividly remembers Obama's speech at Georgetown University in June 2013, a day so hot that the president's teleprompter broke. He was announcing numerous new energy policies that day, including the Clean Power Plan.

At the time, Beinecke said, she and other leaders of major environmental organizations believed the federal government was the answer to the climate problem. Now, she feels differently.

"It is about 'we,'" Beinecke said. "The 'we' represents multiple actors. It represents we as individuals, elected officials, mayors, governors, federal leaders, heads of corporations. In every walk of life, we have a role and can take responsibility for this."

She discussed the IPCC climate report at length, including its finding that a global temperature rise of 1.5 degrees Celsius, rather than 2 degrees, would protect millions of people from some of the most ravaging effects of climate change. At a 1.5 degree increase, 14% of the population would experience extreme heat—but at 2 degrees, that number more than doubles to 37%.

While acknowledging that this statistic can cause feelings of despair, Beinecke urged audience members to find hope. The state of California, she said, is one example of a possible path forward. It's the fifth largest economy in the world, and because of its waiver to enact stricter environmental regulations than other states and the federal government, it's been able to make large strides forward in emissions reductions, clean power sources, and more.

"California's role here is as a global model," Beinecke said. "California is big, powerful, and has the resources to experiment with these things—see how they work, get them right, and create models for the rest of us."

Beinecke said that the power of local communities and companies to determine the climate's future has never been stronger.

"All of those elements are creating something that we're starting to call the new climate federalism," Beinecke said. "Originally, we thought we were going to have a national policy. It's going the other way now. It's happening in cities, in states, in corporations. That will weave together and hopefully, in the early 2020s, will translate into a national policy."

Beyond the power of cities, elected officials, and corporations to advance climate priorities, Beinecke also talked about the impact of public opinion.

She cited a survey (bit.ly/climate-change-usa-yale) by the Yale University Program on Climate Change Communication in March 2018 in which 70% of respondents were supportive of measures such as regulating carbon dioxide as a pollutant and funding more renewable energy research. The same study found that certainty in the existence of climate change has increased 12 percentage points in the past three years, with almost 50% of the public "extremely" or "very" sure that climate change is occurring.

During the event, Beinecke and Armstrong discussed the transition to a low-carbon energy future, highlighting power and transportation as two sectors that have made significant progress. Given that federal research and development funding for energy is at an all-time high, Armstrong zeroed in on where researchers should be investing that money: "What do you see as the big challenges to attack in power and transportation?"

Beinecke answered simply: Technology moves rapidly, and the challenge is keeping up.

"[We need to be] looking at both what's going to be an aid to the transformation and also what could be a block," she said. "What could create a barrier that—if we could identify it early—wouldn't have to be overcome later?"

As part of the solution, Beinecke also talked about innovation, and specifically, innovation at MIT.

"I always find coming to MIT incredibly inspiring, because there's the best and the brightest trying to address some of the most serious issues facing all of us," Beinecke said. "I appreciate all that you do and all that you will do because we need it."

Hannah Bernstein, MITEI

Go to energy.mit.edu/podcast and click on "The human environmental nexus" to hear a MITEI podcast featuring Frances Bienecke talking with Martha Broad, executive director of MITEI.

C3E Symposium celebrates women working in clean energy

Through the Clean Energy Education and Empowerment (C3E) Initiative (www.c3eawards.org), 52 mid-career women with a range of career backgrounds—from research to education to public service—have been recognized for their work advancing and implementing solutions that can transform our global energy system. To celebrate these past and present awardees for the important work they have done in the clean and sustainable energy sector, several hundred energy professionals gathered at Stanford University for the 7th Annual C3E Women in Clean Energy Awards and Symposium held on December 3 and 4, 2018.

The symposium explored developing trends and innovations in clean energy, such as energy storage scale-up, clean energy finance, and sustainable business operation. However, first and foremost, it emphasized what cohost Dian Grueneich, Precourt Energy Scholar and C3E Ambassador emeritus, referred to as the "hallmark of this whole effort"—recognizing women for their achievements across eight professional categories: advocacy, law and finance, business, research, education, international, entrepreneurship, and government. Past awardees and speakers were invited to share their professional journeys and insights to inspire others who are navigating the various stages of their energy careers and the common goal of building a renewables-based, low-carbon energy future.

This annual symposium, which began in 2012, brings together women at all career levels to discuss solutions to pressing energy issues while building a strong and interconnected network of energy professionals. The goals of the US C3E program, led by the US Department of Energy (DOE) in collaboration with the MIT Energy Initiative (MITEI), the Stanford Precourt Institute for Energy, and the Texas A&M Energy Institute, are to close the gender gap and increase women's participation and leadership in the sustainable energy field—subjects that were addressed throughout this year's symposium.

Building a community

"We have a lot of work to do together," said Jane Woodward, founder and CEO

At the 7th Annual C3E Symposium, (from left) Dawn Lippert, CEO of Elemental Excelerator; Carla Peterman, commissioner of the California Public Utilities Commission; Connie Lau, president and CEO of Hawaiian Electric Industries, Inc.; and Erica Mackie, co-founder and CEO of GRID Alternatives, discuss the importance of community engagement in the transition to a low-carbon future. Photo: Maxine Lym of MAP, a natural gas and renewable energy investment management firm, in her opening keynote. "We know what we need to do; how are we going to do it?" Throughout the symposium, as speakers and panelists addressed this very question, a common thread emerged: the importance of building and engaging the community in order to transition to a global clean energy system.

According to Dan Brouillette, deputy secretary of the DOE, there are unmistakable signs of progress in terms of closing the gender gap and empowering women to take on more leadership roles within the field of energy, as exhibited by the presence of the many attendees at the C3E symposium. But he noted that there are still challenges to progressing further, as evidenced by the many not at the conference—those women who were held back due to gender discrimination or because of a challenge he referred to as "a little more subtle": a lack of encouragement from others to pursue STEM (science, technology, engineering, and mathematics) education during their formative years. "Across the United States, the need for STEM professionals far outstrips the supply," said Brouillette. "We simply need more STEM professionals, so we need more STEM outreach."

Valerie Montgomery Rice, the president and dean of Morehouse School of Medicine, stressed the importance of diversifying the workforce. Coming from a perspective driven by improving health equity, Rice demonstrated in her keynote address that "who sits around the table really does matter, particularly as we are trying to change the world." At Morehouse, promoting health equity starts with admitting and creating opportunities for academically diverse students and students from underserved communities; Rice noted that those students are more likely to then practice in underserved communities. "You have to be strategic in your focus if you want to actually change the outcome of the opportunity," she said. "And it has to be a

Valerie Montgomery Rice, president and dean of Morehouse School of Medicine, delivers a keynote speech addressing the need to develop a more diverse workforce. Photo: Maxine Lym

local focus…If kids can't see it, they can't actually believe it. If they can't see what a clean energy geologist looks like, they clearly aren't going to be able to even think about going into that field."

During the "Scaling energy storage" panel, Betar Gallant, Esther and Harold E. Edgerton Career Development Professor and assistant professor of mechanical engineering at MIT, added that for university students, embarking on a clean energy career path may not be so straightforward. "Clean energy, energy storage, these are not the titles of engineering majors. They are not standalone disciplinary subjects where a student can simply declare, 'I want to work on that.' It needs to be more finely honed," Gallant said. "Students really want to engage, and it's a matter of, are we really giving them the buffet of options to understand how to do that early on?" For students, receiving guidance on which disciplines they can enter to work on different energy solutions can be valuable, she explained.

Engaging the community

Speakers and panelists throughout the conference discussed the need to engage local communities to promote acceptance of renewable energy initiatives.

"We know that if we want to achieve that more equitable clean energy future, we have to engage with communities on the front lines," said Melanie Santiago-Moser, who won the Advocacy Award for her work with Vote Solar, a group that strives to make solar a mainstream energy resource across the US. "Engagement doesn't mean coming to those communities and proclaiming that solar is the solution. It means approaching people on the ground who understand these challenges in ways that we can't fathom with humility and building processes that ensure that our work is truly in partnership with theirs."

During the "Powering up the C3E network" panel, Connie Lau, president and CEO of Hawaiian Electric Industries, Inc., and C3E Ambassador, talked about the importance of stakeholder outreach as her company undergoes Hawaii's largest renewable energy procurement process to date. She cited the necessity of working with developers to ensure that they in turn work in the communities to increase public understanding and acceptance of renewable energy projects.

Carla Peterman, commissioner of the California Public Utilities Commission and 2015 C3E Award winner, added that her team supports a participatory model of decision-making: "We need to be communicating with customers, and we need them to be part of the solutions, because if they are not, they are going to be challenging those solutions and slowing them down."

"Opportunities are tied to people"

In keeping with the goals of the US C3E Program, the final panel of the day brought together speakers to discuss the idea of "women helping women"—utilizing professional networks not only for personal success but also for supporting the careers of others. "Dare to guide a female [who] doesn't look like you…try to learn from her, because that's the only way we get more diversity," said Lene Hviid, global manager of Shell Research Connect and GameChanger at Shell Global Solutions. "Dare to support somebody who is outside of your comfort zone."

The speakers made a clear distinction between mentorship and sponsorship. "A mentor is somebody you talk to; a sponsor is someone who talks about you," explained Liji Thomas, head of diversity and inclusion at Southern California Edison. "A sponsor is someone that extends their own social capital in an organization because they have gotten to know you, they've seen what you do." Thomas emphasized the importance of your social capital as well, highlighting that "opportunities are tied to people."

Celebrating achievements

"I feel a sense of kinship—or identity—with all of the women in this room," said Elizabeth A. (Betsy) Moler, retired executive vice president of government affairs and policy at Exelon as she accepted the C3E Lifetime Achievement Award. Moler, a former deputy secretary of the DOE and former chairman of the Federal Energy Regulatory Commission, was recognized for her long history of clean energy leadership and role as a vocal advocate for encouraging women to take leadership positions in the energy industry.

Moler shared the accomplishment she is most proud of, saying it was her work deregulating wholesale markets—a necessity, in her opinion, when addressing future challenges with respect to climate and the electric sector. "Subsequent commissions have refined our efforts as wholesale markets have matured and mutated, but they are an enduring legacy I am proud to say."

"It is important to recognize the achievements of women in the clean energy sector, especially those who are starting down the leadership path, but also those who have paved the way," reflected Martha Broad, executive director of MITEI and a C3E Ambassador. "We need to encourage and empower each other in our efforts if we are to achieve a diverse workforce—which will bring a variety of ideas to bear on the clean energy transformation challenge."

This year's C3E Symposium also celebrated the achievements and work of Melanie Santiago-Mosier, program director for access and equity for Vote Solar (Advocacy Award); Elizabeth Wayman, an investor at Breakthrough Energy Ventures (Business Award); Lilo Pozzo, Weyerhaeuser Associate Professor of Chemical Engineering at the University of Washington (Education Award); Molly Morse, chief executive officer and co-founder of Mango Materials (Entrepreneurship Award); Aimee Barnes, senior advisor to California Governor Edmund G. Brown, Jr. (Government Award); Tania Laden, executive director and co-founder of Livelyhoods (International Award); Lauren Cochran, managing director of Blue Haven Ventures (Law and Finance Award); and Alissa Park, director of the Lenfest Center for Sustainable Energy at Columbia University (Research Award).

"We have the knowledge, we have the power, the skills, to help the new generations," said Valentini Pappa, academic program coordinator at Texas A&M Energy Institute, as she closed the symposium. "Education, mentoring, and empowering are the keys for the future."

Kelley Travers, MITEI

A panel titled "Women helping women" considers strategies to keep women in the workforce and moving in an upward trajectory in their careers. From left: Dian Grueneich, Precourt Energy Scholar at Stanford's Precourt Institute for Energy; Lene Hviid, global manager of Shell Research Connect and GameChanger at Shell Global Solutions; Jennifer Rockwood, global power and utilities practice leader at Russell Reynolds Associates; Liji Thomas, head of diversity and inclusion at Southern California Edison; and Sarah Torkamani, co-president of R&D Women Interest Network, Corporate Strategic Research at ExxonMobil. Photo: Bill Rivard

3 questions: Vladimir Bulović on game-changing solar energy and nanotechnologies

Vladimir Bulović, the Fariborz Maseeh (1990) Chair in Emerging Technology, and the members of his ONE Lab have been creating next-generation, lightweight, flexible photovoltaics that could change the way the world deploys solar energy systems. He's also the founding faculty director of MIT.nano, shepherding the evolution of MIT's new nanoscale research facility that will support thousands of researchers from academia, startups, and industry. He recently spoke with the MIT Energy Initiative (MITEI) for a podcast episode on game-changing technologies (see "Game-changing solar" at energy.mit.edu/podcast). Below is an edited version of his conversation with Francis O'Sullivan, former director of research at MITEI and a senior lecturer at the MIT Sloan School of Management.

Vladimir Bulović, the Fariborz Maseeh (1990) Chair in Emerging Technology, director of the Organic and Nanostructured Electronics (ONE) Laboratory, and founding faculty director of MIT.nano. Photo: Gary Fong/ Genesis Photos, IHS Markit

Q We've seen dramatic reductions in the cost of panels, and we're seeing real deployment today. There's a tremendous amount of excitement about solar energy offering a pathway to very significant decarbonization of electricity systems. With that said, some people, including yourself, have begun to reflect on some of the inherent limitations of today's crystalline silicon technologies. Tell us about the journey that solar has made over the past few decades—and how we can build on the momentum of the low-carbon energy transition.

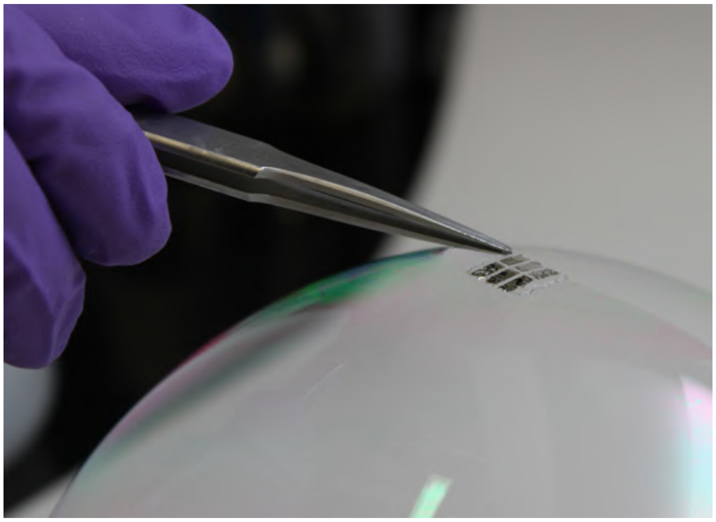
A I would start by emphasizing that the solar technology of yesterday is nothing like the solar technology of today. And the solar technology of tomorrow will be even more different.

Today's solar panels are dramatically improved, both in lifetime and efficiency, and can be made more economically due to standardized and scaled manufacturing. Today, two-thirds of the cost of installed solar is spent on installation and only one-third on the module itself. This implies that if we can make the installation simpler, we might be able to reduce the cost of solar technology by a factor of as much as three. What does that imply for the cost of solar electricity, which today can be bought for as low as 5 cents a kilowatt-hour? Reduce it by a factor of three, and you are at less than 2 cents a kilowatt-hour. That's remarkable. No other electricity-generating technology can reach such a low cost.

As the cost of the solar cells comes down—and as we make them easier to install—it will become obvious that a thirty-year lifetime is not a necessary requirement for installed solar modules. A ten-year lifetime will be sufficient. Costs will be low, and installation could be as simple as stapling rolls of future thin-sheet, lightweight solar modules to the roof. With lightweight solar modules you would not need to reinforce your roof, and delivery of such modules to remote parts of the world that are longing for electrical power will be much easier to do than with the present silicon. The developing world market might be the perfect stepping stone for the broader introduction of this new type of solar into the developed world. The weight of a solar module would become a very significant metric for the deployment of such technology.

I would also say that there are novel modalities that will start coming through in the use of solar. Solar as a power source is brilliant. Sunlight gives us 10,000 times more energy than we consume in the course of a year, but the challenge is collecting it all. If you can collect all the sunlight for one hour, we can power the planet for one year. The catch is that for that one hour, half of the entire planet Earth (the half facing the Sun) needs to be covered with solar cells. The challenge of such large-area deployment is quite significant.

If we can generate solar activity from the surfaces of objects we already build and touch, that might be another way of deploying solar energy. But since by design solar is meant to absorb most of the incident light, a typical solar cell is very dark-looking, or it reflects blue due to the anti-reflective coating that's on top of it. So another technology that you could consider is the so-called invisible solar cells—solar cells that do not absorb any visible light, and hence appear transparent (invisible), but do absorb infrared and ultraviolet light. These transparent solar cells are never going to work as efficiently as silicon or some of the other dark-looking cells, because we're purposefully throwing out a third of the available spectrum (the visible spectrum). Nevertheless, the



MIT researchers have produced solar cells so thin, flexible, and lightweight that they could be placed on almost any material or surface, from a hat to a smartphone to a window pane. Left: To demonstrate, they draped a working cell on top of a soap bubble, without popping the bubble. Photo: Joel Jean and Anna Osherov, MIT

Shockley-Queisser efficiency limit on these cells is on the order of 21 percent for a single junction versus 31 percent for silicon. Yet, when you make them, they look like absolutely nothing. They look like a piece of glass.

With such transparent cells, any surface could become solar active and in a format that is unobservable, hence enabling incidental collection of power by solar windows or even your eyeglasses. With a micron-thick transparent solar coating on your eyeglasses you can, with today's version of transparent solar cells, generate 5 to 10 milliwatts of power in a bright environment. Direct that power along the arms of your glasses toward your ears to power a set of hearing aids or a wireless earpiece, and you'll never have to replace their batteries. If you place such a transparent cell on top of your Kindle's screen, you would never need to charge your Kindle again. Because even with a 1 percent power-efficient version of such a transparent cell, you'll collect enough incidental solar power in the course of a few days to fully recharge the Kindle battery for a couple of weeks.

I think that we can redefine the built environment by the introduction of the next generation of these nanostructured solar technologies, which are just coming around the corner. Although they might not be the most power-efficient solar cells, they will be more easily deployable because they'll be just a value-added, thin-film coating on existing surfaces that we've already built.

Q With your work here at MIT.nano, you are putting together a center for the Institute that's about helping broadly expand and enable the deployment of these new technologies across this wide spectrum of opportunities and helping the innovators to access the technologies that they need to move through the development process in a way that hasn't been available to date. How is this effort with MIT.nano becoming more and more relevant and important as we face these big challenges for technology development?

A MIT.nano has been in the making for over a couple of decades. We built it right in the middle of our campus, right next to the MIT dome, footsteps away from everyone. It is 100,000 square feet of shared laboratory space in a 200,000-square-foot building, with tools for researchers from every department of MIT. It does not belong to a single school; it does not belong to a single department. Two thousand researchers per year will utilize it. As time goes on, it will likely grow to 3,000 to 4,000 users per year, meaning that roughly half of MIT will be stepping into MIT.nano at some point. Right now, about a quarter of MIT researchers will use MIT.nano. Presently, much of the MIT.nano space is awaiting the installation of new equipment, inspired by new ideas from faculty and students. As a researcher at MIT, if you have a fantastic idea, you can develop it in your private lab, then figure out how to scale it. You can try building a new system inside your lab, but typically there's no space for something like that. MIT.nano, though, does have space, and a set of complementary tools. As long as you're willing to engage others, generate a community of people around you, you'll be able to locate the toolsets in MIT.nano and build a grand idea together.

Then there are startups that nurture a unique set of ideas. The big challenge with startups is that ten years ago, 30 percent of the venture capital went into hardware development, as would be needed for solar development, for example. Today, less than 5 percent of the venture capital is invested in the development of hardware ideas, whereas 95 percent is invested in digital ideas. So money is sparse. If you actually want to launch a new technology from scratch using new materials and processes that have never been scaled before, a typical number when it comes to how much money you will need is about $50 million to $100 million over the course of five to ten years of scaling up the idea.

The question in my mind was, Is there a way to utilize facilities like MIT.nano to dramatically reduce the amount of money you'll need to prototype your ideas—or at least to validate them beyond just the initial stages that universities typically work at? I believe the answer is yes.

Looking at startups I was privileged to be a part of, we would generate a great new idea at a university, and the next thing we would do is step out of the university—because universities are not-for-profit, and if you start a for-profit entity, you need to do it off the campus. To launch the startup, the very first thing we needed to do was to reproduce the labs we just left at MIT; refit them with equipment; figure out how to deliver liquid nitrogen or figure out how to set up glove boxes. It's a huge expense—perhaps a few million dollars and a year and a half of work just to get you to the place where you were when you left MIT.

Why not shorten that journey and make it less expensive by simply saying, "The day after you graduate, come back to MIT.nano as a visiting researcher or research scientist from outside and use our toolsets for a fraction of what it would cost you to reproduce your own"? You can start the journey of validating your startup idea, so that two years later, when you are standing in front of venture capitalists to raise your Round A of funding, you will have a much more baked idea in hand. That also means that the journey from the Round A raise to the deployment of your technology to a million people is not going to take five to ten years. Now it will take three to eight, making it much more amenable to being funded. I think MIT.nano can help us accelerate hardware-technology development in ways that we could not have done before on this campus without the central facility that we are now outfitting.

Q You recently participated in an event in Washington, DC, reflecting on some potential game-changing technologies in the energy space, along with some of our colleagues from Stanford, to help policymakers appreciate the need to support the underlying research. Where are we today—nationally and internationally—in this arc of innovation and seizing the opportunities that we see from the work in the lab?

A The new type of solar is coming. In the next five years, we'll have access to more readily deployable, lighter, very inexpensive solar energy, generating electricity at less than 2 cents per kilowatt-hour. If we are not the ones, as the United States, to lead the solar cell technology discovery and scale-up, some of our economic competitors might embrace that challenge. If and when they mature the new solar technology, we risk being in a dramatically reduced position. Our energy would be more expensive than the energy utilized elsewhere for the production of food and for the support of everyday needs. As a result, we would be disadvantaged, just because we haven't opened our eyes to the opportunity today: that we should seize the moment and be the lead—as we are presently—in developing the next and the next set of ideas needed to give us this very inexpensive form of electricity.

MIT Energy Initiative

The MIT.nano building, at the center of campus adjacent to the Great Dome, has expansive glass facades that allow natural light into the labs while giving visitors a clear view of the research in action. Image: Wilson Architects

3 questions: Robert Stoner discusses clean energy for India

India has made great strides in electrification in recent years, but further investment is still needed, especially in rural areas. Here, Robert Stoner, deputy director of the MIT Energy Initiative and director of the Tata Center for Technology and Design, comments on energy and development opportunities and challenges in India and how MIT is supporting the country's transition to a low-carbon future.

Q What is the biggest energy opportunity in India right now?

A What's really exciting and almost hard to believe about India is that this giant country just recently electrified its last unconnected village. In other words, 100% of Indian villages have been connected to the electricity grid. It doesn't mean that every *household* has necessarily been connected, nor that every household that *is* connected receives electricity 24 hours a day, but they've laid out the wires. It's a very strong declaration on the part of the government of its intention to achieve universal *grid* access.

India has a power system with roughly 350 gigawatts (GW) of generation, or about a third as much as the United States. India has four times as many people, so the per capita supply is about one-twelfth of what we experience. They continue to add capacity in India, including the world's largest solar plant, which is capable of producing nearly a gigawatt. In spite of this, there is considerable slack generating capacity, with overall utilization at 60% or less. So there's spare capacity, and at the same time low consumption of electricity—although not necessary in the same place. The Indian government would like to change that in part by expanding rural access, and of course, the people who live in the countryside want electricity.

Q What challenges does India face with energy and the environment?

A One of the difficulties is that the rural population is widely dispersed. It costs a lot of money to provide electricity to them, because the electrical wires have to go a long way from where the generating plants are. Many use only minute quantities of electricity, and it costs a lot to collect from them, so rural electricity users are mostly a losing proposition for the electric utilities, which is why they've been slow to invest in connecting them. But now the government has pushed them to make this huge investment in wires, and it has to pay it off, so the status quo isn't an option—it would bankrupt the utilities. It's in everybody's interest to have more electricity flow through those wires, and it will be interesting to see how the utilities handle their new customers.

India is currently implementing an expanded and improved subsidy regime that will allow transfers of government funds to rural consumers and, hopefully, encourage consumption. They have to do this.

Q What are MIT's most promising contributions to India's energy situation right now?

A Vladimir Bulović's work on thin films deposited on flexible plastic substrates is a very prominent example. He's faculty director of the Tata-MIT GridEdge Solar program (gridedgesolar.org), which is funded by the Tata Trusts (tatatrusts.org). The GridEdge team is now celebrating a milestone: For the first time, they've been able to make thin-film perovskite solar cells on thin plastic in a roll-to-roll process. That's very different and less costly than the conventional and far more complex silicon wafer process. It's an exciting development not only because it

Robert Stoner, deputy director of the MIT Energy Initiative and director of the Tata Center for Technology and Design, addresses the fourth annual Tata Center Symposium. Photo: Kelley Travers, MITEI

moves us closer to a new low-cost regime, but also because the product is flexible and much, much lighter. That makes it easy to transport to rural areas and also to form freely into interesting shapes like awnings and car tops.

Vladimir has been quite focused on India thanks to the GridEdge program. The Tata Trusts have committed $15 million over five years to fund the program, making it by far the largest solar project at MIT and a large fraction of all solar activity at MIT. In a very direct way, much of MIT's current solar technology development is aimed at the developing world.

Turner Jackson, 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 about 400 graduate students and postdoctoral fellows in 20 MIT departments and divisions.

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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

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

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Members as of April 1, 2019

MITEI member news

Sertecpet becomes a MITEI member
Sertecpet, an energy solutions provider based in Ecuador, has joined the MIT Energy Initiative (MITEI) as an Associate Member. The company is interested in increasing its portfolio of sustainable energy generation and developing materials that could be used in sustainable energy applications. MITEI Director Robert C. Armstrong spoke at an event hosted by Sertecpet in February. He discussed the importance of the transition to a low-carbon future with an audience of government officials, industry members, and other stakeholders. Above: Eduardo López Robayo (left), chairman and CEO of Sertecpet, shakes hands with Armstrong during a visit to MIT in December 2018. Photo: Kelley Travers, MITEI

Xignux becomes a MITEI member
Xignux, a corporation based in Mexico, joined MITEI as an Associate Member, along with its affiliates: Viakable, which manufactures and distributes electrical conductors, and Prolec, which specializes in power and distribution transformers. The company has joined MITEI's Low-Carbon Energy Centers for Energy Storage and Electric Power Systems, with plans to broaden its scope and participation in current and future energy sectors by engaging more with MITEI faculty members and their research.

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Students help to make island communities carbon-neutral

During Independent Activities Period in January 2019, the MIT Energy Initiative (MITEI) and MITEI Founding Member Shell co-hosted a weeklong program that gathered MIT, Harvard, and Tufts students to collaboratively come up with strategies to help Martha's Vineyard toward its goal of achieving net-zero carbon emissions by 2030. To generate ideas, the students engaged in a process called design thinking, which combines out-of-the-box thought exercises with fast-paced brainstorming and rapid prototyping. The photo above shows one team in action: Aided by sticky notes, Lego models, and cups of coffee, MIT students Annette Brocks (left), Nelson Lee (right), and Dai Lin (lower right) engage in a rapid prototyping exercise with Tufts student Alexis Washburn (second from left). For more details, please turn to page 30. Photo: Maud Bocquillod