Energy Futures

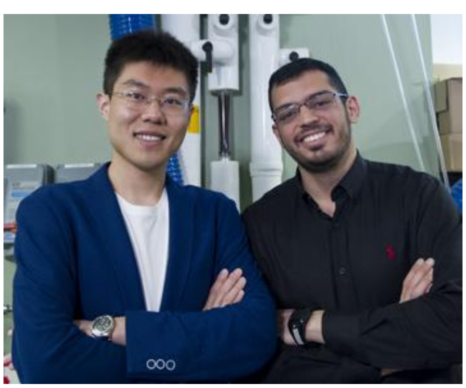
MIT ENERGY INITIATIVE   MASSACHUSETTS INSTITUTE OF TECHNOLOGY   SPRING 2018

Keeping buildings cool in a warming world p. 13

Event highlight: United Nations Climate Change Conference

As negotiators worked to find common ground at the United Nations Climate Change Conference (COP23) in November 2017, MIT researchers from different technology and social science backgrounds shared their ideas for climate action. The MIT delegation, shown above outside the venue in Bonn, Germany, included (from left) Jonas Knapp, Laur Hesse Fisher, Michael Casey, Kathleen Kennedy, Thomas Malone, Jessika Trancik, Stephen Lee, Morgan Edwards, Tom Kiley, and Erick Pinos. Shown below are Horacio Caperan, Michael Mehling, John Sterman, and Bruno Verdini.

Delivered at various side events, their messages to delegates and other climate stakeholders from around the world converged on several key elements that could enhance chances of successful climate policy implementation, including: empowering people and governments by facilitating access to open-source tools and strategies; integrating fairness and transparency into negotiations; and cultivating a deep understanding of the needs and priorities of the other side, to achieve mutual gains that benefit the climate, environment, and each side's economy. Read more at bit.ly/COP23-MITEI. Photos: Emily Dahl, MITEI



On the cover

Graduate students Tianyi Chen (left) and Omar Labban combined their respective expertise in analyzing building energy performance and designing desalination technologies to model systems for cooling and dehumidifying indoor spaces. Their analyses produced new insights into designing energy-efficient systems for specific climates. See page 13. Photo: Stuart Darsch

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

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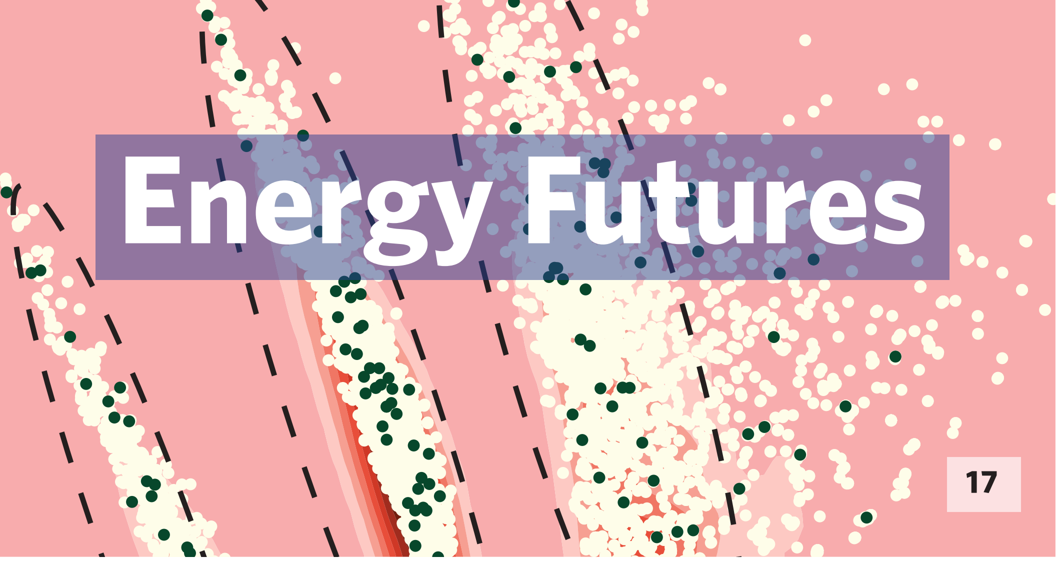


Spring 2018

MITei
MIT Energy Initiative

Massachusetts Institute of Technology

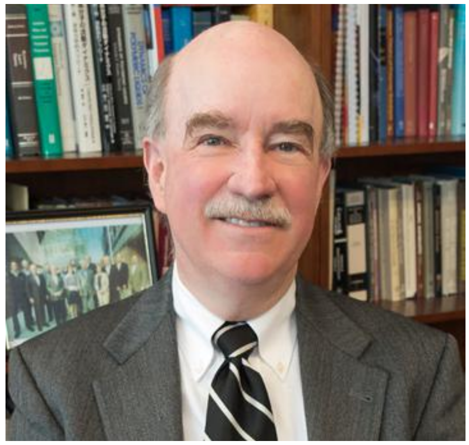
A letter from the director

Dear friends,

When announcing the Plan for Action on Climate Change in 2015, MIT took a strong public stance on addressing climate change as one of the Institute's core priorities. This January, an ad hoc Climate Action Plan Review Committee convened by MIT President L. Rafael Reif submitted a thoughtful report assessing the Institute's progress to date and identifying new opportunities for growth.

The MIT Energy Initiative has been proud to contribute to these efforts. A major focus of our involvement has been to develop, seek funding for, and drive eight interdisciplinary Low-Carbon Energy Centers to tackle the most pressing energy challenges related to climate change from key technological and economic perspectives. Under the guidance of faculty co-directors—many of whom you have heard from in previous issues of *Energy Futures*—and MITEI program managers, these centers continue to grow and evolve to be more accessible to new types of member companies.

An important component of MITEI's mission and its participation in the climate action plan is bringing together industry, government, and academia to foster low-carbon and no-carbon energy research. In this role, MITEI helped facilitate a new, first-of-its-kind collaboration to move the carbon-free promise of fusion power closer to reality. Italian energy company Eni S.p.A., a founding member of MITEI, has committed to funding a new private company with roots at MIT—Commonwealth Fusion Systems (CFS). Eni is also supporting fusion research projects through the MIT Plasma Science and Fusion Center's newly created Laboratory for Innovation in Fusion Technologies.



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

The goal of this collaboration is to advance research on superconducting fusion magnets, which in turn can enable the manufacture of smaller, lower-cost fusion devices. With these advances, fusion energy could reach commercialization within the next 15 years. For more information, turn to page 3.

Additionally, CFS will join MITEI in a new membership category specifically designated for energy startups. The aim is to forge connections between these entrepreneurial companies and more established energy companies to accelerate commercialization of new low-carbon technologies. Speeding the development and deployment of climate solutions with collaborations like these was exactly the kind of outcome MIT had in mind when embarking on the climate plan.

The research articles in this issue provide a sampling of MIT's work to move us toward a lower-carbon future. One team has produced guidance for developing high-efficiency systems for cooling and dehumidifying the world's buildings (page 13); another has generated a design for a clean, efficient engine to replace the dirty diesel engines now used in heavy-duty trucks (page 22); and a third has developed an artificial-intelligence-based method of data mining millions of journal articles to create "recipes" for synthesizing promising new materials (page 17). In policy work, a researcher has produced step-by-step guidelines for conducting high-stakes, mutually beneficial negotiations over transboundary natural resources, including energy and water (page 7).

In January, MITEI awarded $150,000 each to nine new research projects through our Seed Fund Program, which supports innovative, early-stage research at MIT. Chosen from among 98 submissions, the winning projects focus on novel calcium-based battery designs, cost-effective renewables expansion, the economics of energy storage, and more (page 29).

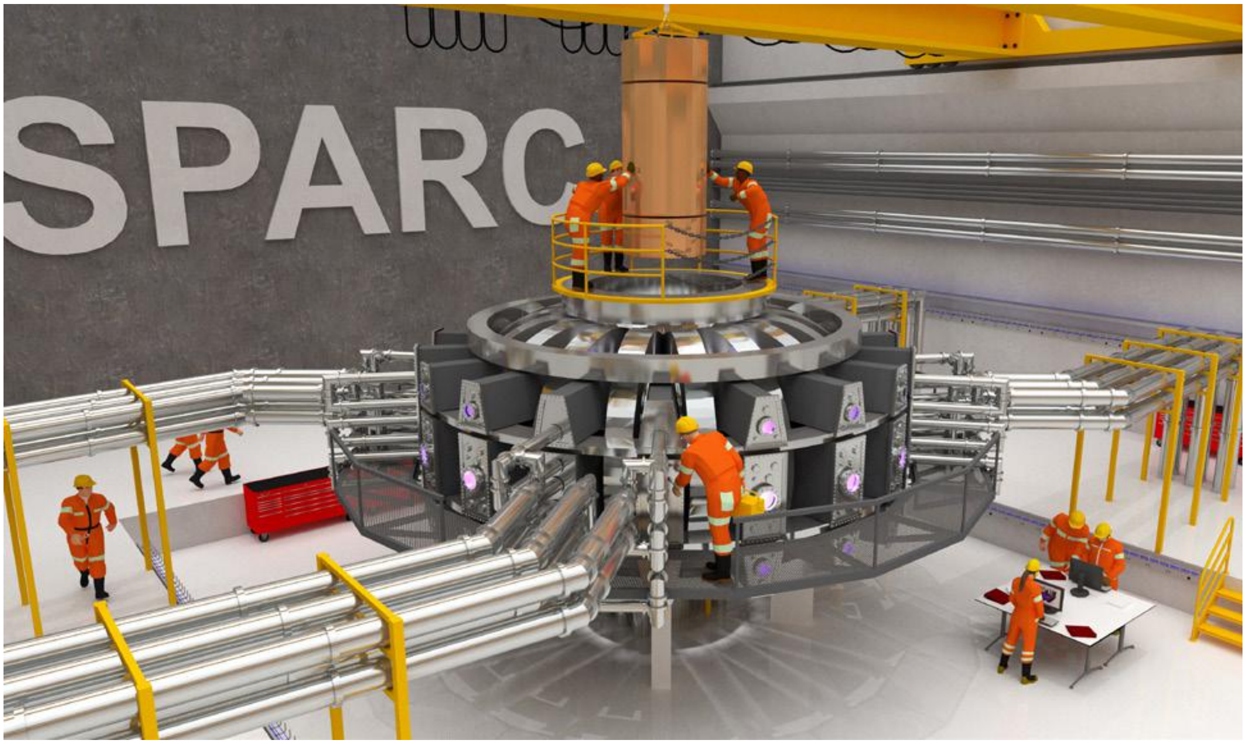
Our education program and energy minor have continued to grow and expand. In one new class, students learn how technologies, economics, policies, and government and private decision-making impact global energy systems—both past and future (page 34). And in a revamped staple class for the Energy Studies Minor, students now learn not only the fundamental physics of energy systems but also how to convey their new understanding in clear, concise prose to policymakers and non-specialists (page 36).

Read on to find out more about our efforts to respond to the ever-changing energy landscape and mounting global energy needs. Thank you for your continued interest in MITEI, our work, and our energy community.

Warm regards,

Robert C Armstrong

Professor Robert C. Armstrong
MITEI Director
May 2018



A new era in fusion research at MIT

Novel collaboration aims to commercialize fusion power

Francesca McCaffrey, MITEI

On March 9, 2018, MIT announced a first-of-its-kind collaboration to advance carbon-free fusion power. Italian energy company Eni S.p.A., a founding member of the MIT Energy Initiative (MITEI), has reached an agreement with MIT to fund fusion research projects run out of the MIT Plasma Science and Fusion Center (PSFC)'s newly created Laboratory for Innovation in Fusion Technologies (LIFT). The expected sponsorship of these research projects will amount to approximately $2 million over the following years. Eni also announced a commitment to a $50 million investment in a new private company with roots at MIT, Commonwealth Fusion Systems (CFS). The overall goal of the research is to develop a working fusion pilot plant within the next 15 years.

"This collaboration by MIT, Eni, and Commonwealth Fusion Systems has significant potential to make commercial-scale fusion power a reality," says Robert C. Armstrong, MITEI's director and the Chevron Professor of Chemical Engineering at MIT. "Commercializing fusion would allow it to take its place as a staple of the global low-carbon energy portfolio—which

Above The overall goal of the MIT-Eni-CFS collaboration is to develop a working fusion pilot plant within the next 15 years. Pictured above is a rendering of the proposed compact and powerful fusion experiment, called SPARC. The experiment, which utilizes high-field magnets with newly available high-temperature superconductors, would be the first controlled fusion plasma system to produce net energy output. Visualization: Ken Filar, PSFC research affiliate will help meet growing energy demand while tackling the challenge of climate change."

Fusion is unique in that it is a zero-carbon, dispatchable, baseload technology, with a limitless supply of fuel, no risk of runaway reaction, and no generation of long-term waste. It also produces thermal energy, so it can be used for heat as well as power. Still, there is much more to do along the way to perfecting the design and economics of compact fusion power plants.

CFS plans to use the Eni funding to advance research and development of superconducting fusion magnets, which in turn can enable the manufacture of smaller, lower-cost fusion devices that PSFC has already been researching. CFS will also use some of the funding to support MIT fusion research efforts. Advances in this area have been made possible by decades of federal funding for basic research.

Eni will fund research projects at LIFT that focus on fusion-specific solutions. "We are thrilled at PSFC to have these projects funded by Eni, who has made a clear commitment to developing fusion energy," says Dennis Whyte, the director of PSFC and the Hitachi America Professor of Engineering at MIT. "LIFT will focus on cutting-edge technology advancements for fusion and will significantly engage our MIT students who are so adept at innovation."

CFS will also join MITEI in a new class of membership specifically geared toward energy startups. This new membership class will enable entrepreneurial companies and larger, more established energy companies to learn from each other—sharing knowledge of the energy sector and accelerating commercialization of new technologies to improve global energy systems.

MIT President L. Rafael Reif (left) and Eni CEO Claudio Descalzi celebrate the new collaboration. Eni will sponsor cutting-edge research into superconducting magnets at Commonwealth Fusion Systems, a private fusion company with roots at MIT, as well as supporting fusion research at MIT itself. Photos: Kelley Travers, MIT

Tackling fusion's challenges

The inside of a fusion device is an extreme environment. The creation of fusion energy requires the smashing together of light elements, such as hydrogen, to form heavier elements, such as helium, a process that releases immense amounts of energy. The temperature at which this process takes place is too hot for solid materials, necessitating the use of magnets to hold the hot plasma in place.

One of the projects PSFC and Eni intend to carry out will study the effects of high magnetic fields on the fluid dynamics of molten salt. One of the key elements of the fusion pilot plant currently being studied at LIFT is the liquid immersion blanket, essentially a flowing pool of molten salt that completely surrounds the fusion energy core. The purpose of this blanket is threefold: to convert the kinetic energy of fusion neutrons to heat for eventual electricity production; to produce tritium, a main component of the fusion fuel; and to prevent the neutrons from reaching other parts of the machine and causing material damage.

It's critical for researchers to be able to predict how the molten salt in such an immersion blanket would move when subjected to high magnetic fields such as those found within a fusion plant. The researchers and their respective teams plan to study the effects of these magnetohydrodynamic forces on the salt's fluid dynamics.

A history of innovation

During the 23 years that MIT's experimental fusion tokamak device, Alcator C-Mod, was in operation, it repeatedly advanced records for plasma pressure in a magnetic confinement device. Its compact, high-magnetic-field fusion design confined superheated plasma in a small donut-shaped chamber.

"The key to this success was the innovations pursued more than 20 years ago at PSFC in developing copper magnets that could access fields well in excess of other fusion experiments," says PSFC Deputy Director Martin Greenwald. "The coupling between innovative technology development and advancing fusion science is in the DNA of the Plasma Science and Fusion Center."

In its final run in 2016, Alcator C-Mod set a new world record for plasma pressure, the key ingredient to producing net energy from fusion. Since then, PSFC researchers have used data from these decades of C-Mod experiments to continue to advance fusion research. Just last year, they used C-Mod data to create a new method of heating fusion plasmas in tokamaks that could result in the heating of ions to energies an order of magnitude greater than previously reached.

PSFC Director Dennis Whyte uses a small, linear plasma experiment to demonstrate the basic principles of magnetic confinement to an audience of visitors from Eni and MIT. In a fusion device, much stronger magnetic fields are used to contain plasmas with temperatures above 100 million degrees.

A commitment to low-carbon energy

MITEI's mission is to advance low-carbon and no-carbon emissions solutions to efficiently meet growing global energy needs. Critical to this mission are collaborations between academia, industry, and government—connections MITEI helps to develop in its role as MIT's hub for multidisciplinary energy research, education, and outreach.

Eni is an inaugural, founding member of MITEI, and it was through their engagement with MITEI that they became aware of the proposed fusion technology commercialization plan and its immense potential for revolutionizing the energy system. It was also through these discussions that Eni researchers learned of the high-potential fusion research projects taking place at the PSFC, spurring them to support the future of fusion at the Institute itself.

Eni CEO Claudio Descalzi said, "Today is a very important day for us. Thanks to this agreement, Eni takes a significant step forward toward the development of alternative energy sources with an ever-lower environmental impact. Fusion is the true energy source of the future, as it is completely sustainable, does not release emissions or waste, and is potentially inexhaustible. It is a goal that we are determined to reach quickly." He added, "We are pleased and excited to pursue such a challenging goal with a collaborator like MIT, with unparalleled experience in the field and a long-standing and fruitful alliance with Eni."

These fusion projects are the latest in a line of MIT–Eni collaborations on low- and no-carbon energy projects. One of the earliest of these was the Eni-MIT Solar Frontiers Center, established in 2010 at MIT. Through its mission to develop competitive solar technologies, the center's research has yielded the thinnest, lightest solar cells ever produced, effectively able to turn any surface, from fabric to paper, into a functioning solar cell. The researchers at the center have also developed new, luminescent materials that could allow windows to efficiently collect solar power.

Other fruits of MIT–Eni collaborations include research into carbon capture systems to be installed in cars; wearable technologies to improve workplace safety; energy storage; and the conversion of carbon dioxide into fuel.

NOTE

For more information on the broader agreement between MIT and Commonwealth Fusion Systems, please visit bit.ly/MIT-CFS.

STEPS *to* EFFECTIVE TRANSBOUNDARY NEGOTIATIONS

Persuade the other side to negotiate

- Form alliances with their back table
- Share surprising insights and data
- Expand the scope of issues at stake

Overcome past grievances

- Identify sources of mistrust
- Map costs of conflict
- Flag outdated practices

Declare the mandate

- Cultivate rapport at high levels
- Stress the benefits of coordination
- Announce collaborative negotiations

Adapt the protocol

- Involve a wider set of stakeholders
- Elicit their creativity and buy-in
- Foster ownership of solutions

Send the best representatives

- Get past agency conventions
- Empower facilitative leaders
- Grant them broad authority

Expand your references

- Examine previous negotiations
- Recruit neutral experts
- Imagine new scenarios

Get on the same page

- Ditch the draft-counterdraft cycle
- Hold joint workshops and tours
- Speak the same modeling language

Highlight the benefits

- Test points of tentative agreement
- Seek trades across differences
- Shape packages around incentives

Lead thoughtfully

- Prioritize recurrent side talks
- Balance reason with emotion
- Build a reputation for empathy

Seize the day

- Embrace unexpected circumstances
- Pursue steps that build momentum
- Target incremental solutions

Communicate strategically

- Engage communities on the ground
- Block spoilers with a unified voice
- Develop a genuinely shared narrative

Follow through for success

- Incentivize dispute resolution
- Promote testing and monitoring
- Reward adaptation and progress

Natural resource negotiations for mutual gains

Resolving conflicts through proactive collaboration

Nancy W. Stauffer, MITEI

IN BRIEF

An MIT researcher has produced step-by-step guidelines for performing high-stakes negotiations that succeed—even after decades of mistrust, confrontation, and deadlock. One case study in his award-winning research—now published in a new book—focused on negotiations that resolved a 70-year dispute between Mexico and the United States over hydrocarbon reservoirs that cross the countries' maritime boundary in the Gulf of Mexico. By interviewing participants and experts on both sides, he identified practices and strategies that all viewed as critical to producing a ground-breaking agreement. One key was a firm commitment by leaders of both countries, across diverse political leanings, to empower their negotiation teams to replace the usual win-lose mentality with an approach focused on joint fact-finding. Also important to crafting a mutually beneficial, robust agreement were commitments to build trust and reciprocity, creatively assess each other's goals and constraints, break traditional protocol to involve a wider array of stakeholders, and issue joint public communications that focus not on conflict but on the merits of coordination and gains for all.

When people think of high-stakes negotiations—whether between countries or interest groups or individuals—they generally picture raised voices and table pounding as each side competes to get an outcome that's in its best interest. But research and experience suggest that a different approach may ensure a more efficient process and a better result.

"There's evidence that one of the best ways to satisfy one's own interests is to find an effective way to meet the core interests of the other side," says Bruno Verdini PhD '15, lecturer in urban planning and negotiation and executive director of the MIT-Harvard Mexico Negotiation Program. "Embracing a

Above Bruno Verdini explored the keys to successful high-stakes negotiations by interviewing dozens of people who worked together to settle long-running disputes between the United States and Mexico over shared natural resources in the Colorado River and the Gulf of Mexico. Photo: Emily Dahl, MITEI

Facing page Based on those interviews and studies of other trans-boundary practices around the world, Verdini prepared a practical guide to performing high-stakes energy, water, and environmental negotiations. This infographic summarizes his step-by-step guide to success. Graphic: Jenn Schlick, MITEI mutual-gains approach to negotiation implies switching away from the traditional, widespread, zero-sum, win-lose mindset in order to structure the negotiation process instead as an opportunity for stakeholders to learn about and respond to each other's core needs. The result tends to be a more robust agreement that both sides *experience* and *view* as beneficial."

Experts have come up with independent theories about how to enhance adaptive leadership, collaborative decision-making, political communication, and dispute resolution in communities. Verdini wanted to integrate those theories for the first time and apply them to the realm of natural resource management, exploring what had happened in real situations where stakes were high.

To that end, he decided to examine two long-running disputes between the United States and Mexico regarding shared natural resources—hydrocarbon reservoirs in the Gulf of Mexico and environmental and water resources from the Colorado River. In both cases, after seven decades of stalemate, the countries came up with joint agreements in 2012. Since then, both deals have been implemented, enhanced, and renewed for the foreseeable future, despite changes in the binational political landscape over the past few years.

The energy dispute

Defining the rules for deep-water energy production along the US-Mexico maritime boundary had been a source of contention for some 70 years. Within 200 nautical miles from either coastline, ownership is clear. But in the middle of the hydrocarbon-rich Gulf of Mexico, the question remained: How do the US and Mexico engage with each other to address the potential for reservoirs straddling the boundary? For decades, the notion of US and Mexican energy companies working together didn't seem feasible. The US adhered to the "rule of capture," which asserts that if a company drills into a reservoir on the US side, regardless of whether the reservoir crosses the border, it owns all of the extracted oil: first-come, first-served. Mexico argued that this unilateral behavior was not fair, but since it had strict constitutional rulings forbidding joint drilling between international energy companies and Petróleos Mexicanos (PEMEX), its national oil company, cooperation seemed unlikely. In 2000, stuck at an impasse, the two countries agreed to place a decade-long moratorium on drilling in the contested area.

In 2010, the US and Mexico agreed to extend that moratorium for another four years, but this time, they had a new plan in the works. By 2012, after less than 18 months at the negotiating table, the two sides had signed a landmark agreement that would overhaul all prior practices and incentivize US and Mexican companies to jointly develop shared hydrocarbon reservoirs—the first significant offshore energy partnership in the history of relations between the two countries. That agreement would later be complemented and further enhanced by a series of landmark domestic energy reforms in Mexico.

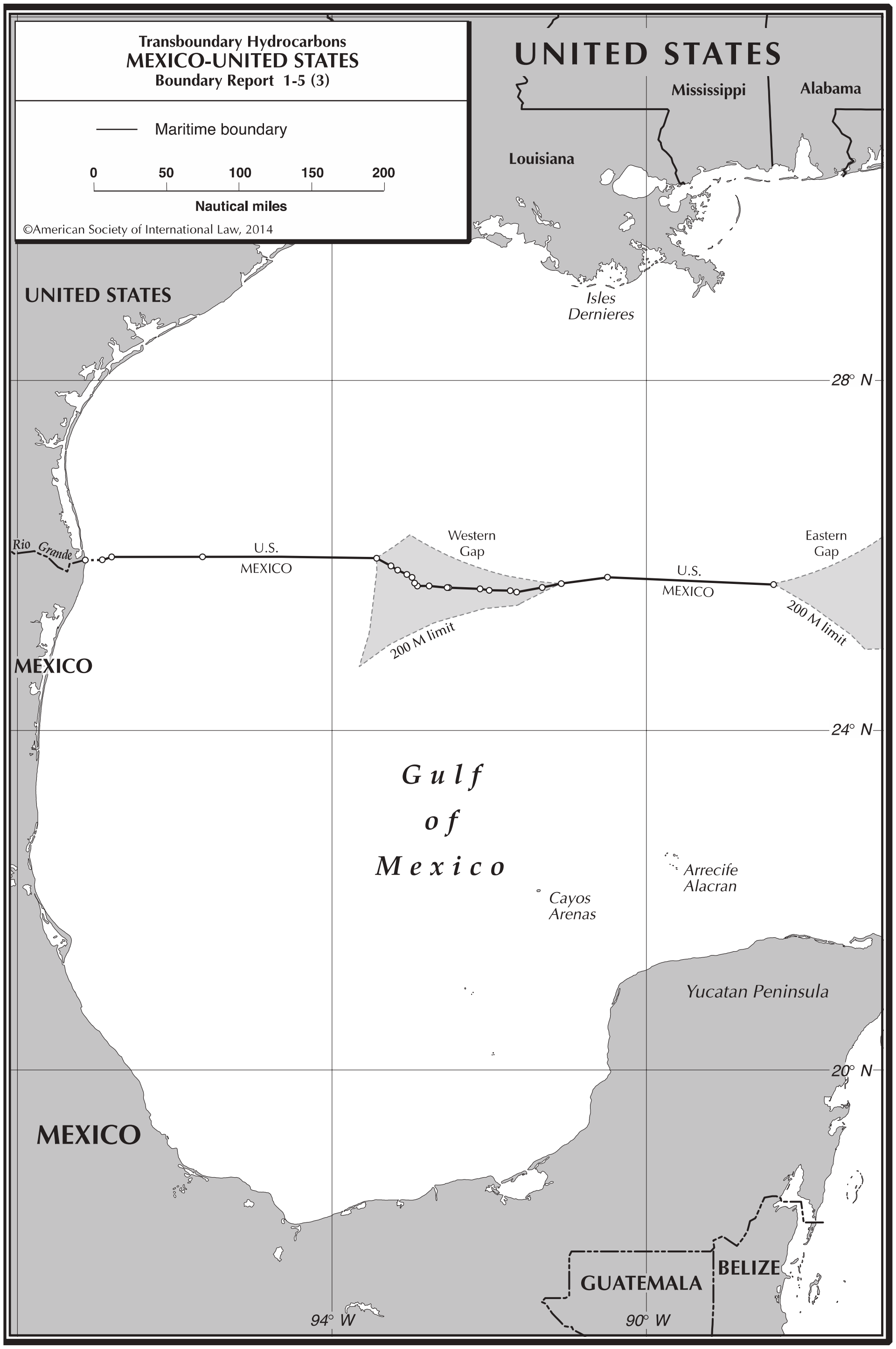
To understand that breakthrough, Verdini talked with the stakeholders from both countries who directly conducted the negotiations. "The idea behind the research was simply to learn from the people who were involved in those high-stakes negotiations," he says. "The focus was not on the features of the agreement but on what they did day-to-day as they negotiated it. What kind of conversations did they set up? What kind of strategies did they follow to resolve these disputes?" Ultimately, his goal was to find out what actors from different organizations and backgrounds on both sides thought worked in practice.

To that end, he interviewed more than 70 individuals, including all key political leaders, such as presidents, secretaries, and ambassadors; CEOs as well as technical and scientific experts in industry; and general managers of environmental organizations. In those in-depth interviews, the US and Mexican negotiators unpacked the decisions and practices they thought transformed the negotiation process and product—allowing Verdini to piece together what both sides considered, unbeknownst to each other, as the key steps and strategies. He has synthesized this research in a new book, *Winning Together: The Natural Resource Negotiation Playbook* (see the note on page 11).

Flexible leadership, unusual first steps

As is the case with any window of opportunity, one factor shaping the start of negotiations was simply that conditions and attitudes had changed. Mexico's production from onshore and shallow-water fields had declined sharply, and the country needed a new source of revenue. Promising new fields were mostly located in deep water, and Mexico needed access to a level of investment, risk-sharing, and technological expertise that would be possible only through international partnerships. While the US still supported the rule of capture, high-ranking US officials noted the potential benefits of cooperation, including opening up Mexico's energy sector to foreign investment and improving US energy security, in tandem with positive impacts on Mexico's economic and social stability. Thus, both sides wanted to end the moratorium on development—but they didn't know how to go about it.

In spring 2010, when the presidents of the two countries publicly announced that they wanted an agreement and specified that they wanted it to be a mutual-gains solution, there was still no blueprint on how to bridge a whole host of divides. However, that unprecedented broad mandate, which had been years in the making, empowered high-level negotiators to take some unusual steps.



The maritime boundary in the Gulf of Mexico The solid line across the Gulf of Mexico on this map indicates the international maritime boundary between the United States and Mexico, including two submerged areas of continental shelf that extend beyond the 200 nautical-mile exclusive economic zones of Mexico and the United States, known as the Western Gap and Eastern Gap. A binational agreement reached in 2012 is structured to incentivize US international energy companies and Petróleos Mexicanos (PEMEX), Mexico's national oil company, to jointly explore, discover, and produce from offshore transboundary reservoirs straddling the 550-nautical-mile-long maritime boundary. The deal establishes the legal and market framework to form partnerships within 15 nautical miles on either side, an area equal in size to three times the state of Massachusetts. Source: US Department of State

For example, several months before negotiations officially started, as per traditional diplomatic protocols, the Mexican authorities sent a draft agreement to the United States. The preliminary review by US agencies found that the draft contained hundreds of terms that the US was unlikely to accept. Typically, the next step would be for the US to send back a counterdraft presenting objections and suggestions, paragraph by paragraph—and the incessant draft–counterdraft cycle would begin.

However, the lead US negotiator—a lawyer in the US State Department who had first-hand experience working in the oil industry—recognized that such a negotiation pattern was doomed to failure because each side couldn't fully know, at the outset, where the other was coming from, given fundamental differences in industry behavior, market incentives, and legal structures. He therefore suggested that before starting any face-to-face negotiations, the two groups of negotiators should launch a series of collaborative workshops to develop a deeper understanding of how each country operated in the Gulf of Mexico.

At first, the Mexican negotiators thought this step was merely a delay tactic by the US. Yet soon enough, as a result of time spent working side by side, all involved felt that those workshops—held monthly in different locations in the US and Mexico—proved critical. The Mexican and US participants learned about each other's political, legal, and economic goals and constraints in a positive environment. Perhaps more important, they got to know one another personally and to build rapport. "So they had the opportunity to start sharing information in ways that they had never done before," says Verdini. "And they were able to genuinely put themselves in the other side's shoes and better appreciate their concerns and interests."

Mismatched assumptions

An unprecedented move by Mexico broke down another barrier to progress, namely, differing assumptions about what was at stake in the dispute. Actors on the US side came into the negotiations claiming that the existence of cross-boundary reservoirs was doubtful—geological formations in the region tend to be tall and narrow—so there was little need for an agreement on how to manage them. Actors on the Mexican side argued that their existence was likely and feared that, without a joint agreement, conflict could erupt if companies drilled on one side, draining hydrocarbons in the shared reservoirs.

Finally, to break the impasse, leaders at the Mexican Ministry of Energy and PEMEX invited US government officials to PEMEX's state-of-the-art, three-dimensional visualization center in Tabasco, where they were allowed to observe proprietary geological data that suggested why Mexico felt there were transboundary hydrocarbons. That action was a game-changer. It demonstrated how serious Mexico was about moving forward with negotiations and showcased the developing trust between the two sides.

To reciprocate, the United States hosted Mexican officials for presentations in New Orleans, providing details about the formal arrangements under which US companies forgo the rule of capture and sign unitization agreements to work with each other in the Gulf of Mexico. Those agreements allocate operating risks and revenues between coordinating parties and ultimately increase total output from a given reservoir. That information clarified that both sides were making strides to collaboratively address their common interests.

Protecting the process

As the negotiations unfolded, the US and Mexican leaders were increasingly committed to protecting the collaborative spirit of the negotiations—a spirit that was tested with some frequency. For example, on several occasions a politically well-connected figure from one side or the other would visit the negotiations and display a confrontational attitude. "When that happened, the operational leader on the side of the errant interloper would ask the other—through private conversation—not to pay mind to this behavior but rather let the person rant and then move on," explains Verdini. Those unusual and reciprocal assurances kept the negotiation process from being derailed by ineffective tactics.

Early engagement of environmental leaders also enhanced the process. Typically, nongovernmental organizations (NGOs) would try to block any proposal to open up new acreage for offshore drilling. However, in proactive and frequent meetings with NGO advocates, the negotiators mapped out the realities of the scenario: Given its dwindling revenues, Mexico would surely drill more in the Gulf of Mexico. If both countries proceeded on their own, multiple wells on both sides of the maritime boundary would be drilled, increasing the likelihood of spills and mishaps. If instead a collaborative agreement were in place, US and Mexican partner companies would have access to the full geological picture. They could then share the most advanced technology and expertise on how to proceed, permitting drilling to occur on fewer, carefully selected, joint sites. That perspective—along with an innovative provision establishing a process for joint safety inspections—led the environmental NGOs to conclude that, while they could not advocate for passage of the agreement, they would not step in to oppose it.

Lecturer Bruno Verdini coaches undergraduates as they debrief a role-play negotiation session in 11.011 The Art and Science of Negotiation. The weekly simulations build on cases, discussions, and one-on-one meetings and empower students to put new communication, collaboration, and leadership strategies into practice. The class has become one of the most popular and highest-ranked electives at MIT. Photo: Tom Gearty, MIT

Communicating with the public

Another notable feature of the negotiations was the careful crafting of all public communications. Reports of high-stakes negotiations generally focus on conflict and mistrust—a unilateral message that engages readers and listeners on both sides but can hinder the process of reaching a mutual resolution. In this case, the two countries agreed to communicate through joint declarations—and to keep those to a minimum. Public releases focused on the real benefits to be seized together, a narrative that gave both sides "victory speeches" they could deliver to their stakeholders and constituents back home.

In addition, PEMEX devised a media campaign that—without mentioning the ongoing negotiations—stressed that production from the usual shallow offshore fields was diminishing and that getting the most out of promising new deepwater fields would require collaboration with international energy companies. The resulting tax revenues would fund pressing education, public health, and security initiatives.

Incentives rather than requirements

The incentives included in the agreement are a remarkable feature derived from the negotiation process itself, according to Verdini. One creative element is the mechanism the binational deal sets up for resolving conflicts. When partner companies are jointly developing a deepwater reservoir, new information can bring the initial allocation of ownership into question, and the partners may not agree on an appropriate redetermination. Mexico wanted such disputes to be settled by an international court, a proposal that for political reasons was unacceptable to the United States.

Working together, the negotiators came up with a dispute-resolution process unlike any other in transboundary deepwater agreements across the world. The process involves three steps: first, a dialogue between industry CEOs; next, mediation aided by neutral third parties; and finally, arbitration by impartial adjudicators who issue a nonbinding ruling. If there's still no agreement, then either of the two governments can step in to stop production. But such a move would mean financial losses of hundreds of millions of dollars, given the investment costs of drilling wells—a strong incentive for the parties not to trigger disputes for mere political reasons and a creative way to reach a resilient agreement without binding resolutions.

Also striking is how the binational deal encourages companies to unitize. Mexico preferred mandated unitization, but the US wouldn't accept such a mandate in light of the precedent it could set against the rule of capture in other parts of the world. That deadlock was broken by an arrangement that may seem surprising but actually demonstrates the deep mutual understanding of the negotiators.

If unitization seems impossible, a company can produce from a transboundary reservoir on its own. However, the agreement states that the company's rights will be based on the estimated percentage of oil resources on its side of the maritime boundary, according to available seismic data—a risky undertaking because seismic estimates before drilling are often incorrect. In addition, it's well known that producing from only one side of the maritime boundary will likely reduce overall recovery rates and thus profits. As a result, the side that begins production first inevitably damages not only the interests of the nonproducing party but also its own.

Since proceeding alone increases the likelihood of subpar outcomes from geological, business, and political perspectives, the agreement provides incentives for unitization without requiring it—an arrangement that's politically feasible and implementable for both sides.

The playbook

Based on his research findings from the Gulf of Mexico and the Colorado River negotiations, as well as a larger review of transboundary water practices around the world, Verdini prepared a practical, step-by-step guide to high-stakes energy, water, and environmental negotiations between developed and developing countries. The guide is graphically presented on page 6 and described in detail in his book.

But identifying those steps was only part of the journey. Verdini now uses his innovative pedagogy in courses and workshops in which all participants—from government leaders and industry executives to students across disciplinary bounds—practice the strategies to further advance their interests without compromising on their principles.

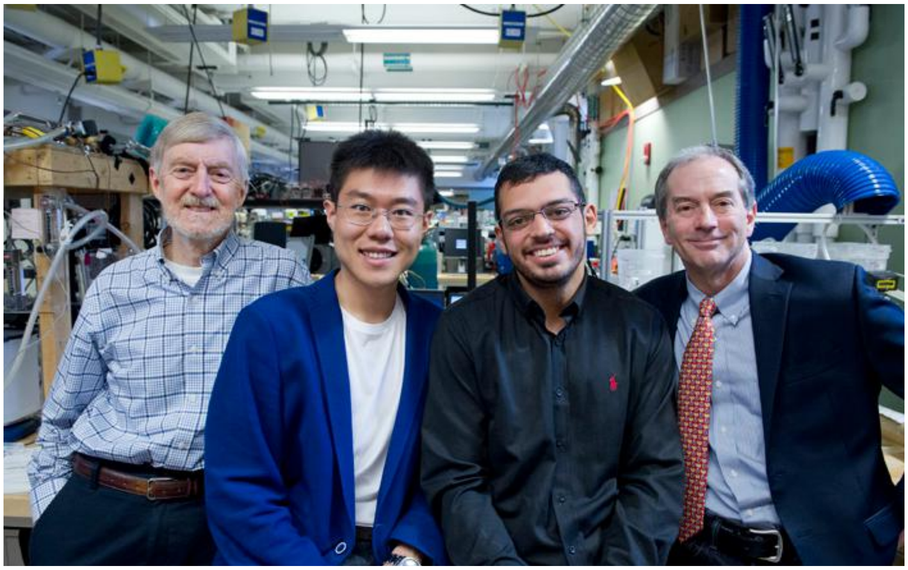
In the end, Verdini wants to empower everyone to be an effective negotiator—as he says, "so you can sit down with someone who might be different from you, who might have different challenges and different priorities, and you can trust that, with these negotiation skills and strategies, you can work together to make the world a better place."

NOTES

This research was supported by the MIT Department of Urban Studies and Planning and the MIT Department of Political Science. Verdini received MIT's first-ever interdisciplinary PhD in Negotiation, Communication, Diplomacy, and Leadership. The research is the recipient of Harvard Law School's award for best research of the year in negotiation, mediation, and conflict resolution, the first time the honor has been awarded to faculty based at MIT. In partnership with several agencies in Mexico, Verdini is now heading the development of a binational negotiation center devoted to training stakeholders and organizations in different fields in the theory and practice of the mutual-gains approach to negotiation. Further information on his research can be found in:

B. Verdini. *Winning Together: The Natural Resource Negotiation Playbook*. The MIT Press, 2017.


NEW YORK
SUBTROPICAL HUMID CLIMATE
DUBAI
TROPICAL DESERT CLIMATE
LAS VEGAS
SUBTROPICAL ARID CLIMATE
SINGAPORE
TROPICAL OCEANIC CLIMATE



Cooling buildings worldwide

Analysis points the way to energy-efficient systems

Nancy W. Stauffer, MITEI

IN BRIEF

A fundamental analysis by MIT researchers confirms that proposed new approaches to air conditioning could significantly reduce the energy required to cool and dehumidify indoor spaces—an escalating need as populations grow and the climate warms. Today's air conditioners dehumidify by condensing water vapor out of air, an inherently energy-inefficient process. The researchers' study focuses on systems that instead use desiccant materials that naturally adsorb moisture or membranes that let water vapor molecules, but not air, pass through. Their thermodynamic analyses show that those technologies can yield high efficiencies—but only when they're incorporated into carefully designed systems with integrated heat-recovery devices. The results also demonstrate that a system's performance can vary significantly at different ambient temperatures and humidity levels. Matching the technology to the climate is thus critical.

About 40% of all the energy consumed by buildings worldwide is used for space heating and cooling. With the warming climate as well as growing populations and rising standards of living—especially in hot, humid regions of the developing world—the level of cooling and dehumidification needed to ensure comfort and protect human health is predicted to rise precipitously, pushing up global energy demand.

Much discussion is now focusing on replacing the greenhouse gases frequently used as refrigerants in today's air conditioners. But another concern is

Facing page MIT researchers found that the performance of a given air conditioning system design varied depending on ambient temperature and humidity level. As a practical test, they analyzed selected designs under conditions representing the climates of the four cities highlighted at the left. In general, the designs would out-perform today's air conditioners, but the highest-performing system varied from city to city. Graphic: Jenn Schlick, MITEI

Above From left: Professor Leslie Norford, graduate students Tianyi Chen and Omar Labban, and Professor John Lienhard performed fundamental studies of systems for cooling and dehumidifying indoor spaces. Chen and Labban began the work when they teamed up for an assignment in an advanced energy conversion class taught by Professor Ahmed Ghoniem (not pictured). Photo: Stuart Darsch that most existing systems are extremely energy-inefficient. “The main reason they’re inefficient is that they have two tasks to perform,” says Leslie Norford, the George Macomber (1948) Professor in Construction Management in the Department of Architecture. “They need to lower temperature and remove moisture, and doing both those things together takes a lot of extra energy.”

The standard approach to dehumidification is to run cold water through pipes inside a building space. If that water is colder than the dew-point temperature, water vapor in the air will condense on the outer surfaces of the pipes. (Think of water droplets beading up on a cold soda can on a hot, humid day.) In an air conditioning system, that water may drop off outside or—in a large-scale system serving a building—into a collection pan.

The problem is that running a chiller to get water that cold takes a lot of electricity—and the water is far colder than needed to lower the temperature in the room. Separating the two functions brings energy savings on two fronts. Removing moisture from outdoor air brought into the building requires cold water but far less of it than is needed to remove heat from occupied areas. With that job done, running cool (not cold) water through pipes in the ceiling or floor will maintain a comfortable temperature.

While working at the Masdar Institute in Abu Dhabi a decade ago, Norford and his colleagues confirmed the energy benefits of maintaining comfortable temperatures using cool-water pipes in the room—especially when indoor spaces are pre-cooled at night, when electricity is cheap and the outside air is cool. But the dehumidification process remained inefficient. Condensing water vapor is inherently energy-intensive. The researchers needed to find another way to remove humidity.

Borrowing from desalination systems

Two years ago, a promising alternative was brought to Norford’s attention by John Lienhard, MIT’s Abdul Latif Jameel Professor of Water and Mechanical Engineering, and Norford’s colleague at the Center for Environmental Sensing and Modeling, a research group at the Singapore-MIT Alliance for Research and Technology. Lienhard was working on energy-efficient technologies for desalination. Boiling seawater to precipitate the salt is very energy-intensive, so Lienhard’s group was looking instead at using “semipermeable” membranes that let water molecules through but stop salt ions. Norford thought a similar membrane could be designed that allows water vapor molecules to pass through so they can be separated from other, larger molecules that make up the indoor air.

That concept became the subject of a project undertaken by two mechanical engineering graduate students: Tianyi Chen, who was working with Norford on the impacts of outdoor airflows on building energy performance, and Omar Labban, who was collaborating with Lienhard on using membranes in desalination systems. The students met in an advanced energy conversion class taught by Ahmed Ghoniem, the Ronald C. Crane (’72) Professor of Mechanical Engineering. Paired up for a class project, they identified air conditioning as a topic that would draw on their respective areas of research interest and use their newly acquired expertise in thermodynamic modeling and analysis.

Their first task was to develop a thermodynamic model of the fundamental processes involved in air conditioning. Using that model, they calculated the theoretical “least work” needed to achieve dehumidification and cooling. They could then calculate the so-called second-law efficiency of a given technology, that is, the ratio of the theoretical minimum to its actual energy consumption. Using that metric as a benchmark, they could perform a systematic, consistent comparison of various designs in different climates.

As an industrial benchmark for comparison, they used the coefficient of performance (COP), a metric that shows how many units of cooling are provided for each unit of input electricity. The COP is used by today’s manufacturers, so it could show how different designs might perform relative to current equipment. For reference, Norford cites the COP of commercially available systems as ranging from 5 to 7. “But manufacturers are constantly coming up with better equipment, so the goalposts for competitors are continually moving,” he notes.

Examining the status quo

Norford’s earlier research had shown that cool-water pipes in the ceiling or floor can efficiently handle indoor cooling loads—that is, the heat coming from people, computers, sunlight, and so on. The researchers therefore focused on removing heat and moisture from outdoor air that’s brought in for ventilation.

They started by examining the performance of a commercially available air conditioner—the standard vapor-compression system (VCS) that has been used for the past century. Their analysis quantified the inefficiency of not separating temperature and humidity control. Further, it pinpointed a major source of that inefficiency: the condensation process.

Using their model, the researchers ran tests to see how performance changed under various assumptions of outdoor temperature and humidity level, thus how well the VCS unit might do in different climates. Not surprisingly, it was least efficient in cool, humid conditions and improved as conditions got hotter and drier. But at its best, the design used five to ten times more energy than the theoretical minimum required. Thus, there was significant opportunity for improvement.

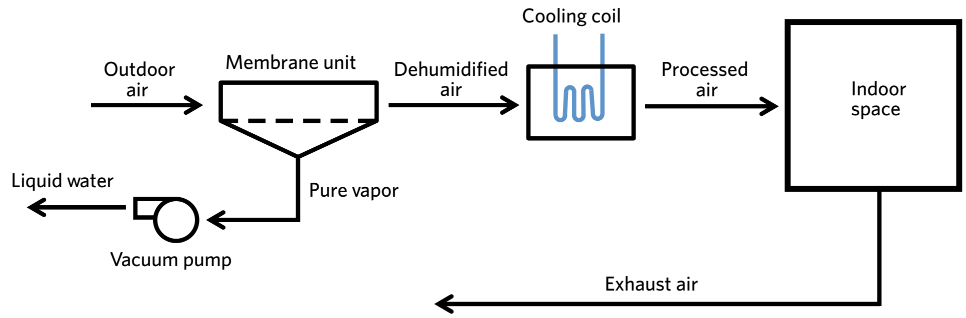
Membranes and desiccants

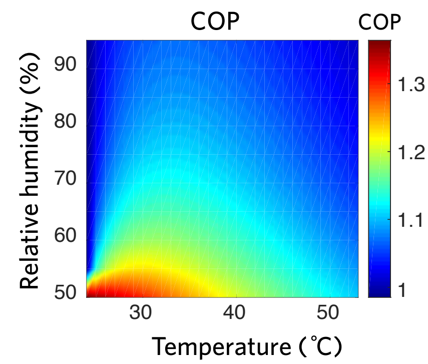
The researchers next considered the membrane technology. The schematic diagram and caption on this page present the simplest membrane-based design they analyzed. Outdoor air enters the membrane unit, and a vacuum pump pulls the water vapor across the membrane. The pump then raises the pressure to ambient levels so the water vapor becomes liquid water before being ejected from the system. The no-longer-humid outdoor air passes from the membrane unit through a conventional cooling coil and enters the indoor space, providing fresh air for ventilation and pushing some warmer, humid exhaust air outdoors.

The colored chart on this page shows the COP of that system under different combinations of temperature and relative humidity. The best performance occurs in relatively dry conditions, but even then it achieves a COP of only 1.3—not high enough to compete with a current system. The problem is that running the vacuum pump with high compression ratios consumes a lot of energy.

To push up the COP of the membrane system, the researchers tried adding more components to help cool the incoming air stream. For example, they inserted a heat exchanger to transfer heat from the warm incoming air to the cool exhaust air. And they added a condenser to turn water vapor captured by the membrane unit into cool water for the cooling coil. Making those changes brought the COP up to 2.4—better but not high enough.

The researchers next considered options using desiccants—materials that have a strong tendency to adsorb water and are often packed with consumer products to keep them dry. In air conditioning systems, a desiccant coating is typically mounted on a wheel that's positioned between the incoming and exhaust airflows. As the wheel rotates, a portion of the desiccant first passes through the incoming air and adsorbs moisture from it. It then passes through the heated exhaust air, which dries it so it's ready to adsorb more moisture on its next pass through the incoming air.





Membrane-based cooling system with vacuum pump At the core of this design is a unit containing a membrane that allows water vapor molecules to pass through but stops other molecules in the incoming air. Outdoor air enters the membrane unit, and a vacuum pump sucks the water vapor out, then raises the air pressure and expels the liquid water that forms. The air exiting the membrane unit then passes through a cooling coil and enters the indoor space. Warmer, humid air from that space is vented outdoors. The colored chart shows the coefficient of performance (COP) of the system at various combinations of ambient temperature and humidity.

The researchers began by analyzing several systems incorporating a desiccant wheel, but the gains in COP were limited. Using an evaporative cooling system in place of the cooling coil pushed up the COP, especially under hot, dry conditions. However, evaporative cooling requires abundant water supplies, so it's impractical in some regions of the world.

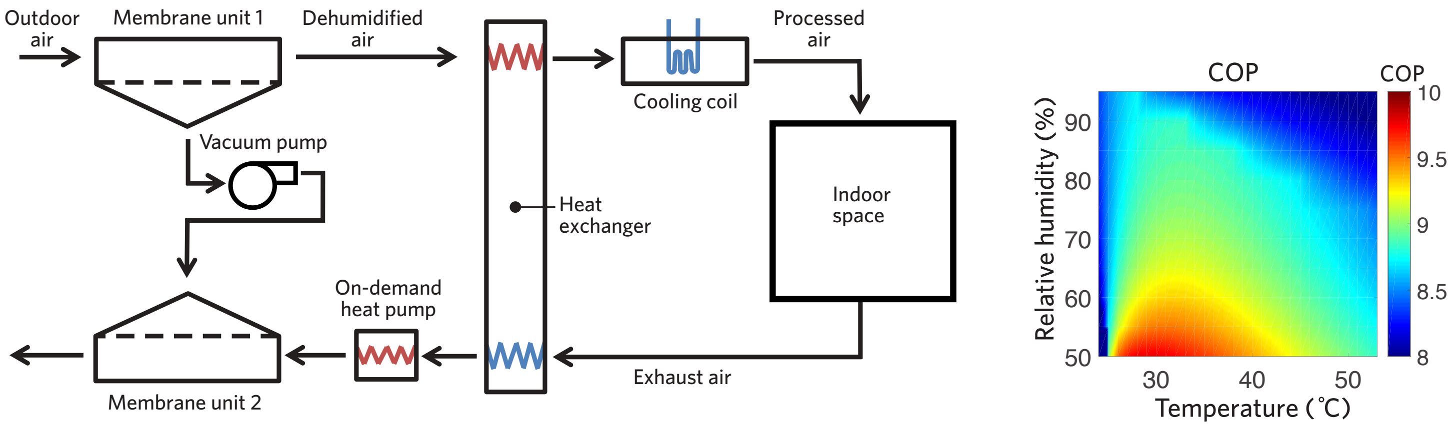
They next tried using the desiccant and membrane technologies together. In this design, a desiccant wheel, a membrane moisture exchanger, and a heat exchanger all transfer moisture and heat from the incoming air to the exhaust air. A cooling coil further cools the incoming air before it's delivered to the indoor space. A heat pump warms the exhaust air, which then passes through the desiccant to dry and regenerate it for continued use.

This complicated "hybrid" system yields a COP of 4 under a wide range of temperatures and humidity. But that's still not high enough to compete.

Two-membrane system

The figure on page 16 shows another configuration that the researchers examined. This novel system omits the desiccant wheel but includes two membrane units, producing a design that's relatively simple but more speculative than the others.

The key new concept here involves the fate of the water vapor in the incoming air stream. As in the system shown on this page, a vacuum pump pulls the water vapor through a membrane—now called membrane unit 1. But the captured water vapor is then pushed across the membrane in unit 2 and joins the exhaust air stream—without ever turning into liquid water.



Two-membrane system In this system, incoming air passes through membrane unit 1, a heat exchanger, and a cooling coil, which together dehumidify and cool it before it's delivered to the indoor space. As in the system shown on page 15, a vacuum pump pulls water vapor molecules out of the incoming air. But in this design, the pump raises the pressure not to an ambient level but just enough to exceed the vapor pressure below membrane unit 2. The resulting pressure difference pushes the water vapor through membrane unit 2 and into the exhaust air stream—without condensing it. Exhaust air from the indoor space passes through the heat exchanger and then through a heat pump, which operates only when the exiting air is saturated, thereby ensuring that vapor doesn't condense and foul the surfaces in membrane unit 2. This novel design achieves a COP of 9 or more under a range of climate conditions.

In this arrangement, the vacuum pump only has to ensure that the vapor pressure is higher on the upstream side of membrane 2 than it is on the downstream side so that the water vapor is pushed through. There's no need for raising the pressure to ambient levels, which would condense the water vapor, so running the vacuum pump takes less work. As the colored chart shows, that novel approach results in a COP that can reach as high as 10 and achieves a COP of 9 at many combinations of temperature and humidity.

Different options for different cities

For most of the systems analyzed, performance varies at different combinations of ambient temperature and humidity level. To investigate the practical impact of that variability, the researchers examined how selected systems would perform in four cities with different climates. In each case, the analysis assumed an average summertime outdoor temperature and relative humidity.

In general, the systems they considered outperformed the conventional VCS operating at COPs consistent with current practice. For example, in Dubai (representing a tropical desert climate), using the hybrid membrane-desiccant system could reduce energy consumption by as much as 30% relative to the standard VCS. In Las Vegas (a subtropical arid climate), where humidity is lower, a desiccant-based system (without the membrane) is the most efficient option, potentially also bringing a 30% reduction. In New York (a subtropical humid climate), all the designs look good, but the desiccant-based system does best with a 70% reduction in overall energy consumption. And in Singapore (a tropical oceanic climate), the desiccant system and the combined membrane-desiccant system do equally well, with a potential savings of as much as 40%—and given the costs of the two options, the desiccant-alone system emerges as the top choice.

Taken together, the researchers' findings provide two key messages for achieving more-efficient indoor cooling worldwide. First, using membranes and desiccants can push up air conditioner efficiency, but the real performance gains come when such technologies are incorporated into carefully designed and integrated systems. And second, the local climate and the availability of resources—both energy and water—are critical factors to consider when deciding what air conditioning system will deliver the best performance in a given area of the world.

NOTES

This research was supported by the National Research Foundation–Singapore under its Campus for Research Excellence and Technological Enterprise program. The Center for Environmental Sensing and Modeling is an interdisciplinary research group of the Singapore–MIT Alliance for Research and Technology. Further information can be found in:

O. Labban, T. Chen, A.F. Ghoniem, J.H. Lienhard V, and L.K. Norford. "Next-generation HVAC: Prospects for and limitations of desiccant and membrane-based dehumidification and cooling." *Applied Energy*, v. 200, pp. 330-346, 2017.

Fabrication of new materials

Designing “recipes” using artificial intelligence

Nancy W. Stauffer, MITEI

IN BRIEF

MIT researchers and their collaborators have demonstrated a novel system using artificial-intelligence techniques to help identify methods of fabricating materials, especially those that look promising in computer simulations. In one test, the system scanned half a million journal articles, recognized those that contained “recipes” for synthesizing various metal oxides, and produced a massive dataset of parameters such as operating temperatures and times. It then scanned the dataset to find patterns that highlight critical parameters. In a test focusing on one compound, the system generated values for certain operating conditions that are realistic but don’t appear anywhere in the literature. Thus, with no guidance, the system leveraged the database to come up with a novel recipe that could be tested in a lab. The researchers are now working to improve the system’s accuracy and to refine its user interfaces so that experts can easily interpret the results, interact with the system, and select directions for further investigation.

During the past decade, much progress has been made in using computer modeling methods to identify new materials with properties optimized for a particular application. Computationally designed materials have been identified for the fields of energy storage, catalysis, thermoelectrics, hydrogen storage, and more.

“Given that we can now identify promising new materials through computer modeling, the bottleneck in materials development has become figuring out how to make them,” says Elsa Olivetti, the Atlantic Richfield Assistant Professor of Energy Studies in the Department of

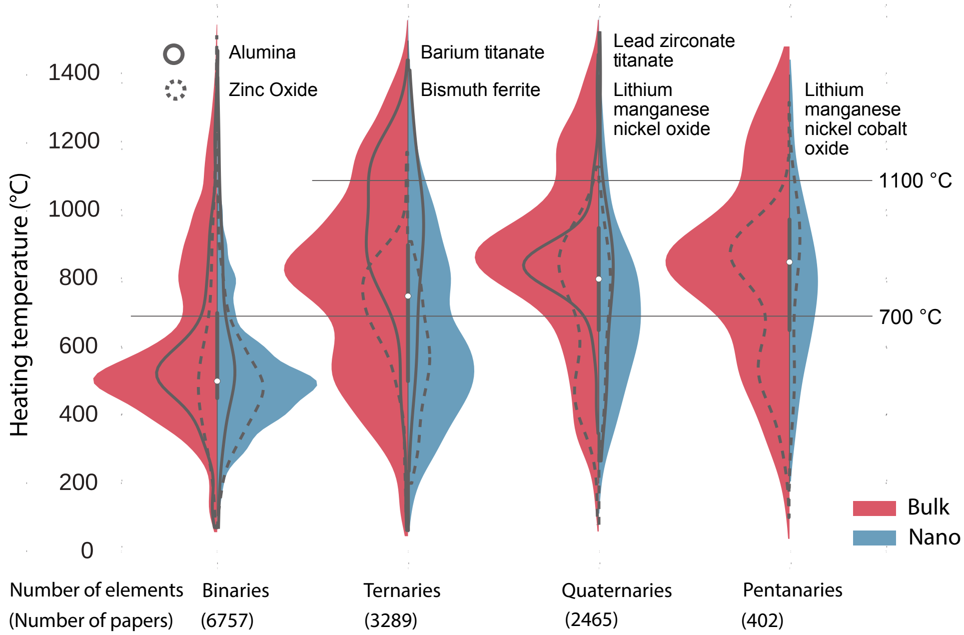
Above Professors Stefanie Jegelka (left) and Elsa Olivetti have developed a new method of formulating procedures for making novel materials for energy and other applications. Key to their method is a natural language processing system that can quickly search thousands of articles in past journals and pick out descriptions of procedures for making specific types of materials. A specially designed neural network then searches the resulting database for patterns that can help guide the materials-development process. Photo: Stuart Darsch

Materials Science and Engineering (DMSE). Synthesizing a new compound suggested by theory can be quite challenging—even in the laboratory. Developing a commercially viable procedure for its large-scale synthesis can take months or even years.

Three years ago, Olivetti and her MIT colleague Gerbrand Ceder, then the R.P. Simmons Professor in Materials Science and Engineering, began discussing whether artificial-intelligence techniques could help identify what Olivetti calls "recipes" for making specific materials. If successful, such an approach could generate recipes for making materials that have been identified through simulation but never before made. And perhaps eventually it could identify more efficient or less costly ways to make known materials.

At about that time, Olivetti learned that Elsevier, a major publisher of scientific journals and books, was opening all of its materials for text- and data-mining activities. She then contacted Andrew McCallum, a professor in the Computer Science Department at the University of Massachusetts at Amherst and a world-renowned expert in natural language processing. Olivetti thus gained access to a wealth of source material and a colleague with the expertise needed to test out her idea.

Joining them in this investigation has been a team including Edward Kim, an MIT graduate student in DMSE; Kevin Huang, a DMSE postdoc; Adam Saunders, another computer scientist at UMass Amherst; Ceder, now a Chancellor's Professor in the Department of Materials Science and Engineering at the University of California at Berkeley; and Stefanie Jegelka, the X-Consortium Career Development Assistant Professor in MIT's Department of Electrical Engineering and Computer Science.



Demonstrating the natural language processing system By analyzing half a million journal articles, the system found almost 13,000 synthesis procedures for making metal oxides. This figure displays the heating temperatures used for making specific compounds, superimposed to form histograms whose width reflects the number of occurrences. Results are divided into four categories based on how many elements are combined with oxygen. Nanostructured target materials appear in blue, "bulk" materials in red. Solid and dashed curves show results for selected compounds in each category. Horizontal rules mark two arbitrary temperatures for ease of comparison. In general, temperatures are lower when fewer compounds are combined and when nanostructured materials are targeted—observations that confirm the system's ability to pick out and sort relevant data.

A database of recipes

The researchers' first challenge was to develop a computer-based system that could automatically examine thousands of papers and recognize, extract, and organize information relevant to materials synthesis. Since there are many ways to describe methods within the text, the team couldn't define restrictive yet comprehensive rules for reliably spotting the relevant words or combinations of words. They therefore developed a natural language processing system that—with training—could learn to perform the task.

During an analysis, the system examines each research paper, identifies paragraphs that include synthesis information, and then classifies words in those paragraphs according to their roles, for example, compound names or operating parameters. By analyzing the collected data, the system can infer general classes of materials, such as those requiring the same synthesis conditions or those with a similar physical structure.

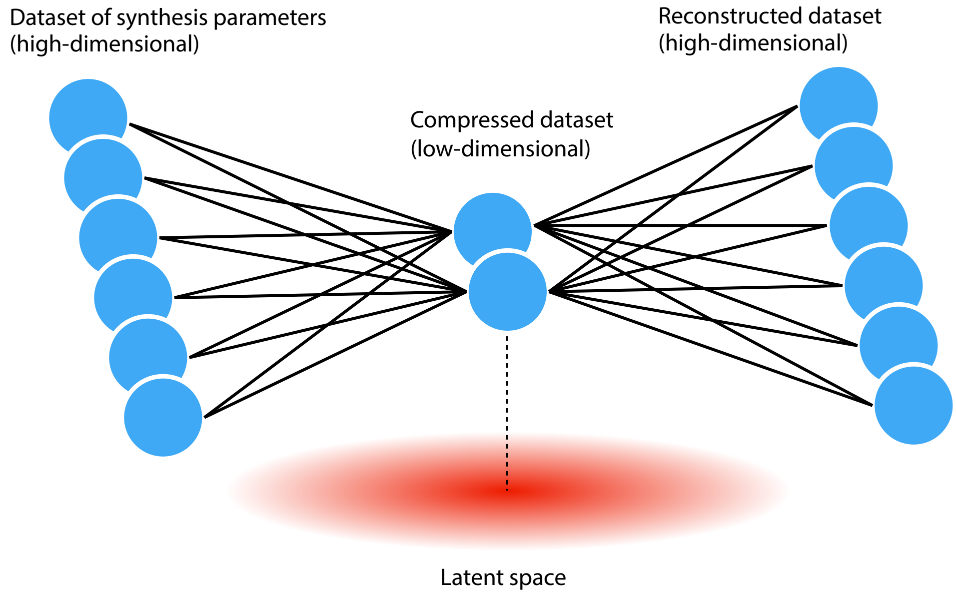
To demonstrate the system's capabilities, the researchers applied it to half a million journal articles to find those describing the synthesis of various metal oxides. They then prepared the figure above, which shows the heating temperatures used in 12,913 recipes for synthesizing metal oxides. The results appear in four groups based on the number of constituent elements. The binaries combine oxygen with one element, the ternaries with two, and so on. Recipes aimed at making a nanostructured material appear in blue; those targeted at materials made in "bulk" (with no nanostructure) are shown in red.

Several observations confirm that the retrieved dataset conforms to expectations. For example, the world has published more about alumina made in bulk than alumina made with a nanostructure.

"That distribution makes sense because we tend to use alumina as a refractory material, so we're going to use it more in bulk form," says Olivetti. The opposite is true for zinc oxide, where nano-architectures are required for applications such as sensors and optoelectronics.

The expected correlation between temperature and complexity is also evident. Higher temperatures occur more frequently in cases where multiple metals must mix up and react. And in the nano examples, temperatures are generally kept as low as possible to prevent crystals from growing.

Olivetti notes that this figure is meant only as a demonstration. "The plot was generated from the material our system pulled out of the literature automatically," she says. "So we used this as a way to say, does what we're learning make any sense?" And it does.



Schematic diagram of the variational autoencoder This diagram shows the architecture of the variational autoencoder. The blue dots at the left represent the high-dimensional dataset of synthesis parameters gathered from the literature. The job of the autoencoder is to find patterns in the data that enable it to compress the full dataset down to two (or a few) dimensions, as shown by the two dots at the center. Given only the compressed data, it must be able to reconstruct the full original dataset. The low-dimensional "latent space" produced during the compression process thus captures key features of the data, generating results that can be displayed on a graph with only X and Y axes.

Mining the database

The researchers' next task was to mine their database to explore different recipe options and suggest new ones. The natural language processing system maps words or phrases from the vocabulary into real numbers, creating a sort of "recipe space" that includes all the parameters for each recipe—temperature, precursor materials, and so on. But getting guidance from that database is difficult. With just two parameters—say, temperature and pressure—the data can easily be plotted using X and Y axes on a two-dimensional graph. Three parameters can be handled by adding a Z axis, making a three-dimensional space that's still fairly easy to comprehend. But here there are many, many parameters forming a "high-dimensional" dataset.

While such a dataset may appear unfathomable, it does actually have patterns hidden in it—underlying relationships between synthesis conditions and the materials produced. The key is to find a way to save the information based on those patterns rather than every data point. And that compressed representation must be good enough that it can be expanded to reconstruct the original information without losing any key features.

The best method to perform that task is to use an artificial-intelligence system called a neural network—a technique that's part of Jegelka's research in machine learning. A neural network consists of layers of interconnected units, or "nodes," each of which performs a simple computation and passes the result to the nodes above it. The connections between nodes of different layers are weighted so that each node has a lot, a little, or no influence on the activation of the next node up. Those weights are determined by flowing training data through the network. To train a network for a particular task, the developer selects well-defined datasets where the true output of the analysis is known. The lowest nodes in the network receive numerical inputs, and in an iterative process, the system automatically adjusts the weights until the final output matches desired values. The network is then ready to perform a similar type of analysis on an unknown dataset.

Challenges for neural networks

However, there are challenges with using neural networks to explore materials syntheses. One problem is that there are lots of zeros in the recipe space. Consider just the precursor. For the computer to analyze the dataset, it needs a position (a coordinate) for every possible precursor. But a given recipe will use only a few of the precursors that appear in the literature. As a result, during an analysis of the whole dataset, the computer will encounter lots of zeros—a problem the researchers call sparsity. Such sparse, high-dimensional data points are likewise hard for a human to make sense of.

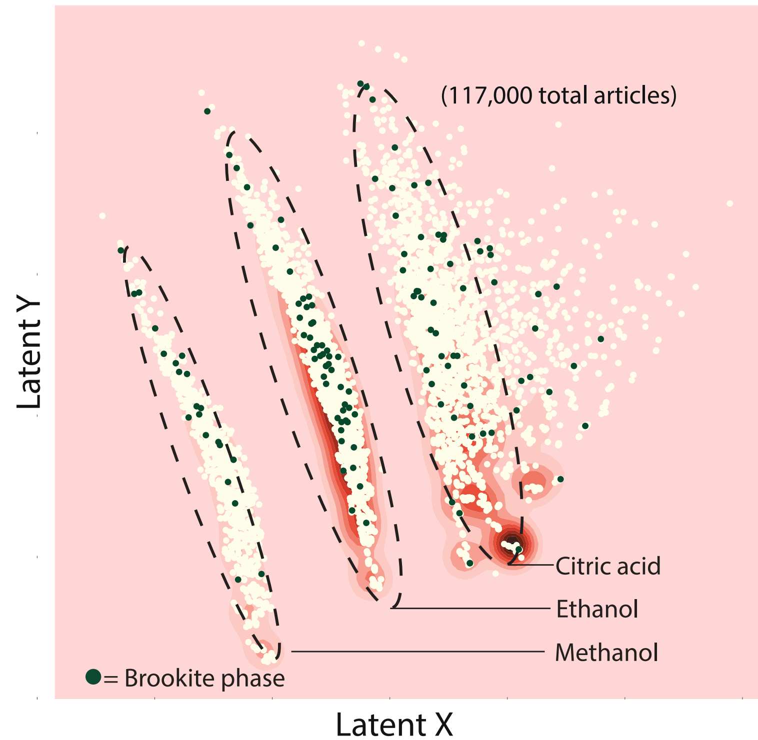
"Because of our data limitations, we use a relatively simple neural network called an autoencoder that can visualize the data in a way that's meaningful for a human expert," says Jegelka. As illustrated in the diagram on page 19, the autoencoder gets the high-dimensional dataset—represented by the blue dots at the left—down to a lower-dimensional dataset—represented by the two dots at the center—that captures the most important aspects of the full dataset. Given an array of input data, the autoencoder learns an encoding model with parameters and weights that can compress the data to two (or a few) dimensions and then a separate decoding model that can take the compressed data as input and reconstruct the original high-dimensional dataset. Since the small number of dimensions at the center restricts the encoding power, the autoencoder is forced to focus on important patterns. Thus, given a full dataset, the autoencoder finds hidden patterns and generates the needed models.

Based on the center encoding, the model creates a so-called "latent space"—the pink area at the bottom of the figure. In this (two-dimensional) space, each of the original input values is represented as a point that can be plotted on two axes—"latent X" and "latent Y." "By analyzing a layout of those data points on a graph, we can learn a lot," says Olivetti.

Jegelka notes one more feature of their neural network: It's a "variational" autoencoder, which means that the model aims to make the low-dimensional representation of the training data look like a standard distribution—in this case, the familiar bell curve. "As a result, a user can sample a point in the latent space and use just the decoding model to generate a new, realistic synthesis recipe," says Jegelka.

Augmenting the dataset

Before using their autoencoder, the researchers had to address one more problem: scarcity. While the synthesis dataset is massive, it may actually include only a few recipes for making certain materials, especially new ones. To deal with that issue, the researchers developed a data augmentation methodology that involves training the autoencoder on recipes for producing not only the specified target material but also materials that are similar to it.



Mapping of two-dimensional latent space from analysis of titanium dioxide synthesis
This plot shows results from an analysis of synthesis procedures for making titanium dioxide, with the compressed dataset mapped onto latent X and latent Y axes. The results fall into three distinct clusters. Further analysis showed that the groupings are dominated by the solvent used: methanol, ethanol, or citric acid. Moreover, almost all of the syntheses involving a given solvent fall into the same cluster. For example, 95% of ethanol-using syntheses appear in the ethanol-labeled cluster. The darkened dots indicate syntheses that form a less common crystalline structure called brookite. Many of them fall into the ethanol cluster, indicating that ethanol may be a preferred solvent for making brookite but that other solvents also work.

In one example, they targeted strontium titanate ($SrTiO_3$), a material used in devices such as capacitors and resistors. Text-mining the literature yielded only 200 temperatures, solvent concentrations, and other descriptors—not enough for a good analysis.

To augment that dataset, they used Word2vec—an algorithm developed at Google—to find materials that appear in similar contexts across journal articles. For example, if recipes for $SrTiO_3$ and another material call for heating to the same temperature, the two materials are linked in the augmented dataset. To further refine the augmented dataset, those related materials are then ranked by how similar they are to $SrTiO_3$ in certain key features of their composition. The higher the similarity, the higher the weight given to those recipes during the $SrTiO_3$ analysis.

As a test, the researchers used the augmented dataset for $SrTiO_3$ plus their variational autoencoder to come up with novel synthesis recipes for making that compound. The autoencoder produced results that mimicked actual recipes well. With no guidance, it defined appropriate categories of operating conditions and generated values for those conditions that look realistic. "So the machine seems to figure out that you need a time and a temperature, and it assigns them in pairs appropriately," says Olivetti. "We didn't explicitly tell it that."

Learning from the latent space

To demonstrate the power of the latent space, the researchers used their overall system to analyze the synthesis of titanium dioxide (TiO_2), a material widely used in photocatalysts and electrodes. The latent space produced should reflect the most important features of the full TiO_2 dataset. Examining it should therefore show what key parameters drive the synthesis of TiO_2 and what factors determine whether the product has a particular crystalline structure. The literature contains many recipes for making the "anatase" and "rutile" form of TiO_2 but few for making the "brookite" form, which is of interest as a potential photocatalyst. What causes the brookite structure to form?

To find out, they used their autoencoder to generate the two-dimensional latent space and then plotted the points, producing the figure on page 20. Interestingly, the recipes fall into three general clusters. With further analysis, the researchers determined that the synthesis parameter dominating each cluster was the solvent used: methanol, ethanol, or citric acid. Many of the darkened dots indicating formation of the brookite version fall within the ethanol cluster, but some are elsewhere, suggesting that ethanol may be a preferred but not critical solvent for brookite synthesis.

Olivetti stresses again that the autoencoder identified that pattern on its own. "We didn't say, give me the solvent that you're dominated by," she says. "We just said, plot yourself in this lower-dimensional space."

Next steps

Thus far, the researchers have been reproducing computationally what's been observed in theoretical and experimental work. "So we have a new approach, but we haven't used it to actually make something new based on a method we've mined from the recipes," says Olivetti. "That will be the next thing."

Olivetti and Jegelka also hope to engage materials-development experts in efforts to further improve their system. Among their goals are finding a way to factor in the knowledge, experience, and intuition of such experts and designing an interface that will allow them to interpret the results and to try out other options. "We aren't looking to replace conventional theoretical studies and high-throughput experimentation. That's all still critical," Olivetti says. "I view our system as another source of information that the experts can leverage in their search for better materials."

NOTES

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E. Kim, K. Huang, S. Jegelka, and E. Olivetti. "Virtual screening of inorganic materials synthesis parameters with deep learning." *npj Computational Materials*, vol. 3, no. 53, 2017. DOI: 10.1038/s41524-017-0055-6.

E. Kim, K. Huang, A. Saunders, A. McCallum, G. Ceder, and E. Olivetti. "Materials synthesis insights from scientific literature via text extraction and machine learning." *Chemistry of Materials,* vol. 29, no. 21, pp. 9436–9444, 2017.

Getting the world off dirty diesels

Gasoline-alcohol engines for heavy-duty trucks

Nancy W. Stauffer, MITEI

IN BRIEF

Using computer simulation analysis, MIT researchers have developed a conceptual design for a half-sized gasoline engine that would be as efficient and powerful as the full-sized diesel engines now used in heavy-duty trucks—without their high emissions of air pollutants and greenhouse gases (GHGs). The small, highly turbocharged, spark-ignition engine gets an extra boost from injected alcohol when it needs to work hard to move a heavy load, especially while accelerating or climbing a hill. The computer analyses show that the gasoline-alcohol design could slash emissions of nitrogen oxides by 90% and also increase power by up to 50%. Cutting the injected alcohol by mixing it with water or making other changes could reduce alcohol consumption. But if reducing GHGs is a priority, the engine could instead run on 100% ethanol or renewable methanol. The engine requires modest changes to an existing engine, so it could come into commercial use quickly and at lower cost than comparable diesels.

Most efforts to reduce the adverse air pollution and climate impacts of today's vehicles focus on cars and light-duty trucks typically fueled by gasoline, with strategies that range from electrification and carpooling to autonomous vehicles. "These strategies can be an important part of the overall solution," says Daniel Cohn, research scientist at the MIT Energy Initiative. "But it's also increasingly important to think about heavy- and medium-duty trucks. Finding a way to clean them up could actually bring a greater improvement in worldwide air quality during the next few decades."

Above Several years ago, Daniel Cohn (left) and Leslie Bromberg took on the challenge of designing a low-emissions, fuel-efficient replacement for the polluting diesel engines traditionally viewed as the only viable option for powering today's 18-wheelers and other heavy-duty trucks. Using a series of sophisticated computer models developed by Bromberg, they've now produced a conceptual design for an engine that should be up to the task. Photo: Stuart Darsch

Powered largely by diesel engines, those trucks are now the largest producer of nitrogen oxide (NO_x) emissions in the transportation sector, contributing to ground-level ozone, respiratory problems, and premature deaths in urban areas. Some estimates project that diesel fuel—used for both trucks and cars—will out-sell gasoline worldwide within the next decade, threatening to further increase already-severe urban air pollution as well as GHG concentrations.

Today's heavy-duty diesel engines provide fuel efficiency and high power, making them ideal for long-haul, high-mileage commercial vehicles. But finding another option is critical, says Cohn. "We need to replace diesel engines with other internal combustion engines that are much cleaner and produce less greenhouse gas."

Cohn and his colleague Leslie Bromberg, principal research engineer at the Plasma Science and Fusion Center and the Sloan Automotive Laboratory, have designed a replacement that should be not only cleaner but also lower-cost and higher-performing—and could be introduced into the fleet of vehicles on the road soon.

Replacing the heavy-duty diesel

Within the United States, pressure on the trucking industry to deal with diesel emissions has been mounting. Indeed, expected regulations in California would require that NO_x emissions from medium- and heavy-duty trucks be cut by about 90% relative to today's cleanest diesels, which use complex and expensive exhaust treatment systems just to meet current regulations. In some parts of the world, such as India and China, those cleanup systems aren't generally used. As a result, NO_x emissions are about 10 times higher, and getting them down to the level of future California regulations would require a reduction of about 98%.

In the United States, some trucks have begun to meet the expected strict NO_x limits using large spark-ignition (SI) engines fueled by natural gas. But large-scale adoption of those engines would be problematic. Storing and distributing a gaseous fuel raises vehicle cost and poses infrastructure challenges, and the use of natural gas can lead to a heightened climate impact because of the leakage of methane, a GHG with high global warming potential.

	Gasoline-alcohol	Diesel
Engine size (liters)	6.7	12
Compression ratio	12	14
Operation	Stoichiometric	Excess air
Rated power (kilowatts)	460	323
Rated torque (newton meters)	2050	2000
Maximum engine speed (rpm)	2500	1850

Comparison of the gasoline-alcohol engine and a full-sized diesel engine (see page 24)

To avoid the challenges of dealing with natural gas, Cohn and Bromberg decided to pursue another approach: a heavy-duty SI engine fueled instead by gasoline. In general, gasoline SI engines produce low NO_x emissions. Guided by their computer models, Cohn and Bromberg took a series of steps to increase the power and efficiency of that design—without sacrificing its emissions benefits.

A quick overview of the processes inside an engine will help clarify the changes they made. During normal operation, burning of the air-fuel mixture in the engine cylinder is started either using a spark or—in a diesel engine—by compressing the combustion gases until they spontaneously ignite. The burning gases then push down the piston, and a system of rods translates that downward motion into a rotational force called torque. Aided by gears in the transmission, that engine torque turns into torque at the wheels. Increasing the engine torque or running the engine faster—or both—will increase power at the wheels.

Inside a typical gasoline SI engine, that process progresses smoothly—until there's a need for high-torque operation. Then, pressures and temperatures inside the cylinder can rise so much that the unburned combustion gases spontaneously ignite. The result is "knock," which causes a metallic clanging noise and can damage the engine. The need to prevent knock has up to now limited improvements in efficiency and performance that would be needed for gasoline engines to compete with diesels.

Cohn and Bromberg dealt with that problem using alcohol. When the SI engine is working hard and knock would otherwise occur, a small amount of ethanol or methanol is injected into the hot combustion chamber, where it quickly vaporizes, cooling the fuel and air and making spontaneous combustion much less likely. In addition, because of alcohol's chemical composition, its inherent knock resistance is higher than that of gasoline. The alcohol can be stored in a small, separate fuel tank—as exhaust-cleanup fluid is stored in a diesel engine. Alternatively, it could be provided by onboard separation of alcohol from the gasoline in the regular fuel tank. (Almost all gasoline sold in the US is now a mix of 90% gasoline and 10% ethanol.)

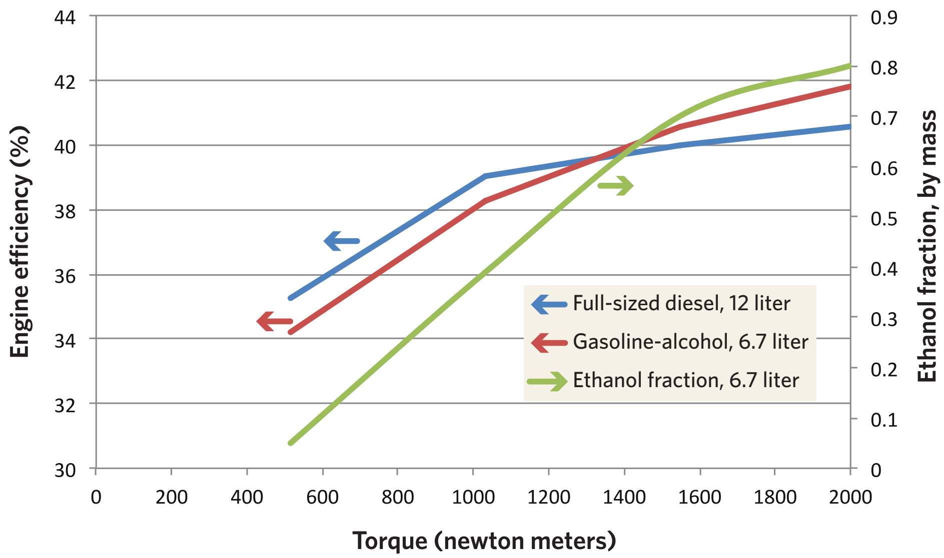
With concern about knock removed, the researchers were able to take full advantage of two techniques used in today's passenger cars. First, they used turbocharging, but at higher levels. Turbocharging involves compressing the incoming air so that more molecules of air and fuel fit inside the cylinder. The result is that a given power output can be achieved using a smaller total cylinder volume. And second, they used a high compression ratio, which is the ratio of the volume of the combustion chamber before compression to the volume after. At a higher compression ratio, the burning gases expand more in each cycle, so more energy is delivered for a given amount of fuel.

The researchers also made use of an important feature of the low-NO_x heavy-duty SI engine fueled by natural gas: They assumed that the mixture of air and fuel inside their engine contained just enough air to burn up all the fuel—no more, no less. That "stoichiometric" operation permitted important changes not possible in the diesel, which must run with lots of extra air to control emissions. With stoichiometric operation, they could utilize a three-way catalyst to clean up the engine exhaust. A relatively inexpensive system, the three-way catalyst removes NO_x, carbon monoxide, and unburned hydrocarbons from engine exhaust and is key to the low NO_x achieved in today's SI engines.

Then, given stoichiometric operation combined with a higher level of turbo-charging and a high compression ratio, the researchers were able to shrink their whole engine. The SI engine doesn't contain all the excess air that's in a diesel, so the total volume of its cylinders can be smaller. "Because of that difference, you can replace a diesel engine with an SI engine about half as big," says Bromberg.

With that reduction in size comes an increase in fuel efficiency. In any engine, the process of pumping air into the cylinders and various sources of friction inevitably reduce fuel efficiency. Those pumping losses depend on engine size. Make an engine smaller, and there's less friction and less wasted fuel.

Taken together, the low-cost three-way catalyst and smaller overall size help make the gasoline-alcohol engine less expensive than the cleanest diesel engine with a state-of-the-art exhaust cleanup system. Indeed, according to the researchers' estimates, the cost of the gasoline-alcohol engine plus its exhaust-treatment system



Changes in efficiency and ethanol use as torque increases This figure shows engine efficiency at various levels of torque (rotational force) in the 12-liter diesel engine (blue) and the 6.7-liter gasoline-alcohol engine (red). The efficiencies of the two engines are comparable, though the gasoline-alcohol engine is somewhat less efficient at lower torque and more efficient at higher torque. Not surprisingly, the amount of ethanol used in the gasoline-alcohol engine (the green curve) increases with increasing torque, as pressures and temperatures inside the cylinder rise and more alcohol is needed to suppress knock.

would be roughly half that of the cleanest diesel engine.

An illustrative comparison

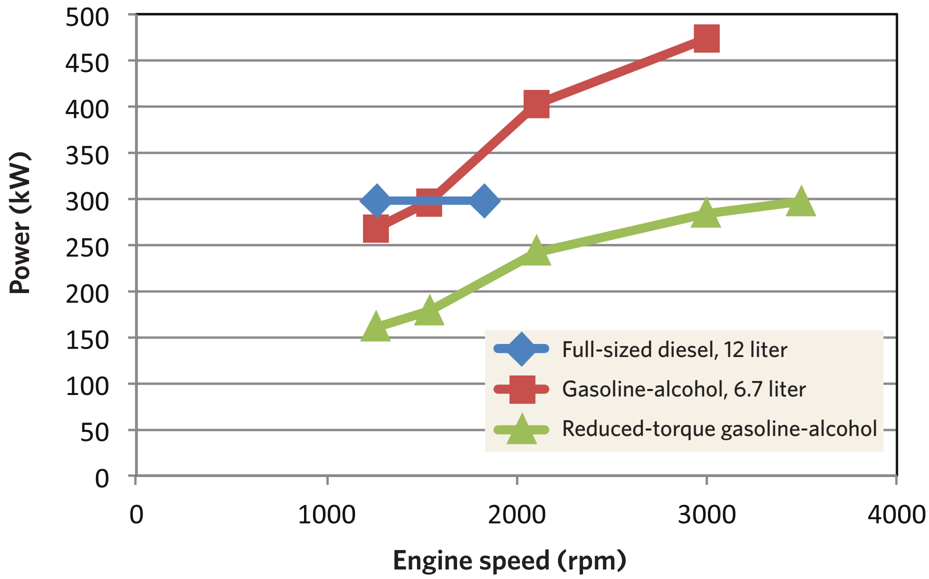
How does the half-sized gasoline-alcohol SI engine compare to today's cleanest full-sized diesel on efficiency and power? To answer that question, the researchers used a series of sophisticated engine and vehicle simulations and chemical kinetic models developed by Bromberg.

For the comparison, they used an illustrative version of their engine based on a 6.7-liter engine that's now manufactured and could—with relatively small alterations—be converted to the gasoline-alcohol configuration either at the factory or after being sold. To keep the conversion simple, the design calls for injecting the alcohol into the cylinder through the standard valve but with the valve wide open. Direct injection into the cylinder would provide greater knock prevention but would require drilling a new hole in the cylinder—hardly a simple conversion. Using a new model of knock developed by Bromberg, the researchers confirmed that the knock resistance from "open-valve" injection isn't quite as high as from direct injection. "But it's a good compromise in order to get the engine introduced into the fleet more quickly," says Bromberg.

Power, efficiency, and alcohol use

The table on page 23 compares the 6.7-liter gasoline-alcohol SI engine to a 12-liter diesel engine on several fronts. The compression ratios and engine torques are about the same in the two engines. But the SI engine can run far faster than the diesel can. (Combustion is faster with spark ignition than with the compression ignition used in diesel engines.) Because of the faster operation and the roughly equivalent torque, the small engine can produce 460 kilowatts (kW) of power as opposed to 323 kW from the diesel—an increase of almost 50%.

The figure above shows how the gasoline-alcohol engine fares in terms of efficiency as torque increases. The blue curve represents the 12-liter diesel engine, the red curve the 6.7-liter gasoline-alcohol engine (assuming



Power versus engine speed in the three engines These curves show the power delivered at various engine speeds by the three engines: a conventional 12-liter diesel (blue), the 6.7-liter gasoline-alcohol engine (red), and the reduced-torque version of the 6.7-liter gasoline/alcohol engine with upspeeding (green). The diesel operates at a maximum speed of about 1800 rpm, with a maximum power output of about 300 kW. The gasoline-alcohol engine can run at a far higher speed and power output, but it would require relatively large quantities of alcohol to prevent knock. The upspeeded gasoline-alcohol engine produces less power, but at an engine speed just over 3,500 rpm, its power output matches the maximum power produced by the diesel. Because it runs at lower torque, its alcohol consumption is relatively low.

direct injection of ethanol and a compression ratio of 14). The engines are assumed to operate at the same speed: 1800 revolutions per minute (rpm). The gasoline-alcohol engine is somewhat more efficient than the diesel at high torque and less efficient at low torque, but in general the small SI engine is about as efficient as the diesel.

The green curve shows consumption of alcohol—here assumed to be ethanol—at different levels of torque. As more torque is required to pull a heavy load at high speed, up a hill, or during acceleration, knock becomes more likely, so more ethanol is needed. At the highest torque, about 80% of the total fuel must be ethanol to prevent knock.

That estimate raises a concern: In the United States, ethanol is widely used in a low-concentration mixture with gasoline, but pure ethanol or a high-concentration ethanol-gasoline blend may not be available or may be too costly. So how much ethanol is likely to be required for a given trip?

As an example, the researchers considered a trip taken by a long-haul, heavy-duty vehicle that requires high torque most of the time. Assuming a compression ratio of 14, ethanol would make up about 40% of its total fuel consumption. Lowering the compression ratio to 12 could cut that ethanol use by about half. In contrast, a delivery truck might operate at low torque most of the time and do just fine with ethanol as 10% of its total fuel over a driving period.

"Such levels of ethanol consumption are doable," notes Cohn. "But the system would be more attractive to people if you had a case where you could use less ethanol."

One way to reduce ethanol use would be to dilute the ethanol with water. Using the knock model, Cohn and Bromberg determined that knock resistance is actually higher when water makes up as much as a third of the secondary fuel. "And in some cases where you don't need any ethanol for antifreeze, you might be able to run with water alone as the secondary fluid," says Cohn.

Another approach to reducing alcohol use—called upspeeding—involves operating the engine at a higher speed. Running the engine faster and adjusting the gearing in the transmission to increase the ratio of engine rpm to wheel rpm make it possible to use less engine torque in the gasoline engine to achieve the same torque at the wheel as in the diesel. That reduction in engine torque further reduces the need for ethanol.

The figure on this page shows engine speed versus power in three engines: the 12-liter diesel engine (the blue curve), the 6.7-liter gasoline-alcohol engine (red curve), and the upspeeded, low-torque, gasoline-alcohol engine (green curve). The diesel engine can operate up to only about 1800 rpm, at which point it generates about 300 kW of power. The gasoline-alcohol engine can run at much higher speeds and deliver far more power—but ethanol consumption would be high. In contrast, the low-torque gasoline-alcohol engine delivers less power at lower rpm, but running at about double the speed of the diesel and using appropriate gearing, it would provide the same power to the wheels.

Further analyses suggest that using upspeeding in a long-haul, heavy-duty engine could reduce efficiency by a few percentage points, but the impact on ethanol use would be dramatic. Ethanol use over a driving period could drop to less than 10% of the total fuel consumed—an amount that could be supplied by onboard fuel separation.

Reducing climate impacts

Cohn points out one more benefit of the gasoline-alcohol SI engine: It's a pathway to reducing GHG emissions. "A somewhat under-recognized aspect in evaluating the environmental impacts of transportation vehicles is that GHG emissions from trucks worldwide will overtake GHG emissions from cars sometime between 2020 and 2030," he notes.

The gasoline-alcohol SI engine can be operated in a flexible-fuel mode where it uses only pure alcohol if desired. Right now, looking at the life cycle of the fuels and assuming comparable engine efficiency, using ethanol produced from corn by state-of-the-art methods generates about 20% lower GHG emissions than using gasoline or diesel fuel. Even greater reductions in GHG emissions could come when ethanol and methanol fuels are produced from agricultural, forestry, and municipal waste or specialty biomass.

"Reducing GHG emissions from trucks by finding an alternative source of power—for example, through electrification—could take a long time," says Cohn. "But if you can operate your engine partially with ethanol or entirely with ethanol, that's a good way to make a start right away."

NOTES

This research was supported by the Arthur Samberg Energy Innovation Fund of the MIT Energy Initiative. More information can be found in:

D. Cohn and L. Bromberg. *Dual-Fuel Gasoline-Alcohol Engines For Heavy Duty Trucks: Lower Emissions, Flexible-Fuel Alternative To Diesel Engines*. Society of Automotive Engineers paper no. 2018-01-0888. April 2018.

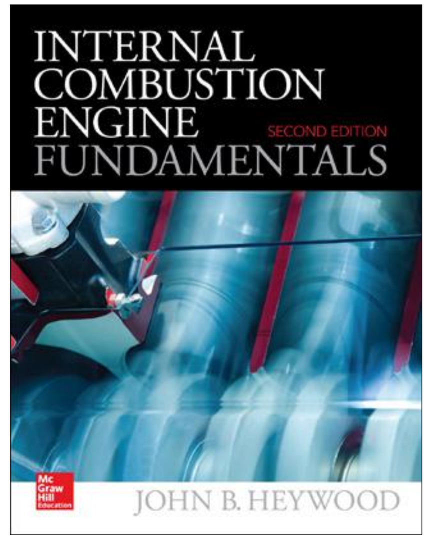
Professor John Heywood: The future of the internal combustion engine

For the past five decades, John Heywood, the Sun Jae Professor Emeritus of Mechanical Engineering at MIT, has been performing research on internal combustion engines, substantially increasing our understanding of how they work and how to reduce their emissions of air pollutants and greenhouse gases and increase their fuel economy. Thirty years after its first publication, Heywood has just completed a second edition of his seminal book, Internal Combustion Engine Fundamentals. *Its publication comes at a critical time when the automotive industry is faced with difficult questions on how to move forward in an era when alternative propulsion options are getting a lot of attention. The following is extracted from an interview with Heywood by Mary Beth O'Leary, Department of Mechanical Engineering, on why development of internal combustion engines should continue.*

Q Much of your career has focused on internal combustion engines. What changes have been made in engine design to reduce air pollutant and greenhouse gas emissions?

A In the past 30 years, there's been a lot of progress in controlling air pollutant emissions using exhaust after-treatment technology. The key technology component is the catalytic converter in the exhaust system that cleans up the exhaust gases before they go out into the atmosphere.... This has been very successful in gasoline engines, but not as successful for diesel engines. As a consequence, the environmental problems presented by diesel engines haven't yet been adequately resolved.

Q Over the past decade or so, there has been a strong focus on electric vehicles as a solution to transportation's greenhouse gas emissions problem. Why is work on internal combustion engines still important?



A Behind this question, there's this implication: "Why are you bothering with these engines when electric vehicles are taking over?" Electric vehicles are certainly going to play a useful role moving forward, but right now it is really difficult to estimate how big a role they will eventually play. I've been researching the critical area of electrical vehicle recharging for the MIT Energy Initiative's "Mobility of the Future" project. If you own a battery electric vehicle, you really need a home recharger. The logistics and cost of having a home charger at most of the homes in America are problematic and expensive.

Various projections for the US suggest that by 2030, some 10% to 25% of vehicles might be electrified. The question then remains, what about the other 90% to 75%? And what about the large trucks and ships that run on diesel fuel? There are, as yet, no convincing electric options for those vehicles. That is why it is still so important to continue working on internal combustion engines and make them as clean and efficient as we can.

Read more online at bit.ly/john-heywood.

Keeping the balance: How flexible nuclear operation can help add more wind and solar to the grid

In the Southwestern United States, the country's sunniest region, sunlight can shine down for up to 14 hours a day. This makes the location ideal for implementing solar energy—and the perfect test bed for MIT Energy Initiative (MITEI) researcher Jesse Jenkins and his colleagues at Argonne National Laboratory to model the benefits of pairing renewable resources with more flexible operation of nuclear power plants. They reported their findings in *Applied Energy* on April 24, 2018.

During summer 2015, Jenkins worked as a research fellow with Argonne National Laboratory on two power systems projects: one on the role of energy storage in a low-carbon electricity grid, and the other on the role of nuclear plants. Linking the two projects, he says, is the goal of using new sources of operating flexibility to integrate more renewable resources into the grid.

In power grids, supply and demand hang in a delicate balance on a second-to-second time frame. Flexible backup energy sources must stay online at all times to maintain this equilibrium by meeting small variations in demand throughout the day or stepping in quickly if a power plant should suddenly go offline. If supply ever gets too far out of step with demand, devices designed to protect transmission lines and sensitive electronics from damage will quickly trip into action, causing blackouts as they work to shed demand or generation and restore the balance. Currently, certain coal, oil, natural gas, and hydro plants take on the important role of providing these standby capacity services, known as frequency regulation and operating reserves.

Nuclear power plants generally operate at full capacity, but they are also technically capable of more flexible operation. This capability lets them respond dynamically to seasonal changes in demand or hourly changes in market prices. Reactors could also provide the standby backup regulation and reserve services needed to balance supply and demand. According to Jenkins, all reactor designs now being licensed or built in the United States, Canada, and Europe are capable of flexible operation, as are many older reactors now in service.

"We primarily rely on gas and coal plants to meet all those flexibility needs today, while we operate our nuclear plants fixed, or 'must-run,' 24/7," says Jenkins. "The question here is, what would the benefits be if we stopped operating them so inflexibly, if we started using more of their technical capabilities to 'ramp' output up and down on different time scales from seconds to hours to seasons?" The answer, he says, is less reliance on the gas and coal plants—and more renewable energy integration.

Modeling for the energy transition

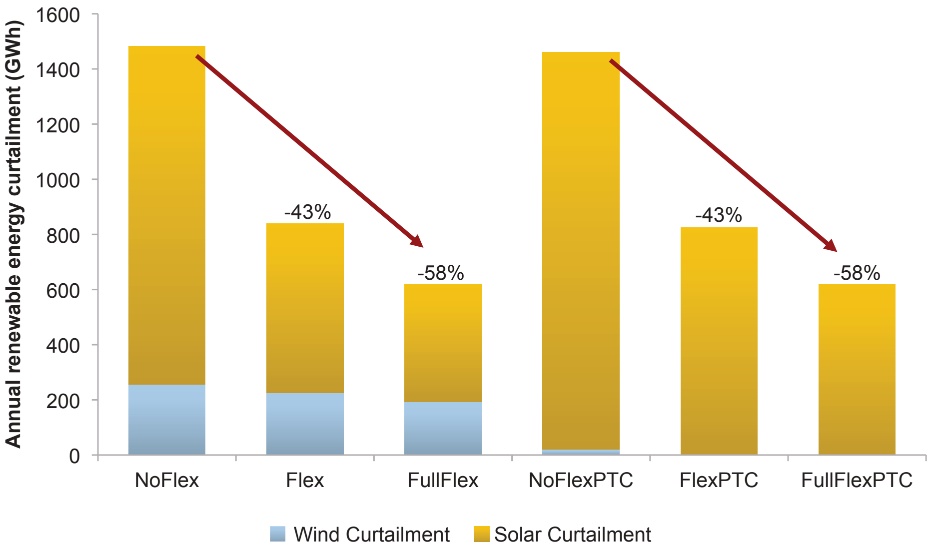
As markets increasingly incorporate variable renewables like wind and solar, maintaining the supply-demand balance becomes more complicated. Energy demand changes over the course of the day, usually staying low overnight, spiking briefly in the morning, and then peaking in the evening when people come home from work.

"Throughout these daily and seasonal changes in electricity use, there is a constant level of demand, known as the 'base load,' which is invariant," says Jenkins. "Since nuclear plants have very low operating costs and cost a lot up-front to build, they are economically well-suited to operating all the time to meet this base load." He adds, "That's why when nuclear plants were originally licensed in the US, it wasn't really necessary for them to play a role in following demand patterns throughout the day, and so nuclear plants in the US weren't licensed to operate that way."

However, nuclear power plants were designed for flexibility "because the engineers who designed them envisioned a world in which nuclear took over the whole system," Jenkins explains. This never really happened, except in France, which gets over 70% of its electricity from nuclear and has accordingly operated some of its nuclear plants to follow changing demand for years.

Now, as power grids around the world incorporate more and more variable renewable resources like wind and solar, the value of flexibility is increasing. Nuclear plants in places with increasing renewable energy penetration, like Germany, are therefore also moving toward flexible operation.

Because power systems today have very little energy storage capability, there are a growing number of places, from California and Iowa to Germany and China, where excess renewable energy might be produced on a sunny or windy day and must simply be wasted. Rather than disabling a solar panel or wind turbine, Jenkins points out, it makes more sense to operate the nuclear plant at a lower output and to absorb as much free wind or sun as possible. And operating nuclear plants flexibly has benefits beyond integrating renewable energy and reducing carbon dioxide emissions: By reducing power output when electricity prices are very low, nuclear plants can cut the amount of wasted fuel and use their spare capacity to provide more valuable reserves and regulation services. Flexible operation can thus increase revenue for reactor owners while enhancing system



Reducing curtailment of renewables This graph projects the amount of renewable energy that would be curtailed (and therefore wasted) for each level of nuclear flexibility, as simulated by the two-stage unit commitment and economic dispatch model: NoFlex, where nuclear plants are operated at their maximum output; Flex, where plants are somewhat flexible; and FullFlex, where plants are highly flexible. In cases with a production tax credit (PTC) applied to wind power, solar energy would be curtailed before wind, as curtailing wind output means forfeiting the tax credit—but overall, total renewable curtailment rates are nearly identical with the PTC. As shown in the graph, nuclear flexibility significantly reduces renewables curtailment. Modest flexibility in the Flex and FlexPTC cases reduces curtailment of wind and solar by 43%, and high flexibility (FullFlex and FullFlexPTC cases) reduces curtailment by 58%. Without any flexible nuclear operation (NoFlex), 16.7% of available renewable energy output is wasted.

reliability and reducing electricity costs for consumers.

Optimization models are helpful in simulating the potential economic and environmental benefits of incorporating renewables, but current models for electric power systems still represent nuclear units as inflexible, must-run resources. Jenkins and the research team at Argonne are closing this gap by developing a new approach to modeling flexible nuclear operation and employing this novel technique to study the potential benefits in power systems with relatively high shares of variable renewable energy sources. They simulated six cases in the American Southwest, ranging from inflexible nuclear plants, to plants with moderate flexibility, to those with high flexibility.

Modeling flexible nuclear plant operation poses its own challenges. A nuclear reactor has a range of operating constraints that arise from the physics of nuclear reactors and are distinct from the technical constraints on more conventional coal- or gas-fired power plants. For example, the minimum stable output of a nuclear reactor changes over the course of the fuel irradiation cycle, and production can't be ramped up or down too quickly without causing a strain on the nuclear fuel rods and the reactor itself. "The task was to try to synthesize the main physical engineering constraints limiting the ability of reactors to change their output on different timescales, and then translate that into the mathematical constraints that we use in modeling and optimization for the power system," says co-author Audun Botterud, a principal research scientist in Argonne's Energy Systems Division and in MIT's Laboratory for Information and Decision Systems.

The research team created a "mixed integer linear programming" (MILP) formulation that accounts for the specific operating constraints on ramp maneuvers of nuclear power plants. "It's a mathematical program that minimizes the cost of operating the power grid over the whole year while respecting the engineering constraints that power system operators and individual power plants have to maintain," Jenkins explains. The simulation works in two stages, optimizing for demand predicted one day in advance and then in real time—matching the way the electricity markets work in the United States.

The MILP formulation has applications beyond the specific region studied. "The general findings would hold in other places with similar shares of these two resources [nuclear and renewables]," says Jenkins. And, importantly, the study demonstrates how one of the world's biggest sources of low-carbon energy (nuclear) and the world's fastest growing energy source (renewables) can work together rather than replace each other.

"What this study shows is that rather than shut down nuclear plants, you can operate them in a way that makes room for renewables," says Jenkins. "It shows that flexible nuclear plants can play much better with variable renewables than many people think, which might lead to re-evaluations of the role of these two resources together.

"Bridging the different knowledge bases, between folks who do power system modeling at the grid level and nuclear engineers and physicists who understand the details of nuclear reactor dynamics, was the most challenging but also the most interesting and productive aspect of this project," says Jenkins. "These are two communities that don't always talk to each other, and they speak different languages and have different backgrounds and expertise. This kind of collaboration is an example of the unique interdisciplinary work that can happen at a place like a national laboratory or the MIT Energy Initiative."

Ivy Pepin, MITEI

This research was supported by Argonne National Laboratory and the National Science Foundation.

MITEI seed grants address energy efficiency, renewables expansion, energy storage, and more

In spring 2018, the MIT Energy Initiative (MITEI) awarded nine grants totaling $1,350,000 through its Seed Fund Program, an annual competition that supports early-stage innovative research across the energy spectrum. The winners will be using the $150,000 grants to explore highly creative and promising energy research projects.

"This is an extremely competitive process," said MITEI Director Robert C. Armstrong, the Chevron Professor of Chemical Engineering. "Every year the submissions we receive are incredibly impressive, and this year was no exception. Our grant winners are remarkable in their creative, interdisciplinary approaches to addressing key global energy and climate challenges."

To date, MITEI has supported 170 projects with grants totaling approximately $22.75 million. These projects have covered a variety of energy research areas, from fundamental physics and chemistry to engineering to policy and economics, and have drawn from all five MIT schools and 28 departments, labs, and centers.

Seed grant awardees run the gamut from established professors to new faculty members. This year, six of the nine grant recipients are first-time awardees—including four researchers early in their careers at MIT.

The chemistry of energy

While research in the lab can be critical to advancing energy technologies, computer simulations are also valuable, serving as an efficient testing ground where new ideas can be explored rapidly and at low risk. Simulations at the atomic level can be especially valuable in discovering new energy materials and in investigating chemical change in energy generation and storage. But the computational cost associated with such "atomistic" simulations can be extremely high—a problem that Professor Rafael Gomez-Bombarelli and his team will be addressing in their project. Gomez-Bombarelli, the Toyota Assistant Professor in Materials Processing, plans to use machine learning to create software that, by leveraging already existing computational results, can accelerate high-accuracy quantum-chemical calculations, reducing the cost incurred.

"We will use existing computer simulations that took many years of computer time to automatically learn consistent patterns about the behavior of matter in energy processes," says Gomez-Bombarelli. "This newly gained information will make chemically accurate simulations thousands of times faster and accelerate the predictive design of more efficient and sustainable fuels, photovoltaic materials, solid-state lighting, battery chemicals, and industrial catalysts."

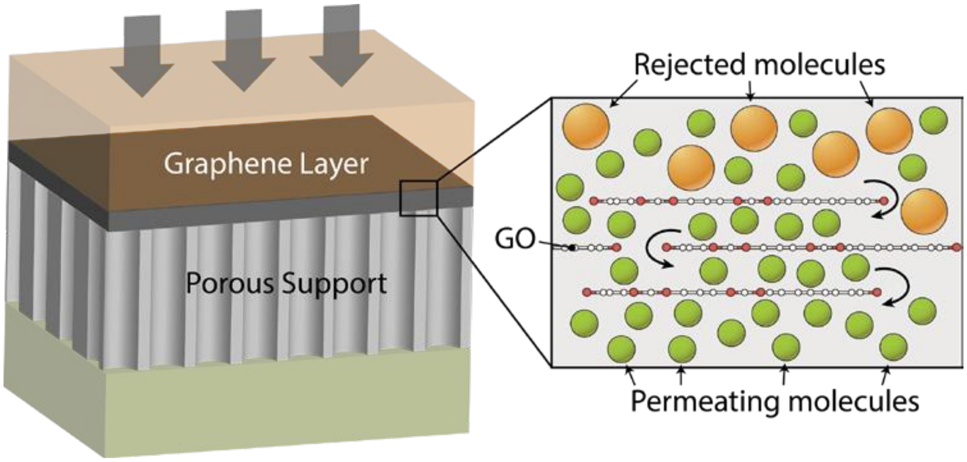
Karthish Manthiram, an assistant professor of chemical engineering, is approaching energy generation and storage from a different angle. His team is investigating lithium-based materials as electrocatalysts for nitrogen reduction, a key step in the production of ammonia, which is a potential route for storing electrical energy from intermittent renewable sources in a liquid fuel. The intrinsic reactivity of lithium makes it a prime candidate for use in catalysis, potentially beginning a new chapter in liquid fuel creation and energy storage.

Making a better grid: Batteries and economics

Betar Gallant, an assistant professor of mechanical engineering, won a seed grant for her team's research into calcium as a promising anode for low-cost, high-energy-density batteries. Such batteries, if successfully developed, can play critical roles in ensuring stability on a renewables-heavy power grid and also in achieving the electrification of our transportation system. Today, the most common electric-vehicle battery pack on the market is the lithium-ion battery, but improvements in gravimetric and volumetric energy density are needed to achieve longer driving ranges. While widespread efforts have focused on developing the lithium anode to replace the graphite electrode in today's lithium-ion batteries, lithium metal cycles poorly, is expensive, and raises significant safety concerns. Gallant and others believe there is substantial room for improvement to be made by pursuing alternative metal anodes. Calcium-based batteries possess particularly attractive volumetric energy densities and potentials compared to lithium-based cells and are also safer, less expensive, and potentially more versatile if key challenges can be overcome.

"This field is very much in its infancy; while the lithium anode has been subject to study for decades, researchers have just begun studying the fundamental behavior of calcium-based electrodes," Gallant says. "Among the most significant challenges facing calcium electrodes are limited round-trip efficiency and poor cycleability. If these challenges can be overcome, the calcium electrode will be unlocked for use in a wide range of advanced battery chemistries and will open new and exciting avenues for research and development."

Jing Li, an incoming MIT Sloan School of Management faculty member, and her team plan to produce a more accurate cost-reduction curve for batteries by developing models based on fundamental



Fabricating membranes with tunable permeability and selectivity Chemical production, petroleum refining, and other industrial separation processes make up one third of US energy consumption. Most processes use thermal distillation, which requires large amounts of heat. Professor Jeffrey Grossman of materials science and engineering and his team are developing a new nanoporous membrane to replace thermal distillation, thereby slashing the energy required for chemical separations by over 80%. The multilayer structure of the membrane is pictured above. The graphene layer comprises sheets of graphene oxide (GO) and is supported by a stabilizing porous layer. As the mixture flows between the GO sheets, larger molecules are blocked. By testing the membranes with crude oil and other industrially relevant solutions, the researchers aim to demonstrate that graphene membranes can be efficiently operated on a commercial scale.

materials and underlying science and then estimating them using data on the design, structure, cost, and quantities of batteries used in commercial products on the market. Results should help clarify why battery costs have decreased dramatically in recent years and whether that trend will continue in the future.

Li's team will also examine what changes in the regulatory structure of electricity markets are needed in light of expanding energy storage capacity. The goal is to understand who should own and operate energy storage units on the grid and the social welfare implications of different options for energy storage ownership. The researchers will model the decision-making strategies of potential owners, including private firms and system operators, to determine possible impacts on market outcomes, including prices, quantities, and costs.

Deep expertise, new ideas

Joining those four early-career researchers were several faculty members with long, deep experience in their areas of expertise.

First-time seed grant winner Ignacio Pérez-Arriaga, a visiting professor at the MIT Sloan School of Management, is leading a study that combines electricity and economic modeling with policy analysis of renewable portfolio standards and other incentives meant to encourage renewable energy growth in the United States. The goal is to determine the mix of renewable energy generation types that will ensure high reliability in a given state as well as the most cost-effective capacity expansion strategy for renewables, given differing natural resources and energy and environmental regulations across the country.

Chemistry Professor Tim Swager is also a first-time seed grantee. His team's research focuses on a new approach to generating polymer membranes with three-dimensional porosity. Such membranes are used in chemical separations to transport ions in fuel cells as well as in processes related to chemical production and water purification. Separations often account for the majority of energy consumed during such processes, so improving their effectiveness is critical. Swager's group is also focusing on related materials that have great potential for gas separations and on applying new ion-conducting materials to enable chemical and electrochemical transformations.

Growing long-term innovation

Seed grants may target early-stage energy research, but MITEI's hope is that this research will continue and lead to practical solutions to real-world problems. Several past seed fund projects have made progress in that direction since their initial grants.

For example, 2016 grantee Marta Gonzalez, a visiting associate professor in the Department of Civil and Environmental Engineering, and her team developed an electric-vehicle planning app called Human Mobility, Energy and Autonomy, or HUMEA. As described in a paper published in *Nature Energy* in April 2018, the app aims to make owning and operating an electric vehicle (EV) in the city easier and less disruptive to the power grid by connecting a network of electric vehicles and optimizing the schedule for when and where they should charge. "Most people begin charging their EV when they get to work and then unplug around 6 pm when they leave," says Gonzalez. "Power operators can't handle that kind of steep peak. We want to incentivize individuals to bring the trend to an overall flatter demand." People using the app can create personalized energy profiles that will point out openings in their schedules when they can charge outside of peak times.

Funding for the new grants comes chiefly from MITEI's founding and sustaining members, supplemented by gifts from generous donors.

Francesca McCaffrey, MITEI

Recipients of MITEI Seed Fund grants, spring 2018

3D porosity: Approaches to new generations of polymer membranes
Tim Swager
Department of Chemistry

Carbon capture from chemical processes in the intermediate temperature range
T. Alan Hatton
Department of Chemical Engineering
Alexie Kolpak
Department of Mechanical Engineering

Deep learning of contracted basis sets for rapid quantum calculation of thermo-chemistry and other energy processes
Rafael Gomez-Bombarelli
Department of Materials Science and Engineering

Economics of energy storage
Jing Li
MIT Energy Initiative

Effective capacity expansion of renewable electricity with mosaic design of state energy and environmental regulations in the United States
Ignacio Pérez-Arriaga
MIT Sloan School of Management

Electrochemical ammonia synthesis for modular electrical energy storage
Karthish Manthiram
Department of Chemical Engineering

Oxidative coupling of methane using ion-conducting ceramic membranes
Ahmed Ghoniem
Department of Mechanical Engineering
Bilge Yildiz
Department of Nuclear Science and Engineering

From left: Seed fund winners Ahmed Ghoniem, Betar Gallant, Karthish Manthiram, and Bilge Yildiz. Gallant holds a type of battery used in her research to test cycling of calcium electrodes. She is exploring calcium as a potentially safer, less expensive, versatile alternative to lithium-based batteries. Manthiram holds a vial of electrochemically synthesized ammonia. His research focuses on storing electrical energy by fixing nitrogen to make ammonia at room temperature and ambient pressure. Photo: Kelley Travers, MITEI

Scalable nanoporous membranes for energy-efficient chemical separations
Jeffrey Grossman
Department of Materials Science and Engineering

Unlocking the rechargeability of calcium for high-energy-density batteries
Betar Gallant
Department of Mechanical Engineering

Advancing energy-efficient biochemistry and training tomorrow's scientists and engineers

Kristala Jones Prather will be the first to tell you the difference between science and engineering. She'll also be the first to tell you how important both are to the research process. "Science is about discovery, and engineering is about application," Prather says. "The beauty of being a scientist and doing discovery work is the freedom and creativity. For engineers, it's all about how these discoveries can be applied and solve problems in the real world." She would know—over the course of her career, she's been both.

While working in Bioprocess Research and Development at Merck, Prather delved into the engineering side of biology and chemistry. "My decision to work in industry before pursuing an academic career was very intentional," she says. "I wanted to get a sense of what to think about when bringing products to market. How is new technology adopted? Can you improve upon existing processes?"

Prather's early years in industry shaped her knowledge of the process pipeline she is currently seeking to streamline through scientific inquiry. As the Arthur D. Little Professor of Chemical Engineering at MIT, she conducts research that ties together the fields of energy, biology, and chemistry. While biology and energy are most often connected in discussions of biofuels, Prather's research focuses on a different kind of energy advancement: more energy-efficient processes for the manufacture of biochemicals.

"I tell my students, look at the carpet in this room," Prather says. "The probability is high that 50% or more of the materials in that carpet were produced using oil. So how do we decrease that number?" Prather's lab works on engineering bacteria to produce biochemicals, thus replacing the fossil-fuel based processes currently responsible for making so many of the world's materials.

Such research requires expertise in chemical engineering, biological engineering, and genetics. Using genetic engineering, Prather and her team can manipulate the genes of microbes to control the kind and quantity of products they produce. These products could be anything from insulin or human growth hormone to the synthetic materials whose production would otherwise have required the use of oil or other fossil-based products. "The goal in exploring bio-based methods for creating these chemicals is to design a less energy-intensive process that is still cost-competitive," Prather says. "We want to use less energy to get to the same molecules."

The next generation of scientists and engineers

For all the engineering knowledge that Prather gained while she was working in industry, something major was missing. "When I looked at the part of my job I liked best, it had to do with mentoring young scientists," she says. "Training and teaching them how to be independent researchers in their fields was the most important and enjoyable part of the job to me." This realization spurred Prather to make the switch back to academia that she had always been planning. "In industry, you eventually move away from mentoring younger researchers as you move up in the ranks," she says. "In academia, mentoring is the kernel at the center that always stays the same."

With her current classes, Prather has ample opportunity to mentor the next generation of MIT scientists and engineers. She teaches 10.10 Introduction to Chemical Engineering to freshman and sophomore undergraduates, as well as

Kristala Jones Prather, the Arthur D. Little Professor of Chemical Engineering.
Photo: David Sella

10.542 Biochemical Engineering for graduate students and advanced undergrads. Opportunities to reach students present themselves outside of the classroom as well. In fall 2017, Prather was invited by MIT President L. Rafael Reif to be part of a small group of professors addressing incoming freshmen at a welcome assembly their first week on campus.

The advice she gave to students then is a message she believes all MIT students need to hear. "You need to embrace failure," she says. "Recognize that not everything you attempt is going to work out." But there's an important corollary to this advice. "Students, especially at MIT, should also remember: You belong here," Prather says. "It doesn't matter how many AP classes you come in with or anything like that. And there are a lot of people here to help you get through."

When asked what the most challenging part of being a professor is, Prather says, "Just how much stuff there is to do. Not the volume, but the diversity—that mix of administrative and academic work." Still, the most rewarding part of the job is easy to pinpoint. "The students," Prather says. "The day a student in my lab defends their thesis is the happiest and saddest day of my life. Happiest because I'm so proud of what they've done. But saddest because the time has come for them to leave."

The future of bioscience

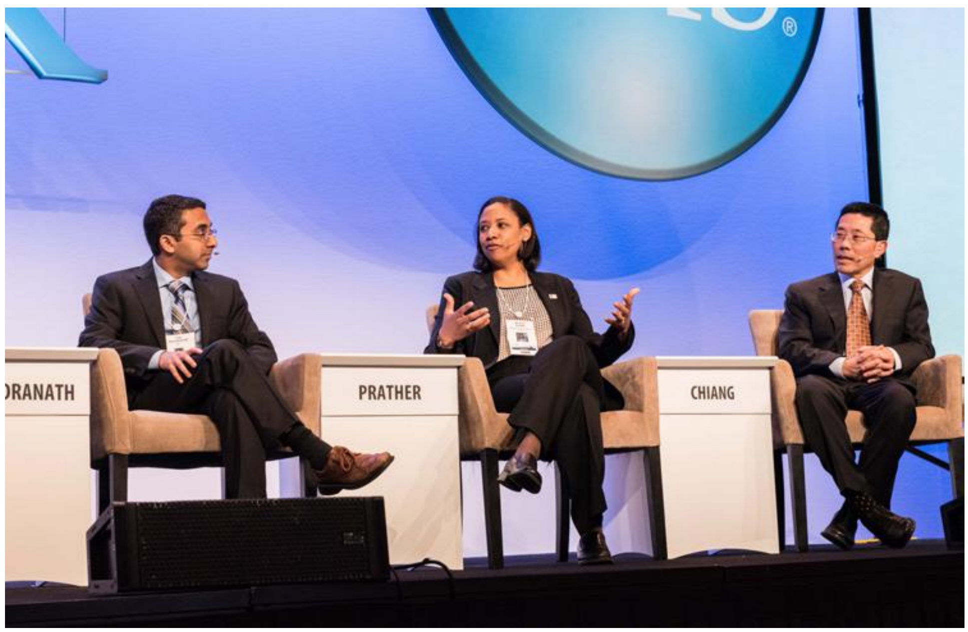
Prather and her colleague Angela Belcher, the James Mason Crafts Professor of Biological Engineering and Materials Science at MIT, are advancing the future of energy bioscience through their work as co-directors of MITEI's Low-Carbon Energy Center for Energy Bioscience Research. The goal of the center, Prather says, is to "use the toolbox of biology to engineer solutions to clean energy challenges."

Prather and Belcher are bringing together a host of biological and chemical engineers from across the Institute to perform research in a wide range of areas. Prather's own work using genetics to engineer biochemicals is complemented by myriad other projects her colleagues have in the works. Research topics range from biochemical remediation, or the use of bacteria to clean up oil spills; to biological generation of liquid fuels from natural gas; to engineering a virus capable of improving solar cell efficiency.

Prather says, "We're really trying to pull together the collective talents of researchers at MIT who are using biology to solve a range of problems." The results could have positive impacts on critical fields including renewable energy, clean fuel sources, infrastructure, storage, and chemical processing and production.

Francesca McCaffrey, MITEI

Prather leads a discussion at MITEI with a group of undergraduates about the future of biofuels—and whether the prime window of time for their deployment has already passed or has not yet come. Prather argued for the latter. "I think it's too early," she said. "We just haven't spent enough time on the problem yet." Photo: Sofia Cardamone, MITEI



At the 2016 IHS CERAWeek conference, the annual meeting of the international energy industry, Prather discussed advancements in synthetic biology, including the creation of new biofuels and the way bioengineers look to nature for inspiration in their energy research. She said, "We consider all of biology to be our playground. Anything nature uses, we try to engineer to use in the same way." She was joined on stage by Paul M. Cook Career Development Assistant Professor Yogesh Surendranath (left) and Kyocera Professor of Materials Science and Engineering Yet-Ming Chiang. Photo: Emily Dahl, MITEI

New energy studies class examines technical and social drivers of global energy systems

During a meeting of Global Energy, Professor Valerie Karplus leads a class discussion of how stakeholders engaged in political and social processes to help shape the fate of the Cape Wind project in Nantucket Sound. Photos: Kelley Travers, MITEI

Valerie Karplus SM '08, PhD '11 examines energy systems through a variety of lenses. This is, perhaps, unsurprising given her background: She holds undergraduate degrees in biophysics and political science, and graduate degrees in civil and environmental engineering, and in technology, management, and policy.

Now, Karplus, the Class of 1943 Career Development Assistant Professor at the MIT Sloan School of Management, has seized an opportunity to incorporate her portfolio of perspectives into a single new class: Global Energy: Politics, Markets, and Policy. Launched in spring 2018, the class is cross-listed in Economics, Management, Political Science, and Urban Studies and Planning.

"It brings together important themes I've nurtured throughout my career," says Karplus. "The class is a natural outgrowth of who I am."

The class investigates energy technologies, markets, and governance, employing methods from economics, political science, and sociology to understand past transitions and prospects for a cleaner energy future. Open to both graduate and undergraduate students, it is offered as a social science pillar of the Energy Studies Minor.

"We tackle a lot of topics from an integrated perspective, providing a broad context for how energy systems work in all parts of the world," Karplus says. "We want students to understand how decision-making is organized, the factors that affect which technologies and solutions can be scaled up to make a difference, and what the barriers and enablers are to developing energy systems, including low-carbon energy solutions."

Michael Kitcher '18, a materials science and engineering major and energy studies and applied international studies minor, finds this approach appealing. "It's important even if you find a good technical solution to be cognizant of problems you might face in the country you're working in, and to understand how your solution fits in," he says. Kitcher, who grew up in Ghana, hopes someday to develop sustainable energy technologies for developing countries.

"I was excited about taking Global Energy because it goes into cultural and societal factors behind energy policies, which is something I hadn't seen offered elsewhere and relates to the research I want to do," says Max Aidas Vilgalys, a doctoral candidate in social and engineering systems. With an electrical engineering degree from Stanford University, Vilgalys hopes to use technology to encourage individual behaviors that align with lower carbon usage.

Filling a gap in the energy curriculum

The class, funded by an S.D. Bechtel, Jr. Foundation grant, was several years in the making. Karplus, who had just joined the faculty at MIT Sloan, was engaged in research supported by the MIT Energy Initiative investigating how China designed and implemented energy and climate policies. She was eager to teach a class that tapped into her area of expertise: integrated analysis of how technologies, economics, and politics affect energy system performance, tying in ground-level experience as well as top-level policy perspectives. She also wanted to identify a unique niche in both the MIT and energy studies curriculum.

"I wanted to equip undergraduate and graduate students to analyze both the technical and human elements of global energy systems in an integrated way," says Karplus. "I designed the class to make comparisons across countries and to give students the means to assess the prospects and challenges for energy solutions, especially clean energy solutions, to succeed at scale."

With political scientist Christopher Warshaw, who has since left MIT for George Washington University, Karplus began to design a class with an interdisciplinary focus on energy development and decision-making by governments and by the private sector. She sought to connect theory and practice through interactive class exercises, such as classroom visits by practitioners and the Climate Interactive "World Climate" negotiation simulation, which confront students with real-world problems and ask them to think through solutions. "I wanted to make potentially distant global energy issues really come alive for students," says Karplus.

Homework assignments place students in roles where they must identify governance structures shaping a country's energy flows, provide guidance on policy decisions, and evaluate business decisions to invest in clean energy. One such assignment asks students to write a memo for India's environmental ministry arguing for or against a carbon tax as the primary instrument for achieving the nation's pledged level of carbon dioxide emissions. Another asks students to justify locating a new solar photovoltaic construction company in a particular city and country. Graduate students must fulfill more of these assignments than undergraduates.

Karplus hopes to drive home a key point with these exercises: "Human decisions—by individuals as well as groups—often determine the success or failure of what may at first seem to be purely technical solutions to our energy challenges," she says. MIT students, she notes, "are phenomenal technically," so it's "often a big leap for them to understand that even if they have the best machine or most elegant solution, it doesn't always compete in the marketplace or succeed in having the intended effect at large scale."

Michael Kitcher '18, a materials science and engineering major and energy studies and applied international studies minor, contributes to a class discussion on the Cape Wind case.

Spanning schools and academic levels

Multidisciplinary analysis is one way to encourage a complex view of energy problems. Another way is to bring together students from different majors and different stages of their education.

"Global Energy is a unique opportunity to enable real cross-pollination across the schools at MIT," says class teaching assistant Aaron Thom '11, who is simultaneously pursuing a master's degree in civil and environmental engineering and an MBA at MIT Sloan. "More than just a cross-listed class, the material has been designed to maximize opportunities for students to work together, particularly across different backgrounds."

Among the 19 undergraduates (including seven energy studies minors) and nine graduate students enrolled in the inaugural Global Energy class are students concentrating in physics, math, economics, architecture, materials science, management, and urban studies. Undergraduates and graduate students team up for a final project: reporting on the prospects for an energy technology, policy, or practice in a particular market, wielding approaches from the social sciences.

Class assignments are framed to take advantage of academic and experiential diversity. "We want to highlight opposing viewpoints on energy and environmental issues," says Thom. "We'd like to prepare students to argue successfully for their ideas in the world outside of MIT, where there will likely be less consensus about such issues as combating climate change."

"I hope students come away from the class with a good dose of reality, humility, and optimism about the magnitude of the challenge in finding solutions to energy and climate problems," says Karplus. "At the same time, I want to make energy systems more accessible and less intimidating. I also want to help students recognize that by thoughtfully combining technical and social insights, it is possible to accelerate progress and make a lasting impact."

Leda Zimmerman, MITEI correspondent

NOTES

In 2017, the Bechtel curriculum development grant supported a team that contributed to developing background material and reading summaries for the class. Two Undergraduate Research Opportunities Program students from Wellesley College, seniors Shaina Ma and Zarina Patwa, worked with Karplus and Melissa Webster MBA '09, now a lecturer at MIT Sloan, to assemble class material and summarize readings and lecture content as well as test in-class simulations. Bechtel funds also supported Arun Singh SM '17 and PhD candidate Michael Davidson of the Institute for Data, Systems, and Society to attend global climate talks, generating firsthand observations shared with students during a negotiation exercise using the World Climate simulation developed by Climate Interactive. Early on, former MIT political science professor Christopher Warshaw and graduate student Parrish Bergquist of urban studies and planning also worked to develop materials on the political economy of energy in the United States, which have been incorporated into the first offering. The Global Energy class will be offered again in spring 2019.

Writing takes center stage in Physics of Energy class

MIT students had to polish their prose in 8.21 Physics of Energy this year, as the science foundation class for the Energy Studies Minor became a communication-intensive (CI) subject.

"This class gives students a chance to learn to write in a particularly effective way if they're interested in energy issues," says Robert L. Jaffe, the Jane and Otto Morningstar Professor of Physics, who teaches the class. "We hope we're educating the person who can advise the policymaker on issues of science or hold their own in policy as well as technical discussions with experts outside their own fields."

Offered since 2008, 8.21 introduces the fundamental physics of energy systems with an emphasis on quantitative analysis. Historically, the subject has been conducted as a typical physics class, with a workload of problem sets and exams. This year, however, the Department of Physics was looking for ways to offer more subjects that fulfill the Institute's CI requirement, which calls for students to produce a variety of communication-oriented assignments.

Jaffe, who co-founded and for many years co-taught Physics of Energy with Professor Washington Taylor of physics, says he agreed to restructure 8.21 as a CI because he thinks reading and writing about energy is an important skill. "Writing clear, convincing, even interesting prose is a skill any scientist or engineer needs. Critical writing for non-specialists and editing effectively play almost as important a role as writing up your own work," he says.

Exploring, evaluating, and explaining

Physics of Energy is a survey course covering a broad swath of material, including mechanical energy, thermal energy, electromagnetic energy, and solar and nuclear energy. The writing assignments balance this breadth with depth by giving students an opportunity to research selected topics more thoroughly, Jaffe says.

"Writing papers offers students the chance to drill down in a couple areas they find interesting and study these more deeply," he says. "We still have problem sets, but it's a more rounded experience that involves honing your thoughts to a particular kind of audience."

Writing in 8.21 is centered on exploring, evaluating, and explaining energy topics in a way that would provide useful guidance to a policymaker, Jaffe says. Students are required to produce two papers for the class, each focused on a scientific issue related to energy sources, systems, or uses.

For example, Jaffe says, a student might present the pros and cons of erecting a tidal barrage across the Bay of Fundy in Canada. "What are the dynamics? What's the capacity? What are the problems associated with it? What does it do to the marine environment?" Jaffe says. Whatever the students decide to research—from the advantages of flywheel energy storage to the benefits of different wind turbine designs—they are expected to explain he underlying physics carefully. "You need a scientific structure in which to analyze assumptions," Jaffe says.

Claire Halloran '20, a materials science and engineering major who chose 8.21 to fulfill a requirement for the Energy Studies Minor, says choosing a research topic was an appealing feature of the class. "I think it's nice in that it lets me explore a topic that's interesting to me and to do so on my own terms."

Shannon Hwang '20, an electrical engineering and computer science major

Robert L. Jaffe, the Jane and Otto Morningstar Professor of Physics, explains the concept of thermal resistance during a meeting of 8.21 Physics of Energy. The redesigned class now includes a variety of communication-oriented assignments, and it fulfills the Institute's communication-intensive requirement. Photos: Kelley Travers, MITEI

Rodger LeGrand, a lecturer in Writing, Rhetoric, and Professional Communication (WRAP) within Comparative Media Studies/Writing at MIT, leads a once-weekly interactive writing session for the students of Physics of Energy.

Left to right: Nathaniel Johnson '18 (a mechanical engineering major), Rebecca Eisenach '19 (materials science and engineering), and Hengameh Bagherianlemraski '19 (physics) workshop their writing during a weekly session led by WRAP.

who also plans to complete the Energy Studies Minor, agrees. "I'm probably not going to work in a quantitative energy field, so it's probably going to be more useful to me to write papers," she says.

Team of advisors

Transforming the class into a CI required a change in staffing, Jaffe says. While the class was previously taught by two physics faculty members and one teaching assistant (TA), this year 8.21 is being taught by Jaffe and a specialist from Writing, Rhetoric, and Professional Communication (WRAP), an MIT center focused on providing support for CI courses.

WRAP staffer Rodger LeGrand, a lecturer in Comparative Media Studies/Writing, conducts one interactive session every week in which students read and analyze writing, discuss what works well in communicating technical topics, and practice. "That's our lab," says LeGrand, who also provides one-on-one coaching to help students plan, draft, revise, and polish their written work. "They're making observations, and we're talking a lot about those [observations] as writers and readers."

In addition to Jaffe and LeGrand, 8.21 is also staffed by a TA from physics and a corps of eight subject matter consultants lined up to help students take deep dives into energy topics for the subject's two writing assignments. "It's nice to have so many advisors," says Andrew Turner, a PhD student in physics who serves as TA for the class and leads a weekly recitation section focused on the physics content of the course. "Because the course covers such a broad range of topics, it's impossible to find someone to cover all the material."

Antje Danielson, education director for the MIT Energy Initiative (MITEI) and one of the advisors, says, "Undergraduates get more attention with this team of people. They have a much larger number of mentors and teachers available to them."

In addition to Danielson, MITEI provided two additional advisors for the class: postdoctoral associate Emre Gençer—an expert in carbon capture, utilization, and storage technologies—and physics postdoc Patrick Brown, who has a background in solar technology. "Postdocs and PhD students also gain experience by mentoring undergraduates," Danielson says. Danielson notes that Gençer and Brown's role in the class is funded by a generous gift from donor William Wynott that supports the Energy Studies Minor.

In another first, students in 8.21 are getting the chance to use a brand-new textbook, *The Physics of Energy* (Cambridge University Press, 2018), which was written by Jaffe and Taylor. "It's intended to serve not only as a resource for courses and a document to stimulate the creation of courses in energy science, but also as a desk reference for workers in the field," Jaffe says.

Jaffe notes that teaching 8.21 as a CI is still an "experiment," and he says he will be eyeing class evaluations to see how the students handle all the course material with the addition of writing assignments.

However, there are signs the remodeled subject is fitting a niche. "[The students] are coming in really excited about talking about energy for a general audience," LeGrand says. "They're engaged."

Kathryn M. O'Neill, MITEI correspondent

Energy alumni: Where are they now?

Kanchana Nanduri SM '13

Department of Civil and Environmental Engineering; Eni-MIT Energy Fellow, 2011–2012

When Kanchana Nanduri joined MIT in 2011 to pursue a master's degree in transportation, she received an energy fellowship that would pay for a year of research in any field she chose. "I spoke to my professor," she recalls, "and I told her I love transportation and I'm really motivated by sustainability. Is there any way we can come up with a problem that connects the two?"

Working alongside Associate Professor of Civil and Environmental Engineering Carolina Osorio, Nanduri developed a transportation thesis based on an energy-focused idea: optimizing traffic signals in a city to cut down emissions.

"Most of the research regarding traffic signals tended to be in the area of reducing travel time," she says. "How do you make sure people at the signal experience minimal delays? The focus was mainly on the commute, not in terms of what these signals are doing for the car engines or for the environment."

Using data on traffic lights and timing from 17 key intersections in the Swiss city of Lausanne, Nanduri and Osorio worked together to build a case study. "We came up with this really nice mathematical model using algorithms to figure out the optimal trade-off among signal timing, fuel consumption, and emissions when designing traffic lights in a city," says Nanduri. "That's how I really got into the field of energy."

From simulations to the streets

Nanduri's long-term goals involve transportation reform in the developing world. The summer after her first year at MIT, she flew to Mumbai—the most populated city in India—to intern with a transportation think tank called Embarq (wrirosscities.org/about/embarq-network). Her work focused on collaborating with the city to reduce pedestrian fatalities by creating a handbook for city planners on how they should design intersections to improve driver visibility.

"It was different from my work at MIT, because everything in India is extremely chaotic," she says. "In America, you can assume that when there's a red light, the cars will stop. In India, you can't assume that." Faced with the challenge of quantifying behavior, Nanduri realized that even the best possible model on a computer might still be guaranteed to fail in the mayhem of city streets.

"It gives perspective to the fact that you shouldn't get too comfortable," she says. "You should always be thinking—when you go into the streets, into the chaos—is your work actually helping?"

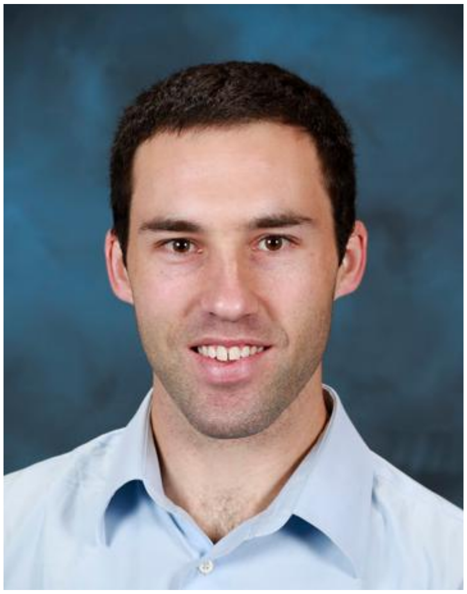
During her 10-week internship, Nanduri asked exactly that question, drawing conclusions about where street design in Indian cities could be improved. Was the bus stop's location obstructing traffic? Was the crosswalk too long for the timing of the signal? "There was no modeling involved—just plain application of common sense," she says. "It was really an eye-opener for me. After that, I came back and resumed my graduate research, but it was a good reminder that there are things out in the real world that aren't so easy."

Building the experience

Now, as a member of the transportation planning team at Amazon, Nanduri focuses on ensuring that the company's package-delivery system runs as energy-efficiently as possible. From placing delivery stations to determining truck routes, she thinks about how the team's digital models will unfold off the screen.

As for the advice she has for students just starting out in the energy sector, Nanduri believes an open attitude is key. "Don't set yourself on a career path too soon or decide you won't do a certain kind of work," she says. "Do everything challenging that's thrown at you. You can figure out what it is that really motivates you, and soon you'll be far enough along that path that you can really have an influence."

Photo: Amuthan Arulraj



Samuel Shaner SM '14, PhD '18

Department of Nuclear Science and Engineering; ExxonMobil-MIT Energy Fellow, 2015–2016

Raised on the central coast of California, MIT alumnus and Energy Fellow Samuel Shaner grew up next to the state's last remaining nuclear power plant. Conversations with his neighbors, many of whom worked at the plant, gave him a sense of what nuclear looked like in a real setting.

Today, with a startup company and a two-year US Department of Energy fellowship through the Innovation Crossroads program at Oak Ridge National Laboratory, Shaner is designing an advanced nuclear reactor that is optimized to meet the needs of future energy markets characterized by high renewables penetration. "I've always been interested in clean energy," says Shaner. "It's one of the key problems for my generation to solve."

From the start of his undergraduate studies at the University of California, Santa Barbara, Shaner sought out coursework and research in clean energy. Guided by his advisor, Professor Eric McFarland, his efforts eventually brought him to MIT for a PhD in nuclear science and engineering. As for why he chose nuclear energy, Shaner says, "Ultimately, it was the technology I was most interested in and thought had the greatest potential for positive impact on our society."

Understanding the supply chain

As a member of the MIT Computational Reactor Physics Group while a grad student, Shaner became familiar with the inner workings of a reactor. "The physics of what goes on in a nuclear reactor is pretty complex, and since it's so hard to do experimental work on nuclear reactors, you need really high-fidelity models to form a virtual environment for reactor analysis," he explains. "So, we were developing methods to be able to perform these high-fidelity simulations."

Shaner's work also extended beyond computer modeling. As an Energy Fellow, he studied the implementation side of nuclear, looking at the supply chain challenges of moving to uranium enrichments above the current 5% limit—a change that would allow nuclear reactors to run longer between refueling, produce less waste, and reduce costs. "It opened my eyes to the practical challenges of bringing new nuclear fuels and technologies to market," he says. "That motivated the project I'm working on now."

Shaner's current focus is on his startup, Yellowstone Energy. He and his co-founder Matt Ellis saw the challenges that companies experience in moving to new fuel forms and systems that are not supported by current supply chains. "Our mission is to design an advanced nuclear reactor that leverages mature and commercially proven fuels and systems to enable a time- and capital-efficient pathway to market," he says. Already, with a $25,000 grant from the MIT Sandbox Fund, they have filed for a patent on the enabling technologies for their design.

A long but rewarding road

Shaner and Ellis now spend "100% of the time" working on the startup, pushing their new design forward on all fronts. For example, they're developing high-fidelity models of their design, are talking with experts in industry about licensing and regulation challenges, and will soon start experimental testing on key components.

But they acknowledge the time it'll take to see results. "It's a long road," Shaner admits. "It's probably the longest road for any technology other than fusion."

Shaner urges students with an interest in energy to seek out an understanding of the markets along with the technologies. "As academics, we get really focused on the technology and somewhat lose sight of the market where energy fits in and what attributes customers are interested in," he says. He encourages students to take multidisciplinary energy classes and to get involved with the MIT Energy Initiative if possible, since many of MITEI's members are key players in the energy industry. "The MITEI fellowship was really helpful for what I'm doing now," says Shaner. "It really provided the motivation and clear picture of the challenges in bringing new technologies to market."

Photo: courtesy of Samuel Shaner

Nan Zhao PhD '17

Media Arts and Sciences;
Shell-MIT Energy Fellow,
2013–2014

When Nan Zhao looks up at a building, she doesn't just see a structure of glass or concrete. She sees a complex ecosystem, with factors from lighting to acoustics—and an opportunity to optimize those factors not only for energy efficiency, but also for human happiness and productivity. "I think there's much to improve in buildings," says Zhao. "There's great potential for reducing energy use based on understanding how the building is used."

Zhao's upbringing in Germany and China cultivated her understanding of the distinct character of living spaces. "I saw a lot of different living environments and habits of managing the home," she says. "How people saved energy in Germany was different from how people saved energy in China." When she came to MIT, Zhao focused her research on intelligent lighting, hoping to reduce lighting's high energy consumption.

Illuminating disciplines

From 2011 to 2017, Zhao worked as a research assistant in the MIT Media Lab's Responsive Environments group. "I took it very literally, making responsive environments," she laughs. "I worked on combining lighting networks with sensors and physiological monitoring to enable personalized, closed-loop control. Knowing people's respiration, heart rate, and brain activity in response to changes in the environment can inform how the environment should change and adapt to their activities."

At first, Zhao concentrated on optimizing aspects like brightness level and color to improve energy efficiency. She quickly realized, though, that intelligent lighting wasn't just an opportunity to save energy; it could also tailor spaces to their inhabitants. "The size of the space, acoustics, objects, smells—all of it has a measurable impact on people's psychology," says Zhao. "It became another dimension in my work: tuning the environment to create restorative conditions for the person."

Over time, Zhao felt her work stretch across disciplines. "My interests grew in different domains, such as psychology and design, and I started to see connections between them," she says. For example, she points to the human biological clock: "One dimension of lighting relates to productivity and people's ability to focus, learn, and memorize. We're discovering more and more how light plays a role in terms of alertness and circadian rhythm."

Her 2013 energy fellowship not only supported her research but also enabled her to connect with industry leaders over their common goal of energy efficiency. "It was great to show them our vision of how light can play a role in the dynamic design of indoor environments," she says.

Creating intelligent spaces

In 2015, Zhao and two other women co-founded a smart urban furniture startup called Soofa. "We started with the idea of bringing clean power to public spaces, with solar-powered benches that anyone could use to charge their phone," she says. "We deployed 12 of them around Boston, and people responded very quickly and positively. They became a sort of symbol for a smart city."

Most recently, the startup has set up free-standing, solar-powered sidewalk displays that allow users to upload content with an app. "The idea is to create a networked community blackboard where people can easily upload content about events," Zhao explains. Displays in Boston feature local artist performances, subway schedules, and even birthday wishes.

As a research scientist at the MIT Media Lab, Zhao now focuses her efforts on refining the workspace. "I'm working on a platform for offices that controls different parameters in the space, such as light and sound, to re-create the feeling of being somewhere," she says. She notes that we choose different places for different activities—perhaps a coffee shop to answer email, a quiet library to study, or an outdoor bench to write something creative. "We naturally choose different environments for different things, because they help us in achieving those things," she says. "I'm trying to bring some of those elements into offices to make them more dynamic and adaptable so they can better support people's well-being and productivity."

Photo: Yoav Reches

Ivy Pepin, MITEI

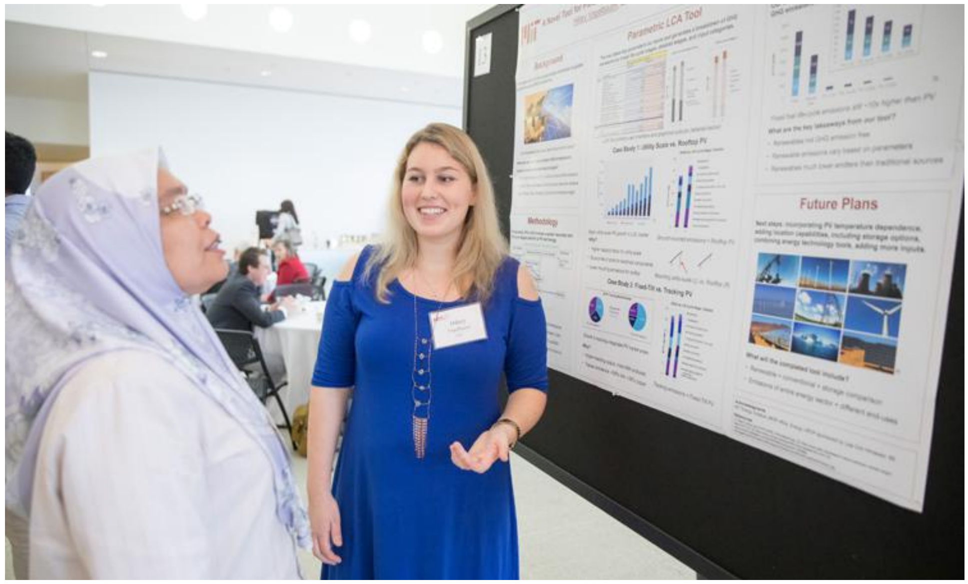
Undergrads present research at MITEI conference

Undergraduate research was a highlight of the MIT Energy Initiative (MITEI) Annual Research Conference for the first time in December 2017, as 15 students presented posters of energy-related work in a wide range of disciplines from electrochemistry to architecture.

The conference, which took place December 5–6 in the MIT Media Lab, offered students a rare opportunity to network with a wide range of energy professionals while showcasing research skills and training applicable to future careers. (For more on the MITEI Annual Research Conference, go to page 43.)

"I really liked that this was a conference of professionals, not just MIT students," says Hilary Vogelbaum '20, a materials science and engineering major and energy studies minor who presented research on a tool for conducting life-cycle analyses of various energy technologies. "A couple people from Iberdrola came by and were very enthusiastic that undergraduates like myself were doing serious, applicable work with industry."

All the poster presenters were MITEI-sponsored participants in the Undergraduate Research Opportunities Program (UROP), which gives students hands-on research experience. The undergraduates applied for the program in April 2017 and then spent approximately 10 weeks of the summer working for faculty on a rich variety of projects.



Materials science and engineering major Hilary Vogelbaum '20 presents her poster comparing life-cycle greenhouse gas emissions of renewable energy technologies in various scenarios. Photos: Bryce Vickmark

Civil and environmental engineering major Rayna Higuchi '20 discusses her research on the potential use of the bacterium *pseudomonas putida* in bioremediation efforts.

Rayna Higuchi '20, a civil and environmental engineering major, conducted research on directed evolution in hopes of producing bacteria that can degrade toxic compounds. She says she enjoyed presenting her work at the conference because it prompted her to consider how the work might be applicable to industry. "That was interesting to think about," she says.

Ian J. McNally '20, who is majoring in mathematics with computer science, spent his UROP analyzing the market for congestion revenue rights (CRRs) in California. CRRs are a little-known financial instrument used to make money by betting on grid congestion. At the conference, McNally says, "I brushed shoulders with a lot of important people in energy and finance, and not a lot of people knew what it was. It was interesting to be researching something not a lot of people knew even exists."

Vogelbaum, whose ambition is to become "a voice of influence in the energy industry," says the conference presented an ideal opportunity for her to meet energy professionals. "Getting connected to people in all parts of industry…is especially important for me," she says.

Preparing to present

MITEI has sponsored UROP students for many years, but the conference poster session was added this year because MITEI Education Director Antje Danielson thought having such a high-profile project would enhance the UROP experience.

"We have always had undergraduates practice giving presentations, but we've had them present orally, and only to each other," says Danielson, noting the conference presentations gave everyone an extra incentive to work hard. "There was quite a bit of pressure for the students to do well but also for the faculty members and postdocs to engage with the undergraduates at an extra level to make sure the posters were presentable."

To ensure that the undergraduates were well-prepared for their conference presentations, Rachel Shulman, academic coordinator at MITEI, enlisted help from MIT's Writing and Communication Center (WCC). WCC arranged for Thalia Rubio, a lecturer in Comparative Media Studies/Writing, to conduct three workshops centered on how to distill complex scientific ideas and present them in a way that makes them accessible to a broad audience. "When people come around at a poster session, you don't know what their background is, so you have to be prepared to have this conversation," Rubio says. "You can't launch into a 20-minute speech."

Alexander Alabugin '20, a chemistry major whose UROP focused on replacing expensive membranes in polymer electrolyte fuel cells with a solid composite, says the workshops helped him improve his poster and adjust his material for a more general audience. "I think I was writing for a pretty pure electrochemistry audience," he says. "I had to realign some of the details."

At the poster session, physics major Ebrahim Al Johani '19 describes his work to develop a small, efficient device that uses infrared light as an energy source to power a small, blue LED. This device could be implemented in chip implants and battery-powered applications that can utilize its miniature, minimally invasive design.

McNally says, "I had never made a professional research poster before, and I wanted to make a good one, so I'm glad they gave us an opportunity to improve."

Connecting with industry

MITEI's UROP students were sponsored by leading companies as well as by individuals, and several sponsors who attended the conference say they were quite impressed by the undergraduates' research.

"The undergraduate poster session was a highlight of the conference," says Dave Marler, senior scientific advisor for ExxonMobil Research and Engineering. "The science and engineering students applied their academic learnings to real-world energy challenges. Their research was of high quality—on par with what you would see from early-year graduate students. Equally important, the poster session provided an opportunity for MITEI member organizations—like ExxonMobil—and MIT students to network."

Michael Pomrehn, sales and innovation manager at Shell in Hamburg, Germany, was so impressed with the work of UROP student Caralyn Cutlip '18 that he has since arranged for her to do an internship at Shell—with the possibility that the assignment could lead to a full-time job. A mechanical engineering major, Cutlip investigated passive cooling for low-cost housing—work that dovetails with Shell's interest in home energy, Pomrehn says.

"I was particularly impressed with how she managed to use sensing and data to underpin her work," Pomrehn says. "We at Shell see big, big benefits from the skill pool at MIT."

The connections made at the conference were equally important for the students. "It was definitely uplifting to see the support from different players in industry," Vogelbaum says. "That's why I chose MIT. I looked at all these schools and thought, 'I don't think there's anywhere else I can make these connections.'"

To learn more about the goals of the Energy UROP program, please visit energy.mit.edu/urop.

Kathryn M. O'Neill, MITEI correspondent

Maximizing innovation for an energy sector in flux

The fall 2017 gathering of the MIT Energy Initiative's Annual Research Conference (ARC) had added meaning: 2017 marked 10 years since the inaugural ARC. The conference, always filled with news from the forefront of energy research, was also a chance to reflect on the past decade of energy breakthroughs at MIT and to look forward to the advances being made toward a low-carbon future.

In his welcoming remarks, MITEI Director Robert C. Armstrong described the energy sector as "a field in flux." He laid out the seismic changes taking place across the energy landscape, from increased distributed generation to rapidly improving technology to the importance of digitization for our electric power system. He also noted the advances being made toward decarbonization. He said, "As of just recently, the power sector is no longer the largest emitter of CO_2 in the US, showing the enormous potential for change when a sector commits to decreasing emissions. Now our focus must be on the urgent need for decarbonization in other sectors, such as transportation, which now holds the number one spot."

Armstrong was joined by 13th US Secretary of Energy Ernest Moniz, the founding director of MITEI. Moniz, who is a professor emeritus of physics and special advisor to the MIT President, reflected on the philosophy that led to MITEI's launch by then-MIT President Susan Hockfield. "The core of the MITEI model is the conviction that, especially in the energy business, industry is key to solutions," Moniz said. "The job of the MITEI director is to run a dating service, matching companies, faculty, and researchers based on common interests to stimulate projects with real-world industry applications that can move the needle on energy technology."

Fresh ideas from faculty members

Introducing a panel featuring MITEI-affiliated faculty whose work the initiative has supported, Robert Stoner, MITEI's deputy director for science and technology and director of the Tata Center for Technology and Design, described how new faculty "often come to us with the freshest ideas and the most openness to the idea of projecting their knowledge onto a new field."

Elsa Olivetti, the Atlantic Richfield Assistant Professor of Energy Studies in the Department of Materials Science and Engineering, recently published a study with her team on a technique for using natural language processing applications to pore through immense amounts of materials science literature to compile "recipes" for potential new materials. The aim of the research, which was supported in part by the MITEI Seed Fund Program, was to evaluate the value of text and data mining from peer-reviewed articles to accelerate the materials synthesis process.

"We try to link systems thinking to the development of new technologies and the design of new materials," Olivetti said. She added, "As our systems become more complex, our supply chains more intricate, our ability to innovate by leveraging the work that's been done to date will be critical." (See page 17 for more about Olivetti's research.)

Jing Li '11 deferred becoming a faculty member at the MIT Sloan School of Management to spend a few years as a postdoctoral associate. Her research this year is focusing on the economics of technology diffusion and adoption.

"Economics has a lot to offer when thinking about energy issues," she said. "Determining, for example, when policy should step in and when policy should let the market do its own thing." On her panel, she discussed, in particular, battery recharging infrastructure for electric cars. Auto manufacturers have designed different brands of electric cars with different style plugs and different communication protocols between the

During his opening remarks at the Annual Research Conference, MITEI Director Robert C. Armstrong points to the significant decrease in carbon dioxide emissions in the power sector as an example of what can be achieved when a sector commits to making a change. Photos: Bryce Vickmark car and its charging equipment, making achieving compatibility on the charging network difficult but not technologically infeasible, in Li's view.

In her presentation, Li discussed two key trade-offs in setting policies that seek to impose a uniform standard on fast-charging technology for electric vehicles: consumers would be better off with a single, better network of charging stations than the existing fragmented ones, but auto manufacturers may invest less in such a common network. Li's research found that a uniform fast-charging standard would increase the number of electric vehicles purchased and reduce costly duplicative investment.

In addition to research presented by faculty members, MIT undergraduate students had the chance to share their own research as poster presentations, offering them a chance to engage with industry members one-on-one about the real-world implications of their work. (Turn to page 41 for more about the poster session.)

Industry perspectives on the energy transition

At the conference, industry perspectives on the state of the energy sector provided a valuable balance to faculty research. Pratima Rangarajan, CEO of Climate Investments, the investment arm of the Oil and Gas Climate Initiative (OGCI), said that the 10 global oil and gas companies that founded and support OGCI and Climate Investments are well aware of the challenges posed when an ever-increasing need for energy on a global scale is set on a collision course with the dangers of a changing climate—which is why they started the initiative. "They are fierce competitors on a global scale, yet they are keen to come together to collaborate on these important issues," she said. "That's something we need more of as we tackle climate challenges."

During a panel titled "Industry Perspectives on the Energy Transition," CEO of OGCI Climate Investments Pratima Rangarajan discusses the need to collaborate to tackle climate challenges. Looking on are MITEI's Robert C. Armstrong (left), who served as moderator, and Regina García Cuéllar, chief of staff of Petreolos Méxicanos (right).

Nick Pudar, the director and general manager of strategic initiatives at General Motors, described how his company is looking to the future, saying, "We are aggressively electrifying our portfolio." He discussed early-stage opportunities for electric vehicle technology, from ride-sharing applications to autonomous vehicles. Agreeing with Li, Pudar noted the challenges inherent in a charging infra-structure that is still under development.

For all of these challenges, though, there are immense opportunities. "When we look at this overall space, we see an ecosystem that is ripe for innovation in every facet, and ripe for partnerships in every dimension," Pudar said.

The three "D's"

Many panelists discussed how this innovation landscape is being remade by a suite of change agents—what speakers referred to as "the three D's": digitization, decarbonization, and decentralization. The trends this alliterative trio describes are as follows: an electric grid increasingly digitally connected; the movement toward renewables and other forms of low-carbon energy; and the evolution of the utility grid from a system based on central power plants to an ecosystem that also includes smaller-scale production capacity, such as individual consumer's energy-generating systems and microgrids.

On a panel about digitization in the energy sector, MIT Computer Science and Artificial Intelligence Laboratory (CSAIL) Principal Research Scientist Una-May O'Reilly remarked, "Computation is allowing us to observe all of our systems far more frequently than we used to and at a level of observation and a modality of observation that we've never done before." All of this observational capacity leads to more data than companies have ever had access to in the past. "It's where humans and data meet," O'Reilly said. "Now, you've got a glut of data, but that data isn't necessarily expressed in human terms." The role of computation in industry is twofold: to aid both observation and interpretation. O'Reilly painted the central importance of computation in this way: "Computation is the new electricity, and it will transform your businesses."

This transformation comes with its own specific challenges and dangers, though. O'Reilly's fellow panelists included experts on cybersecurity, machine learning, and blockchain, and discussed everything from payment methods like Bitcoin—designed for anonymity and privacy—to questions of security on an institutional level. Daniel J. Weitzner, founding director of the MIT Internet Policy Research Initiative and principal research scientist at CSAIL, laid out common misconceptions about cybersecurity. One of the most prevalent, Weitzner said, is the idea that better technology alone is the key to preventing cyber attacks. He noted that attacks that might be blamed on technological gaps are more often cases of "institutional failure," where openings are made for attackers through human error—most notably, with employees failing to upload security updates.

"I'd argue that rather than just trying to figure out how you can lock down these Internet-of-Things devices more securely, we're trying to look very carefully at what is the right regulatory environment. How do we understand user behavior to try to encourage better cyber hygiene, and how do we make sure that we get the right market forces operating toward better security as opposed to just lowering short-term costs?" Accordingly, part of Weitzner's work at MIT involves consulting with policymakers about the best way to address cybersecurity concerns. "We're in the process of working with this administration and with other governments around the world to try to encourage governments to think about cybersecurity in a more systematic way," he said.

Digitization and cybersecurity aren't the only areas in which today's electricity sector is changing. In remarks on the evolution of the electric power system, MITEI Director of Research Francis O'Sullivan said, "Renewables are at energy's big table right now, and that's going to drive the capacity market forward. That's changing how the grid itself works at that centralized level." Christopher Knittel, the George P. Shultz Professor of Applied Economics at the MIT Sloan School of Management, elaborated on decentralization on a panel titled "The Evolving Power Market Landscape." "Distribution companies and utilities are going to have to gain, or at least harness, new core capabilities," he said. "Utilities and distribution companies are going to have to rethink what products they offer and how they bring the most value to their customers."

Francis O'Sullivan, MITEI's director of research and co-director of the Low-Carbon Energy Center for Electric Power Systems Research (right), discusses decentralizing the energy grid. O'Sullivan moderated the panel "The Digitization of Energy: Machine Learning, Blockchain, and Cybersecurity." Other panelists (left to right) are Una-May O'Reilly, principal research scientist, Computer Science and Artificial Intelligence Laboratory (CSAIL) at MIT; Christian Catalini, assistant professor, MIT Sloan School of Management; and Daniel J. Weitzner, principal research scientist at CSAIL and founding director of the MIT Internet Policy Research Initiative.

"Gone are the days of a captive audience," Knittel continued. "Now it's very easy for me [as a consumer] to partially cut the cord, and I could cut the cord completely if I wanted to. But it's actually the partial cutting of the cord that's the problem, because if I put photovoltaics on my rooftop, I'm still using the grid, and effectively, the grid is my battery. And that's creating all sorts of issues with pricing and the utility side of things." Knittel went on to describe a host of areas in which utilities will need to evolve if they are to keep up with these changes in the energy sector, including pricing, data-driven products, and consumer-centric policies.

MITEI's response to these questions and many more is the Low-Carbon Energy Center for Electric Power Systems Research, which is co-directed by Knittel and O'Sullivan. O'Sullivan introduced the center's inaugural workshop, which took place immediately following the ARC's closing panel and was open to all participants.

"With this open workshop, we will begin to discuss how we bring all of that capability together, so that we understand the important trade-offs on today's and future systems, to see what's going to be sensible from an economic point of view, from a technical performance point of view, and from a customer engagement point of view," he said.

Regarding MIT's role in working to solve these issues, O'Sullivan expressed confidence in the Institute's faculty expertise and ability to address the challenges head-on, saying, "We're excited to go after this topic through the center.…Without a doubt, electric power systems transitions will be a core element of the changing energy landscape in the coming years."

Francesca McCaffrey, MITEI

MIT Energy Conference speakers say transformation can happen fast

The pace of advances in key clean energy technologies has been faster than many experts predicted, to the point that solar and wind power, combined with systems for storing their output, can often be the least expensive options for new types of power-generating capacity. In fact, a radical transformation of the world's energy landscape is well underway, said several speakers at the annual MIT Energy Conference, held on March 2–3, 2018, in Kendall Square in Cambridge, Massachusetts.

In the opening keynote talk, Tony Seba, co-founder of ReThink X and author of the book *Clean Disruption of Energy and Transportation*, kicked off the event on an upbeat note that carried through many of the event's keynote talks and panel discussions. He reflected on the increasingly rapid adoption of transformative technologies over time, from cars replacing horses on the streets a century ago to the explosion of smartphones in the last decade.

Seba listed several promising trends in low-emissions technologies for power production and storage, as well as in economic and regulatory models. For example, when a Colorado utility recently put out bids to replace the generating capacity of two large coal plants, they got bids for far more capacity than they needed—with the vast majority of prices for wind or solar power plus storage actually lower than those of coal power in the state.

"It's over, people!" Seba said. "Solar and wind power plus storage is already the cheapest by far." As a result, he said, these greenhouse-gas-free options will inevitably take over the energy market, for purely economic reasons. Some other experts, including some of the conference's other speakers, foresee a slower and more difficult path away from fossil fuels. But when truly disruptive new technologies come along, Seba said, "It's usually the experts and the insiders and the mainstream analysts who dismiss it." As an example, he showed how, year after year, the International Energy Agency's projections of the future growth of installed solar capacity have lagged far behind the actual results.

Left to right: Howard J. Herzog, senior research engineer at the MIT Energy Initiative, moderated a panel on strategies for portfolio diversification in major energy companies. Joining him were Tim Barckholtz, senior scientific advisor, corporate strategic research, ExxonMobil; Tim Polega, renewable investment and technology leader, Saudi Arabia; and Joseph B. Powell, chief scientist, chemical engineering, Shell. Photos: JC Woodard Photography

Now in its 13th year, the conference is run by the MIT Energy Club, a student-run organization that is the largest such club in the world, with about 5,000 members, MIT Energy Initiative Director Robert C. Armstrong said in his introduction to the conference.

The world is facing two great interconnected challenges in energy, Armstrong said: the expected doubling of the global demand for energy through both population growth and rising incomes, and the need to drastically curb the greenhouse gas emissions associated with that energy. "It's made doubly difficult by the fact that most of that energy demand growth is going to be in the developing world," he said.

The transformation of the electricity sector toward low-carbon or zero-carbon fuels is underway, to the point that "transportation is now the largest sector" of emissions in the United States, Armstrong said, "because we've done so well with electricity. There's been astounding progress on the solar side."

That theme was echoed in the official launch at the conference of a new book from the MIT Press called *Taming the Sun*, by Varun Sivaram, a fellow at the Council on Foreign Relations and an adjunct professor at Georgetown University School of Foreign Service. In a keynote address, Sivaram described specific areas where innovations are needed in order to propel the next stages in harnessing solar energy's potential. Those include new ways of financing such things as solar and battery installations, for example by bundling many projects into investment vehicles to spread out the risk of individual projects.

The next hurdle to be overcome, Sivaram said, is "value deflation," an ironic side

A panel discussion on how blockchain technology can transform energy markets featured (left to right) Michael Casey of MIT's Media Lab, Lawrence Orsini of LO3 Energy, Robert Trinnear of the Energy Authority, and William Bubinicek of ConnectM Technology Solutions.

In a keynote address, Varun Sivaram, a fellow at the Council on Foreign Relations and an adjunct professor at Georgetown University School of Foreign Service, described specific areas where innovations are needed in order to propel the next stages in harnessing solar energy's potential.

effect of the rapid growth and plunging costs in the industry. As more solar capacity comes online at ever-lower prices, the value of new installations and existing ones goes down, reflecting the lower revenue from a given amount of power delivered. Some advances that could help counter this effect, he said, would include efficiently converting solar energy to heat that could then be used throughout the night or be converted back to electricity when needed, or harnessing the batteries in electric vehicles to help smooth the demand and supply curves of electricity.

"These innovations would help preserve solar's value by ensuring solar can be used no matter when it's produced or how it fluctuates," he said. By pursuing these approaches, he said, "if we get this right, the 21st century will be one in which humanity finally secures cheap, clean, and virtually limitless energy" from the sun.

Mark Jacobson, a professor of civil and environmental engineering at Stanford University, described his research suggesting that it's possible for the United States, and the world, to reduce fossil fuel use almost entirely by midcentury, largely by converting most energy systems to electrical ones powered by hydro, offshore wind, and solar power with thermal storage, and using highly efficient heat pumps for all heating and cooling rather than less-efficient fuels, electric resistance heating, and conventional air conditioning.

"Transitioning to 100% renewables in all energy sectors is technically and economically feasible," he said, "and there are many ways to do it." (Jacobson's work has faced some criticism, and in February 2018 he dropped a controversial lawsuit he had brought against the authors of a paper that contested some of his claims.)

In another keynote, Jesse Jenkins, an MIT PhD student and researcher in the MIT Energy Initiative, said that "electricity is the linchpin" of efforts to get to net-zero emissions. "It has the most options today and can cut emissions the fastest of any sector." That, in turn, would have a domino effect leading those using other energy systems to convert to electricity, he said. But Jenkins argued that getting to 100% renewable energy is not necessarily the target to shoot for; rather, the goal should be zero carbon dioxide emissions from the power sector, which may provide a more practical and economic path to emissions reduction.

"There is a strong argument in the literature," he said, "that a strong mix of low-carbon dioxide generation," which could include natural gas plants and possibly other fossil-fuel plants with a carbon-capture system, "offers the most choices in achieving deep decarbonization goals."

David L. Chandler, MIT News Office

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

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MITEI member news

Kouichi Murakami (left), managing executive officer at Tokyo's IHI Corporation, meets with MIT Energy Initiative Director Robert Armstrong. With sights set on reducing greenhouse gas emissions, IHI, a global engineering, construction, and manufacturing company, signed a three-year membership agreement with MITEI's Low-Carbon Energy Center for Carbon Capture, Utilization, and Storage. The company is also interested in research projects focusing on low-carbon energy technologies as well as on energy management systems. More online at bit.ly/IHI-MITEI. Photo: Kelley Travers, MITEI

To enhance the sustainability of homes and property projects in Thailand, Bangkok-based property developer Magnolia Quality Development Corporation Limited (MQDC) has joined the MIT Energy Initiative as a member, with a three-year membership agreement in MITEI's Low-Carbon Energy Center for Electric Power Systems Research. Above: Lihong (Wendy) Duan, manager of MITEI's Asia Pacific Energy Partnership Program, and Singh Intrachooto, chief advisor of MQDC's Research and Innovation for Sustainability Center, celebrate the launch of the new collaboration. More online at bit.ly/MQDC-MITEI. Photo courtesy of MQDC

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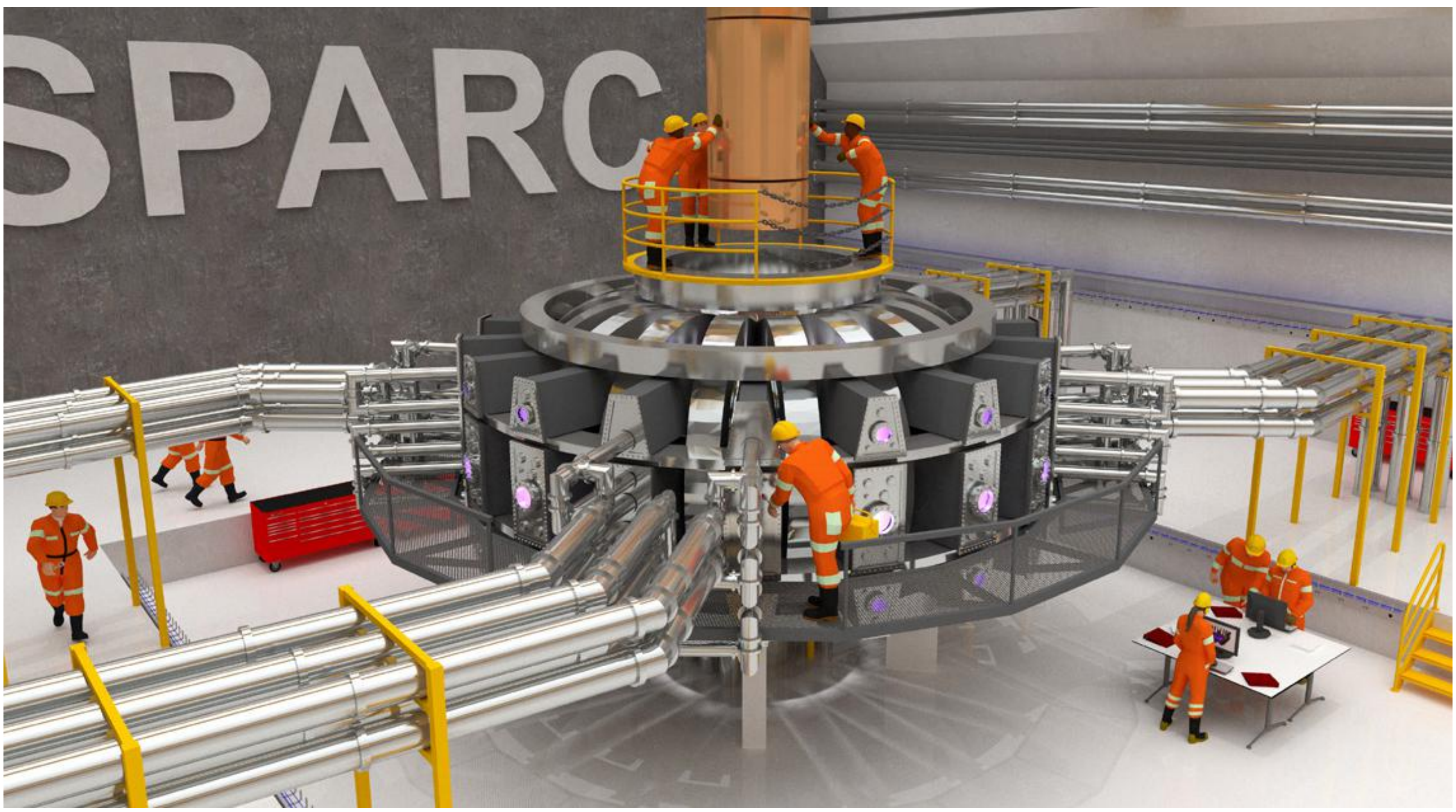

A new chapter in the history of fusion energy research at MIT is beginning

This spring, MIT announced that Italian energy company Eni S.p.A., a founding member of the MIT Energy Initiative, had reached an agreement with MIT to fund fusion research projects run out of the MIT Plasma Science and Fusion Center's newly created Laboratory for Innovation in Fusion Technologies. Eni also announced a commitment to invest in a new private company with roots at MIT, Commonwealth Fusion Systems. The overall goal of the research is to develop a working fusion pilot plant within the next 15 years. For more information, turn to page 3.

Pictured above is a rendering of the proposed compact and powerful fusion experiment, called SPARC. Using high-field magnets built with newly available high-temperature superconductors, the experiment would be the first controlled fusion plasma system to produce net energy output.

Visualization: Ken Filar, PSFC research affiliate