Energy Futures

MIT ENERGY INITIATIVE MASSACHUSETTS INSTITUTE OF TECHNOLOGY AUTUMN 2019

MIT Climate Action Symposia Series

"I believe that those of us committed to this cause need to come together to seek out new ways to support the advanced science and technology that will enable political action to succeed on the path to a sustainable future for us all."

—MIT President L. Rafael Reif at "Progress in climate science," the first in MIT's Climate Action Symposium Series, on October 2, 2019.

During the 2019–2020 academic year, MIT is hosting six symposia to examine the urgent challenge of climate change. This series draws on MIT's work to date on the MIT Plan for Action on Climate Change to consider the current state of knowledge on key aspects of this global problem. These discussions provide an important opportunity for engagement among members of the MIT community, other leading researchers, industry leaders, and policymakers to explore options for facilitating the necessary transition to a low-carbon economy.

Progress in climate science
Wednesday, October 2, 2019

Challenges of climate policy
Tuesday, October 29, 2019

Decarbonizing the electricity sector
Wednesday, December 4, 2019

Economy-wide deep decarbonization
Tuesday, February 25, 2020

MIT climate initiatives and the role of research universities
Thursday, April 2, 2020

Summing up: Why is the world waiting?
Wednesday, April 22, 2020

Tune into the livestream of each symposium in the series at climate.mit.edu/symposia/live.

Read about MIT's Plan for Action on Climate Change by visiting climate.mit.edu/climateaction.

On the cover
In November 2019, MITEI released the results of a three-year study of the evolution of personal mobility through 2050. A diverse team of MIT faculty, researchers, and students examined key factors that will shape personal mobility, from global and national markets to policy and mobility choices at the city and individual levels. The report, *Insights into Future Mobility,* presents findings to help stakeholders anticipate and navigate the challenges that lie ahead. Read more on page 3.
Illustration courtesy of MITEI

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Nancy W. Stauffer, editor
stauffer@mit.edu

Kathryn Luu, assistant editor
keluu@mit.edu

Emily Dahl, MITEI communications director
edahl@mit.edu

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MIT Energy Initiative
Massachusetts Institute of Technology
77 Massachusetts Avenue, E19-307
Cambridge, MA 02139-4307

617-258-8891

For more information and the latest news from MITEI, go to **energy.mit.edu.**

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Energy Futures

Autumn 2019

MITei
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Massachusetts Institute
of Technology

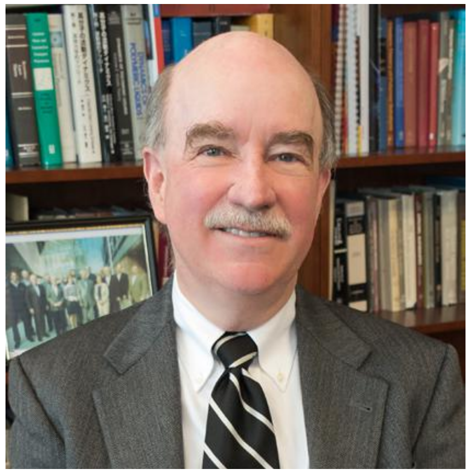
A letter from the director

Dear friends,

In recent months, youth around the world have brought the urgent need for immediate action to address climate change into sharp focus. They understand that we need to accelerate and scale climate action, as the impacts of climate change have already started to affect every part of the globe—from rising sea levels to prolonged droughts to economic instability. Their voices are an important reminder of the pressing work we need to do in research, education, and outreach to help mitigate the effects of climate change and leave future generations with a healthy planet.

To examine the serious challenge of climate change, MIT is hosting a series of six Climate Action Symposia during the 2019–2020 academic year. The symposia cover climate science and policy; pathways for decarbonization of the global economy; and what universities can do to accelerate progress, including MIT's efforts under our Plan for Action on Climate Change. In addition to enhancing the MIT community's understanding of this range of issues, we hope that the series will spark new ideas for collaborations and solutions.

A particularly important aspect of our energy transition is how to alleviate energy poverty in the developing world and ensure that the approximately 1 billion global citizens without adequate access to electricity can benefit from affordable, sustainable power. To this end, the MIT Energy Initiative (MITEI) has received a grant to conduct research supporting the Rockefeller Foundation's newly launched Global Commission to End Energy Poverty. The commission aims to develop an efficient and economic path forward to providing universal electrification.



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

This November, our Mobility of the Future study team shared its report, *Insights into Future Mobility*, with events in Washington, D.C., and on the MIT campus (page 3). This study analyzes many key aspects of mobility systems and how they are affected by new technologies, business models, and government policies. This report, which underscores that decarbonizing the transportation sector is vital for achieving greenhouse gas reduction targets, lays out the study team's findings for policymakers and industry and discusses potential implications for the transition to more environmentally and economically sustainable personal mobility solutions.

In this issue of *Energy Futures,* you will read about other impactful research at MIT, from a look at the effects of renewable energy and carbon pricing policies on improved human health (page 5) to a study on Chinese coal power plant emissions and the response to stricter emissions limits in highly populated regions (page 23). You will also learn about a new approach using electricity and electrocatalysts to reduce the amount of carbon dioxide produced when manufacturing consumer products (page 11), and about a transparent version of silica aerogel that, when inserted into a double-pane window, can provide both insulation and clear visibility (page 17).

In addition to these research initiatives, MITEI remains committed to our energy-based Undergraduate Research Opportunities Program (UROP). In this issue, you will read about several UROP students and how their experiences in interdisciplinary collaboration impacted their education (page 35). You will also read about other education collaborations, including a "Science Slam" that brought together students from MIT and the University of Massachusetts Amherst to compete in presenting their summer research projects (page 37), as well as a new international field trip program with the University of Kiel, Germany, that brings students from both universities to each other's regions to learn about energy-related technologies and facilities (page 38).

To realize our global emissions goals and create a decarbonized future, we must not only continue to accelerate the creation and scale-up of game-changing technologies but also engage with our communities—from local to global—to grow awareness and create opportunities for our young people to connect with government and industry. We will keep working toward these goals, and as we do so, I welcome your feedback and comments. Thank you for reading.

Warm regards,

Robert C Armstrong

Professor Robert C. Armstrong
MITEI Director
November 2019

Pathways for sustainable personal transportation

MITEI report identifies need for technological innovations, policies, and behavioral changes

Kathryn Luu, MITEI

In our daily lives, we all make choices about how we travel and what type of vehicle we own or use. We consider these choices within the constraints of our current transportation system and weigh concerns including costs, convenience, and—increasingly—carbon emissions. *Insights into Future Mobility*, a new multidisciplinary report from the MIT Energy Initiative (MITEI), explores how individual travel decisions will be shaped by complex interactions between technologies, markets, business models, government policies, and consumer preferences—and the potential consequences as personal mobility undergoes tremendous changes in the years ahead. Members of the study team presented their findings on November 19, 2019, in Washington, D.C., and at an event on MIT's campus on November 21.

The *Insights into Future Mobility* report is the culmination of MITEI's three-year Mobility of the Future study, which is part of MIT's Plan for Action on Climate Change. The report highlights the importance of near-term action to ensure the long-term sustainability of personal mobility. The researchers ultimately find that continued technological innovation is necessary and must be accompanied by cross-sector policies and changes to consumer behavior in order to meet Paris Agreement targets for greenhouse gas emissions reductions.

"Understanding the future of personal mobility requires an integrated analysis of technology, infrastructure, consumer choice, and government policy," says MITEI Director Robert C. Armstrong, a professor of chemical engineering at MIT. "The study team has examined how these different dimensions will develop and interact, and the report offers possible pathways toward achieving a more sustainable personal transportation system."

The study team of MIT faculty, researchers, and students focused on five main areas of inquiry. They investigated the potential impact of global climate policies on fleet composition and fuel consumption, and the outlook for vehicle ownership and travel, with a focus on the U.S. and China. They also researched characteristics and future market share of alternative fuel vehicles, including plug-in electric and hydrogen fuel cell vehicles, and infrastructure considerations for charging and fueling, particularly as they affect future demand. Another main area of focus was the future of urban mobility, especially the potentially disruptive role of ride-hailing services and autonomous vehicles.

The researchers find that there is considerable opportunity for reducing emissions from personal mobility by improving powertrain efficiency and deploying alternative fuel vehicles in the coming decades. These changes must be accompanied by decarbonization of the production of the fuels and electricity that power these vehicles in order to reach global emissions mitigation targets and achieve cleaner air and other environmental and human health benefits.

"Our analysis shows that reducing the carbon intensity of the light-duty vehicle fleet contributes to climate change mitigation goals, as part of the larger solution," says Sergey Paltsev, deputy director of the MIT Joint Program on the Science and Policy of Global Change and senior research scientist at MITEI. "If we are to reach international goals for limiting temperature rise and other climate change-related impacts, we will need comprehensive climate policies that promote the adoption of alternative fuel vehicles in the transportation sector and simultaneously decarbonize the electricity sector."

Several factors influence an individual's decision to adopt an alternative fuel vehicle, such as a battery electric vehicle. The researchers found that the most important, interrelated factors that impact alternative vehicle adoption include cost, driving range, and charging convenience.

They conclude that as production volumes increase, battery costs and the purchase price of electric vehicles will decrease, which will in turn drive sales. Improved batteries would extend the vehicle range, reinforcing the attractiveness of alternative fuel vehicles to consumers. Greater deployment of electric vehicles creates a larger market for publicly available charging infrastructure, which is critical for supporting charging convenience. Early government support for alternative fuel vehicles and charging and fueling infrastructure can help launch a self-reinforcing trajectory of adoption—and has already contributed to an increase in alternative fuel vehicle deployment.

"We found that substantial uptake of battery electric vehicles is likely and that the extent and speed of this transition to electrification is sensitive to evolving battery costs, availability of charging infrastructure, and policy support," says William H. Green, a professor of chemical engineering at MIT and the study chair. This large-scale deployment of battery electric vehicles is expected to help them reach total cost-of-ownership parity with internal combustion engine vehicles in approximately 10 years in the U.S. It should also lead to new business opportunities, including solutions for developing cost-effective methods of recycling batteries on an industrial scale.

The researchers also examined the role of consumer attitudes toward car ownership and use in both established and emerging economies. In the U.S., the researchers analyzed trends in population and socioeconomic factors to estimate future demand for vehicles and vehicle travel. While many have argued that lower car ownership and use among millennials may lead to a reduced personal vehicle fleet in coming decades, the study team found that generational differences could be completely explained by differences in socioeconomics—meaning that there is no significant difference in preferences for vehicle ownership or use between millennials and previous generations. Therefore, the stock of light-duty vehicles and number of vehicle-miles traveled will likely increase by approximately 30% by 2050 in the U.S. In addition, the analysis indicates that "car pride"—the attribution of social status and personal image to owning and using a car—has an effect on car ownership as strong as that of income. An analysis of car pride across countries revealed that car pride is higher in emerging vehicle markets; among established markets, car pride is highest in the U.S.

The adoption of new technologies and business models for personal mobility at scale will require major shifts in consumer perceptions and behaviors, notes Joanna Moody, research program manager of MITEI's Mobility Systems Center and a coordinating author of the report. "Symbolic and emotional attachments to car ownership and use, particularly among individuals in emerging economies, could pose a significant barrier to the widespread adoption of more sustainable alternatives to privately owned vehicles powered by petroleum-based fuels," Moody says. "We will need proactive efforts through public policy to establish new social norms to break down these barriers."

The researchers also looked at China, the largest market for new vehicle sales, to analyze how cities form transportation policies and to estimate how those local-level policies might impact the future size of China's vehicle stock. To date, six major Chinese cities and one province have implemented car ownership restriction policies in response to severe congestion and air pollution. Our researchers found that if the six megacities continue with these restrictions, the country's light-duty vehicle fleet could be 4% (12 million vehicles) smaller by 2030 than it would be without these restrictions. If the policies are adopted in more of China's cities facing congestion and air pollution challenges, the fleet could be up to 10% (32 million vehicles) smaller in 2030 than it would be without those restrictions.

Finally, the team explored how the introduction of low-cost, door-to-door autonomous vehicle (AV) mobility services will interact with existing modes of transportation in dense cities with incumbent public transit systems. They find that introducing this low-cost mobility service without restrictions can lead to increased congestion, travel times, and vehicle miles traveled—as well as reduced public transit ridership. However, these negative impacts can be mitigated if low-cost mobility services are introduced alongside policies such as "first/last mile" policies (using AVs to transport riders to and from public transit stations) or policies that reduce private vehicle ownership. The findings apply even to cities with vastly different levels of public transit service.

The Mobility of the Future study received support from an external consortium of international companies with expertise in various aspects of the transportation sector, including energy, vehicle manufacturing, and infrastructure. The report, its findings, and analyses are solely the work of the MIT researchers.

For more information and an online version of *Insights into Future Mobility,* visit energy.mit.edu/insightsintofuturemobility.

Mobility Systems Center launches from the Mobility of the Future study

The Mobility Systems Center, MITEI's newest Low-Carbon Energy Center, brings together MIT's extensive expertise in mobility research to understand current and future trends in global passenger and freight mobility. Approaching mobility from a sociotechnical perspective, the center identifies key challenges, investigates potential trends, and analyzes the societal and environmental impact of emerging solutions for the movement of people and goods. For more information, visit mobilitysystemscenter.mit.edu.

Renewable energy and carbon pricing policies

State-level adoption saves money and lives

Nancy W. Stauffer, MITEI

IN BRIEF

U.S. legislators in a number of states are now evaluating the costs and benefits of policies that require adoption of renewable energy. But they don't generally consider the significant impacts of those policies on air pollution. Using linked economic and air pollution models, MIT researchers have found that renewable energy policies in the Rust Belt region could reduce air pollution so much that the savings from improved human health would exceed the costs of the policies by 2030. Moreover, making the policies more stringent would increase the health-related savings more rapidly than it would drive up the policy costs. The study also shows that imposing a price on carbon emissions would bring even greater health benefits at lower cost, but enacting such policies has proved politically challenging.

In the absence of federal adoption of climate change policy, states and municipalities in the United States have been taking action on their own. In particular, 29 states and the District of Columbia have enacted Renewable Portfolio Standards (RPSs) requiring that a certain fraction of their electricity mix come from renewable power technologies such as wind or solar. But now some states are rethinking their RPSs. A few are making them more stringent, but many more are relaxing or even repealing them.

Above Associate Professor Noelle Eckley Selin (left) and former graduate student Emil Dimanchev SM '18 used a new method to analyze the impacts of current and proposed state-level renewable energy and carbon pricing policies. Their study yielded some unexpected outcomes on the health benefits of the policies they examined. Photo: Stuart Darsch

To Noelle Eckley Selin, an associate professor in the Institute for Data, Systems, and Society and the Department of Earth, Atmospheric and Planetary Sciences, and Emil Dimanchev SM '18, a senior research associate at the MIT Center for Energy and Environmental Policy Research, that's a double concern: The RPSs help protect not only the global climate but also human health.

Past studies by Selin and others have shown that national-level climate policies designed to reduce carbon dioxide (CO_2) emissions also significantly improve air quality, largely by reducing coal burning and related emissions, especially those that contribute to the formation of fine particulate matter, or $PM_{2.5}$. While air quality in the United States has improved in recent decades, $PM_{2.5}$ is still a threat. In 2016, some 93,000 premature deaths were attributed to exposure to $PM_{2.5}$, according to the Institute of Health Metrics and Evaluation. Any measure that reduces those exposures saves lives and delivers health-related benefits, such as savings on medical bills, lost wages, and reduced productivity.

If individual states take steps to reduce or repeal their RPSs, what will be the impacts on air quality and human health in state and local communities? "We didn't really know the answer to that question, and finding out could inform policy debates in individual states," says Selin. "Obviously, states want to solve the climate problem. But if there are benefits for air quality and human health within the state, that could really motivate policy development."

Selin, Dimanchev, and their collaborators set out to define those benefits. Most studies of policies that change electricity prices focus on the electricity sector and on the costs and climate benefits that would result nationwide. The MIT team instead wanted to examine electricity-consuming activities in all sectors and track changes in emissions, air pollution, human health exposures, and more. And to be useful for state or regional decision making, they needed to generate estimates of costs and benefits for the specific region that would be affected by the policy in question.

A novel modeling framework

To begin, the researchers developed the following framework for analyzing the costs and benefits of renewable energy and other "sub-national" climate policies.

- They start with an economywide model that simulates flows of goods and services and money throughout the economy, from sector to sector and region to region. For a given energy policy, the model calculates how the resulting change in electricity price affects human activity throughout the economy and generates a total cost, quantified as the change in consumption: How much better or worse off are consumers? The model also tracks CO_2 emissions and how they're affected by changes in economic activity.

- Next they use a historical emissions data set published by the U.S. Environmental Protection Agency that maps sources of air pollutants nationwide. Linking outputs of the economic model to that emissions data set generates estimates of future emissions from all sources across the United States resulting from a given policy.

- The emissions results go into an air pollution model that tracks how emitted chemicals become air pollution. For a given location, the model calculates resulting pollutant concentrations based on information about the height of the smoke stacks, the prevailing weather circulation patterns, and the chemical composition of the atmosphere.

- The air pollution model also contains population data from the U.S. census for all of the United States. Overlaying the population data onto the air pollution results generates human exposures at a resolution as fine as 1 square kilometer.

- Epidemiologists have developed coefficients that translate air pollution exposure to a risk of premature mortality. Using those coefficients and their outputs on human exposures, the researchers estimate the number of premature deaths in a geographical area that will result from the energy policy being analyzed.

- Finally, based on values used by government agencies in evaluating policies, they assign monetary values to their calculated impacts of the policy on CO_2 emissions and human mortality. For the former, they use the "social cost of carbon," which quantifies the value of preventing damage caused by climate change. For the latter, they use the "value of statistical life," a measure of the economic value of reducing the risk of premature mortality.

With that modeling framework, the researchers can estimate the economic cost of a renewable energy or climate policy and the benefits it will provide in terms of air quality, human health, and climate change. And they can generate those results for a specific state or region.

Case study: RPSs in the U.S. Rust Belt

As a case study, the team focused on the Rust Belt—in this instance, 10 states across the Midwest and Great Lakes region of the United States (see top map on page 7). Why? Because they expected lawmakers in some of those states to be reviewing their RPSs in the near future.

On average, the RPSs in those states require customers to purchase 13% of their electricity from renewable sources by 2030. What will happen if states weaken their RPSs or do away with them altogether, as some are considering?

To find out, the researchers evaluated the impacts of three RPS options out to 2030. One is business as usual (BAU), which means maintaining the current renewables requirement of 13% of generation in 2030. Another boosts the renewables share to 20% in 2030 (RPS+50%), and another doubles it to 26% (RPS+100%). As a baseline, they modeled a so-called counterfactual (no-RPS), which assumes that all RPSs were repealed in 2015. (In reality, the average RPS in 2015 was 6%.)

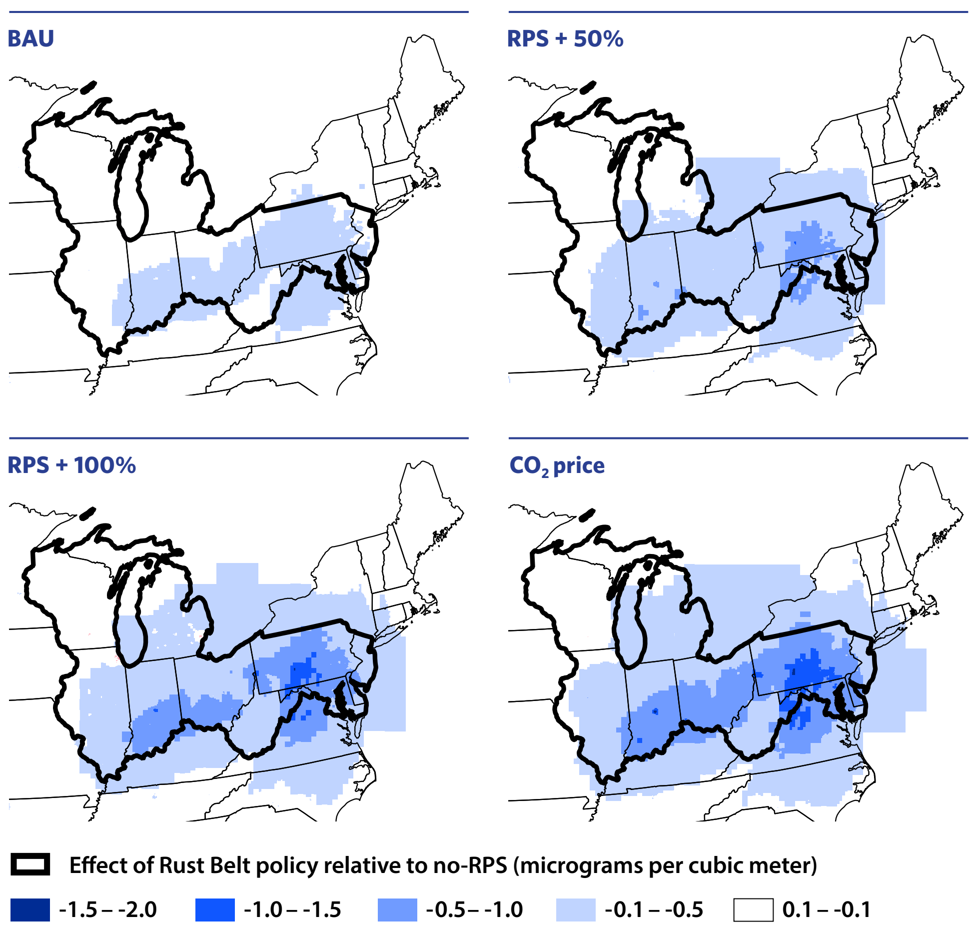
Finally, they modeled a scenario that adds to the BAU-level RPS a "CO_2 price," a market-based climate strategy that caps the amount of CO_2 that industry can emit and allows companies to trade carbon credits with one another. To the researchers' knowledge, there have been no studies comparing the air quality impacts of such carbon pricing and an RPS using the same model plus consistent scenarios. To fill that gap, they selected a CO_2 price that would achieve the same cumulative CO_2 reductions as the RPS+100% scenario does.

Results of the analysis

The four maps at the right show how the enactment of each policy would change air pollution—in this case, $PM_{2.5}$ concentrations—in 2030 relative to having no RPS. The results are given in micrograms of $PM_{2.5}$ per cubic meter. For comparison, the national average $PM_{2.5}$ concentration was 8 micrograms per cubic meter in 2018.

The effects of the policy scenarios on $PM_{2.5}$ concentrations (relative to the no policy case) mostly occur in the Rust Belt region. From largest to smallest, the reductions occur in Maryland, Delaware, Pennsylvania, Indiana, Ohio, and West Virginia. Concentrations of $PM_{2.5}$ are lower under the more stringent climate policies, with the largest reduction coming from the CO_2 price scenario. Concentrations also decline in states such as Virginia and New York, which are located downwind of coal plants on the Ohio River.

The Rust Belt
This map highlights the 10 states that the researchers defined as the Rust Belt for their case study of the costs, climate benefits, and health benefits of various RPS policy options.

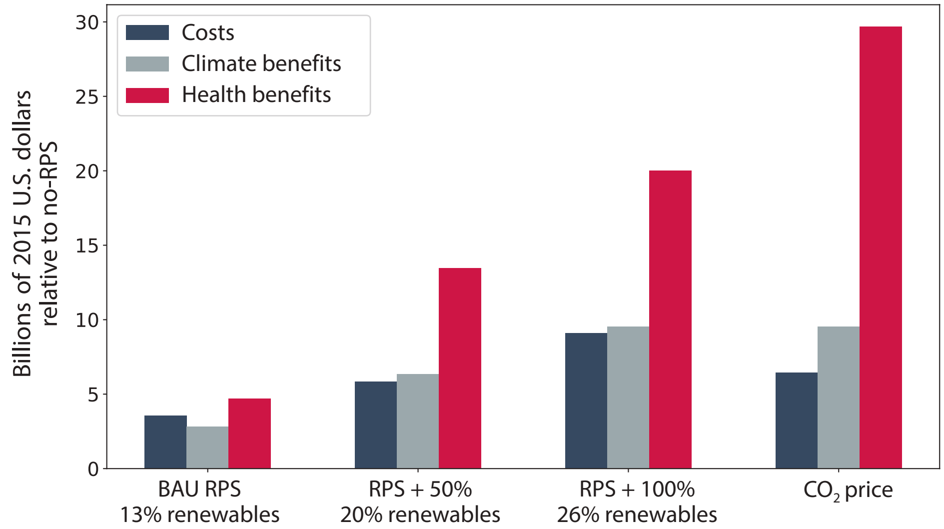


Reductions in $PM_{2.5}$ concentrations in 2030 under different policy scenarios
These maps show how the four policy scenarios would affect $PM_{2.5}$ concentrations in 2030 relative to the outcome if all energy policies had been repealed in 2015. The policies have the greatest impact within the Rust Belt region, although Virginia and New York also reap some benefit. Concentrations become lower as the RPS grows more stringent, but the greatest impact comes from the CO_2 price. Images courtesy of the researchers

The bar chart on this page presents an overview of the costs (black), climate benefits (gray), and health benefits (red) in 2030 of the four scenarios relative to the no-RPS assumption. (All costs and benefits are reported in 2015 U.S. dollars.) A quick glance at the BAU results shows that the health benefits of the current RPSs exceed both the total policy costs and the estimated climate benefits. Moreover, while the cost of the RPS increases as the stringency increases, the climate benefits and—especially—the human health benefits jump up even more. The climate benefit from the CO_2 price and the RPS+100% are, by definition, the same, but the cost of the CO_2 price is lower and the health benefit is far higher.

The table to the right presents the quantitative results behind the bar chart. (Depending on the assumptions used, the analyses produced a range of results; the numbers here are the central values.) According to the researchers' calculations, maintaining the current average RPS of 13% from renewables (BAU) would bring health benefits of $4.7 billion and implementation costs of $3.5 billion relative to the no-RPS scenario. (For comparison, Dimanchev notes that $3.5 billion is 0.1% of the total goods and services that U.S. households consume per year.) Boosting the renewables share from the BAU level to 20% (RPS+50%) would result in additional health benefits of $8.8 billion and $2.3 billion in costs. And increasing from 20% to 26% (RPS+100%) would result in additional health benefits of $6.5 billion and $3.3 billion in costs.

CO_2 reductions due to the RPSs would bring estimated climate benefits comparable to policy costs—and maybe larger, depending on the assumed value for the social cost of carbon. Assuming the central values, the climate benefits come to $2.8 billion for the BAU scenario, $6.4 billion for RPS+50%, and $9.5 billion for RPS+100%.



Cost, climate benefit, and health benefit under different policy scenarios This bar chart shows costs and benefits under the four scenarios analyzed. (The table below presents the quantitative results.) In the business-as-usual scenario, the health benefits of the existing RPS exceed both the policy cost and the climate benefit. As the RPS becomes most stringent, costs increase, but the climate and health benefits increase more quickly. By design, the CO_2 price and the RPS+100% deliver the same climate benefit, but the cost of the CO_2 price is lower, and the human health benefit is far higher.

Policy scenarios	Climate benefits	Health benefits	Costs
BAU	$2.8	$4.7	$3.5
RPS+50%	$6.4	$13.5	$5.8
RPS+100%	$9.5	$20.0	$9.1
CO_2 price	$9.5	$29.7	$6.4

Costs and benefits are in billions of 2015 U.S. dollars.

The analysis that assumes a carbon price yielded some unexpected results. The carbon price and the RPS+100% both bring the same reduction in CO_2 emissions in 2030, so the climate benefits from the two policies are the same—$9.5 billion. But the CO_2 price brings health benefits of $29.7 billion at a cost of $6.4 billion.

Dimanchev was initially surprised that health benefits were higher under the CO_2 price than under the RPS+100% policy. But that outcome largely reflects the stronger effect that CO_2 pricing has on coal-fired generation. "Our results show that CO_2 pricing is a more effective way to drive coal out of the energy mix than an RPS policy is," he says. "And when it comes to air quality, the most important factor is how much coal a certain jurisdiction is burning, because coal is by far the biggest contributor to air pollutants in the electricity sector."

The politics of energy policy

While the CO_2 price scenario appears to offer economic, health, and climate benefits, the researchers note that adopting a carbon pricing policy has historically proved difficult for political reasons—both in the United States and around the world. "Clearly, you're forgoing a lot of benefits by doing an RPS, but RPSs are more politically attractive in a lot of jurisdictions," says Selin. "You're not going to get a CO_2 price in a lot of the places that have RPSs today."

And steps to repeal or weaken those RPSs continue. In summer 2019, the Ohio state Legislature began considering a bill that would both repeal the state's RPS and subsidize existing coal and nuclear power plants. In response, Dimanchev performed a special analysis of the benefits to Ohio of its current RPS. He concluded that by protecting human health, the RPS would generate an annual economic benefit to Ohio of $470 million in 2030. He further calculated that, starting in 2030, the RPS would avoid the premature deaths of 50 Ohio residents each year. Given the estimated cost of the bill at $300 million, he concluded that the RPS would have a net benefit to the state of $170 million in 2030.

When the state Legislature took up the bill, Dimanchev presented those results on the Senate floor. In introductory comments, he noted that Ohio topped the nation in the number of premature deaths attributed to power plant pollution in 2005, more than 4,000 annually. And he stressed that "repealing the RPS would not only hamper a growing industry but also harm human health."

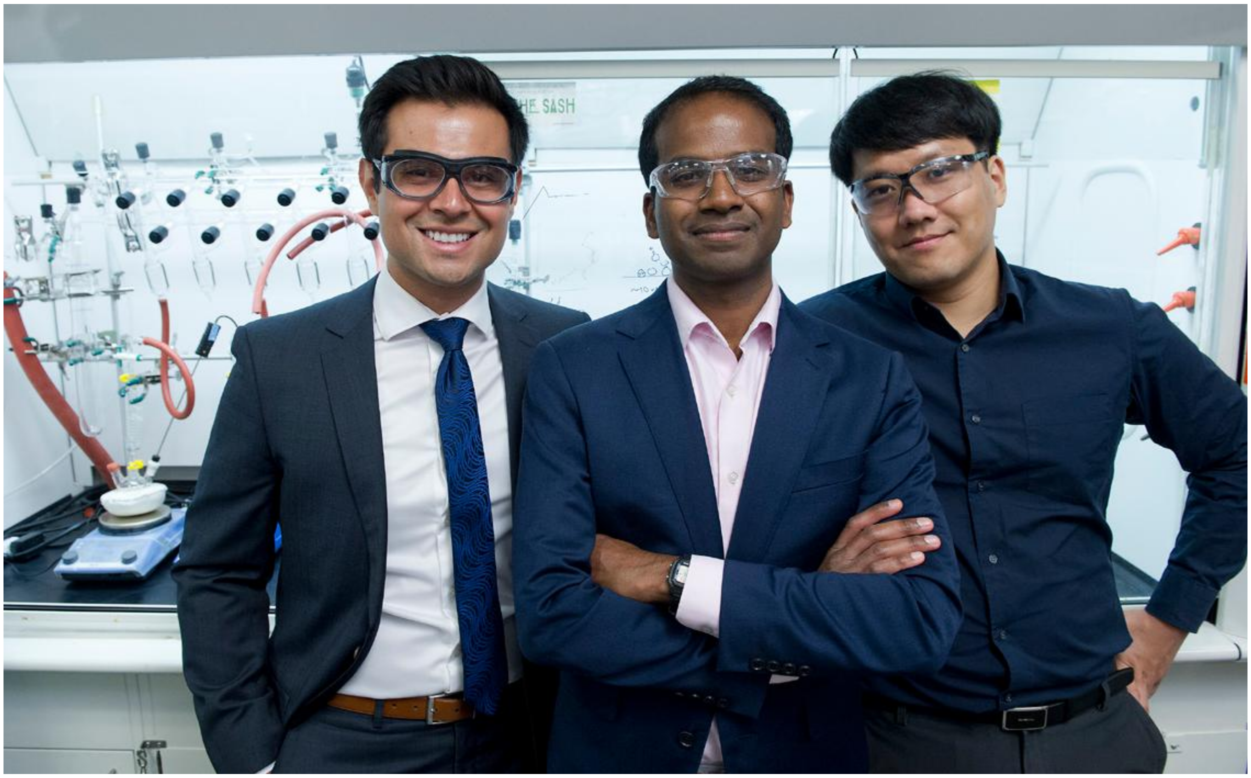
The bill passed, but in a form that significantly rolled back the RPS requirement rather than repealing it completely. So Dimanchev's testimony may have helped sway the outcome in Ohio. But it could have a broader impact in the future. "Hopefully, Emil's testimony raised some awareness of the trade-offs that a state like Ohio faces as they reconsider their RPSs," says Selin. Observing the proceedings in Ohio, legislators in other states may consider the possibility that strengthening their RPSs could actually benefit their economies and at the same time improve the health and well-being of their constituents.

NOTES

Emil Dimanchev is a 2018 graduate of the MIT Technology and Policy Program and a former research assistant at the MIT Joint Program on the Science and Policy of Global Change (the Joint Program). This research was supported by the U.S. Environmental Protection Agency (EPA) through its Air, Climate, and Energy Centers Program, with joint funding to MIT and Harvard University. The air pollution model was developed as part of the EPA-supported Center for Clean Air and Climate Solutions. The economic model—the U.S. Regional Energy Policy model—is developed at the Joint Program, which is supported by an international consortium of government, industry, and foundation sponsors (see the list at globalchange.mit.edu/sponsors/current). Dimanchev's outreach relating to the Ohio testimony was supported by the Policy Lab at the MIT Center for International Studies. Further information can be found in:

E. Dimanchev. *Air Quality Co-benefits of Renewable Energy Policy in the U.S.* Master's thesis, MIT Institute for Data, Systems, and Society, 2018. Online: globalchange.mit.edu/publication/17130.

E.G. Dimanchev, S. Paltsev, M. Yuan, D. Rothenberg, C.W. Tessum, J.D. Marshall, and N.E. Selin. "Health co-benefits of sub-national renewable energy policy in the U.S." *Environmental Research Letters*, vol. 14, no. 8, August 2019. Online: doi.org/10.1088/1748-9326/ab31d9.



Manufacturing consumer products

A greener way to make raw materials

Nancy W. Stauffer, MITEI

IN BRIEF

Making raw materials for the manufacture of consumer goods produces high levels of carbon dioxide (CO_2) emissions, involves hazardous materials, and requires high temperatures and pressures, usually generated by burning fossil fuels. MIT chemical engineers have now demonstrated a new approach that can operate on water plus electricity from renewable sources. Energized by a well-known catalyst, the process forms no CO_2 emissions, requires no hazardous materials or extreme operating conditions, and generates just one byproduct—hydrogen. While much work remains, this new approach—relying on electricity and electrocatalysts—could one day significantly reduce the vast amounts of CO_2 produced by the chemical industry today.

Most efforts to reduce energy consumption and carbon emissions have focused on the transportation and residential sectors. Little attention has been paid to industrial manufacturing, even though it consumes more energy than either of those sectors and emits high levels of CO_2 in the process.

To help address that situation, Assistant Professor Karthish Manthiram, postdoc Kyoungsuk Jin, graduate students Joseph H. Maalouf and Minju Chung, and their colleagues, all of chemical engineering,

Facing page An MIT researcher pipettes an electrolyte solution containing an olefin material into a specially designed electrochemical cell. Inside the cell, voltage plus an electrocatalyst converts the olefin into an epoxide widely used in making consumer products. Photos: Stuart Darsch

Above Assistant Professor Karthish Manthiram (center), postdoc Kyoungsuk Jin (right), graduate student Joseph Maalouf (left), and their colleagues are working to help decarbonize the chemical industry by finding ways to drive critical chemical reactions using electricity from renewable sources.

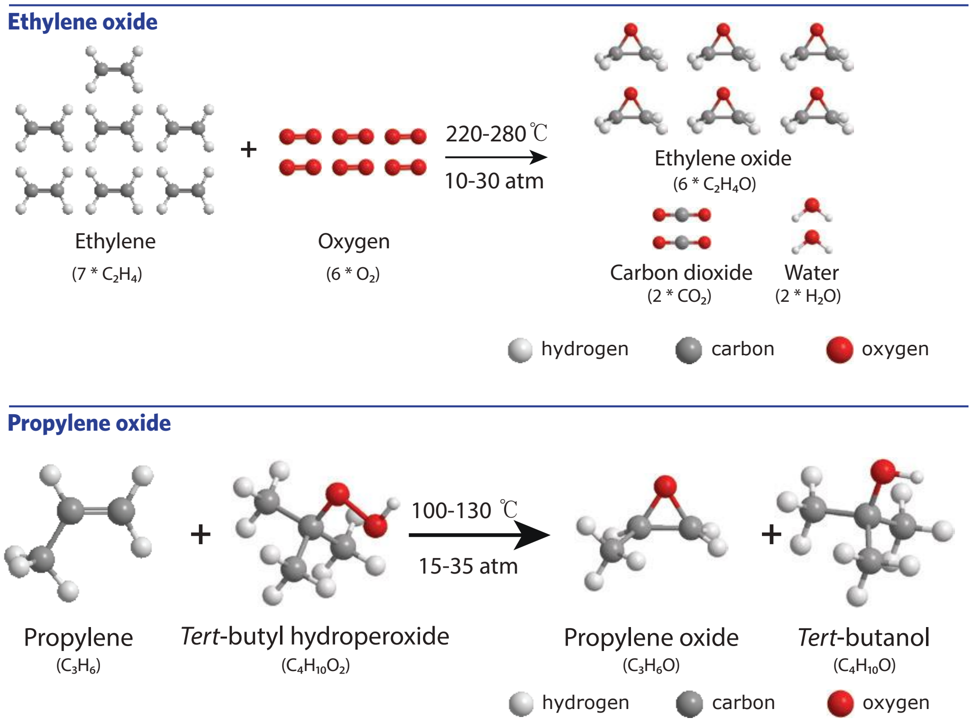
have been devising new methods of synthesizing epoxides, a group of chemicals used in the manufacture of consumer goods ranging from polyester clothing, detergents, and antifreeze to pharmaceuticals and plastics.

"We don't think about the embedded energy and carbon dioxide footprint of a plastic bottle we're using or the clothing we're putting on," says Manthiram. "But epoxides are everywhere!"

As solar and wind and storage technologies mature, it's time to address what Manthiram calls the "hidden energy and carbon footprints of materials made from epoxides." And the key, he argues, may be to perform epoxide synthesis using electricity from renewable sources along with specially designed catalysts and an unlikely starting material: water.

The challenge

Epoxides can be made from a variety of carbon-containing compounds known generically as olefins. But regardless of the olefin used, the conversion process generally produces high levels of CO_2 or has other serious drawbacks.



Industrial synthesis of epoxides
These figures show methods now used to synthesize two widely used epoxides. Above: Ethylene molecules and oxygen molecules are combined and subjected to high temperatures and pressures. Products of the reaction are ethylene oxide, water, and CO_2. Below: Propylene is reacted with *tert*-butyl hydroperoxide to form propylene oxide plus a side product called *tert*-butanol. Both methods have drawbacks. The first produces CO_2 emissions and involves extreme reaction conditions requiring combustion of fossil fuels and use of a massive pressure vessel. The second involves hazardous chemicals and creates a side product that must be dealt with. Images: Kyoungsuk Jin, MIT

To illustrate the problem, Manthiram describes processes now used to manufacture ethylene oxide, an epoxide used in making detergents, thickeners, solvents, plastics, and other consumer goods. Demand for ethylene oxide is so high that it has the fifth-largest CO_2 footprint of any chemical made today.

The top panel in the figure on this page shows one common synthesis process. The recipe is simple: Combine ethylene molecules and oxygen molecules, subject the mixture to high temperatures and pressures, and separate out the ethylene oxide that forms.

However, as the diagram shows, those ethylene oxide molecules are accompanied by molecules of CO_2—a problem, given the volume of ethylene oxide produced nationwide. In addition, the high temperatures and pressures required are generally produced by burning fossil fuels. And the conditions are so extreme that the reaction must take place in a massive pressure vessel. The capital investment required is high, so epoxides are generally produced in a central location and then transported long distances to the point of consumption.

Another widely synthesized epoxide is propylene oxide, which is used in making a variety of products, including perfumes, plasticizers, detergents, and polyurethanes. In this case, the olefin—propylene—is combined with *tert*-butyl hydroperoxide, as illustrated in the bottom panel above. An oxygen atom moves from the *tert*-butyl hydroperoxide molecule to the propylene to form the desired propylene oxide. The reaction conditions are somewhat less harsh than in ethylene oxide synthesis, but a side product must be dealt with. And while no CO_2 is created, the *tert*-butyl hydroperoxide is highly reactive, flammable, and toxic, so it must be handled with extreme care.

In short, current methods of epoxide synthesis produce CO_2, involve dangerous chemicals, require huge pressure vessels, or call for fossil fuel combustion. Manthiram and his team believed there must be a better way.

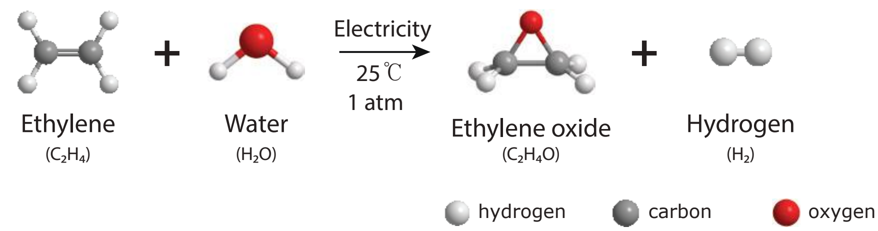
A new approach

The goal in epoxide synthesis is straightforward: Simply transfer an oxygen atom from a source molecule onto an olefin molecule. Manthiram and his lab came up with an idea: Could water be used as a sustainable and benign source of the needed oxygen atoms? The concept was counterintuitive. "Organic chemists would say that it shouldn't be possible because water and olefins don't react with one another," he says. "But what if we use electricity to liberate the oxygen atoms in water? Electrochemistry causes interesting things to happen—and it's at the heart of what our group does."

Using electricity to split water into oxygen and hydrogen is a standard practice called electrolysis. Usually, the goal of water electrolysis is to produce hydrogen gas for certain industrial applications or for use as a fuel. The oxygen is simply vented to the atmosphere.

To Manthiram, that practice seemed wasteful. Why not do something useful with the oxygen? Making an epoxide seemed the perfect opportunity—and the benefits could be significant. Generating two valuable products instead of one would bring down the high cost of water electrolysis. Indeed, it might become a cheaper, carbon-free alternative to today's usual practice of producing hydrogen from natural gas. The electricity needed for the process could be generated from renewable sources such as solar and wind.

Ethylene oxide



Proposed synthesis of epoxides using water and electricity This figure shows the synthesis method proposed by the MIT team, using ethylene oxide as an example. Ethylene molecules are mixed with water in an electrochemical cell, and a voltage is induced across the mixture. The reaction products are ethylene oxide and hydrogen gas. No extreme conditions are required, the electricity can be generated using renewable sources, and just two products are made—both of them valuable.

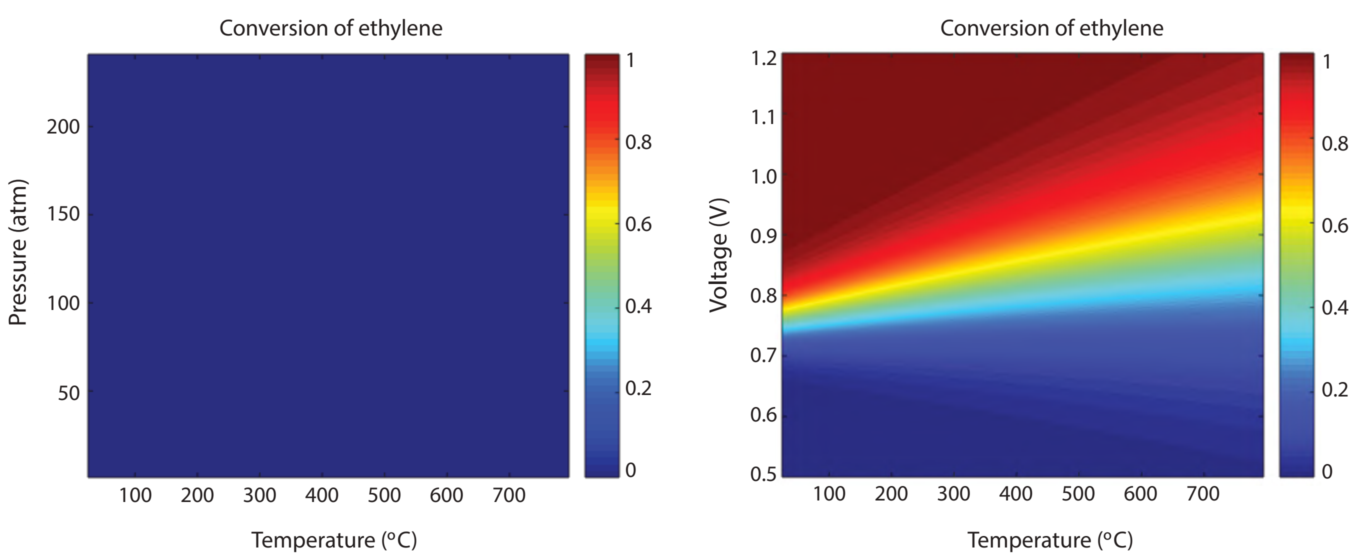
There wouldn't be any hazardous reactants or undesirable byproducts involved. And there would be no need for massive, costly, and accident-prone pressure vessels. As a result, epoxides could be made at small-scale, modular facilities close to the place they're going to be used—no need to transport, distribute, or store the chemicals produced.

Will the reaction work?

However, there was a chance that the proposed process might not work. During electrolysis, the oxygen atoms quickly pair up to form oxygen gas. The proposed process—illustrated in the diagram above—would require that some of the oxygen atoms move onto the olefin before they combine with one another.

To investigate the feasibility of the process, Manthiram's group performed a fundamental analysis to find out whether the reaction is thermodynamically favorable. Does the energy of the overall system shift to a lower state by making the move? In other words, is the product more stable than the reactants were?

They started with a thermodynamic analysis of the proposed reaction at various combinations of temperature and pressure—the standard variables used



Thermodynamic analyses of the proposed reaction These figures show results of thermodynamic analyses of the proposed reaction between water and ethylene to form ethylene oxide. As the left-hand figure shows, no ethylene oxide forms, even at high temperatures and pressures. The right-hand figure shows results of the same analysis using voltage rather than pressure. Now ethylene oxide formation begins at a low voltage and essentially room temperature.

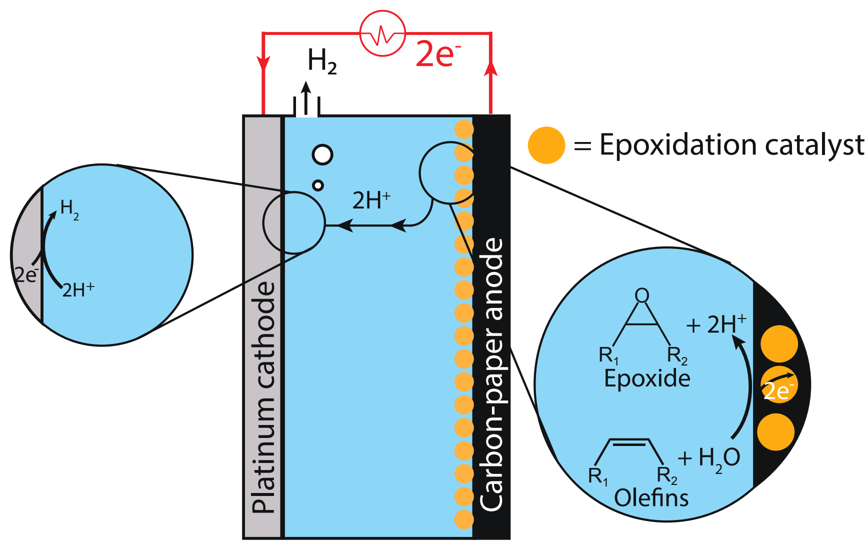
in hydrocarbon processing. As an example, they again used ethylene oxide. The results, shown on page 13, were not encouraging. As the uniform blue in the left-hand figure shows, even at elevated temperatures and pressures, the conversion of ethylene and water to ethylene oxide plus hydrogen doesn't happen—just as a chemist's intuition would predict.

But their proposal was to use voltage rather than pressure to drive the chemical reaction. As the right-hand figure on page 13 shows, with that change, the outcome of the analysis looked more promising. Conversion of ethylene to ethylene oxide occurs at around 0.8 volts. So the process is viable at voltages below that of an everyday AA battery and at essentially room temperature.

While a thermodynamic analysis can show that a reaction is possible, it doesn't reveal how quickly it will occur, and reactions must be fast to be cost-effective. So the researchers needed to design a catalyst—a material that would speed up the reaction without getting consumed.

Designing catalysts for specific electrochemical reactions is a focus of Manthiram's group. For this reaction, they decided to start with manganese oxide, a material known to catalyze the water-splitting reaction. And to increase the catalyst's effectiveness, they fabricated it into nanoparticles—a particle size that would maximize the surface area on which reactions can take place.

The diagram on this page shows the special electrochemical cell they designed. Like all such cells, it has two electrodes—in this case, an anode where oxygen is transferred to make an olefin into an epoxide, and a cathode where hydrogen gas forms. The anode is made of carbon paper decorated with the nanoparticles of manganese oxide (shown in yellow). The cathode is made of platinum. Between the anode and the cathode



Schematic diagram of electrochemical cell and reaction process This diagram shows the electrochemical cell the researchers designed to explore the conversion of water and an olefin (here, cyclooctene) to an epoxide and hydrogen gas. Key to the conversion are nanoparticles of a catalyst—shown in yellow—that facilitate the reaction under ambient conditions. As the magnified views show, the epoxide forms at the carbon-paper anode, and the hydrogen gas forms at the platinum cathode.

is an electrolyte that ferries electrically charged ions between them. In this case, the electrolyte is a mixture of a solvent, water (the oxygen source), and the olefin.

The magnified views show what happens at the two electrodes. The right-hand view shows the olefin and water (H_2O) molecules arriving at the anode surface. Encouraged by the catalyst, the water molecules break apart, sending two electrons (negatively charged particles, e^-) into the anode and releasing two protons (positively charged hydrogen ions, H^+) into the electrolyte. The leftover oxygen atom (O) joins the olefin molecule on the surface of the electrode, forming the desired epoxide molecule.

The two liberated electrons travel through the anode and around the external circuit (shown in red), where they pass through a power source—ideally, fueled by a renewable source such as wind or solar—and gain extra energy. When the two energized electrons reach the cathode, they join the two protons arriving in the electrolyte and—as shown in the left-hand magnified view—they form hydrogen gas (H_2), which exits the top of the cell.

Experimental results

Experiments with that setup have been encouraging. Thus far, the work has involved an olefin called cyclooctene, a well-known molecule that's been widely used by people studying oxidation reactions. "Ethylene and the like are structurally more important and need to be solved, but we're developing a foundation on a well-known molecule just to get us started," says Manthiram.

Results have already allayed a major concern. In one test, the researchers applied 3.8 volts across their mixture at room temperature, and after 4 hours, about half of the cyclooctene had converted into its epoxide counterpart, cyclooctene oxide. "So that result confirms that we can split water to make hydrogen and oxygen and then intercept the oxygen atoms so they move onto the olefin and convert it into an epoxide," says Manthiram.

But how efficiently does the conversion happen? If this reaction is perfectly efficient, one oxygen atom will move onto an olefin for every two electrons that go into the anode. Thus, one epoxide molecule will form for each hydrogen molecule that forms. Using special equipment, the researchers counted the number of epoxide molecules formed for each pair of electrons passing through the external circuit to form hydrogen.

That analysis showed that their conversion efficiency was 30% of the maximum theoretical efficiency. "That's because the electrons are also doing other reactions—maybe making oxygen, for instance, or oxidizing some of the solvent," says Manthiram. "But for us, 30% is a remarkable number for a new reaction that was previously unknown. For that to be the first step, we're very happy about it."

Manthiram recognizes that the efficiency might need to be twice as high or even higher for the process to be commercially viable. "Techno-economics will ultimately guide where that number needs to be," he says. "But I would say that the heart of our discoveries so far is the realization that there is a catalyst that can make this happen. That's what has opened up everything that we've explored since the initial discovery."

Encouraging results and future challenges

Manthiram is cautious not to overstate the potential implications of the work. "We know what the outcome is," he says. "We put olefin in, and we get epoxide out." But to optimize the conversion efficiency they need to know at a molecular level all the steps involved in that conversion. For example, does the electron transfer first by itself, or does it move with a proton at the same time? How does the catalyst bind the oxygen atom? And how does the oxygen atom transfer to the olefin on the surface of the catalyst?

In this device, the researchers synthesize the manganese oxide nanoparticles that catalyze olefin-to-epoxide conversion inside their electrochemical cell when voltage is applied. Nanoparticle synthesis begins with the injection of a precursor called manganese acetate into a solvent, as shown above. Photo: Stuart Darsch

According to Manthiram, he and his group have hypothesized a reaction sequence, and several analytical techniques have provided a "handful of observables" that support it. But he admits that there is much more theoretical and experimental work to do to develop and validate a detailed mechanism that they can use to guide the optimization process. And then there are practical considerations, such as how to extract the epoxides from the electrochemical cell and how to scale up production.

Manthiram believes that this work on epoxides is just "the tip of the iceberg" for his group. There are many other chemicals they might be able to make using voltage and specially designed catalysts. And while some attempts may not work, with each one they'll learn more about how voltages and electrons and surfaces influence the outcome.

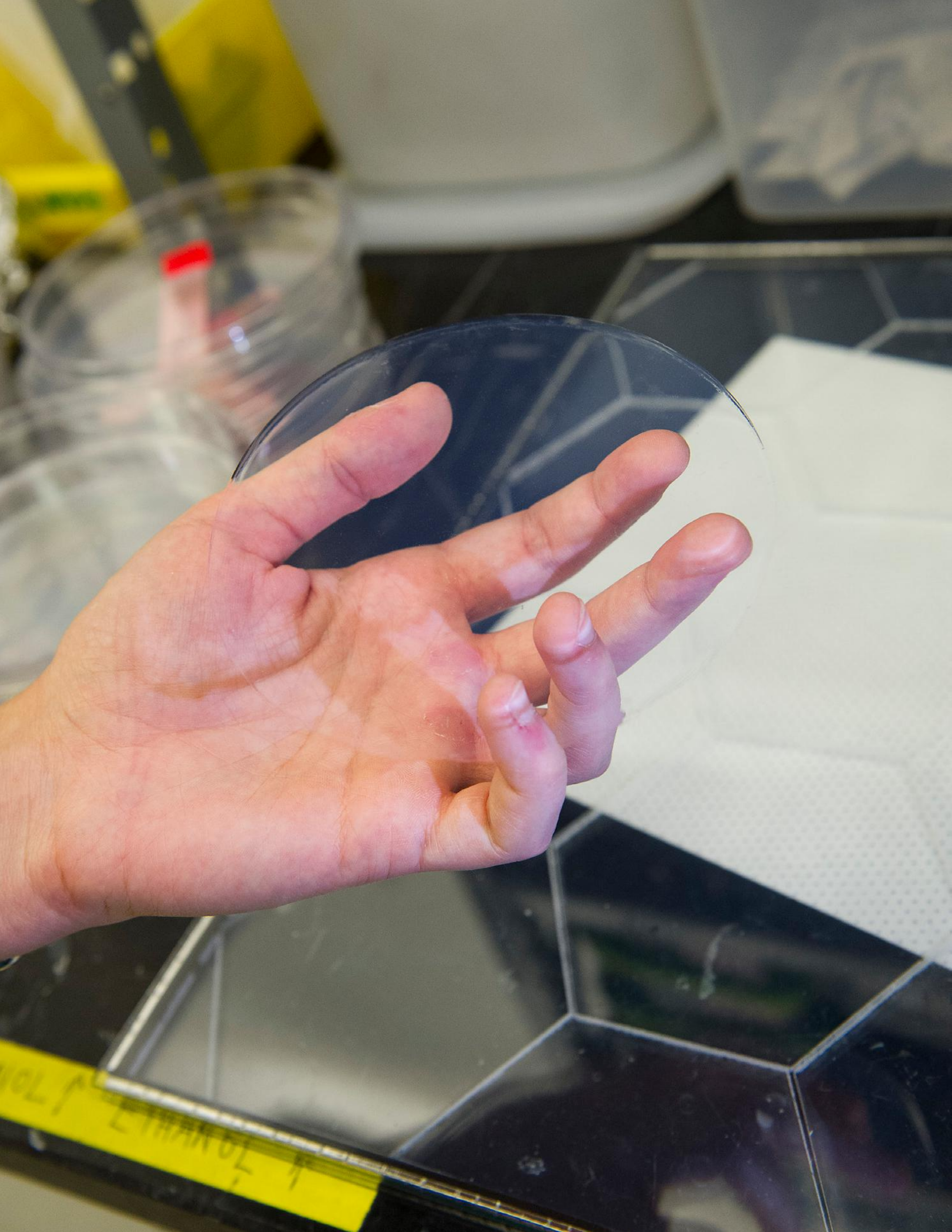
He and his team predict that the face of the chemical industry will change dramatically in the years to come. The need to reduce CO_2 emissions and energy use is already pushing research on chemical manufacturing toward using electricity from renewable sources. And that electricity will increasingly be made at distributed sites. "If we have solar panels and wind turbines everywhere, why not do chemical synthesis close to where the power is generated, and make commercial products close to the communities that need them?" says Manthiram. The result will be a distributed, electrified, and decarbonized chemical industry—and a dramatic reduction in both energy use and CO_2 emissions.

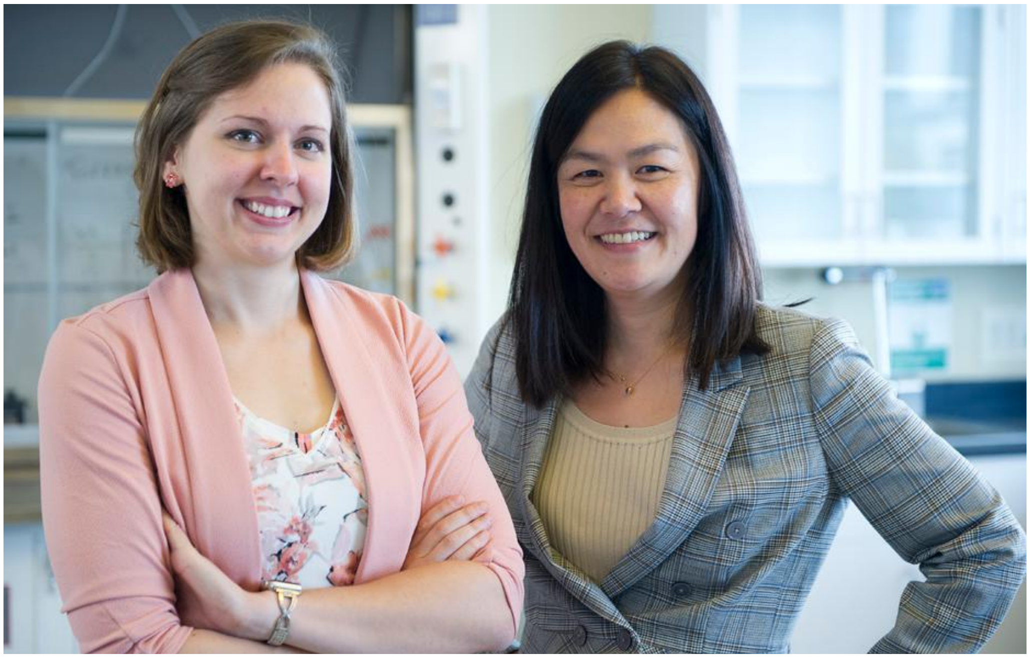
NOTES

This research was supported by MIT's Department of Chemical Engineering and by National Science Foundation Graduate Research Fellowships. Further information can be found in:

K. Jin, J.H. Maalouf, N. Lazouski, N. Corbin, D. Yang, and K. Manthiram. "Epoxidation of cyclooctene using water as the oxygen atom source at manganese oxide electrocatalysts." *Journal of the American Chemical Society*, vol. 141, pp. 6413–6418, 2019. Online: doi.org/10.1021/jacs.9b02345.

Z.J. Schiffer and K. Manthiram. "Electrification and decarbonization of the chemical industry." *Joule*, vol. 1, pp. 10–14, September 6, 2017. Online: doi.org/10.1016/j.joule.2017.07.008.





Making a remarkable material even better

Transparent aerogels for solar devices, windows

Nancy W. Stauffer, MITEI

IN BRIEF

After five years' work, an MIT team can now fabricate a transparent version of a silica aerogel, an ultralight material that blocks heat transfer. They have used their aerogel in a solar thermal collector to generate temperatures suitable for water and space heating and more—without using the expensive concentrators, special materials, and vacuum enclosures that have kept current solar thermal systems from being widely adopted. They have also demonstrated that inserting an aerogel into the gap in a double-pane window will make a product that's both affordable and highly insulating. Finally, their work has generated guidelines that will help innovators design and fabricate aerogels with nanoscale structures tailored for high performance in other critical technologies.

In recent decades, the search for high-performance thermal insulation for buildings has prompted manufacturers to turn to aerogels. Invented in the 1930s, these remarkable materials are translucent, ultraporous, lighter than a marshmallow, strong enough to support a brick, and an unparalleled barrier to heat flow, so ideal for keeping heat inside on a cold winter day and outside when summer temperatures soar.

Five years ago, researchers led by Evelyn Wang, a professor and head of the

Facing page Graduate student Elise Strobach displays a sample silica aerogel that's clear enough to see through. She is now developing aerogel panes that will fit inside today's double-pane windows so they can easily be incorporated into existing production lines. Photos: Stuart Darsch

Above Professor Evelyn Wang (right), graduate student Elise Strobach (left), and their colleagues have been performing theoretical and experimental studies of low-cost silica aerogels optimized to serve as a transparent heat barrier in specific devices.

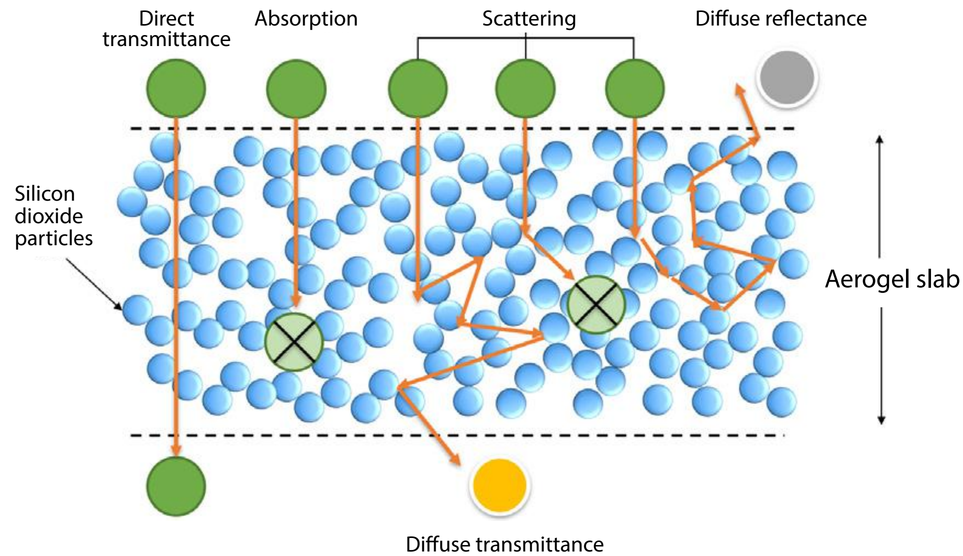
Department of Mechanical Engineering, and Gang Chen, the Carl Richard Soderberg Professor in Power Engineering, set out to add one more property to that list. They aimed to make a silica aerogel that was truly transparent.

"We started out trying to realize an optically transparent, thermally insulating aerogel for solar thermal systems," says Wang. Incorporated into a solar thermal collector, a slab of aerogel would allow sunshine to come in unimpeded but prevent heat from coming back out—a key problem in today's systems. And if the transparent aerogel were sufficiently clear, it could be incorporated into windows, where it would act as a good heat barrier but still allow occupants to see out.

When the researchers started their work, even the best aerogels weren't up to those tasks. "People had known for decades that aerogels are a good thermal insulator, but they hadn't been able to make them very optically transparent," says Lin Zhao PhD '19 of mechanical engineering. "So in our work, we've been trying to understand exactly why they're not very transparent and then how we can improve their transparency."

Aerogels: Opportunities and challenges

The remarkable properties of a silica aerogel are the result of its nanoscale structure. To visualize that structure, think of holding a pile of small, clear particles in your hand. Imagine that the particles touch one another and slightly stick together, leaving gaps between them that are filled with air. Similarly, in a silica aerogel, clear, loosely connected nanoscale silica particles form a three-dimensional solid network within an overall structure that is mostly air. Because of all that air, a silica aerogel has an extremely low density—in fact, one of the lowest densities of any known bulk material—yet it's solid and structurally strong, though brittle.



Light transmission through an aerogel
Some incident light is absorbed within the aerogel or passes straight through and emerges from the other side—labeled above as "direct transmittance." The remainder can be redirected every time it encounters a particle-pore interface, which means it can be scattered many times in multiple directions before it emerges as "diffuse reflectance" or "diffuse transmittance," depending on which surface the light exits the aerogel from. Making a transparent aerogel requires maximizing all the light that is transmitted, both direct and diffuse. Making it clear enough to be used in a window requires minimizing the diffuse portion of the total. Image: Lin Zhao, MIT

If a silica aerogel is made of transparent particles and air, why isn't it transparent? Because the light that enters doesn't all pass straight through. It is diverted whenever it encounters an interface between a solid particle and the air surrounding it. The diagram above illustrates the process. When light enters the aerogel, some is absorbed inside it. Some—called direct transmittance—travels straight through. And some is redirected along the way by those interfaces. It can be scattered many times and in any direction, ultimately exiting the aerogel at an angle. If it exits from the surface through which it entered, it is called diffuse reflectance; if it exits from the other side, it is called diffuse transmittance.

Lin Zhao PhD '19 formulated a model that guides the development of aerogels with transparency, clarity, and thermal insulation tailored for specific applications. Photo courtesy of Lin Zhao

To make an aerogel for a solar thermal system, the researchers needed to maximize the total transmittance: the direct plus the diffuse components. And to make an aerogel for a window, they needed to maximize the total transmittance and simultaneously minimize the fraction of the total that is diffuse light. "Minimizing the diffuse light is critical because it'll make the window look cloudy," says Zhao. "Our eyes are very sensitive to any imperfection in a transparent material."

Developing a model

The sizes of the nanoparticles and the pores between them have a direct impact on the fate of light passing through an aerogel. But figuring out that interaction by trial and error would require synthesizing and characterizing too many samples to be practical. "People haven't been able to systematically understand the relationship between the structure and the performance," says Zhao. "So we needed to develop a model that would connect the two."

To begin, Zhao turned to the radiative transport equation, which describes mathematically how the propagation of light (radiation) through a medium is affected by absorption and scattering. It is generally used for calculating the transfer of light through the atmospheres of Earth and other planets. As far as Wang knows, it has not been fully explored for the aerogel problem.

Both scattering and absorption can reduce the amount of light transmitted through an aerogel, and light can be scattered multiple times. To account for those effects, the model decouples the two phenomena and quantifies them separately—and for each wavelength of light.

Based on the sizes of the silica particles and the density of the sample (an indicator of total pore volume), the model calculates light intensity within an aerogel layer by determining its absorption and scattering behavior using predictions from electromagnetic theory. Using those results, it calculates how much of the incoming light passes directly through the sample and how much of it is scattered along the way and comes out diffuse.

The next task was to validate the model by comparing its theoretical predictions with experimental results.

Synthesizing aerogels

Working in parallel, graduate student Elise Strobach of mechanical engineering had been learning how best to synthesize aerogel samples—both to guide development of the model and ultimately to validate it. In the process, she produced new insights on how to synthesize an aerogel with a specific desired structure.

Her procedure starts with a common form of silicon called silane, which chemically reacts with water to form an aerogel. During that reaction, tiny nucleation sites occur where particles begin to form. How fast they build up determines the end structure. To control the reaction, she adds a catalyst, ammonia. By carefully selecting the ammonia-to-silane ratio, she gets the silica particles to grow quickly at first and then abruptly stop growing when the precursor materials are gone—a means of producing particles that are small and uniform. She also adds a solvent, methanol, to dilute the mixture and control the density of the nucleation sites, thus the pores between the particles.

The reaction between the silane and water forms a gel containing a solid nanostructure with interior pores filled with the solvent. To dry the wet gel, Strobach needs to get the solvent out of the pores and replace it with air—without crushing the delicate structure. She puts the aerogel into the pressure chamber of a critical point dryer and floods liquid CO_2 into the chamber. The liquid CO_2 flushes out the solvent and takes its place inside the pores. She then slowly raises the temperature and pressure inside the chamber until the liquid CO_2 transforms to its supercritical state, where the liquid and gas phases can no longer be differentiated. Slowly venting the chamber releases the CO_2 and leaves the aerogel behind, now filled with air. She then subjects the sample to 24 hours of annealing—a standard heat-treatment process—which slightly reduces scatter without sacrificing the strong thermal insulating behavior. Even with the 24 hours of annealing, her novel procedure shortens the required aerogel synthesis time from several weeks to less than four days.

Validating and using the model

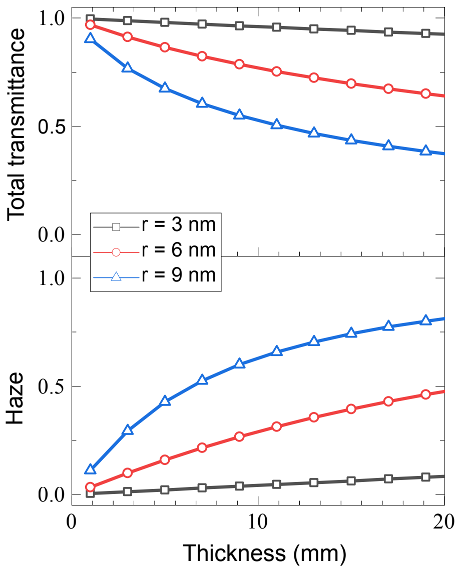
To validate the model, Strobach fabricated samples with carefully controlled thicknesses, densities, and pore and particle sizes—as determined by small-angle X-ray scattering—and used a standard spectrophotometer to measure the total and diffuse transmittance.

The data confirmed that, based on measured physical properties of an aerogel sample, the model could calculate total transmittance of light as well as a measure of clarity called haze, defined as the fraction of total transmittance that is made up of diffuse light.

The exercise confirmed simplifying assumptions made by Zhao in developing the model. Also, it showed that the radiative properties are independent of sample geometry, so his model can simulate light transport in aerogels of any shape. And it can be applied not just to aerogels but to any porous materials.

Wang notes what she considers the most important insight from the modeling and experimental results: "Overall, we determined that the key to getting high transparency and minimal haze—without reducing thermal insulating capability—is to have particles and pores that are really small and uniform in size," she says.

One analysis demonstrates the change in behavior that can come with a small change in particle size. Many applications call for using a thicker piece of transparent aerogel to better block heat transfer. But increasing thickness may decrease transparency. The figures on page 20 show total transmittance (top) and haze (bottom) in aerogel samples of increasing thickness and fixed density. The curves represent model results for samples with different particle sizes. As thickness increases, the samples with particles of 6 nanometer (nm) and 9 nm radius quickly do worse on both transmittance and haze. In contrast, the performance of the samples with particles of 3 nm radius



Effects of sample thickness on performance
These figures show total transmittance (top) and haze (bottom) in aerogel samples as sample thickness increases. (Density in all samples is 200 kilograms per cubic meter.) The curves show results assuming nano-particles with a mean particle radius of 3 nanometers (nm, black), 6 nm (red), and 9 nm (blue). As thickness increases, samples made with 6 nm and 9 nm particles show a decrease in total transmittance and an increase in haze. In contrast, with the 3 nm particles, increasing thickness to increase thermal insulation has little effect on total transmittance or haze.

remains essentially unchanged. As long as particle size is small, increasing thickness to achieve greater thermal insulation will not significantly decrease total transmittance or increase haze.

Comparing aerogels from MIT and elsewhere

How much difference does their approach make? The figure at the right shows total transmittance and haze from three MIT samples (with different thicknesses) and from nine state-of-the-art silica aerogels, which typically have particles and pores that are as large as 10 nm and vary widely in size, which gives most aerogels a slightly blue tint, notes Wang.

In the figure, the ideal transparent aerogel—one with 0% haze and 100% total transmittance—would appear in the bottom right corner. Only the MIT aerogel samples fall in that vicinity. The green bar represents common glass. The MIT samples have significantly better optical properties, with haze about the same and transmittance even greater than glass. "Our aerogels are more transparent than glass because they don't reflect—they don't have that glare spot where the glass catches the light and reflects to you," says Strobach.

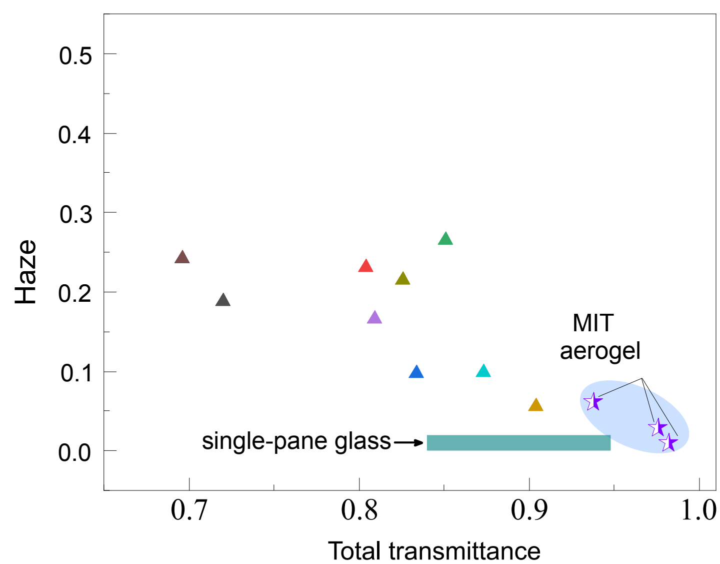
To Lin, a main contribution of their work is the development of general guidelines for material design, as demonstrated by the figure on page 21. Aided by such a "design map," users can tailor an aerogel for a particular application. Based on the contour plots, they can determine the combinations of controllable aerogel properties—namely, density and particle size—needed to achieve a targeted haze and transmittance outcome for many applications.

Aerogels in solar thermal collectors

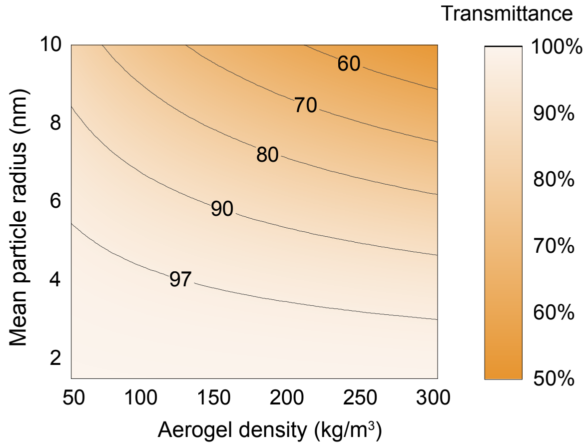
The researchers have already demonstrated the value of their new aerogels for solar thermal energy conversion systems, which convert sunlight into thermal energy by absorbing radiation and transforming it into heat. Current solar thermal systems can produce thermal energy at so-called intermediate temperatures—between 120°C and 220°C—which can be used for water and space heating, steam generation, industrial processes, and more. Indeed, in 2016, U.S. consumption of thermal energy exceeded the total electricity generation from all renewable sources.

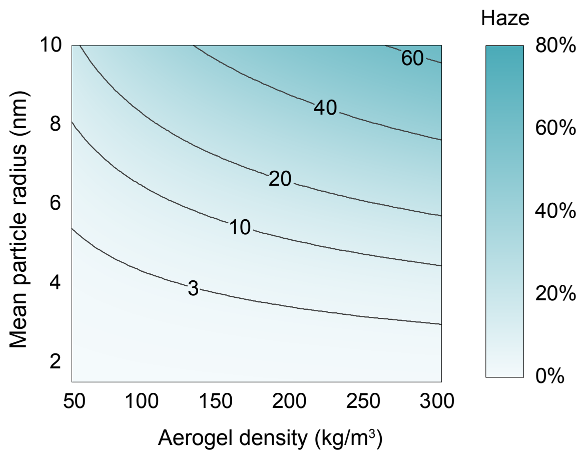
However, state-of-the-art solar thermal systems rely on expensive optical systems to concentrate the incoming sunlight, specially designed surfaces to absorb radiation and retain heat, and costly and difficult-to-maintain vacuum enclosures to keep that heat from escaping. To date, the costs of those components have limited market adoption.

Zhao and his colleagues thought that using a transparent aerogel layer might solve those problems. Placed above the absorber, it could let through incident solar radiation and then prevent the heat from escaping. So it would essentially replicate the natural greenhouse effect that's causing global warming—but

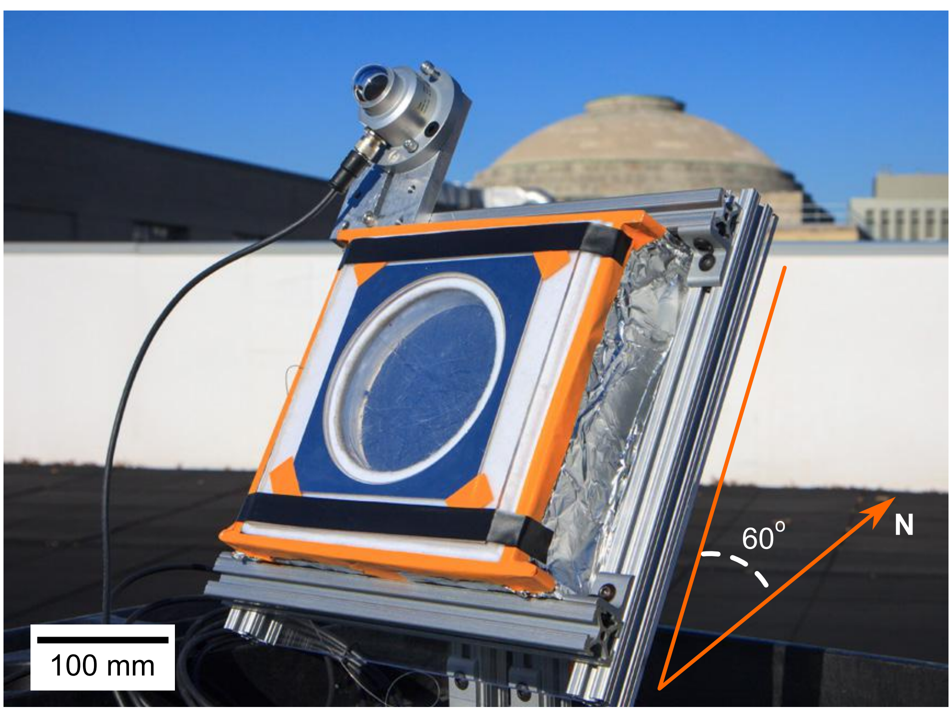


Comparison of performance by MIT and state-of-the-art silica aerogels
The data points show total transmittance and haze from three MIT samples and nine state-of-the-art silica aerogels. An aerogel that is 100% transparent with 0% haze would fall in the bottom right corner of this plot. The MIT samples do best—even when compared to single-pane glass, which is represented by the green bar. (Sources for the non-MIT data can be found in *Optics Express*, as cited at the end of this article.)





Design map: Performance as a function of mean particle radius and density
These figures show total transmittance (top) and haze (bottom) as a function of mean particle radius and aerogel density. The contour plots show the particle size and density—two controllable properties—that are required to achieve a targeted transmittance and haze. The figure thus provides a "design map" that can be used to tailor a transparent aerogel for a particular application.



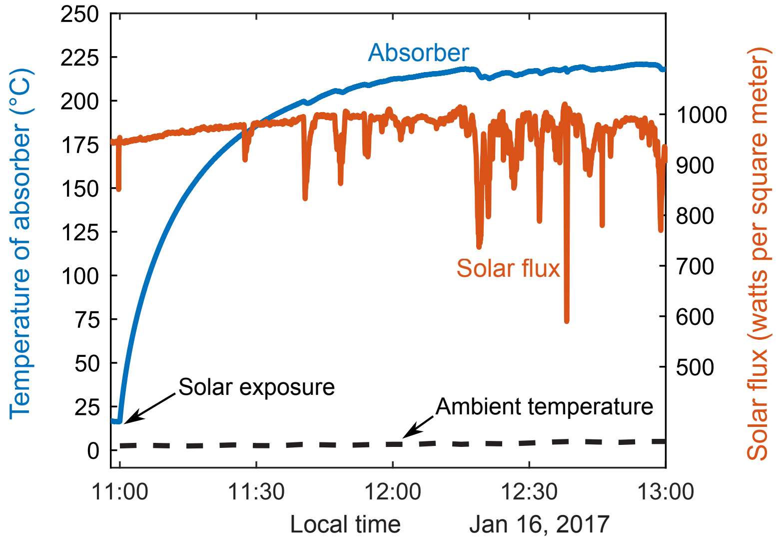
To test the viability of an aerogel-enhanced solar thermal receiver, the researchers designed and built the device shown above. They started with a conventional blackbody absorber, which absorbs radiation and turns it into heat. Above the absorber they placed a stack of silica aerogel blocks, optimized to let sunlight in and prevent heat from escaping. The result was a low-cost, high-performance solar thermal system. Photo courtesy of the researchers

to an extreme degree, on a small scale, and with a positive outcome.

To try it out, the researchers designed an aerogel-based solar thermal receiver (see photo on this page). The device consists of a nearly "blackbody" absorber (a thin copper sheet coated with black paint that absorbs all radiant energy that falls on it), and above it a stack of optimized, low-scattering silica aerogel blocks, which efficiently transmit sunlight and suppress conduction, convection, and radiation heat losses simultaneously. The nanostructure of the aerogel is tailored to maximize its optical transparency while maintaining its ultralow thermal conductivity. With the aerogel present, there is no need for expensive optics, surfaces, or vacuum enclosures.

After extensive laboratory tests of the device, the researchers decided to test it "in the field"—in this case, on the roof of an MIT building. On a sunny day in winter, they set up their device, fixing the receiver toward the south and tilted 60° from horizontal to maximize solar exposure. They then monitored its performance between 11 a.m. and 1 p.m. Despite the cold ambient temperature (less than 1°C) and the presence of clouds in the afternoon, the temperature of the absorber started increasing right away and eventually stabilized above 220°C (see the figure on page 22).

To Zhao, the performance already demonstrated by the artificial greenhouse effect opens up what he calls "an exciting pathway to the promotion of solar thermal energy utilization." Already, he and his colleagues have demonstrated that it can convert water to steam that is greater than 120°C. In collaboration with researchers at IIT Bombay, they are now exploring possible process steam applications in India and performing field tests of a low-cost, completely passive solar autoclave for sterilizing medical equipment in rural communities.



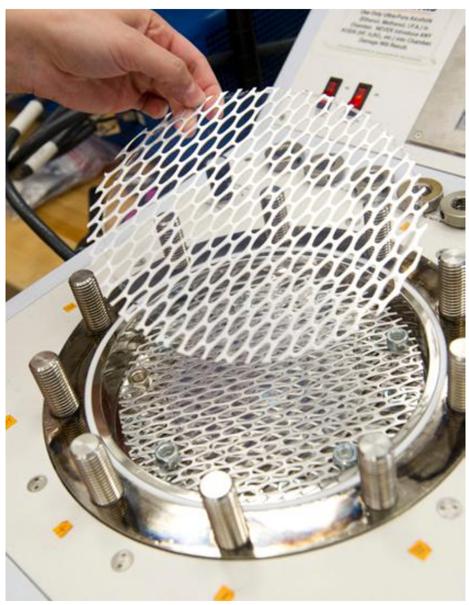
Field test of aerogel-enhanced solar thermal receiver These curves show the temperature achieved by the researchers' aerogel receiver under natural sunlight on a winter day between 11 a.m. and 1 p.m. Despite the cold ambient temperature (less than 1°C), the absorber in the system rapidly rose to above 220°C, and the receiver maintained its temperature even when the sky became cloudy during the afternoon. The experiment confirmed that the simple aerogel system could perform well—without costly optics, solar absorbers, or vacuum enclosures.

Windows and more

Strobach has been pursuing another promising application for the transparent aerogel—in windows. "In trying to make more transparent aerogels, we hit a regime in our fabrication process where we could make things smaller, but it didn't result in a significant change in the transparency," she says. "But it did make a significant change in the clarity," a key feature for a window.

The availability of an affordable, thermally insulating window would have several impacts, says Strobach. Every winter, windows in the United States lose enough energy to power over 50 million homes. That wasted energy costs the economy more than $32 billion a year and generates about 350 million tons of CO_2—more than is emitted by 76 million cars. Consumers can choose high-efficiency triple-pane windows, but they're so expensive that they're not widely used.

Analyses by Strobach and her colleagues showed that replacing the air gap in a conventional double-pane window with an aerogel pane could be the answer. The



A completed aerogel disk is carefully lifted out of the pressure vessel, its interior pores now filled with air. The disk is almost invisible on top of the metal mesh that supports it. Photo: Stuart Darsch

result could be a double-pane window that is 40% more insulating than traditional ones and 85% as insulating as today's triple-pane windows—at less than half the price. Better still, the technology could be adopted quickly. The aerogel pane is designed to fit within the current two-pane manufacturing process that's ubiquitous across the industry, so it could be manufactured at low cost on existing production lines with only minor changes.

Guided by Zhao's model, the researchers are continuing to improve the performance of their aerogels, with a special focus on increasing clarity while maintaining transparency and thermal insulation. In addition, they are considering other traditional low-cost systems that would—like the solar thermal and window technologies—benefit from sliding in an optimized aerogel to create a high-performance heat barrier that lets in abundant sunlight.

NOTES

This research was supported by the Full-Spectrum Optimized Conversion and Utilization of Sunlight (FOCUS) program of the U.S. Department of Energy's Advanced Research Projects Agency-Energy (ARPA-E); the Solid-State Solar Thermal Energy Conversion (S3TEC) Center, an Energy Frontier Research Center funded by the U.S. Department of Energy, Office of Science, Basic Energy Sciences; and the MIT Tata Center for Technology and Design. Elise Strobach received funding from the National Science Foundation Graduate Research Fellowship Program. Lin Zhao PhD '19 is now an optics design engineer at 3M in St. Paul, Minnesota. Further information about this research can be found in:

E. Strobach, B. Bhatia, S. Yang, L. Zhao, and E.N. Wang. "High temperature annealing for structural optimization of silica aerogels in solar thermal applications." *Journal of Non-Crystalline Solids*, vol. 462, pp. 72–77, 2017. Online: doi.org/10.1016/j.jnoncrysol.2017.02.009.

L. Zhao, B. Bhatia, S. Yang, E. Strobach, L.A. Weinstein, T.A. Cooper, G. Chen, and E.N. Wang. "Harnessing heat beyond 200°C from unconcentrated sunlight with nonevacuated transparent aerogels." *ACS Nano*, vol. 13, pp. 7508–7516, 2019. Online: doi.org/10.1021/acsnano.9b02976.

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Tracking emissions in China

Good news, some concerns

Nancy W. Stauffer, MITEI

IN BRIEF

An MIT investigator and her colleagues have confirmed that power plant emissions in China declined when strict new limits went into effect in 2014—but the response by plants was not uniform. They compared sulfur dioxide (SO_2) concentrations measured at power plant stacks with atmospheric SO_2 concentrations detected by satellite in the same area. In highly populated regions that faced the toughest new limits, the satellite data didn't show the large reductions reported by power plants—a sign that some firms may have falsified their stack measurements, perhaps due to the difficulty of meeting the tighter standards. The study shows the importance of setting clear, long-term emissions targets that give plants time to adjust, and it demonstrates an effective means of monitoring compliance.

In January 2013, many people in Beijing experienced a multiweek period of severely degraded air, known as the "Airpocalypse," which made them sick and kept them indoors. As part of its response, the central government accelerated implementation of tougher air pollution standards for power plants, with limits to take effect in July 2014. One key standard limited emissions of SO_2, which contributes to the formation of airborne particulate pollution and can cause serious lung and heart problems. The limits were introduced nationwide but varied by

Above Assistant Professor Valerie Karplus and her collaborators have demonstrated that measurements of air pollutants taken by NASA satellites are often a good indicator of emissions on the ground. Their approach provides regulators with a low-cost tool to ensure that industrial firms are complying with emissions standards. Photo: Kelley Travers, MITEI location. Restrictions were especially stringent in certain "key" regions, defined as highly polluted and populous areas in Greater Beijing, the Pearl River Delta, and the Yangtze River Delta.

All power plants had to meet the new standards by July 2014. So how did they do? "In most developing countries, there are policies on the books that look very similar to policies elsewhere in the world," says Valerie J. Karplus, an assistant professor of global economics and management at the MIT Sloan School of Management. "But there have been few attempts to look systematically at plants' compliance with environmental regulation. We wanted to understand whether policy actually changes behavior."

Adjusted SO_2 concentrations reported by a sampling of Chinese power plants This figure shows the monthly average of SO_2 concentrations measured by continuous emissions monitoring systems (CEMS) on the exhaust stacks of 256 power plants and reported by firms. To account for the different emissions levels across plants, the long-term average for each plant is normalized to zero. This curve shows emissions above or below that level on average for all plants. The figure shows a clear decline in emissions leading up to the July 2014 compliance deadline as well as following it.

Focus on power plants

For China, focusing environmental policies on power plants makes sense. Fully 60% of the country's primary energy use is coal, and about half of it is used to generate electricity. With that use comes a range of pollutant emissions. In 2007, China's Ministry of Environmental Protection required thousands of power plants to install continuous emissions monitoring systems (CEMS) on their exhaust stacks and to upload hourly, pollutant-specific concentration data to a publicly available website.

Among the pollutants tracked on the website was SO_2. To Karplus and two colleagues—Shuang Zhang, an assistant professor of economics at the University of Colorado, Boulder, and Douglas Almond, a professor in the School of International and Public Affairs and the Department of Economics at Columbia University—the CEMS data on SO_2 emissions were an as-yet-untapped resource for exploring the on-the-ground impacts of the 2014 emissions standards, over time and plant by plant.

To begin their study, Karplus, Zhang, and Almond examined changes in the CEMS data around July 2014, when the new regulations went into effect. Their study sample included 256 power plants in four provinces, among them 43 that they deemed "large," with a generating capacity greater than 1,000 megawatts (MW). They examined the average monthly SO_2 concentrations reported by each plant starting in November 2013, eight months before the July 2014 policy deadline.

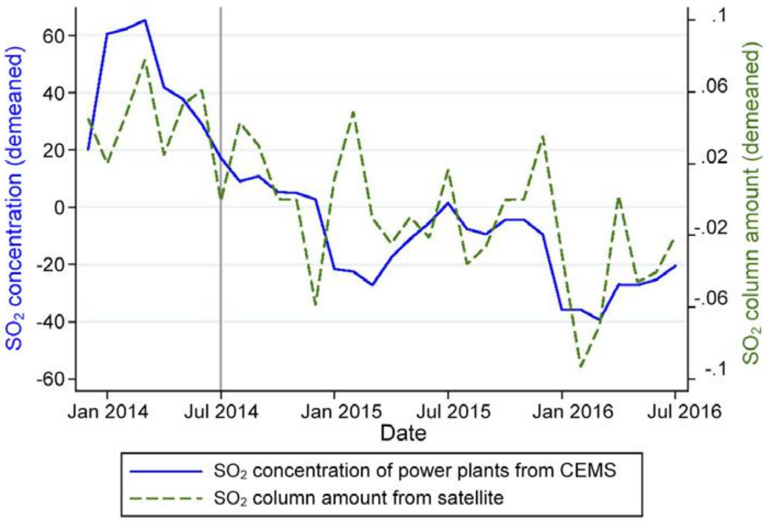
Emissions levels from the 256 plants varied considerably. The researchers were interested in relative changes within individual facilities before and after the policy, so they determined changes relative to each plant's average emissions—a calculation known as demeaning. For each plant, they calculated the average emissions level over the whole time period being considered. They then calculated how much that plant's reading for each month was above or below that baseline. By taking the averages of those changes-from-baseline numbers at all plants in each month, they could see how much emissions from the group of plants changed over time.

The demeaned CEMS concentrations are plotted in the figure above. At zero on the Y axis, levels at all plants—big emitters and small—are on average equal to their baseline. Accordingly, in January 2014 plants were well above their baseline, and by July 2016 they were well below it. So average plant-level SO_2 concentrations were declining slightly before the July 2014 compliance deadline, but they dropped far more dramatically after it.

Checking the reported data

Based on the CEMS data from all the plants, the researchers calculated that total SO_2 emissions fell by 13.9% in response to the imposition of the policy in 2014. "That's a substantial reduction," notes Karplus. "But are those reported CEMS readings accurate?"

To find out, she, Zhang, and Almond compared the measured CEMS concentrations with SO_2 concentrations detected in the atmosphere by NASA's Ozone Monitoring Instrument. "We believed that the satellite data could provide a kind of independent check on the policy response as captured by the CEMS measurements," she says.



CEMS measurements and satellite observations of SO_2 concentrations These curves show SO_2 concentrations reported by large power plants and detected by satellite in nearby regions (reported as total column amounts). The general patterns in the two measures are similar both leading up to and following July 2014.

For the comparison, they limited the analysis to their 43 1,000-MW power plants—large plants that should generate the strongest signal in the satellite observations. The figure above shows data from both the CEMS and the satellite sources. Patterns in the two measures are similar, with substantial declines in the months just before and after July 2014. That general agreement suggests that the CEMS measurements can serve as a good proxy for atmospheric concentrations of SO_2.

To double-check that outcome, the researchers selected 35 relatively isolated power plants whose capacity makes up at least half of the total capacity of all plants within a 35 km radius. Using that restricted sample, they again compared the CEMS measurements and the satellite data. They found that the new emissions standards reduced both SO_2 measures. However, the SO_2 concentrations in the CEMS data fell by 36.8% after the policy, while concentrations in the satellite data fell by only 18.3%. So the CEMS measurements showed twice as great a reduction as the satellite data did. Further restricting the sample to isolated power plants with capacity larger than 1,000 MW produced similar results.

Key versus non-key regions

One possible explanation for the mismatch between the two datasets is that some firms overstated the reductions in their CEMS measurements. The researchers hypothesized that the difficulty of meeting targets would be higher in key regions, which faced the biggest cuts. In non-key regions, the limit fell from 400 to 200 milligrams per cubic meter (mg/m^3). But in key regions, the limit went from 400 to 50 mg/m^3. Firms may have been unable to make such a dramatic reduction in so short a time, so the incentive to manipulate their CEMS readings may have increased. For example, they may have put monitors on only a few of all their exhaust stacks or turned monitors off during periods of high emissions.

The table below shows results from analyzing non-key and key regions separately. At large, isolated plants in non-key regions, the CEMS measurements show a 29.3% reduction in SO_2 and the satellite data a 22.7% reduction. The ratio of the estimated post-policy declines is 77%—not too far out of line.

But a comparable analysis of large, isolated plants in key regions produced very different results. The CEMS measurements showed a 53.6% reduction in SO_2, while the satellite data showed no statistically significant change at all.

One possible explanation is that power plants actually did decrease their SO_2 emissions after 2014, but at the same time nearby industrial facilities or other sources increased theirs, with the net effect being that the satellite data showed little or no change. However, the researchers examined emissions from neighboring high-emitting facilities during the same time period and found no contemporaneous jump in their SO_2 emissions. With that possibility dismissed, they concluded that manipulation of the CEMS data in regions facing the toughest emissions standards was "plausible," says Karplus.

Compliance with the new standards

Another interesting question was how often the reported CEMS emissions levels were within the regulated limits. The researchers calculated the compliance rate at individual plants—that is, the fraction of time their emissions were at or

	CEMS measurements	Satellite data
Non-key regions	-29.3% (10.4%)	-22.7% (10.5%)
Key regions	-53.6% (31.1%)	-1.6% (10.4%)

Changes in CEMS and satellite SO_2 measurements after the July 2014 policy deadline This table shows the change in SO_2 concentrations between November 2013 and July 2016 as measured by CEMS on stacks of large, isolated power plants and by satellite detectors in the same area. (Below each number is its standard error, a measure that accounts for statistical uncertainty in the point estimate.) In non-key regions, the correlation between the CEMS and satellite data is fairly close. In key regions, the CEMS data show SO_2 emissions cut in half, while the satellite data show no statistically significant change.

below their limits—in non-key and key regions, based on their reported CEMS measurements. The results appear in the figure on this page. In non-key regions, the compliance rate at all plants was about 90% in early 2014. It dropped a little in July 2014 when plants had to meet their (somewhat) stricter limits and then went back up to almost 100%. In contrast, the compliance rate in key regions was almost 100% in early 2014 and then plummeted to about 50% at and after July 2014.

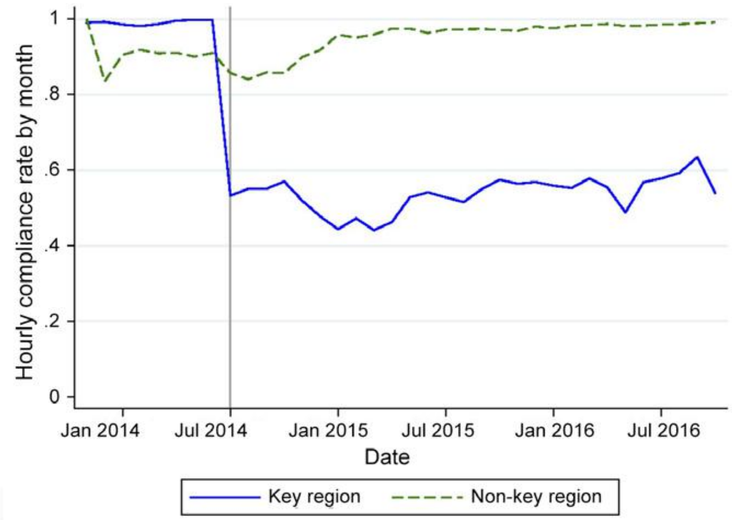
Karplus, Zhang, and Almond interpret that result as an indication of the toughness of complying with the stringent new standards. "If you think about it from the plant's perspective, complying with tighter standards is a lot harder than complying with more lenient standards, especially if plants have recently made investments to comply with prior standards, but those changes are no longer adequate," she says. "So in these key regions, many plants fell out of compliance."

She makes another interesting observation. Their analyses had already produced evidence that firms in key areas may have falsified their reported CEMS measurements. "So that means they could be both manipulating their data and complying less," she says.

Encouraging results plus insights for policymaking

Karplus stresses the positive outcomes of their study. She's encouraged that the CEMS and satellite data both show emission levels dropping at most plants. Compliance rates were down at some plants in key regions, but that's not surprising when the required cuts were large. And she notes that even though firms may not have complied, they still reduced their emissions to some extent as a result of the new standard.

She also observes that, for the most part, there's close correlation between the CEMS and satellite data. So the quality



Plant-level hourly compliance rates in key and non-key regions These curves show the fraction of time that power plants in non-key regions (green dashed line) and key regions (blue solid line) were in compliance with their SO_2 emissions standards before and after the July 2014 deadline for meeting the new standards. Plants in non-key areas did well over the entire time period. But compliance at plants in key areas fell from 100% to 50% in July 2014 and remained there—perhaps an indication of how difficult it was for them to meet the stringent new standards.

of the CEMS data isn't all bad. And where it's bad—where firms may have manipulated their measurements—it may have been because they'd been set a seemingly impossible task and timeline. "At some point, plant managers might just throw up their hands," says Karplus. The lesson for policymakers may be to set emissions-reduction goals that are deep but long-term so that firms have enough time to make the necessary investment and infrastructure adjustments.

To Karplus, an important practical implication of the study is "demonstrating that you can look at the alignment between ground and remote data sources to evaluate the impact of specific policies." A series of tests confirmed the validity of their method and the robustness of their results. For example, they performed a comparable analysis focusing on July 2015, when there was no change in emissions standards. There was no evidence of the same effects. They accounted for SO_2 emitted by manufacturing facilities and other sources, and their results were unaffected. And they demonstrated that when clouds or other obstructions interfered with satellite observations, the resulting data gap had no impact on their results.

The researchers note that their approach can be used for other short-lived industrial air pollutants and by any country seeking low-cost tools to improve data quality and policy compliance, especially when plants' emissions are high to begin with. "Our work provides an illustration of how you can use satellite data to obtain an independent check on emissions from pretty much any high-emitting facility," says Karplus. "And over time, NASA will have instruments that can take measurements that are even more temporally and spatially resolved, which I think is quite exciting for environmental protection agencies and for those who would seek to improve the environmental performance of their energy assets."

NOTES

This research was supported by a seed grant from the Samuel Tak Lee Real Estate Entrepreneurship Laboratory at MIT and by the U.S. National Science Foundation. Further information can be found in:

V.J. Karplus, S. Zhang, and D. Almond. "Quantifying coal power plant responses to tighter SO_2 emissions standards in China." *Proceedings of the National Academy of Sciences of the United States of America*, vol. 115, no. 27, pp. 7004–7009, June 2018. Online: doi.org/10.1073/pnas.1800605115.

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

The MIT Energy Initiative (MITEI) recently awarded seven grants totaling approximately $1 million through its Seed Fund Program, which supports early-stage innovative energy research at MIT through an annual competitive process.

"Supporting basic research has always been a core component of MITEI's mission to transform and decarbonize global energy systems," says MITEI Director Robert C. Armstrong, the Chevron Professor of Chemical Engineering. "This year's funded projects highlight just a few examples of the many ways that people working across the energy field are researching vital topics to create a better world."

The newly awarded projects will address topics such as developing efficient strategies for recycling plastics, improving the stability of high-energy metal-halogen flow batteries, and increasing the potential efficiency of silicon solar cells to accelerate the adoption of photovoltaics. Awardees include established energy faculty members and others who are new to the energy field, from disciplines including applied economics, chemical engineering, biology, and other areas.

Demand-response policies and incentives for energy efficiency adoption

Most of today's energy growth is occurring in developing countries. Assistant Professor Namrata Kala and Professor Christopher Knittel, both of whom focus on applied economics at the MIT Sloan School of Management, will use their grant to examine key policy levers for meeting electricity demand and renewable energy growth without jeopardizing system reliability in the developing world. Kala and Knittel plan to design and run a randomized control trial in New Delhi, India, in collaboration with a large Indian power company. "We will estimate the willingness of firms to enroll in services that reduce peak consumption, and also promote energy efficiency," says Kala, the W. Maurice Young (1961) Career Development Professor of Management. "Estimating the costs and benefits of such services, and their allocation across customers and electricity providers, can inform policies that promote energy efficiency in a cost-effective manner."

Efficient conversion of methane to methanol

Methane, the primary component of natural gas, has become an increasingly important part of the global energy portfolio. However, the chemical inertness of methane and the lack of efficient methods to convert this gaseous carbon feedstock into liquid fuels has significantly limited its application. Yang Shao-Horn, the W.M. Keck Professor of Energy in the departments of Mechanical Engineering and Materials Science and Engineering, seeks to address this problem using her seed fund grant. Shao-Horn and Shuai Yuan, a postdoc in the Research Laboratory of Electronics, will focus on achieving efficient, cost-effective gas-to-liquid conversion using metal-organic frameworks (MOFs) as electrocatalysts.

Current methane activation and conversion processes are usually accomplished by costly and energy-intensive steam reforming at elevated temperature and high pressure. Shao-Horn and Yuan's goal is to design efficient MOF-based electrocatalysts that will permit the methane-to-methanol conversion process to proceed at ambient temperature and pressure.

"If successful, this electrochemical gas-to-liquid concept could lead to a modular, efficient, and cost-effective solution that can be deployed in both large-scale industrial plants and remotely located oil fields to increase the utility of geographically isolated gas reserves," says Shao-Horn.

Using machine learning to solve the "zeolite conundrum"

The energy field is replete with opportunities for machine learning to expedite progress toward a variety of innovative energy solutions. Rafael Gómez-Bombarelli, the Toyota Assistant Professor in Materials Processing in the Department of Materials Science and Engineering, received a grant for a project that will combine machine learning and simulation to accelerate the discovery cycle of zeolites.

Zeolites are materials with wide-ranging industrial applications as catalysts and molecular sieves because of their high stability and selective nanopores that can confine small molecules. Despite decades of abundant research, only 248 zeolite frameworks have been realized out of the millions of possible structures that have been proposed using computers—the so-called zeolite conundrum.

The problem, notes Gómez-Bombarelli, is that discovery of these new frameworks has relied mostly on trial-and-error in the lab—an approach that is both slow and labor-intensive.

In his seed grant work, Gómez-Bombarelli and his team will be using theory to speed up that process. "Using machine learning and first-principles simulations, we'll design small molecules to dock on specific pores and direct the formation of targeted structures," says Gómez-Bombarelli. "This computational approach will drive new synthetic outcomes in zeolites faster."

Effective recycling of plastics

Professor Anthony Sinskey of the Department of Biology, Professor Gregory Stephanopoulos of the Department of Chemical Engineering, and graduate student Linda Zhong of biology have joined forces to address the environmental and economic problems posed by polyethylene terephthalate (PET). One of the most synthesized plastics, PET exhibits an extremely low degradation rate, and its production is highly dependent on petroleum feedstocks.

"Due to the huge negative impacts of PET products, efficient recycling strategies need to be designed to decrease economic loss and adverse environmental impacts associated with single-use practices," says Sinskey.

"PET is essentially an organic polymer of terephthalic acid and ethylene glycol, both of which can be metabolized by bacteria as energy and nutrients. These capacities exist in nature, though not together," says Zhong. "Our goal is to engineer these metabolic pathways into *E. coli* to allow the bacterium to grow on PET. Using genetic engineering, we will introduce the PET-degrading enzymes into *E. coli* and ultimately transfer them into bioremediation organisms."

The long-term goal of the project is to prototype a bioprocess for closed-loop PET recycling, which will decrease the volume of discarded PET products as well as the consumption of petroleum and energy for PET synthesis.

The researchers' primary motivation in pursuing this project echoes MITEI's overarching goal for the seed fund program: to push the boundaries of research and innovation to solve global energy and climate challenges. Zhong says, "We see a dire need for this research because our world is inundated in plastic trash. We're only attempting to solve a tiny piece of the global problem, but we must try when much of what we hold dear depends on it."

The MITEI Seed Fund Program has awarded new grants each year since it was established in 2008. Funding for the grants comes chiefly from MITEI's founding and sustaining members, supplemented by gifts from generous donors. To date, MITEI has supported 177 projects with grants totaling approximately $23.6 million.

Kathryn Luu, MITEI

Recipients of MITEI Seed Fund grants, 2019

Development and prototyping of stable, safe, metal-halogen flow batteries with high energy and power densities
Martin Bazant
Departments of Chemical Engineering and Mathematics
T. Alan Hatton
Department of Chemical Engineering

Silicon solar cells sensitized by exciton fission
Marc Baldo
Department of Electrical Engineering and Computer Science

Automatic design of structure-directing agents for novel realizable zeolites
Rafael Gómez-Bombarelli
Department of Materials Science and Engineering

Demand response, energy efficiency, and firm decisions
Namrata Kala, Christopher Knittel
Sloan School of Management

Direct conversion of methane to methanol by MOF-based electrocatalysts
Yang Shao-Horn
Departments of Mechanical Engineering and Materials Science and Engineering

Biodegradation of plastics for efficient recycling and bioremediation
Anthony Sinskey
Department of Biology
Gregory Stephanopoulos
Department of Chemical Engineering

Asymmetric chemical doping for photocatalytic CO_2 reduction
Michael Strano
Department of Chemical Engineering.

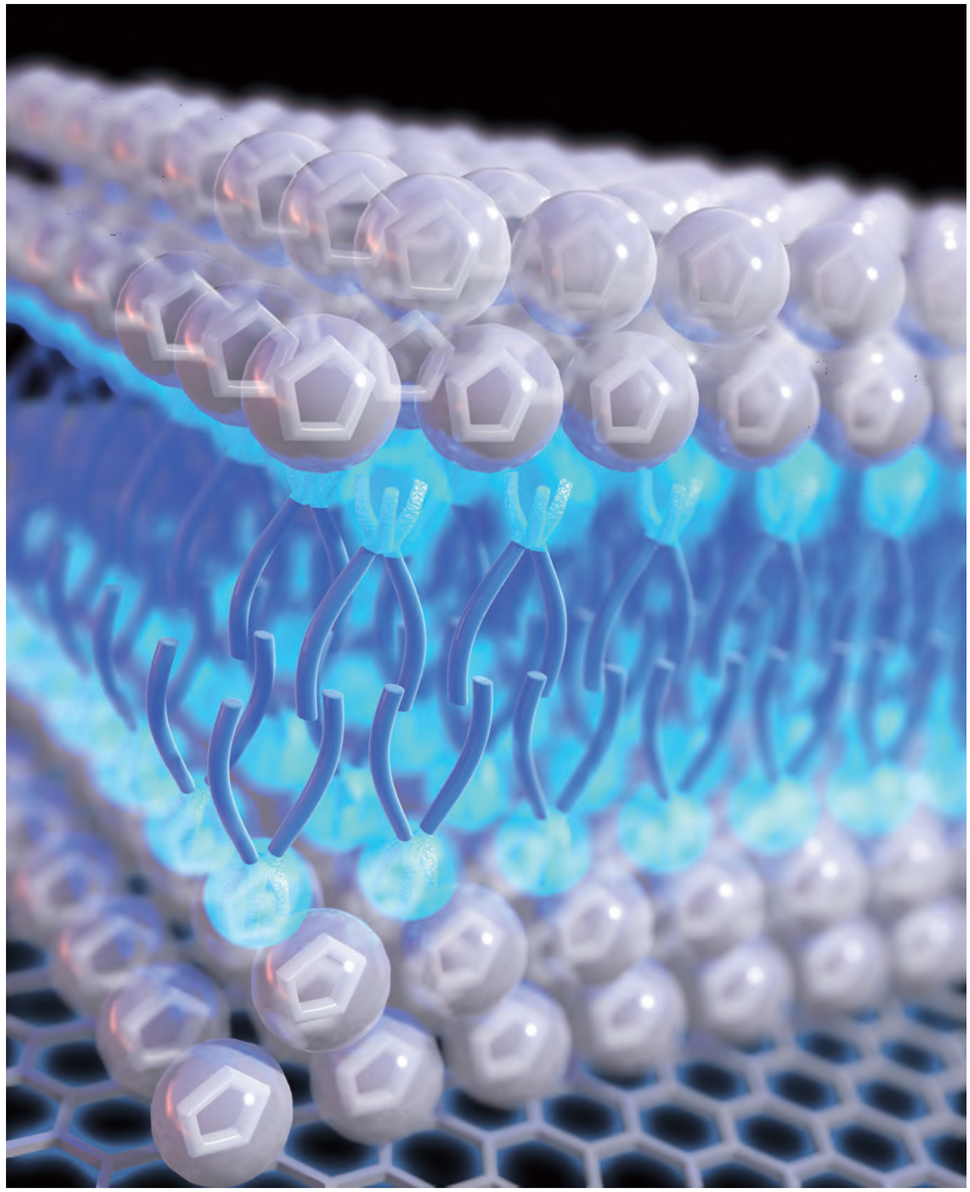
New type of electrolyte could enhance supercapacitor performance

Supercapacitors, electrical devices that store and release energy, need a layer of electrolyte—an electrically conductive material that can be solid, liquid, or somewhere in between. Now, researchers at MIT and several other institutions have developed a novel class of liquids that may open up new possibilities for improving the efficiency and stability of such devices while reducing their flammability.

"This proof-of-concept work represents a new paradigm for electrochemical energy storage," the researchers say in their paper describing the finding, which appeared in the journal *Nature Materials* on August 12, 2019.

For decades, researchers have been aware of a class of materials known as ionic liquids—essentially, liquid salts—but this team has now added to these liquids a compound that is similar to a surfactant, like those used to disperse oil spills. With the addition of this material, the ionic liquids "have very new and strange properties," including becoming highly viscous, says MIT postdoc Xianwen Mao PhD '14, the lead author of the paper.

"It's hard to imagine that this viscous liquid could be used for energy storage," Mao says, "but what we find is that once we raise the temperature, it can store more energy, and more than many other electrolytes."



Large anions with long tails (blue) in ionic liquids can make them self-assemble into sandwich-like bilayer structures on electrode surfaces. Ionic liquids with such structures have much improved energy storage. Image: Xianwen Mao, MIT

That's not entirely surprising, he says, since with other ionic liquids, as temperature increases, "the viscosity decreases and the energy-storage capacity increases." But in this case, although the viscosity stays higher than that of other known electrolytes, the capacity increases very quickly with increasing temperature. That ends up giving the material an overall energy density—a measure of its ability to store electricity in a given volume—that exceeds those of many conventional electrolytes, and with greater stability and safety.

The key to its effectiveness is the way the molecules within the liquid automatically line themselves up, ending up in a layered configuration on the metal electrode surface. The molecules, which have a kind of tail on one end, line up with the heads facing outward toward the electrode or away from it, and the tails all cluster in the middle, forming a kind of sandwich (see the image above). This is described as a self-assembled nanostructure.

"The reason why it's behaving so differently" from conventional electrolytes is because of the way the molecules intrinsically assemble themselves into an ordered, layered structure where they come in contact with another material, such as the electrode inside a supercapacitor, says T. Alan Hatton, a professor of chemical engineering at MIT and the paper's senior author. "It forms a very interesting, sandwich-like, double-layer structure."

This highly ordered structure helps to prevent a phenomenon called "overscreening" that can occur with other ionic liquids, in which the first layer of ions (electrically charged atoms or molecules) that collect on an electrode surface contains more ions than there are corresponding charges on the surface. This can cause a more scattered distribution of ions, or a thicker ion multilayer, and thus a loss of efficiency in energy storage, "whereas with our case, because of the way everything is structured, charges are concentrated within the surface layer," Hatton says.

The new class of materials, which the researchers call SAILs, for surface-active ionic liquids, could have a variety of applications for high-temperature energy storage, for example for use in hot environments such as in oil drilling or in chemical plants, according to Mao. "Our electrolyte is very safe at high temperatures, and even performs better," he says. In contrast, some electrolytes used in lithium-ion batteries are quite flammable.

The material could help to improve the performance of supercapacitors, Mao says. Such devices can be used to store electrical charge and are sometimes used to supplement battery systems in electric vehicles to provide an extra boost of power. Using the new material instead of a conventional electrolyte in a supercapacitor could increase its energy density by a factor of four or five, Mao says. Using the new electrolyte, future supercapacitors may even be able to store more energy than batteries, he says, potentially even replacing batteries in applications such as electric vehicles, personal electronics, or grid-level energy storage facilities.

The material could also be useful for a variety of emerging separation processes, Mao says. "A lot of newly developed separation processes require electrical control," in various chemical processing and refining applications and in carbon dioxide capture, for example, as well as in resource recovery from waste streams. These ionic liquids, being highly conductive, could be well-suited to many such applications, he says.

The material they initially developed is just an example of a variety of possible SAIL compounds. "The possibilities are almost unlimited," Mao says. The team will continue to work on different variations and on optimizing its parameters for particular uses. "It might take a few months or years," he says, "but working on a new class of materials is very exciting to do. There are many possibilities for further optimization."

The research team included Paul Brown, Yinying Ren, Agilio Padua, and Margarida Costa Gomes at MIT; Ctirad Cervinka at École Normale Supérieure de Lyon, in France; Gavin Hazell and Julian Eastoe at the University of Bristol, in the United Kingdom; Hua Li and Rob Atkin at the University of Western Australia; and Isabelle Grillo at the Institut Max-von-Laue-Paul-Langevin in Grenoble, France. The researchers dedicate their paper to the memory of Grillo, who recently passed away.

"It is a very exciting result that surface-active ionic liquids (SAILs) with amphiphilic structures can self-assemble on electrode surfaces and enhance charge storage performance at electrified surfaces," says Yi Cui, a professor of materials science and engineering at Stanford University, who was not associated with this research. "The authors have studied and understood the mechanism. The work here might have a great impact on the design of high energy density supercapacitors and could also help improve battery performance," he says.

Nicholas Abbott, the Tisch University Professor at Cornell University, who also was not involved in this work, says, "The paper describes a very clever advance in interfacial charge storage, elegantly demonstrating how knowledge of molecular self-assembly at interfaces can be leveraged to address a contemporary technological challenge."

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David Chandler, MIT News Office

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X. Mao, P. Brown, C. Cervinka, G. Hazell, H. Li, T. Ren, D. Chen, R. Atkin, J. Eastoe, I. Grillo, A.A.H. Padua, M. F. Costa Gomes, and T.A. Hatton. "Self-assembled nanostructures in ionic liquids facilitate charge storage at electrified interfaces." *Nature Materials*, 12 August 2019. Online: doi.org/10.1038/s41563-019-0449-6.

Study: Even short-lived solar panels can be economically viable

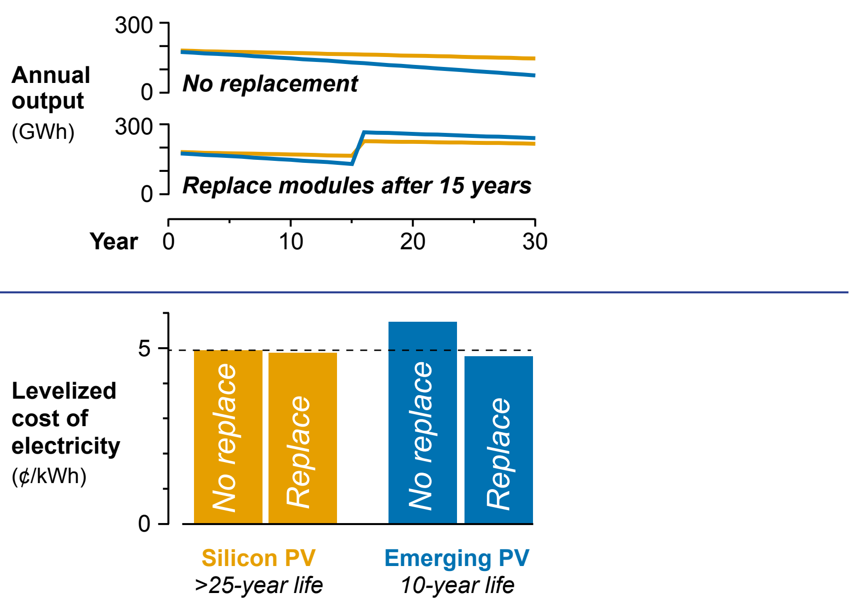
A new study shows that, contrary to widespread belief within the solar power industry, new kinds of solar cells and panels don't necessarily have to last for 25 to 30 years in order to be economically viable in today's market.

Rather, solar panels with initial lifetimes of as little as 10 years can sometimes make economic sense, even for grid-scale installations—thus potentially opening the door to promising new solar photovoltaic (PV) technologies that have been considered insufficiently durable for widespread use.

The new findings are described in a paper in the journal *Joule*, by Joel Jean, a former MIT postdoc and CEO of the startup company Swift Solar (swiftsolar.com); Vladimir Bulović, professor of electrical engineering and computer science and director of MIT.nano; and Michael Woodhouse of the National Renewable Energy Laboratory (NREL) in Colorado.

"When you talk to people in the solar field, they say any new solar panel has to last 25 years," Jean says. "If someone comes up with a new technology with a 10-year lifetime, no one is going to look at it. That's considered common knowledge in the field, and it's kind of crippling."

Jean adds that "that's a huge barrier, because you can't prove a 25-year lifetime in a year or two, or even 10." That presumption, he says, has left many promising new technologies stuck on the sidelines, as conventional crystalline silicon technologies overwhelmingly dominate the commercial solar marketplace. But, the researchers found, that does not need to be the case.



Module-replacement strategy for silicon PV and emerging PV systems The top panel shows the annual output of the two systems. Top curves: Over 30 years, the output of both systems declines as the solar panels degrade. Bottom curves: The output from both systems increases when module are replaced at year 15, the emerging PV more than the silicon PV. The bottom panel shows lifetime cost per kilowatt-hour. Left bars: The cost of the silicon PV is about the same with and without module replacement. Right bars: Without replacement, the cost is higher for the emerging PV than for the silicon PV system. With replacement at 15 years, the emerging PV system is cost-competitive. Assuming continuing technological advances, the newer modules will always be better than the ones they replace.

"We have to remember that ultimately what people care about is not the cost of the panel; it's the levelized cost of electricity," he says. In other words, it's the actual cost per kilowatt-hour delivered over the system's useful lifetime, including the cost of the panels, inverters, racking, wiring, land, installation labor, permitting, grid interconnection, and other system components, along with ongoing maintenance costs.

Part of the reason that the economics of the solar industry look different today than in the past is that the cost of the panels (also known as modules) has plummeted so far that now, the "balance of system" costs—that is, everything except the panels themselves—exceeds that of the panels. That means that, as long as newer solar panels are electrically and physically compatible with the racking and electrical systems, it can make economic sense to replace the panels with newer, better ones as they become available, while reusing the rest of the system.

"Most of the technology is in the panel, but most of the cost is in the system," Jean says. "Instead of having a system where you install it and then replace everything after 30 years, what if you replace the panels earlier and leave everything else the same? One of the reasons that might work economically is if you're replacing them with more efficient panels," which is likely to be the case as a wide variety of more efficient and lower-cost technologies are being explored around the world.

He says that what the team found in their analysis is that "with some caveats about financing, you can, in theory, get to a competitive cost, because your new panels are getting better, with a lifetime as short as 15 or even 10 years."

Although the costs of solar cells have come down year by year, Bulović says, "the expectation that one had to demonstrate a 25-year lifetime for any new solar panel technology has stayed as a tautology. In this study we show that as the solar panels get less expensive and more efficient, the cost balance significantly changes."

He says that one aim of the new paper is to alert the researchers that their new solar inventions can be cost-effective even if relatively short-lived, and hence may be adopted and deployed more rapidly than expected. At the same time, he says, investors should know that they stand to make bigger profits by opting for efficient solar technologies that may not have been proven to last as long, knowing that periodically the panels can be replaced by newer, more efficient ones.

"Historical trends show that solar panel technology keeps getting more efficient year after year, and these improvements are bound to continue for years to come," says Bulović. Perovskite-based solar cells, for example, when first developed less than a decade ago, had efficiencies of only a few percent. But recently their record performance exceeded 25% efficiency, compared to 27% for the record silicon cell and about 20% for today's standard silicon modules, according to Bulović. Importantly, in novel device designs, a perovskite solar cell can be stacked on top of another perovskite, silicon, or thin-film cell, to raise the maximum achievable efficiency limit to over 40%, which is well above the 30% fundamental limit of today's silicon solar technologies. But perovskites have issues with longevity of operation and have not yet been shown to be able to come close to meeting the 25-year standard.

Bulović hopes the study will "shift the paradigm of what has been accepted as a global truth." Up to now, he says, "many promising technologies never even got a start, because the bar is set too high" on the need for durability.

For their analysis, the team looked at three different kinds of solar installations: a typical 6-kilowatt residential system, a 200-kilowatt commercial system, and a large 100-megawatt utility-scale system with solar tracking. They used NREL benchmark parameters for U.S. solar systems and a variety of assumptions about future progress in solar technology development, financing, and the disposal of the initial panels after replacement, including recycling of the used modules. The models were validated using four independent tools for calculating the levelized cost of electricity (LCOE), a standard metric for comparing the economic viability of different sources of electricity.

In all three installation types, they found, depending on the particulars of local conditions, replacement with new modules after 10 to 15 years could in many cases provide economic advantages while maintaining the many environmental and emissions-reduction benefits of solar power. The basic requirement for cost-competitiveness is that any new solar technology that is to be installed in the United States should start with a module efficiency of at least 20%, a cost of no more than 30 cents per watt, and a lifetime of at least 10 years, with the potential to improve on all three.

Jean points out that the solar technologies that are considered standard today, mostly silicon-based but also thin-film variants such as cadmium telluride, "were not very stable in the early years. The reason they last 25 to 30 years today is that they have been developed for many decades." The new analysis may now open the door for some of the promising newer technologies to be deployed at sufficient scale to build up similar levels of experience and improvement over time and to make an impact on climate change earlier than they could without module replacement, he says.

"This could enable us to launch ideas that would have died on the vine" because of the perception that greater longevity was essential, Bulović says.

The study was supported by the Tata-MIT GridEdge Solar research program.

David Chandler, MIT News Office

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J. Jean, M. Woodhouse, and V. Bulović. "Accelerating photovoltaic market entry with module replacement." *Joule*, vol. 3, pp. 1–18, September 2019. Online: doi.org/10.1016/j.joule.2019.08.012.

Julia Ortony: Concocting nanomaterials for energy and environmental applications

A molecular engineer, Julia Ortony performs a contemporary version of alchemy.

"I take powder made up of disorganized, tiny molecules, and after mixing it up with water, the material in the solution zips itself up into threads five nanometers thick—about one hundred times smaller than the wavelength of visible light," says Ortony, the Finmeccanica Career Development Assistant Professor of Engineering in the Department of Materials Science and Engineering (DMSE). "Every time we make one of these nanofibers, I am amazed to see it."

Julia Ortony, the Finmeccanica Career Development Assistant Professor of Engineering in the Department of Materials Science and Engineering. Photo: Lillie Paquette, MIT School of Engineering

But for Ortony, the fascination doesn't simply concern the way these novel structures self-assemble, a product of the interaction between a powder's molecular geometry and water. She is plumbing the potential of these nanomaterials for use in renewable energy and environmental remediation technologies, including promising new approaches to water purification and the photocatalytic production of fuel.

Tuning molecular properties

Ortony's current research agenda emerged from a decade of work into the behavior of a class of carbon-based molecular materials that can range from liquid to solid.

During doctoral work at the University of California, Santa Barbara, she used magnetic resonance (MR) spectroscopy to make spatially precise measurements of atomic movement within molecules and of the interactions between molecules. At Northwestern University, where she was a postdoctoral fellow, Ortony focused this tool on self-assembling nanomaterials that were biologically based, in research aimed at potential biomedical applications such as cell scaffolding and regenerative medicine.

"With MR spectroscopy, I investigated how atoms move and jiggle within an assembled nanostructure," she says. Her research revealed that the surface of the nanofiber acted like a viscous liquid, but as one probed further inward, it behaved like a solid. Through molecular design, it became possible to tune the speed at which molecules that make up a nanofiber move.

A door had opened for Ortony. "We can now use state-of-matter as a knob to tune nanofiber properties," she says. "For the first time, we can design self-assembling nanostructures, using slow or fast internal molecular dynamics to determine their key behaviors."

Slowing down the dance

When she arrived at MIT in 2015, Ortony was determined to tame and train molecules for nonbiological applications of self-assembling "soft" materials.

"Self-assembling molecules tend to be very dynamic, where they dance around each other, jiggling all the time and coming and going from their assembly," she explains. "But we noticed that when molecules stick strongly to each other, their dynamics get slow, and their behavior is quite tunable." The challenge, though, was to synthesize nanostructures in nonbiological molecules that could achieve these strong interactions.

"My hypothesis coming to MIT was that if we could tune the dynamics of small molecules in water and really slow them down, we should be able to make self-assembled nanofibers that behave like a solid and are viable outside of water," says Ortony.

Her efforts to understand and control such materials are now starting to pay off.

"We've developed unique, molecular nanostructures that self-assemble, are stable in both water and air, and—since they're so tiny—have extremely high surface areas," she says. Since the nanostructure surface is where chemical interactions with other substances take place, Ortony has leapt to exploit this feature of her creations—focusing in particular on their potential in environmental and energy applications.

Clean water and fuel from sunlight

One key venture, supported by Ortony's Professor Amar G. Bose Fellowship, involves water purification. The problem of toxin-laden drinking water affects tens of millions of people in underdeveloped nations. Ortony's research group is developing nanofibers that can grab deadly metals such as arsenic out of such water. The chemical groups she attaches to nanofibers are strong, stable in air, and in recent tests "remove all arsenic down to low, nearly undetectable levels," says Ortony.

She believes an inexpensive textile made from nanofibers would be a welcome alternative to the large, expensive filtration systems currently deployed in places like Bangladesh, where arsenic-tainted water poses dire threats to large populations.

"Moving forward, we would like to chelate arsenic, lead, or any environmental contaminant from water using a solid textile fabric made from these fibers," she says.

In another research thrust, Ortony says, "My dream is to make chemical fuels from solar energy." Her lab is designing nanostructures with molecules that act as antennas for sunlight. These structures, exposed to and energized by light, interact with a catalyst in water to reduce carbon dioxide to different gases that could be captured for use as fuel.

In recent studies, the Ortony Lab found that it is possible to design these catalytic nanostructure systems to be stable in water under ultraviolet irradiation for long periods of time. "We tuned our nanomaterial so that it did not break down, which is essential for a photocatalytic system," says Ortony.

Students dive in

While Ortony's technologies are still in the earliest stages, her approach to problems of energy and the environment are already drawing student enthusiasts.

Dae-Yoon Kim, a postdoctoral fellow in the Ortony Lab, won the 2018 Glenn H. Brown Prize from the International Liquid Crystal Society for his work on synthesized photo-responsive materials and started a tenure track position at the Korea Institute of Science and Technology this fall. Ortony also mentors Ty Christoff-Tempesta, a DMSE doctoral candidate, who was recently awarded a Martin Fellowship for Sustainability. Christoff-Tempesta hopes to design nanoscale fibers that assemble and disassemble in water to create environmentally sustainable materials. And Cynthia Lo '18 won a best senior thesis award for work with Ortony on nanostructures that interact with light and self-assemble in water, work that will soon be published. She is "my superstar MIT Energy Initiative UROP [undergraduate researcher]," says Ortony.

Ortony hopes to share her sense of wonder about materials science not just with students in her group but also with those in her classes. "When I was an undergraduate, I was blown away at the sheer ability to make a molecule and confirm its structure," she says. With her new lab-based course for grad students—3.65 Soft Matter Characterization—Ortony says she can teach about "all the interests that drive my research."

While she is passionate about using her discoveries to solve critical problems, she remains entranced by the beauty she finds pursuing chemistry. Fascinated by science starting in childhood, Ortony says she sought out every available class in chemistry, "learning everything from beginning to end, and discovering that I loved organic and physical chemistry, and molecules in general."

Today, she says, she finds joy working with her "creative, resourceful, and motivated" students. She celebrates with them "when experiments confirm hypotheses, and it's a breakthrough and it's thrilling," and reassures them "when they come with a problem, and I can let them know it will be thrilling soon."

Leda Zimmerman, MITEI correspondent

Professor Julia Ortony (right) and graduate student William Lindemann discuss his experiments on self-assembling nanofibers. Work at the Ortony Lab focuses on molecular design and synthesis to create new soft nanomaterials for tackling problems related to energy and the environment. Photo: Lillie Paquette, MIT School of Engineering

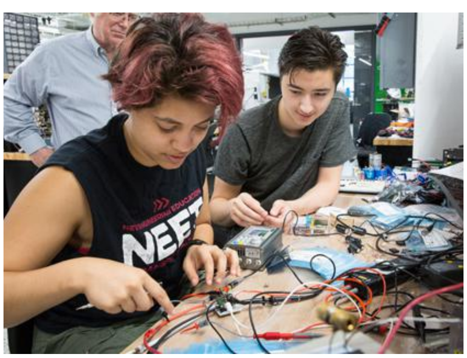
Collaboration adds extra dimension to undergraduate research

Grace Bryant is a junior at MIT, but it wasn't until this summer that she got a chance to team up with students outside her major through the Undergraduate Research Opportunities Program (UROP), supported by the MIT Energy Initiative (MITEI). She says she found the experience eye-opening.

"I rarely interact with people doing something different from what I study," says Bryant, who is majoring in urban studies and planning with computer science. "Talking to people with other majors about what they think their careers will look like was pretty cool and something I don't think I would have had without this experience."

Every summer, UROP students work with faculty on ground-breaking, real-world research; roughly 90% of MIT undergraduates will do a UROP before they graduate. Most undertake individual projects, but for those who team up with other undergraduates there are often added benefits—the chance to collaborate, learn from peers, and literally lend a hand—reflecting the kind of experience they're likely to find in the workplace.

Luis Garcia (left) discusses findings with Yeva Yin (center) and Professor David Hsu. Garcia and Yin, along with Grace Bryant (not pictured), worked with Hsu to analyze political spending and corresponding utility rates during their summer UROP through the MIT Energy Initiative. Photos: Kelley Travers, MITEI



PJ Hernandez (left) and Jackson Gray (right) build circuits in the lab of Professor James Kirtley (background) as part of their summer energy UROP. One of the problems they worked on together was how to develop an improved cell voltage balancer, a device used to extend the life of batteries by working to ensure that cells remain evenly charged as the battery cycles.

"You never know who is going to change your perspective on your own work," says Rachel Shulman, the undergraduate academic coordinator for MITEI, which funded 22 UROP students this summer, including multiple teams. "Energy is by definition multidisciplinary."

"It's a realistic working environment," says William Lynch, a research specialist in the Research Laboratory of Electronics (RLE) who supervised two MITEI UROP students on a project focused on extending battery life. "In industry, people work together in teams."

A helping hand

Some of the payoffs of collaboration are obvious. One of Lynch's advisees, PJ Hernandez, was at work this summer and suddenly noticed their lab partner Jackson Gray struggling to wire a circuit with one hand; he'd recently broken his wrist. Hernandez had often turned to Gray for help on their project because he had a stronger background in electronics. Helping him build the circuit provided a chance to return the favor.

"I'm really lucky there is another UROP," says Hernandez, a senior majoring in electrical engineering. "Jackson has been helping me understand a lot."

Gray says working with Hernandez was great for him too—and not just because of his bad wrist. "We can work through the math together to be sure we're not doing something fundamentally wrong," says Gray, a junior in electrical engineering. "It's useful just to have someone to question you and make you justify your ideas."

James Kirtley, professor of electrical engineering and principal investigator for the RLE project, says he likes to team up students for just this reason. "The very best teachers are students, so it is reasonable to expect that the experienced student will teach the less experienced students what he or she knows," he says. "And the ambitious but less experienced student will, by asking questions, prod the more experienced student to think more broadly about the problem."

For Hernandez and Gray, the problem was how to develop an improved cell voltage balancer, a device used to extend the life of batteries by working to ensure that cells remain evenly charged as the battery cycles (charges and discharges current). They were hoping to improve on existing designs, since most balancers today work by dissipating extra charge as heat. As Gray explains, "If the battery management system sees that some cells are more charged than others, it will just waste that energy."

Gray says he hopes to find a way to balance batteries more efficiently—perhaps by moving charge from one cell to another—in part because batteries are so important to his hobbies. "I enjoy working on electric vehicles and small robots, both of which use lithium ion batteries," a major focus of the project, he says.

Hernandez's interest in the project stems more from an interest in environmentalism, since making batteries more efficient should reduce waste: "Reducing our carbon footprint, reducing energy consumption, is really important," they say.

Learning from others

Hernandez and Gray bolstered each other coming from the same field, but UROPs from different majors gain additional benefits from teaming up—as Bryant discovered by working with Yeva Yin, a junior in business analytics, and Luis Garcia, a senior math major, on a project for David Hsu, associate professor of urban and environmental planning.

Hsu's project follows up on research conducted over a decade ago that showed that electricity rates are higher in areas where the local utility has spent money on lobbying. Hsu hypothesizes that this connection has grown in the wake of the Citizens United ruling by the U.S. Supreme Court, which declared corporate spending on political candidates to be protected free speech—a decision that has led to a huge increase in such spending.

Hsu employed the UROP team to gather data on state and federal campaign contributions, examine the voting patterns of utility regulators, and dig into the biographies of regulators to see what industries and companies they came from and went to after their service. The team also gathered information about the rates requested by companies, the cases presented for those rates, and the rates ultimately set for electricity—all public information.

Hsu divvied up tasks so that each student took a different dive through the material, and he said each individual's work really complemented the others'. "I like to give each student a piece to be responsible for and make it overlap with the larger project," Hsu says. "It gives students more independence and more ownership.… They can learn more than they would by themselves."

"We all have different ideas and strengths, and that helps in coming up with different ways to approach topics," says Yin. For example, she says she often uses applied skills in business analytics but knows less about the underlying theory; Garcia has had almost the exact opposite experience as a math major.

"Studying math, there's a lot of theory," Garcia says. "So it's easier for me to come up with a plan and visualize it. But when it comes time to implement the plan, that's a newer experience."

Garcia investigated lobbying data—the amount of money donated by whom and to whom—and he says he learned a lot. "Working with real-world data… you have to decide what you won't need, what's actually important," he says. By contrast, in math, "nothing is a strong judgment call," he says.

Expanding horizons

Students on UROP teams agree that collaboration speeds up the research. As Bryant remarks, "If you have a lot of work on your plate, you can redistribute the work, which is super useful."

Bryant also says the UROP gave her new insight into American government and finance. "I just really wasn't aware of how the energy system was regulated. I get electricity in my house, and that's it. It's really exciting to have that insight into how that system works and how it plays into the larger economy."

Garcia says the lessons he's learned about utility lobbying and regulation are helping him decide his next career steps. "I'm maybe going into public policy or political science, so I feel like having exposure to this type of work could be really helpful," he says.

Teaming up on a UROP isn't just valuable in terms of research and education, as Bryant discovered. In her case, talking about Hsu's project led to a discussion about how government works and how big corporations behave. This, in turn, led to a thoughtful conversation about career options.

"We talked about careers, and it's a conversation I haven't had with people outside my major," Bryant says, noting that she and her fellow UROPs discussed the trade-offs of going into well-paid jobs in industry versus focusing on a career that gives back to the community. "There was this whole ethical portion of the discussion," she says. "It was pretty influential in how I think about jobs now."

According to Shulman, this kind of experience is just what MITEI hopes to foster by sponsoring team-based undergraduate research. "I'm a big believer in serendipity," she says. "How can we engender serendipity? You throw people together who might not otherwise have met each other."

Kathryn O'Neill, MITEI correspondent

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MITEI UROPs are supported by generous donations from Shell, ExxonMobil, Chevron, Equinor, and individual alumni donors.

MIT and UMass students come together for Science Slam

Six students each from MIT and the University of Massachusetts Amherst took turns presenting their summer research in an inaugural joint Science Slam on August 5, 2019, hosted by the MIT Energy Initiative. Students presented on topics ranging from transparent solar panels to energy in Nigeria, as well as on non-energy-related subjects such as arthritis, spider eyes, and chlamydia.

Students had five minutes to present their work with the aid of a PowerPoint presentation, and a panel of judges selected first-, second-, and third-place winners. The four winners (including a tie for third place) each received a gift card.

The slam also provided a networking opportunity for the students; the preceding catered lunch was a chance to meet students from another university. In addition, presenters encouraged interested audience members to approach them later for further discussion on their topics.

The chemical engineering Communications Lab played a vital role in helping MIT students prepare for the slam.

A sophomore chemical engineering major who tied for third place presented their research on redox flow batteries, which they worked on with Fikile Brushett, the Cecil and Ida Green Career Development Chair and an associate professor of chemical engineering.

"I think it's really interesting to talk to people who are doing different kinds of research, especially in the fields of energy," says the third-place winner, Jane Bonesteel. "Additionally, I was able to do a lot of work toward presentation skills and communication. Overall, I'd say my favorite part has just been learning about what everyone's doing here."

MITEI academic coordinator Rachel Shulman, who developed the slam with Tracie Gibson, director of student success and diversity at UMass Amherst's College of Natural Sciences, with organizational support from Jesse Hinricher SB '19, says the slam was developed to help students learn to communicate with a wide variety of audiences.

Dimee Livingston-Padilla of UMass earned first place in the slam thanks to an energetic and demonstrative presentation on arthritis and potential remedies currently being researched. She used Jell-O to demonstrate what arthritis does to the human body.

"The slam was a fun way to teach and practice those skills," she says. "Collaborating with students from UMass Amherst allowed [MIT students] to widen their perspective."

The slam laid the groundwork for future collaboration. Gibson and Shulman hope to include additional universities in next year's event.

Charlie Wolfson, MITEI

Awele Uwagwu, a junior at MIT studying chemical engineering, spoke about energy sources in Nigeria. Photos: Charlie Wolfson, MITEI

Winners of the Science Slam (from left): UMass' Dimee Livingston-Padilla (first), MIT's Jane Bonesteel (tied for third), and UMass' Erik Bratland (second) and Vincent Clark (tied for third).

New intercontinental energy workshop sparks educational connections beyond the classroom

Six MIT students were the first to take part in a field trip led by MIT Energy Initiative (MITEI) Director of Education Antje Danielson this summer. For nine days, the group toured energy-related facilities in Denmark and Germany along with a delegation of students from Germany's University of Kiel before hosting the Kiel students for a week of reciprocal activities in New England.

The Siemens Gamesa offshore wind turbine factory in Denmark was among the first items on the MIT group's itinerary and a favorite stop for several. Photos: Antje Danielson, MITEI

Learning in the field

The journey began in Denmark and finished in Germany, spanning several cities and historical sites and, most importantly, a number of renewable energy facilities. These included the Maersk Drilling Innovation Lab in Copenhagen, Denmark; the self-sufficient Danish island of Samsø; the Siemens Gamesa wind turbine factory in Brande, Denmark; the University of Kiel in Kiel, Germany; and an underground radioactive waste storage facility in Morsleben, Germany.

All of these activities had educational benefits, but the participants agree that the most fascinating was the trip to Samsø, an island with about 3,700 residents situated in the Kattegat Sea.

The group spent two nights in cabins on the island, the first Danish island to become self-sufficient in sustainable energy, 10 years after beginning its efforts in 1997. All of the island's electricity comes from an offshore wind farm, and 70% of its heat comes from solar and biofuel-powered central heating plants.

"I was really inspired by their hospitable, humble, community-oriented culture and lifestyle, as well as their political system, which allowed Denmark to adopt green legislation and to implement these changes so smoothly," says Jessica Nicole Horowitz, a sophomore mechanical engineering major who enrolled in MIT's Energy Studies Minor in spring 2019.

Thinking of home

Another sophomore MIT student who went on the trip, biology major Eduardo Canto, was interested in renewables because of their potential to help his home of Puerto Rico, which depends on a power grid largely reliant on traditional, nonrenewable energy sources that was damaged badly by Hurricane Maria in 2017 and other recent storms.

"There's a lot of sun and wind down there, but most of the energy is from imported diesel and oils," Canto says. "Electricity is very expensive back home, but there's plenty of sunlight, so it should be a viable option. I wanted to learn about it more and see if there's a chance that Puerto Rico can eventually become renewable in terms of electricity production."

His interest was piqued by the visit to a Siemens factory that makes offshore wind turbines.

"In the next year, they're going to be producing wind turbines with rated capacities of 10 megawatts each, and with about 300 of those we could power a lot of the electricity needs on the island," he says. "With some of the hurricane funds, maybe we could pay for a more resilient energy grid structure."

A perfect match

The German delegation to MIT consisted of five geoscience graduate students led by Professor Astrid Holzheid, all from the University of Kiel. Holzheid was a postdoc at MIT when she met Danielson 22 years ago, and their long professional relationship was a big reason the program came together between the two universities.

Holzheid says she was aware of the German government's interest in funding programs that would help students meet students from other countries as well as programs that promote renewable energy.

One of the University of Kiel students, Malte Juerchott, says, "I think the coolest part is to meet other people and get new connections. It's nice to see how the world runs in other areas and to see new kinds of laboratories and find out how people think. What's very interesting to me is the technical aspect. This morning we went to some labs, for example, and we don't have these kinds of labs in Kiel. You can see how the lab works and gain new experience."

The Kiel students had a number of sessions on a wide range of energy topics while they were in the United States, mostly on MIT's campus. They toured MIT labs focused on nuclear materials, solar electric vehicles, fusion, electrochemical energy storage, and wind technology. And they visited the lab of Professor Timothy Grove of the Department of Earth, Atmospheric and Planetary Sciences, with whom Holzheid worked when she was a postdoc at MIT.

The students also made a trip north to Maine, where they toured the Bates-Mores Mountain Conservation Area with Bates College geologist Marita Bryant, and spoke with marine scientist Andrew Pershing at the Gulf of Maine Research Center to learn about the impacts of climate change on the region.

The experiences provided useful technical knowledge to the visiting students, but Holzheid's main goals for her students consisted of broader, more practical skills. Holzheid believes that the students gained important interdisciplinary research skills as a result of the trips.

"Looking at materials science, if you are a geoscientist, you could think 'this is kind of over my head, and I don't understand it at all,'" Holzheid says. But she added that joint programs for students of material sciences and geosciences will help students to overcome the initial barrier and to venture into something new. "Some materials scientists know a lot about their specific materials but don't know where the raw material originated and if it could get replaced by highly

The group ventured underground during their time in Germany to explore a salt mine used to contain radioactive waste.

abundant geomaterials in a processed form. Geoscientists should have knowledge about the sources," she says.

"Proof of concept"

Danielson, who worked with the Energy Education Task Force to launch this program, says the trip is meant to give students experience in the field while attracting more students to the Energy Studies Minor earlier in their college careers.

"Currently, most of the students enroll in the Energy Studies Minor either in their junior or senior year," Danielson says. "But by then it's a struggle to get all the credits, and they're losing a lot of the resources that MITEI has to offer."

The program had an excellent conversion rate in its first year. Of the six students, three decided to enroll in the minor after going on the trip; two had decided to enroll just before the trip during the spring 2019 semester; and one who graduated shortly before going on the trip is continuing in energy research as a graduate student. Danielson calls this "proof of concept" for the field trip—evidence that the program enriches students' energy education and entices them to further it through the minor.

Sarah Lohmar, a sophomore urban studies and planning and computer science student at MIT, says the visit to Samsø played a role in persuading her to enroll in the Energy Studies Minor directly after the trip.

"I was convinced after visiting the Energy Academy on Samsø and learning about the complexities of convincing residents to support going carbon neutral," Lohmar says. "I realized the Energy Studies Minor would provide a well-rounded view of energy considerations to support my more technical materials science classes."

Breaking the campus mold

On top of learning about renewable energy sources outside the United States and meeting German peers, the MIT students saw the benefits of taking their education outside the classroom and laboratory settings.

"I would say that it's important because you see the actual result of engineers' work, the implementation in the real world," Canto says. "You see that you're actually making progress. If you spend all of your years at MIT inside of a lab, and you don't see what you're doing outside of the lab, you get a feeling like 'why did I do that?'"

Michal Gala, a senior chemical engineering student, adds that the trip gave him an appreciation for the "scale of the companies, the resources, and the technologies" that are involved in the renewable energy field.

Sarah Coleman, who graduated in May with a bachelor's degree in chemical engineering and wants to focus on biofuels in her PhD program at the University of Texas, says the trip shows students that they can make change in the energy field: "It's great to introduce students to the state of renewable energy in Europe, which you're able to aggressively compare with the state of energy in America, and additionally to help you understand what you can do and how you can help make a difference."

Charlie Wolfson, MITEI

Energy Studies Minor updates: Changes offer students broader engagement with energy field

Since 2009, the Energy Studies Minor (ESM) has been a key component of energy education for undergraduate students at MIT. The minor helps students to develop the skills required of future leaders in clean energy and gain a comprehensive understanding of diverse energy topics—including renewable energy, architecture and urban planning, and energy policy. Students also benefit from hands-on learning opportunities to work with world-renowned researchers, policy analysts, and thought leaders.

For the past two years, the Energy Minor Oversight Committee has worked to update the ESM curriculum. During that time, the committee was chaired by David Hsu, an associate professor of urban and environmental planning in the Department of Urban Studies and Planning (fall 2017–fall 2018), and Ruben Juanes, a professor in the Department of Civil and Environmental Engineering and the director of the Henry L. Pierce Laboratory for Infrastructure Science and Engineering (spring 2019–present). The committee unveiled the new curriculum in August 2019.

"We are pleased to launch the revamped curriculum this fall. This update marks the first time the curriculum has been updated in its 10-year existence," says Juanes. "The new curriculum is the result of a multiyear effort from energy leaders across MIT. Our goal is to help students better integrate the energy studies course requirements into their overarching academic plans."

The ESM curriculum is composed of two sections: the core curriculum and electives. The updates mainly affect the core curriculum, which previously consisted of three areas: Energy Science Foundations, Social Science Foundations of Energy, and Energy Technology/Engineering in Context. The new curriculum defines Economics as a fourth, separate core area because the subject underpins the energy landscape. The redesigned curriculum also offers a wider variety of classes that are taught every semester, resulting in a more flexible and customizable minor.

A generous grant from the S.D. Bechtel, Jr. Foundation allowed for two particularly exciting developments: the redesign of 12.021 Earth Science, Energy, and the Environment, taught by Bradford Hager, the Cecil and Ida Green Professor of Earth Sciences in the Department of Earth, Atmospheric and Planetary Sciences, and the creation of an entirely new class—15.2191J/17.399J Global Energy: Politics, Markets, and Policy. Taught by Valerie Karplus, an assistant professor of global economics and management at the MIT Sloan School of Management, the new Global Energy class prepares students to use a wide array of skills to interpret developments in energy politics, markets, and policy in a range of national and global contexts.

Designed by MITEI, the energy minor complements the deep expertise obtained in any MIT major with broad, interdisciplinary training in science, technology, and the social sciences, including policy issues related to energy and climate change. With these updates, the Energy Studies Minor will continue to facilitate students' ground-breaking discoveries in clean energy and to prepare them for exciting careers in industry, government, and academia.

Turner Jackson, MITEI

Energy Studies Minor graduates, June 2019

Janak Agrawal
Electrical Engineering and Computer Science

Patrick Callahan
Mechanical Engineering

Rebecca Eisenach
Materials Science and Engineering

Seiji Engelkemier
Mechanical Engineering

Ciera Gordon
Architecture, Mechanical Engineering

Christopher Goul
Mechanical Engineering

Wenyu Ma
Mechanical Engineering

Christopher Mutty
Mechanical Engineering

Tim Roberts
Civil and Environmental Engineering

Keldin Sergheyev
Nuclear Science and Engineering

Allison Shepard
Chemical Engineering

Thulith Suwanaka Edirisinghe
Mechanical Engineering

Geneva Werner
Chemical Engineering

Ka-Yen Yau
Nuclear Science and Engineering

Energy Fellows, 2019–2020

The Society of Energy Fellows at MIT welcomed 37 new members in fall 2019. Their fellowships were made possible through the generous support of five MITEI Member companies.

Photo: Mira Whiting Photography

Chevron

Funmilola Asa
System Design and Management

Kayhan Babakan
System Design and Management

Brandon Baylor
System Design and Management

Katherine Brown
System Design and Management

Brian Heilbrun
System Design and Management

Brendan Horton
System Design and Management

Allison Johnson
System Design and Management

Mollie LeBlanc
System Design and Management

Benjamin Partington
System Design and Management

Michael Pickering
System Design and Management

Daniel Rahill
System Design and Management

James Ruckdaschel
System Design and Management

Vrindaa Somjit
Nuclear Science and Engineering

Michael Trevathan
System Design and Management

Caitlin Williams
System Design and Management

Oliver Wilson
System Design and Management

Fei Yang
System Design and Management

Commonwealth Fusion Systems

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

Eni S.p.A.

Benjamin Dacus
Nuclear Science and Engineering

Eric Fadel
Materials Science and Engineering

Sara Ferry, PhD
Nuclear Science and Engineering
Assignment in Plasma Science and Fusion Center

Francesca Freyria, PhD
Chemistry

Thaneer Narayanan
Materials Science and Engineering

Alex O'Brien
Nuclear Science and Engineering

Bora Ozaltun
Institute for Data, Systems, and Society
Assignment in Center for Energy and Environmental Policy Research

Sean Robertson
Nuclear Science and Engineering

ExxonMobil

Francesco Benedetti, PhD
Chemical Engineering

Suzane Cavalcanti
Chemical Engineering

Sarah Khanniche, PhD
Chemical Engineering

Aliza Khurram
Mechanical Engineering

Laureen Meroueh
Mechanical Engineering

Justin Montgomery
Civil and Environmental Engineering

Alice Jia Li Song
Architecture

Max Vilgalys
Institute for Data, Systems, and Society

Kevin Ye
Materials Science and Engineering

Shell

Jack Lake
Mechanical Engineering

Ellen Lalk
Earth, Atmospheric and Planetary Sciences

3 Questions: Energy Fellows reflect on their time at MITEI

The Society of Energy Fellows at MIT gives graduate and postdoctoral energy researchers the unique opportunity to conduct sponsored research in their areas of expertise, with support from MIT Energy Initiative (MITEI) member companies. The society has a network of 468 fellows and spans 20 MIT departments and all five MIT schools. Two Energy Fellows, Laureen Meroueh and Erica Salazar, discuss their research and the impact of this program on their time at MIT.

Laureen Meroueh

Laureen Meroueh graduated from the University of Florida with a dual degree in mechanical and civil engineering. She is currently pursuing her PhD in mechanical engineering and is an ExxonMobil-MIT Energy Fellow focusing on the conversion of scrap aluminum into hydrogen. Meroueh is also a mentor at MIT's Sandbox Innovation Fund, which provides support and mentorship for student entrepreneurs, and a member of GradSAGE, the graduate student advisory group for the School of Engineering.

Q Can you describe how you see hydrogen being used to support the clean energy transition and how your research supports development of hydrogen as a fuel?

A Hydrogen is an attractive sustainable fuel because it can be used in a range of different energy sectors, including transportation, power, and heat generation, to replace natural gas or other harmful hydrocarbon fuels. Additionally, in contrast to many other renewable energy technologies, the infrastructure already exists for converting hydrogen into power.

One of the challenges posed by widespread use of hydrogen as a fuel is that it is typically produced in one location and then transported to another, which presents a number of logistical issues. My work could provide a pathway to solving that problem. I am studying the materials science behind using scrap aluminum as an energy-dense carrier for hydrogen generation. Theoretically, aluminum should react with water to produce hydrogen. However, aluminum naturally forms a protective oxide layer on its surface that prohibits it from reacting with water. Many years of research have gone into solving this problem, which has thus far limited aluminum from being a safe and economical source for hydrogen generation.

The good news is that we recently discovered a practical method of activating aluminum, meaning that we've bypassed the protective oxide layer. The activation method consists of applying a liquid metal to aluminum's surface. Once a piece of aluminum is activated, you can drop it in water and generate hydrogen. With our new approach, all that is needed is a pile of aluminum and a small reactor next to an industrial facility so that the hydrogen can be created on demand, right on site. I believe that on-demand hydrogen generated from aluminum will be a critical enabler of the clean energy transition because it solves the cost, storage, and transportation obstacles.

Q How did you become interested in energy studies and what advice would you give to new students interested in the topic?

A I've always been amazed by the vast amounts of renewable energy all around us. We have an entire star shining down on us that could provide enough energy to power our planet for billions of years, if we could figure out how to harness and optimize its use. And there are so many other ways that we can power and advance our world without doing so at the expense of the Earth. That's what inspired me: trying to capture the natural resources around us without harming our environment.

For new energy students, I would say, first, find the subject matter that most excites you, whether that is materials science, chemistry, physics, or mechanical engineering. Then, based on that subject, you will discover many, many different technologies and specific energy fields to which you can contribute. I highly encourage everyone to pursue energy studies because we need all of the minds we can get to help us quickly transition to a world powered solely by clean energy.

Q How has being an Energy Fellow impacted your time at MIT?

A Not only is it great to know that there are industry partners eager to sponsor the research—which reassures you that you're working on something with potential for real impact—but also, the MITEI community is just wonderful. The Energy Fellowship provides access to a strong network of people who are passionate about working together toward a low-carbon future.

Erica Salazar

After receiving her bachelor's and master's degrees in mechanical engineering from Stanford University, Erica Salazar worked at General Atomics on ITER, a multinational research project aimed at creating a large-scale working nuclear fusion reactor. Now she is pursuing her PhD in nuclear science and engineering at MIT, where she is a Commonwealth Fusion Systems–MIT Energy Fellow. Salazar is conducting research on superconducting magnets for the SPARC fusion project (psfc.mit.edu/sparc).*

Q What inspired you to work in the field of clean energy—especially on such a cutting-edge technology as fusion?

A My favorite classes in undergrad were thermodynamics and energy systems. My interest and excitement really grew whenever these classes involved combustion engines. I enjoyed learning about the extreme conditions of combustion processes and how combustion applications seemed endless: cars, airplanes, rockets, energy production, and so on. Additionally, I worked with jet engines and other advanced combustion cycles during two summer internships and enjoyed both my technical work and the community. However, I realized that the impact of my work on overall system efficiency remained relatively small: Any improvement would probably be less than 1%. This sparked a search to find an industry where I could make a greater impact.

My search ended when I learned about fusion energy and the long global effort to make fusion energy—a clean, nearly limitless energy source—a possibility. This field had a huge impact factor! Before I started my PhD working on the SPARC fusion project at MIT, I worked on the ITER experimental fusion project as a mechanical engineer at General Atomics. The majority of my job dealt with manufacturing large, low-temperature superconducting magnets, which help contain and drive the plasma current in the ITER fusion device. After working in industry for five years on low-temperature superconductors, I learned about the SPARC project at MIT, which strives to be the first fusion device to produce a fusion plasma with net positive energy generation using advanced high-temperature superconducting magnet technology. I was immediately hooked and quickly applied to the nuclear science and engineering doctoral program at MIT, where I now continue to make an impact on fusion and clean energy production.

Q What advice would you give to new students interested in energy studies?

A Although learning and studying different energy concepts, reactions, and processes through textbooks and classes is critical to understanding the scientific fundamentals of energy systems, it is equally important to gain hands-on experience and apply that knowledge in the real world. Gaining research, internship, and volunteering experience on energy projects is rewarding. Finding a passion within an energy studies career occurs when you see firsthand how your favorite energy concepts can directly affect a community you care about. For example, my specific work focuses on designing superconducting electromagnets. Although I find the technical work interesting, my drive and motivation come from the fact that my superconducting technology will be applied in the energy industry to produce clean, limitless fusion energy. On the other hand, others may find their passion in superconductors by working in the medical industry to design superconducting MRIs to save lives, or in the computer industry to design superconducting quantum computers. The fact that there is a large, impactful goal for my individual work is very rewarding.

Q How has being an Energy Fellow influenced your time at MIT?

A The MITEI Energy Fellows program is wonderful. The fellows program is a community where we can easily connect with other students, faculty, scientists, and industry professionals with similar passions in energy research. I find it inspiring to talk with current and former Energy Fellows and learn how they have advanced their research at MIT by launching a startup or by continuing as a postdoc so that they can teach younger students about their work.

*ITER means "The Way" in Latin. For more information about the ITER project, visit www.iter.org.

Turner Jackson, MITEI
Photos: Eric Haynes Photography

Chemistry bonds "quirky" researchers in hard-working Surendranath Lab

When Sneaky the Lizard received his PhD in chemistry from MIT, an enthusiastic team of researchers in the lab of Yogesh "Yogi" Surendranath was there to celebrate. Although Sneaky is just a fictional, Photoshopped character, he's an important part of the lab culture, and his "graduation" was akin to a family milestone.

"Sneaky the Lizard graduated in 2018, despite never showing up to work," says Surendranath, the Paul M. Cook Career Development Associate Professor of Chemistry, while proudly showing off a lab photo with Sneaky up-front and center. "My group is so weird, but I love them so much."

The Surendranath Lab is a tight-knit group that enjoys a lot of inside jokes—about mangoes and coconuts, as well as imaginary lizards. But it's also about ground-breaking work in electrochemistry that is opening up new paths to a low-carbon future.

Those who work in the lab say the two are related.

"At the end of the day, we work on really, really hard problems, and in order to work in that environment and stay sane, you need a culture that's supportive and makes it fun and exciting and interesting," says Surendranath, who this summer received a Presidential Early Career Award for Scientists and Engineers, the highest honor the U.S. government gives to outstanding scientists and engineers beginning independent careers.

"We're one community wherever we are, and we all take pleasure in solving these problems at the electrochemical interfaces," says postdoc Marcel Schreier. "This allows us to be a little bit ahead sometimes. We ask more questions and try and try and try to answer them."

Professor Yogesh Surendranath (far right) and members of his group display some of their favorite things. Photos: Kelley Travers, MITEI

All of the work in the Surendranath Lab centers on using electricity to rearrange chemical bonds—fundamental scientific research with a host of possible applications. A key focus is finding ways to make carbon dioxide (CO_2), a major greenhouse gas, useful—research central to addressing climate change. Surendranath, who serves as the associate director of the Carbon Capture, Utilization, and Storage Center, one of the Low-Carbon Energy Centers run by the MIT Energy Initiative (MITEI), says, "Our whole group works on the grand challenges MITEI undertakes on the low-carbon future of energy."

A wealth of applications

Already, the Surendranath group has made major advances in the design of catalysts for converting CO_2 into carbon monoxide—work that holds promise for one day using renewable energy to turn CO_2 emissions into high-quality fuels. The lab has also developed a new graphite-based catalyst that could potentially replace expensive and rare metals in fuel cells.

"Our work is so fundamental, there isn't a specific application we're targeting. Batteries, fuel cells, any electrochemical transduction technology is going to have an interfacial question that we're hoping to address," says postdoc Michael Pegis.

Interestingly, the 18 members of the lab tackle many different kinds of questions within the broad spectrum of electrochemical research. While Pegis works on how electric fields influence the rate of bond-breaking and bond-forming reactions in oxygen reduction reactions—work that could improve fuel cells, for example—Jonathan "Jo" Melville, a PhD candidate and Tata Fellow, is researching nitrogen fixation for fertilizers in an effort to find a less energy-intensive way to produce food.

"Nitrogen is key for feeding billions around the world," Melville says, noting that without nitrogen-rich fertilizers, there would not be enough arable land on earth to feed the population. Since the current system of production uses fossil fuels, generating roughly 2% of anthropogenic CO_2 emissions, Melville is hoping to develop a sustainable alternative process. "I went into chemistry because I really care about solving the energy crisis," he says.

Schreier's work takes on the challenge of reaching a low-carbon future from another angle. He focuses on the catalytic capabilities of copper in the hope of finding new ways to store energy chemically—work broadly applicable to the challenge of improving the storage of energy generated by such intermittent sources as solar and wind.

PhD candidate Soyoung Kim, meanwhile, works to make useful chemicals from natural gas using metal-ion catalysts driven by electricity—a method she says could make it possible to sustain the reaction with energy from renewable sources.

For lab members—including specialists in inorganic chemistry, physical chemistry, chemical engineering, and electrochemistry—the wide variety of work taking place in the lab expands the opportunities for useful collaboration. "There's so much knowledge in so many fields, I've been able to learn about new things—like computational chemistry from a postdoc who sits behind me," Pegis says.

Surendranath deliberately fosters this synergy through regular team meetings as well as off-site activities such as hiking trips and retreats. "I think of science as a gift economy," he says—with each researcher giving the gift of time and skills to other lab members in full expectation that similar gifts will be returned.

"We help each other all the time informally," Schreier says. "If someone has a problem, they will start drawing on the white board, and everyone will chime in and offer solutions."

This esprit de corps carries through to everyday lab chores. There is no lab manager in the Surendranath Lab;

Graduate students Onyu Jung (left) and An Chu set up a carbon dioxide conversion experiment.

responsibilities are shared by the team, with individuals taking on such jobs as overseeing safety procedures, caring for particular instruments, ordering solvents, and organizing cleanups. Recently, the group worked in shifts to bar-code 35,000 chemicals. "In some cases, a lab manager can be useful, but it can be good to get together to make sure the lab is a cleaner and safer place," Pegis says.

"We have lab tasks," Schreier explains. "This works quite smoothly."

Lab members also make their own hours and work out disputes among themselves. "I give my students enormous freedom," says Surendranath, who was recently awarded the Nobel Laureate Signature Award for Graduate Education in Chemistry from the American Chemical Society together with his graduate student Anna Wuttig PhD '18. (Wuttig is now a postdoc at the University of California, Berkeley.) "All I care about is that they care about the science and do great work," says Surendranath.

Mangoes, kites, and coconuts

With so much independent thinking, it's perhaps not surprising that the word "quirky" comes up a lot when members are asked about the lab.

"Yogi is very supportive and approachable as a boss, while super energetic and engaging when it comes to discussing science. That has attracted many hard-working and sometimes quirky people to the lab," Kim says.

"It's definitely a very quirky group of people," Pegis agrees.

Indeed, the description applies even to Surendranath himself, who is crazy for mangoes, fascinated by tumbleweeds, and passionate about kite-flying. Perhaps that's why he built a team that supports each member—quirks and all.

Schreier tells a story to illustrate. The lab was on a hike together in the White Mountains and running behind schedule because Surendranath needed to bring a coconut with him—a lab tradition with somewhat obscure origins—and he had had trouble finding one. So, once the team reached the peak, everyone was eager to head back—except Schreier. He had spotted a radio tower (a passion of his) and could not resist dashing off for a closer look, delaying everyone.

When he got back, "the whole group, with Yogi in the center, was waiting for me very patiently. It seemed to them the most normal thing that I would need to check out this transmitting tower," he says. The experience really warmed Schreier's heart and is one reason the team is so special to him. "It's the way the group works. Everyone's interests are taken seriously."

Melville agrees, saying this depth of support has made it easier for him to cope with the pressures of grad school and noting that it all comes from the top. "Yogi sets the gold standard for proactive and ethical mentorship," he says. "We love him."

The feeling is mutual. "I love my people," Surendranath says. "It is a true joy to interact with enthusiastic, like-minded, passionate people every day and engage with them on really stimulating problems. …I think the culture day-to-day is more rewarding than the science, because you have an impact on people's lives—how they mature."

Kathryn O'Neill, MITEI correspondent

Q&A: James Bushnell on electricity markets and deep decarbonization

James Bushnell, a professor of economics at the University of California, Davis, discusses electricity markets and deep decarbonization at a MITEI seminar on September 11, 2019.
Photos: Charlie Wolfson, MITEI

James Bushnell, a professor of economics at the University of California, Davis, and a research associate at the National Bureau of Economic Research, recently spoke at an MIT Energy Initiative (MITEI) seminar titled "More or less than zero: Can electricity markets survive deep decarbonization?" His talk drew on research at the wholesale and retail level to contrast differing regional approaches to the economic challenges of integrating renewable electricity into electric power systems.

Q How does the approach to investing in electricity markets by states, utilities, and consumers need to change as we move to more renewable energy sources?

A The approach doesn't have to fundamentally change due to renewable energy. More precisely, while U.S. markets are certainly not perfect, the rise of renewable energy doesn't fundamentally change the things we should be paying close attention to. Two examples of what I mean are the pricing of scarcity and the role of forward contracts. I will talk more about contracts in later responses and deal with scarcity pricing here. Short-term electricity markets have continuously evolved to better reflect the costs of true scarcity in their prices. In U.S. markets, "scarcity" doesn't necessarily mean blackouts but rather tighter conditions for reserves or transmission capacity. Prices are supposed to rise to very high levels when system conditions get tight—to price levels that are well above the operating costs of all generation technologies.

There is still work to do on this front, but things are much more sophisticated than they were 15 years ago. The role of scarcity pricing will be more prominent in the future because it will often be playing a role in setting prices during periods of low renewable output. Prices will be very low (or zero) when there is abundant renewable supply and likely very high during periods of low renewable supply. Appropriate scarcity prices are important in the short run in order to properly deploy resources like demand-side response and storage, and in the long run as a source of revenue that can help pay for the recovery of fixed costs.

Q Solar photovoltaic (PV) power has emerged as the primary source of renewable energy in California. What are the potential impacts of this trend?

A The solar boom wasn't a top-down decision but rather the result of a collection of incentives that, taken together, meant that it made sense for utilities and individual consumers to make investments in solar, even if those investments were not always the most efficient renewable energy options for the state as a whole.

First, one has to make the important distinction between utility-scale solar PV and residential rooftop solar. Both have been growing rapidly in California over the last decade. At the residential level, the boom has been driven in no small part by distortions in electric rates that charge prices to residential customers well in excess of the cost of energy to the utility. The "savings" experienced by residential solar customers are largely due to the shifting of fixed grid costs to other non-solar homes.

At the grid level, California's solar capacity has grown from less than 1 gigawatt (GW) in 2012 to more than 10 GW today.

One obvious consequence of this is that the California system experiences a huge daily swing in renewable energy production when the sun rises and sets. Wholesale market prices reflect this. Wholesale prices are now at their lowest at 11 a.m. and highest in the early evening. One result of this, which I document in my work with Kevin Novan at UC Davis, is that the wholesale market is rewarding resources that can flexibly provide energy during the periods before sunup and after sundown, while it is punishing resources that operate inflexibly all day long.

Another consequence is that new solar facilities are considerably less valuable now. This is because their output is concentrated in periods in which the system already has a relative glut of power. Working on this project brought home to me an obvious but underappreciated point about renewable resource diversity: The wind can blow at different times in different places, but the sun only shines during the day.

Q What are the key factors at play in preparing U.S. electricity markets for a low-carbon future?

A The key drivers of decarbonization have been aggressive mandates for renewable energy by some states combined with the rapid decline in costs of grid-scale renewables. Low natural gas prices have contributed to decarbonization by playing a large role in the decline of coal. However, there is concern that while gas is "cleaner" than coal, it's not clean enough.

One side effect of the renewable energy boom has been its contribution to the financial stress of nuclear generation. Most policies supporting renewables have generally acted in ways that reduce wholesale energy prices. If instead renewables support were provided primarily through carbon pricing, the result would be higher wholesale market prices and a potentially viable role for nuclear.

Jing Li, the William Barton Rogers Career Development Chair of Energy Economics at the MIT Sloan School of Management, introduces Professor James Bushnell at his seminar, "More or less than zero: Can electricity markets survive deep decarbonization?"

Q What are examples of regional differences and/or "fault lines" in energy markets, and what causes those differences?

A Different U.S. states are pursuing different priorities when it comes to their electricity systems. Some are focused on green electricity, others on lowering costs and prices, and others on protecting the economic viability of their local nuclear and coal plants. In pursuit of these goals, many states are subsidizing or otherwise providing benefits to generation types or specific plants. From a federal perspective, the challenge is that these policies are causing spillovers—both economic and environmental—for neighboring states.

Is it fair for a gas plant in Pennsylvania to have to compete with a nuclear plant in New York that is getting special credits from New York state? Is it fair that some states are imposing carbon prices on their power plants when others are not? Both federal and state regulators are searching for ways to balance the policy choices of individual states with laws governing interstate trade and competition. The problem is that sometimes the "solutions" to these spillovers can be worse than the spillovers themselves.

Charlie Wolfson, MITEI

NOTES

The full interview with James Bushnell is available at bit.ly/jbushnellqa.

More information about Professor Bushnell, including his publications and blog, can be found at bushnell.ucdavis.edu. His working paper with Kevin Novan is available at bushnell.ucdavis.edu/working-papers.html.

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 177 seed grant projects across the campus as well as fellowships for more than 460 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.

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

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Members as of September 15, 2019

MITEI member news

Eni renews as a Founding Member
Eni has extended its tenure as a Founding Member of MITEI through 2023. Eni first joined MITEI in 2008. As a new element of the collaboration, Eni will join the Mobility Systems Center, MITEI's newest Low-Carbon Energy Center. Eni will also join the MIT Quest for Intelligence, which seeks to advance research in human and machine intelligence and deliver transformative new technology for society. Advancing magnetic fusion energy technology has been a major focus of the collaboration since 2018. With this membership renewal, Eni will continue to support magnetic fusion energy research through MIT's Laboratory for Innovation in Fusion Technologies. Read more at bit.ly/eni-renews.

ExxonMobil renews as a Founding Member
ExxonMobil has extended its support of MITEI's low-carbon energy research and education mission by renewing its status as a Founding Member for another five years. ExxonMobil first signed on as a member of the Initiative in 2014. With its renewed membership, ExxonMobil will expand its participation in MITEI's Low-Carbon Energy Centers. The company will continue its membership in MITEI's Center for Carbon Capture, Utilization, and Storage; and it will join MITEI's Center for Energy Storage as well as the Mobility Systems Center, MITEI's newest Low-Carbon Energy Center. Read more at bit.ly/exxonmobil-renews.

MIT Energy Initiative
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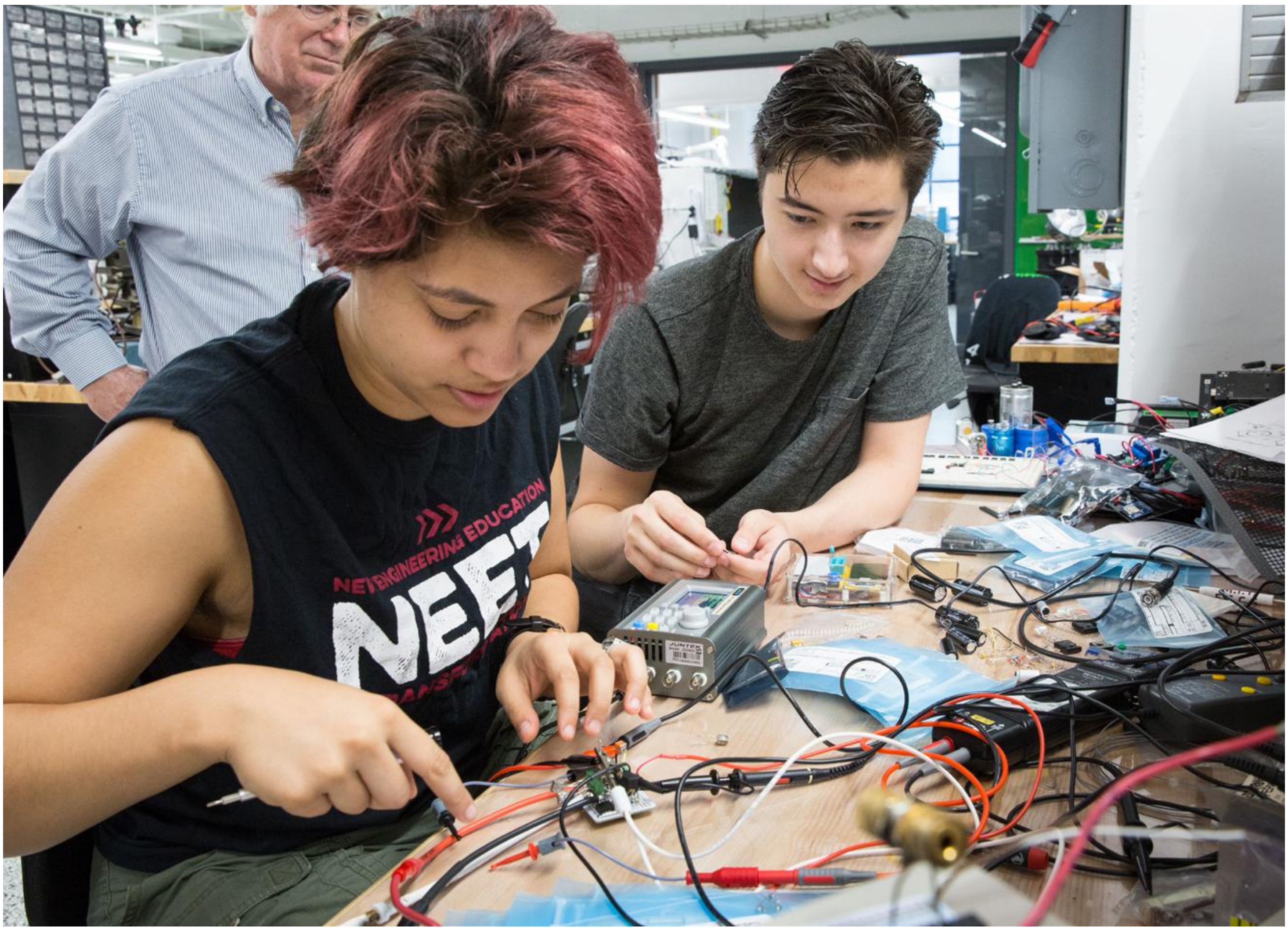

Collaboration adds extra dimension to undergraduate research

During summer 2019, some of the students who took part in the MIT Energy Initiative's Undergraduate Research Opportunities Program (UROP) benefited from working on the same project. Above: Working under Professor James Kirtley (background), PJ Hernandez (left) and Jackson Gray helped each other with lab work and brought their different backgrounds to bear on tackling their common problem: improving a device used to extend the life of batteries. In another case, three UROP students from different majors worked on a project to analyze political spending by utilities. They found that their collaboration sped up the research, helped them come up with new approaches to their assigned topics, and opened their eyes to possible career opportunities they hadn't known about before. Read more on page 35. Photo: Kelley Travers, MITEI