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Energy Futures

MIT
ENERGY
INITIATIVE

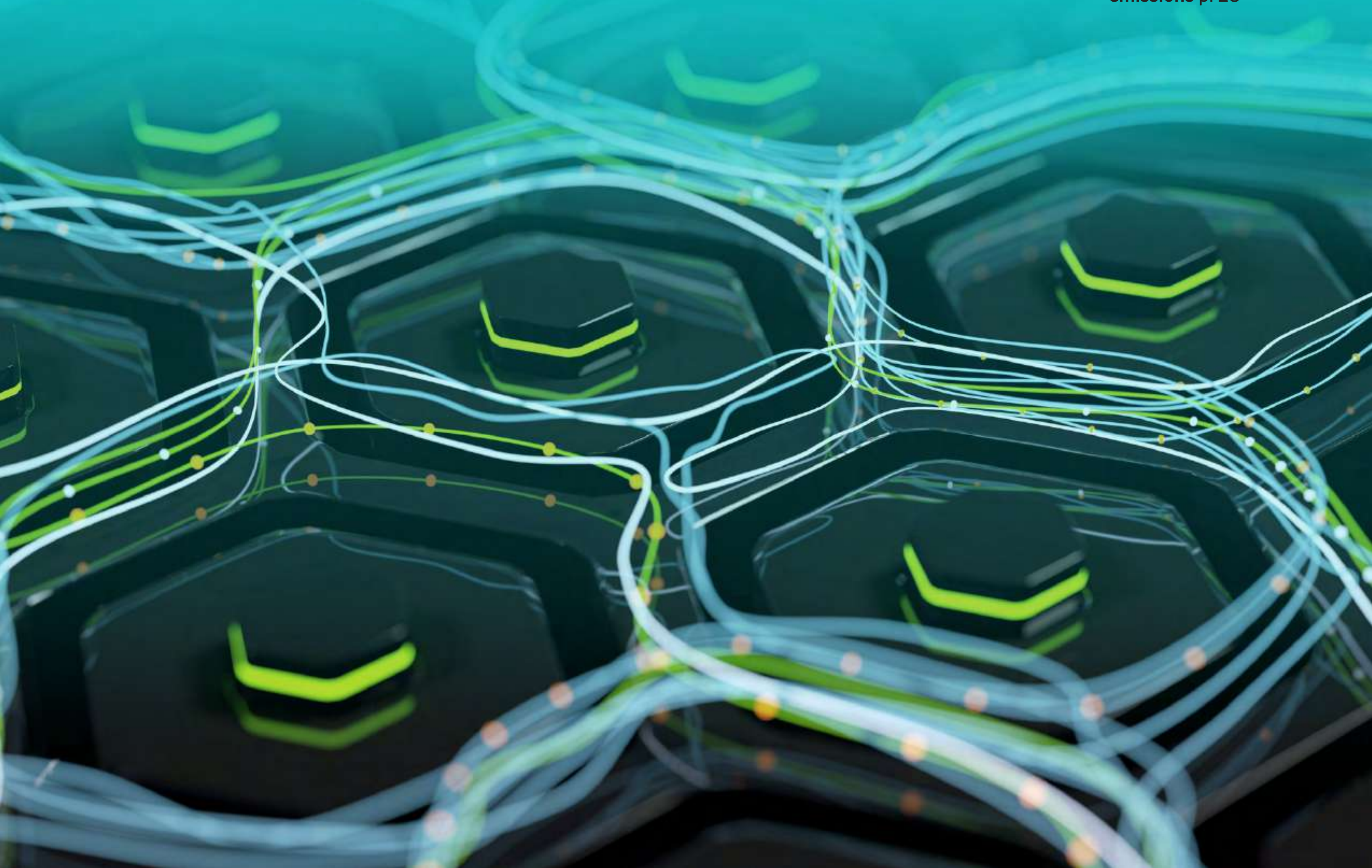
SPRING 2022

The Future of Energy Storage p. 3

Creating porous materials for exhaust gas cleanup and more p. 6

Designing a carbon tax that's both effective and equitable p. 11

New class challenges students to find ways to reduce urban transportation emissions p. 28



The MIT Energy Initiative has a new podcast! Energy Reads features hand-picked audio articles covering the latest in energy from MIT. Find them on our website at energy.mit.edu/audioarticles or subscribe in your favorite podcast app, including Apple Podcasts, Google Podcasts, and Spotify.

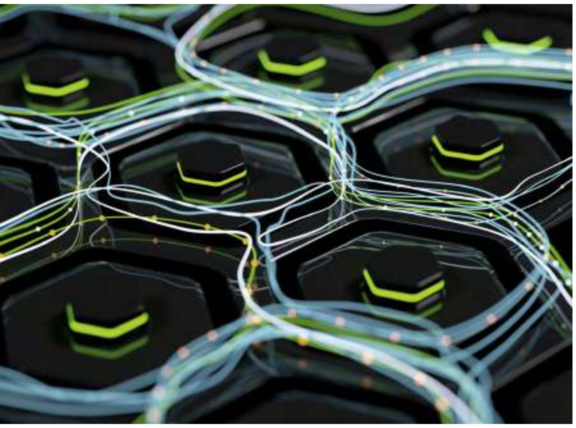
What are we currently reading?

"Investors awake to the risks of climate change," by Calvin Hennick
At the MIT Energy Initiative's Fall Colloquium, finance executive Poppy Allonby laid out the current state of sustainability thinking among the investor class.

"Francesco Benedetti: Building communities, founding a startup with people in mind," by Kathryn M. O'Neill
Inspired by the MIT community and assisted by his collaborators, postdoc Francesco Benedetti launched a startup to provide innovative technology for energy-efficient, high-performance chemical separations—and won the MIT $100K Entrepreneurship Competition.

"Making the case for hydrogen in a zero-carbon economy," by Leda Zimmerman
Analyzing California's power system, MIT Energy Initiative researchers show that hydrogen-generated electricity is a cost-competitive candidate for backing up wind and solar.

…and more



On the cover
In May 2022, the MIT Energy Initiative concluded a wide-ranging, three-year study of the role that existing and new energy storage technologies and related policies can play in fighting climate change and in the global adoption of clean energy grids. The findings, presented in a 400-page report titled *The Future of Energy Storage*, show that energy storage is a key element in making renewable energy sources, such as wind and solar, financially and logistically viable at the scales needed to decarbonize power grids by 2050. Read more on page 3. The cover image is a 3D concept illustration of battery cells by Olemedia/GettyImages.

Energy Futures

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

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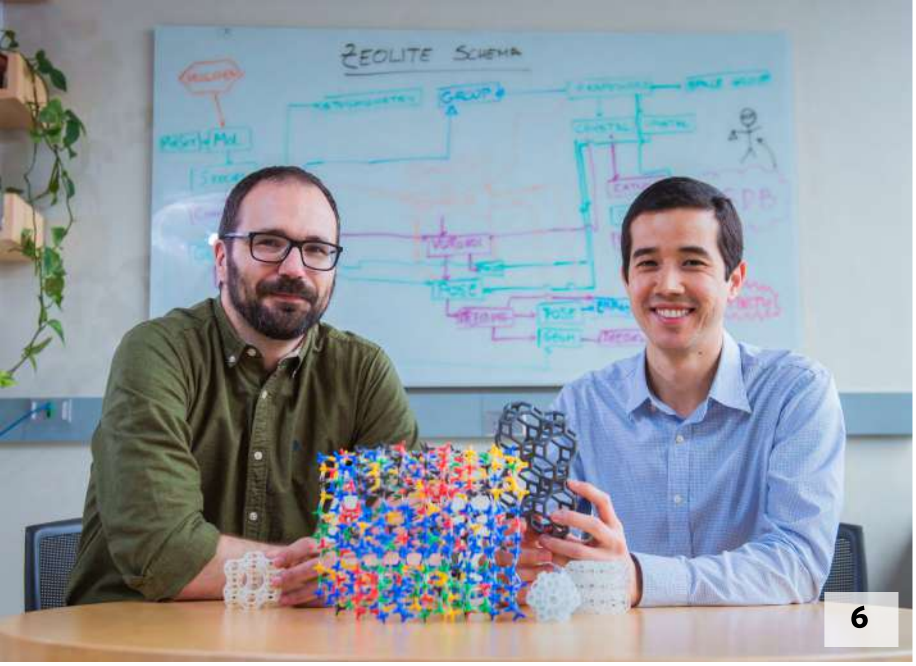


Spring 2022

MIT*ei*
MIT Energy Initiative

MIT
Massachusetts Institute of Technology

A letter from the director

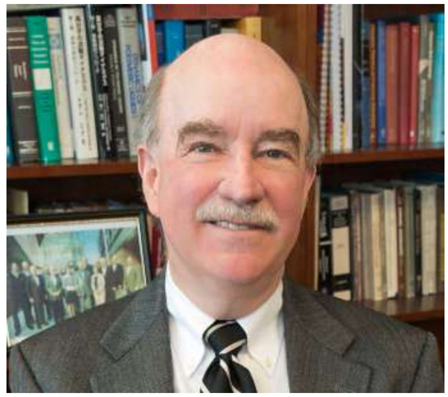
Dear friends,

Welcome to *Energy Futures*!

In this edition we look at our recently published report, *The Future of Energy Storage*, the ninth in MITEI's *"Future of"* series. The report details how energy storage can play a major role in removing greenhouse gases from our energy systems and meeting the world's energy needs. As we bring more wind and solar energy into our electricity systems, energy storage complements these sources of variable renewable energy, allowing us to keep electricity flowing when the sun is behind the clouds and the wind is not blowing. After more than three years of research into energy storage technologies and policies, the study team not only demonstrates that developing and deploying new energy storage technologies is key to achieving a deeply decarbonized electric power system that is both reliable and affordable but also describes the types and amounts of storage technologies needed in different parts of the United States and the world. Read more on page 3.

MIT recently announced five flagship projects in its Climate Grand Challenges competition (page 21). These multiyear efforts—a key element of "Fast Forward: MIT's Climate Action Plan for the Decade"—present a powerful research agenda. The projects seek to solve some of the world's most vexing climate problems by pursuing impactful, science-based solutions with speed and vigor. The flagships represent the most promising ideas from the two-year competition. MIT and others will provide ongoing support to these projects to develop their ideas and bring them quickly to scale.

One flagship project of particular interest to MITEI, highlighted on page 23, is led by Professors Yet-Ming Chiang and Bilge Yildiz. With their team, they plan to



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

create an innovation hub on campus to investigate the decarbonization of four hard-to-abate industries: steel, cement, ammonia, and ethylene.

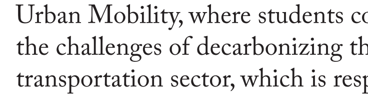
As always, *Energy Futures* includes reports on some of the most dynamic energy-related research on the MIT campus. On page 6, you will read about researchers who have developed a new technique for creating porous materials called zeolites specially designed to capture certain molecules, removing them from an incoming stream or trapping them to catalyze a chemical reaction. The team has posted an interactive website to help others in the field explore and discover promising new zeolites, some of which could greatly help efforts to decarbonize energy and the chemical industry.

On page 11, you will read about work led by Christopher Knittel, MITEI's deputy director for policy, on the economic impacts of a carbon tax to address climate change. The results show that minor adjustments in the distribution of revenues from the tax can make its impacts equitable. You can also read about a new way to speed up a chemical reaction that is key to converting captured carbon dioxide emissions into useful, valuable products (page 16); a new technique for removing dust from the surface of solar panels without using water—especially valuable in arid regions of the world (page 25); and use of an exciting new modeling strategy to explore global development pathways to keep the earth's warming well below two degrees Celsius (page 27).

Other articles in this issue demonstrate MITEI's continuing commitment to education. For example, on page 30, read about a new course called "Leading the Energy Transition," offered during January's Independent Activities Period. The course explores the economic, social, and political challenges of low-carbon mandates. On page 28, find out about another new course, Decarbonizing Urban Mobility, where students confront the challenges of decarbonizing the transportation sector, which is responsible for nearly a quarter of all energy-related carbon dioxide emissions worldwide.

We also like to highlight the work of our current and former students. Joy Dunn '08 is now head of operations at Commonwealth Fusion Systems (CFS), an MIT spinoff and MITEI Startup Member company. Joy's career story is truly inspiring: She is helping CFS pursue carbon-free fusion energy while committing herself and CFS to diversity, equity, and inclusion (page 32). Hers is just one of many stories that give us hope as we race to remove greenhouse gas emissions from our economy.

Hoping you enjoy *Energy Futures*,



Professor Robert C. Armstrong
MITEI Director
June 2022

MIT Energy Initiative report supports energy storage paired with renewable energy to achieve affordable, reliable, decarbonized electricity systems

In deeply decarbonized energy systems utilizing high penetrations of variable renewable energy (VRE), energy storage is needed to keep the lights on and the electricity flowing when the sun isn't shining and the wind isn't blowing—when generation from these VRE resources is low or demand is high. The MIT Energy Initiative's Future of Energy Storage study makes clear the need for energy storage and explores pathways using VRE resources and storage to reach decarbonized electricity systems efficiently by 2050.

The Future of Energy Storage, a new multidisciplinary report from the MIT Energy Initiative (MITEI), urges government investment in sophisticated analytical tools for planning, operation, and regulation of electricity systems in order to deploy and use storage efficiently. Because storage technologies will have the ability to substitute for or complement essentially all other elements of a power system, including generation, transmission, and demand response, these tools will be critical to electricity system designers, operators, and regulators in the future. The study also recommends additional support for complementary staffing and upskilling programs at regulatory agencies at the state and federal levels.

The MITEI report shows that energy storage makes deep decarbonization of reliable electric power systems affordable. "Fossil fuel power plant operators have traditionally responded to demand for electricity—in any given moment—by adjusting the supply of electricity flowing into the grid," says MITEI Director Robert Armstrong, the Chevron Professor of Chemical Engineering and chair of the Future of Energy Storage study. "But VRE resources such as wind and solar depend on daily and seasonal variations as well as weather fluctuations; they aren't always available to be dispatched to follow electricity demand. Our study finds that energy storage can help VRE-dominated electricity systems balance electricity supply and demand while maintaining reliability in a cost-effective manner—that in turn can support the electrification of many end-use activities beyond the electricity sector."

The three-year study is designed to help government, industry, and academia chart a path to developing and deploying

The Future of Energy Storage report is the culmination of a three-year study exploring the long-term outlook and recommendations for energy storage technology and policy. As the report details, energy storage is a key component in making renewable energy sources, such as wind and solar, financially and logistically viable at the scales needed to decarbonize our power grid and combat climate change. Image: petrmalinak/Shutterstock electrical energy storage technologies as a way of encouraging electrification and decarbonization throughout the economy, while avoiding excessive or inequitable burdens.

Focusing on three distinct regions of the United States, the study shows the need for a varied approach to energy storage and electricity system design in different parts of the country. Using modeling tools to look out to 2050, the study team also focuses beyond the United States, to emerging market and developing economy (EMDE) countries, particularly as represented by India. The findings highlight the powerful role storage can play in EMDE nations. These countries are expected to see massive growth in electricity demand over the next 30 years due to rapid overall economic expansion and to increasing adoption of electricity-consuming technologies such as air conditioning. In particular, the study calls attention to the pivotal role battery storage can play in decarbonizing grids in EMDE countries that lack access to low-cost gas and currently rely on coal generation.

The authors find that investment in VRE combined with storage is favored over new coal generation over the medium and long term in India, although existing coal plants may linger unless forced out by policy measures such as carbon pricing.

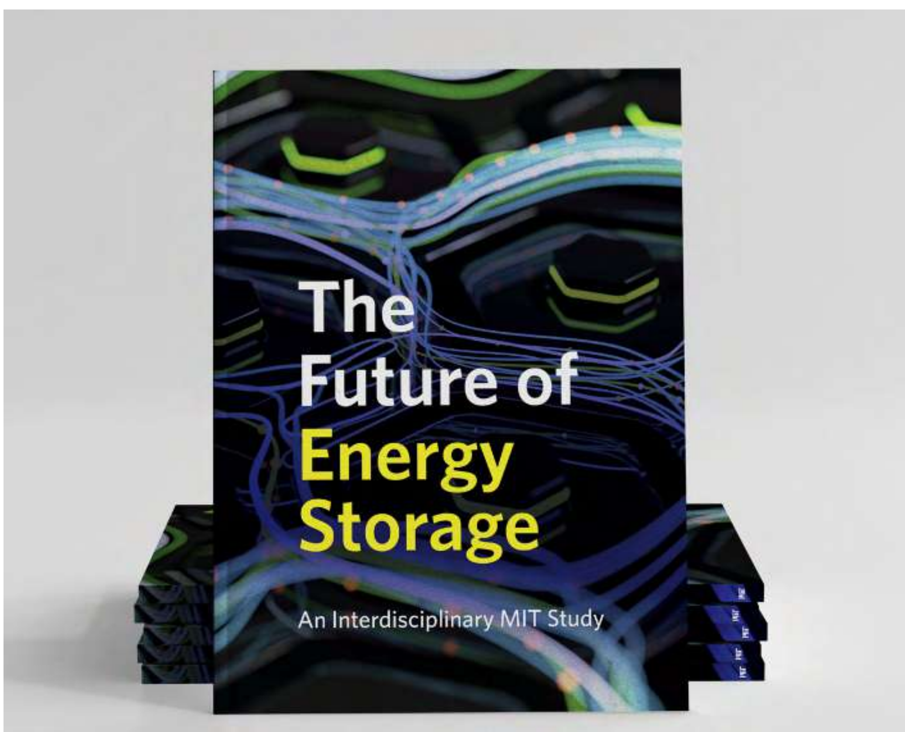
"Developing countries are a crucial part of the global decarbonization challenge," says Robert Stoner, the deputy director for science and technology at MITEI and one of the report authors. "Our study shows how they can take advantage of the declining costs of renewables and storage in the coming decades to become climate leaders without sacrificing economic development and modernization."

The study examines four kinds of storage technologies: electrochemical, thermal, chemical, and mechanical. Some of these technologies, such as lithium-ion batteries, pumped storage hydro, and some thermal storage options, are proven and available for commercial deployment. The report recommends that the government focus R&D efforts on other storage technologies, which will require further development to be available by 2050 or sooner—among them, projects to advance alternative electrochemical storage technologies that rely on earth-abundant materials. The report suggests government incentives and mechanisms that reward success but don't interfere with project management. The report also calls for the federal government to change some of the rules governing technology demonstration projects to enable more projects on storage. Policies that require cost-sharing in exchange for intellectual property rights, the report argues, discourage the dissemination of knowledge. The report advocates for federal requirements for demonstration projects that share information with other U.S. entities.

The report says many existing power plants that are being shut down can be converted to useful energy storage facilities by replacing their fossil fuel boilers with thermal storage and new steam generators. This retrofit can be done using commercially available technologies and may be attractive to plant owners and communities—using assets that would otherwise be abandoned as electricity systems decarbonize.

The study also looks at hydrogen and concludes that its use for storage will likely depend on the extent to which hydrogen is used in the overall economy. That broad use of hydrogen, the report says, will be driven by future costs of hydrogen production, transportation, and storage—and by the pace of innovation in hydrogen end-use applications.

The MITEI study predicts that the distribution of hourly wholesale prices or the hourly marginal value of energy will change in deeply decarbonized power systems—with many more hours of very low prices and more hours of high prices compared to today's wholesale markets. So the report recommends that systems adopt retail pricing and retail load management options that reward all consumers for shifting electricity use away from times when high wholesale prices indicate scarcity, to times when low wholesale prices signal abundance.



The Future of Energy Storage study is the ninth in MITEI's "*Future of*" series, which aims to shed light on a range of complex and important issues involving energy and the environment.
Image: Jenn Schlick, MITEI

The Future of Energy Storage study is the ninth in MITEI's *"Future of"* series, which explores complex and vital issues involving energy and the environment. Previous studies have focused on nuclear power, solar energy, natural gas, geothermal energy, and coal (with capture and sequestration of carbon dioxide emissions), as well as on systems such as the U.S. electric power grid. The Alfred P. Sloan Foundation and the Heising-Simons Foundation provided core funding for MITEI's Future of Energy Storage study. MITEI Members Equinor and Shell provided additional support.

Tom Melville, MITEI

To access the report and more information, please visit energy.mit.edu/futureofenergystorage.

On May 16, 2022, members of the study team presented findings from the Future of Energy Storage study at the American Association for the Advancement of Science in Washington, D.C. Above: MITEI Director Robert C. Armstrong (left) and study leaders and researchers share key insights, addressing how evolving policies and regulations may transform energy storage systems. Photo: Allison Bailey

MITEI Future of Energy Storage study: Key conclusions

Energy storage makes deep decarbonization of reliable electric power systems affordable. Modeling of three U.S. regions shows how substantial investments in energy storage contribute to reducing the cost of deeply decarbonized electric power systems that rely heavily on wind and solar generation. Storage can make regionally tailored, net-zero electricity systems affordable.

Better tools for planning, operation, and regulation are needed to deploy and use storage efficiently. Energy storage can substitute for, or complement, virtually any element of the power grid, including generation, transmission, and demand response. This wide range of uses, coupled with uncertain climate change impacts on electricity supply and demand, requires new tools to design, operate, and regulate reliable future electricity systems. Market designs and regulatory policies need to be reformed to enable equitable and efficient decarbonization.

To enable economical long-duration energy storage (more than about 12 hours), the U.S. Department of Energy should support research, development, and demonstration to advance alternative storage technologies that rely on earth-abundant materials. The availability of emerging long-duration energy storage technologies can reduce the cost of grid decarbonization.

Existing power plants can be repurposed for storage. Inactive or retiring thermal generating plants are prime candidates for storage placement, enabling the reuse of grid interconnections and some power plant components. Reusing sites can lower the costs of energy storage infrastructure and accelerate the transition from fossil fuels. Thermal storage retrofits of fossil energy power plants can provide near-term benefits in providing electricity storage capacity while eliminating carbon dioxide emissions from these generators.

Emerging market and developing economy (EMDE) nations will likely become very large markets for energy storage. Trends in EMDE countries will play a key role in the success or failure of global carbon reduction efforts. Modeling of India shows that the availability of low-cost storage, together with low-cost wind and solar, significantly lowers carbon emissions while providing inexpensive electricity.

Hydrogen-based storage is subject to the element's use in the wider economy. The ease with which hydrogen can be stored and its high energy density make it an important tool, especially in long-duration applications. However, the use of hydrogen in storage will depend on the extent to which its use in other parts of the economy drives its price down.

Lithium-ion batteries possess high energy density, high power density, and high roundtrip efficiency, facilitating their near-ubiquitous use in electric vehicles and their widespread use in short-duration (typically 4 hours or less) electricity system storage applications.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Porous materials designed to trap molecules: Controlling pore openings for maximum capture

IN BRIEF

For decades, researchers worldwide have searched for ways to synthesize porous materials called zeolites with pore openings the right size and shape to filter out incoming molecules or to trap them and catalyze a chemical reaction. A new MIT approach should help. The challenge has been to identify a "templating molecule" to add during synthesis to create the pores needed for a targeted zeolite. Using new performance metrics and rapid atomic-level simulations, an MIT-led team evaluated nearly every molecule-zeolite pair ever proposed. The researchers then used machine learning to examine thousands of journal articles to identify pairs that had been tried experimentally. Their analyses correctly predicted zeolites formed by each molecule. Experiments with a molecule they designed yielded a zeolite that could improve catalytic converters for vehicles and factories. To help other investigators, the researchers created a publicly accessible, searchable, online database that includes their results for each molecule-zeolite combination, the articles identified by their machine learning analysis, and more.

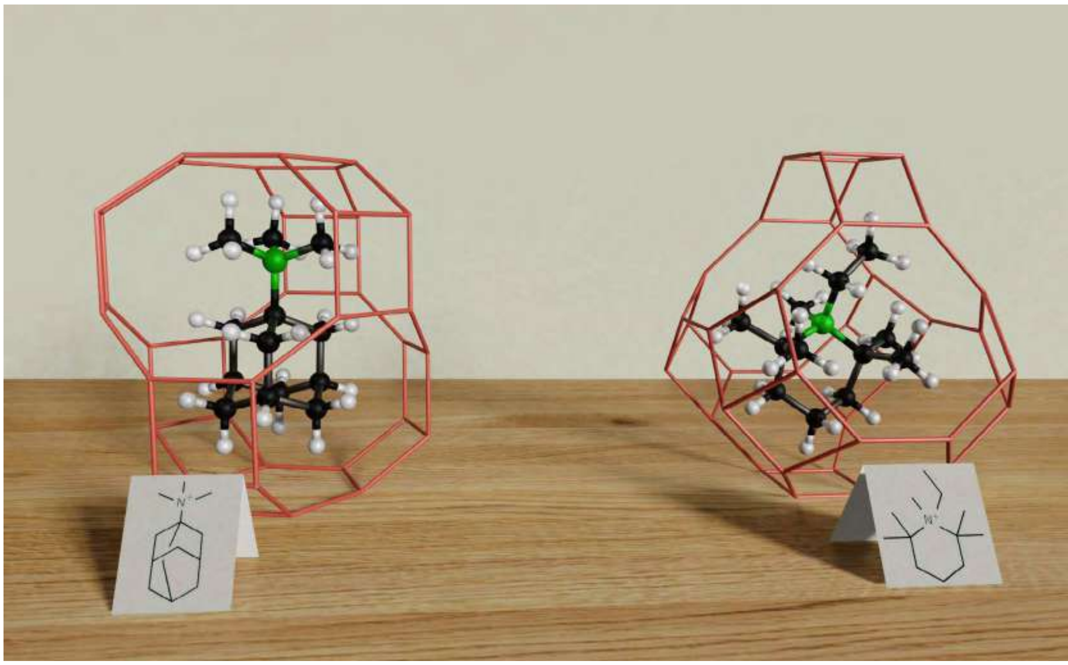
Zeolites are a class of minerals used in everything from industrial catalysts and chemical filters to laundry detergents and cat litter. They are mostly composed of silicon and aluminum—two abundant, inexpensive elements—plus oxygen; they have a crystalline structure; and most significantly, they are porous. Among the regularly repeating atomic patterns in them are tiny interconnected openings, or pores, that can trap molecules that just fit inside them, allow smaller ones to pass through, or block larger ones from entering. A zeolite can remove unwanted molecules from gases and liquids, or trap them temporarily and then release them, or hold them while they undergo rapid chemical reactions.

Some zeolites occur naturally, but they take unpredictable forms and have variable-sized pores. "People synthesize artificial versions to ensure absolute purity and consistency," says Rafael Gómez-Bombarelli, the Jeffrey Cheah Career Development Chair in Engineering in the Department of Materials Science and Engineering (DMSE). And they work hard to influence the size of the internal pores in hopes of matching the molecule or other particle they're looking to capture.

The basic recipe for making zeolites sounds simple. Mix together the raw ingredients—basically, silicon dioxide and aluminum oxide—and put them in a reactor for a few days at a high temperature and pressure. Depending on the ratio between the ingredients and the temperature, pressure, and timing, as the initial gel slowly solidifies into crystalline form, different zeolites emerge.

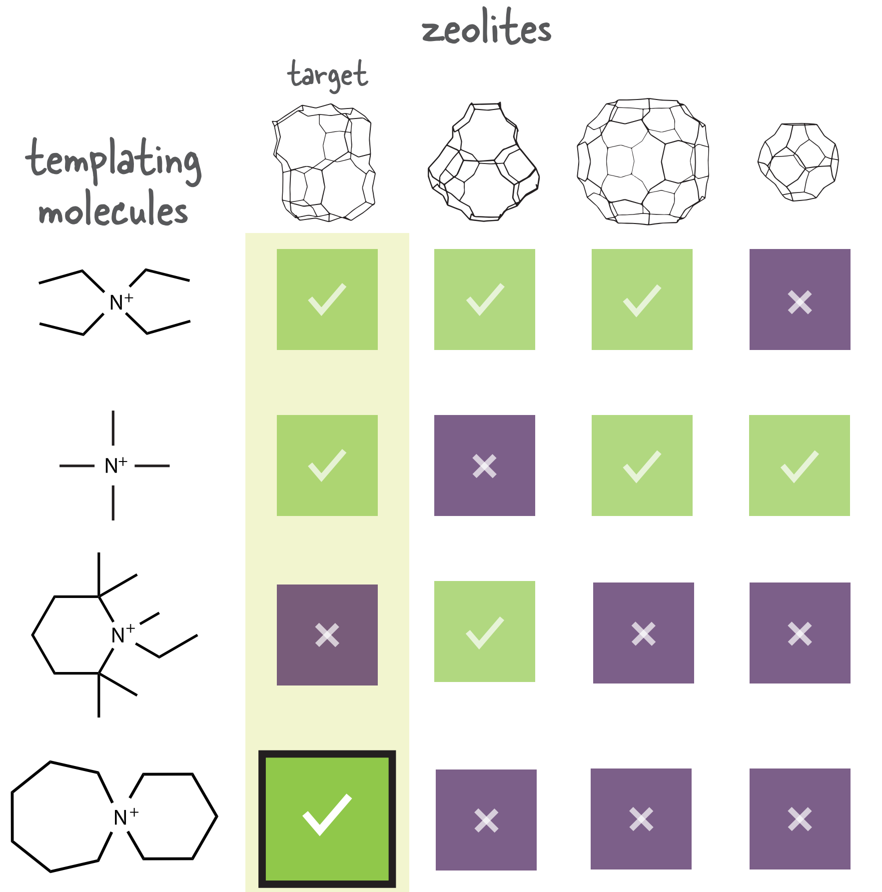
But there's one special ingredient to add "to help the system go where you want it to go," says Gómez-Bombarelli. "It's a molecule that serves as a template so that the zeolite you want will crystallize around it and create pores of the desired size and shape."

The so-called templating molecule binds to the material before it solidifies. As crystallization progresses, the molecule directs the structure, or "framework," that forms around it, as illustrated by the models shown below. After crystallization,



Right: Determining the size and shape of the zeolite pores. To control the size and shape of the open pores in a zeolite, experts add a "templating molecule" that determines how the pores form as the zeolite gel solidifies. Computational methods can guide the design of a templating molecule that will produce an opening of a certain size and shape. In the models shown here, the templating molecule at the center (shown in black, white, and green) leads to the formation of the pore around it (shown in red). N^+ indicates a positively charged nitrogen atom. Image: Daniel Schwalbe-Koda, MIT

Facing page: Professor Rafael Gómez-Bombarelli (left), Daniel Schwalbe-Koda PhD '22, and their collaborators have demonstrated a new approach to making porous materials called zeolites for specific uses, including cleaning up exhaust gases from trucks. Photo: Gretchen Ertl the temperature is raised and the templating molecule burns off, leaving behind a solid aluminosilicate material filled with open pores that are—given the correct templating molecule and synthesis conditions—just the right size and shape to recognize the targeted molecule.



Matching the templating molecule and intended zeolite to ensure the expected outcome.
This graphic illustrates the researchers' novel approach. Using a detailed metric, they evaluate the affinity between templating molecules (listed at left) and zeolites (shown across the top); high affinity is indicated by a check, low affinity by an "X." Using the bottom molecule to make the first zeolite (marked "target") is a good choice as that molecule is unlikely to form anything else.
Image: Daniel Schwalbe-Koda, MIT

The zeolite conundrum

Theoretical studies suggest that there should be hundreds of thousands of possible zeolites. But despite some 60 years of intensive research, only about 250 zeolites have been made. This is sometimes called the "zeolite conundrum." Why haven't more been made—especially now, when they could help ongoing efforts to decarbonize energy and the chemical industry?

One challenge is figuring out the best recipe for making them: Factors such as the best ratio between the silicon and aluminum, what cooking temperature to use, and whether to stir the ingredients all influence the outcome. But the real key, the researchers say, lies in choosing a templating molecule that's best for producing the intended zeolite framework. Making that match is difficult: There are hundreds of known templating molecules and potentially a million zeolites, and researchers are continually designing new molecules because millions more could be made and might work better.

For decades, the exploration of how to synthesize a particular zeolite has been done largely by trial and error—a time-consuming, expensive, inefficient way to go about it. There has also been considerable effort to use "atomistic" (atom-by-atom) simulation to figure out what known or novel templating molecule to use to produce a given zeolite. But the experimental and modeling results haven't generated reliable guidance. In many cases, researchers have carefully selected or designed a molecule to make a particular zeolite; but when they tried their molecule in the lab, the zeolite that formed wasn't what they expected or desired. So they needed to start over.

Those experiences illustrate what Gómez-Bombarelli and his colleagues believe is the problem that's been plaguing zeolite design for decades. All the efforts—both experimental and theoretical—have focused on finding the templating molecule that's best for forming a specific zeolite. But what if that templating molecule is also really good—or even better—at forming some other zeolite?

To determine the "best" molecule for making a certain zeolite framework, and the "best" zeolite framework to act as host to a particular molecule, the researchers decided to look at both sides of the pairing. Daniel Schwalbe-Koda PhD '22, a former member of Gómez-Bombarelli's group and now a postdoctoral fellow at Lawrence Livermore National Laboratory, describes the process as a sort of dance with molecules and zeolites in a room looking for partners. "Each molecule wants to find a partner zeolite, and each zeolite wants to find a partner molecule," he says. "But it's not enough to find a good dance partner from the perspective of only one dancer. The potential partner could prefer to dance with someone else, after all. So it needs to be a particularly good pairing." The upshot: "You need to look from the perspective of each of them."

To find the best match from both perspectives, the researchers needed to try every molecule with every zeolite and quantify how well the pairings worked.

A broader metric for evaluating pairs

Before performing that analysis, the researchers defined a new "evaluating metric" that they could use to rank each templating molecule-zeolite pair. The standard metric for measuring the affinity between a molecule and a zeolite is "binding energy," that is, how strongly the molecule clings to the zeolite or, conversely, how much energy is required to separate the two. While recognizing the value of that metric, the MIT-led team wanted to take more parameters into account.

Their new evaluating metric therefore includes not only binding energy but also the size, shape, and volume of the molecule and the opening in the zeolite framework. And their approach calls for turning the molecule to different orientations to find the best possible fit.

Affinity scores for all molecule-zeolite pairs based on that evaluating metric would enable zeolite researchers to answer two key questions: What templating molecule will form the zeolite that I want? And if I use that templating molecule, what other zeolites might it form instead?

The figure on page 8 illustrates the process. Four zeolites are shown across the top, and four templating molecules are shown down the left side. The boxes indicate how well each pair matches up, with a check indicating a good match and an "X" a poor one. (In practice, the researchers used quantitative affinity scores in place of those qualitative indicators.) Suppose the goal is to synthesize the first zeolite from the left—marked "target." The first and second templating molecules look like good matches for making the desired zeolite. However, they also could be good matches for making other zeolites, so they'd be a risky choice. The third molecule down wouldn't work. But the bottom molecule is a good match for making the target zeolite and not for making any of the others. So it's deemed "highly selective"; it's a better, safer choice.

Validating the approach: A rich literature

But does their new metric work better than the standard one? To find out, the team needed to perform atomistic simulations using their new evaluating metric and then benchmark their results against experimental evidence reported in the literature. There are many thousands of journal articles reporting on experiments involving zeolites—in many cases, detailing not only the molecule-zeolite pairs and outcomes but also synthesis conditions and other details. Ferreting out articles with the information the researchers needed was a job for machine learning—in particular, for natural language processing.

For that task, Gómez-Bombarelli and Schwalbe-Koda turned to their DMSE colleague Elsa Olivetti PhD '07, the Esther and Harold E. Edgerton Associate Professor in Materials Science and Engineering. Using a literature-mining technique that she and a group of collaborators had developed, she and her DMSE team processed more than 2 million materials science papers, found some 90,000 relating to zeolites, and extracted 1,338 of them for further analysis. The yield was 549 templating molecules tested, 209 zeolite frameworks produced, and 5,663 synthesis routes followed.

Based on those findings, the researchers used their new evaluating metric and a novel atomistic simulation technique to examine more than half a million templating molecule-zeolite pairs. Their results reproduced experimental outcomes reported in more than a thousand journal articles. Indeed, the new metric outperformed the traditional binding energy metric, and their simulations were orders of magnitude faster than traditional approaches.

Ready for experimental investigations

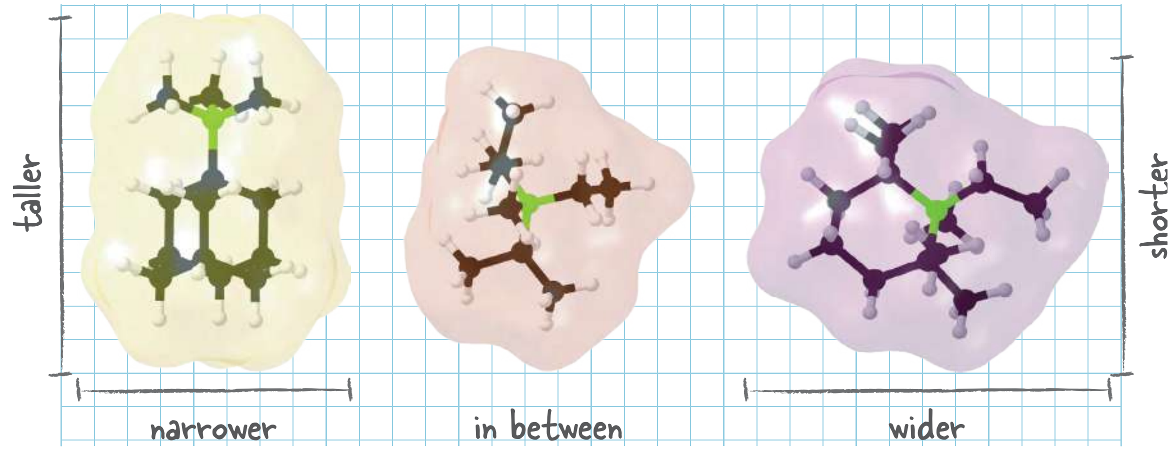
Now the researchers were ready to put their approach to the test: They would use it to design new templating molecules and try them out in experiments performed by a team led by Yuriy Román-Leshkov, the Robert T. Haslam (1911) Professor of Chemical Engineering, and a team from the Instituto de Tecnologia Química in Valencia, Spain, led by Manuel Moliner and Avelino Corma.

One set of experiments focused on a zeolite called chabazite, which is used in catalytic converters for vehicles. Using their techniques, the researchers designed a new templating molecule for synthesizing chabazite, and the experimental results confirmed their approach. Their analyses had shown that the new templating molecule would be good for forming chabazite and not for forming anything else. "Its binding strength isn't as high as other molecules for chabazite, so people hadn't used it," says Gómez-Bombarelli. "But it's pretty good, and it's not good for anything else, so it's selective—and it's way cheaper than the usual ones."

In addition, in their new molecule, the electrical charge is distributed differently than in the traditional ones, which led to new possibilities. The researchers found that by adjusting both the shape and charge of the molecule, they could control where the negative charge occurs on the pore that's created in the final zeolite. "The charge placement that results can make the chabazite a much better catalyst than it was before," says Gómez-Bombarelli. "So our same rules for molecule design also determine where the negative charge is going to end up, which can lead to whole different classes of catalysts."

Schwalbe-Koda describes another experiment that demonstrates the importance of molecular shape as well as the types of new materials made possible using the team's approach. In one striking example, the team designed a templating molecule with a shape that's halfway between the shapes of two molecules that are usually used, as illustrated in the figure on page 10. On the left is the best-ever molecule for making chabazite, and on the right is the best-ever molecule for making a zeolite called AEI. (Every new zeolite structure is examined by the International Zeolite Association and—once approved—receives a three-letter designation.) In the center is the molecule that Schwalbe-Koda determined to be halfway between them in width and height.

Experiments using that in-between templating molecule resulted in the formation of not one zeolite or the other



Designing a templating molecule that forms two zeolites combined in one solid. The molecule on the left is usually used to produce one zeolite, while the molecule on the right is used to produce a different one. The MIT researchers designed the templating molecule at the center, which is between the two in width and height. In experiments, that in-between molecule produced a solid that's a combination of the two zeolites. Tests showed that the new material would be better at converting pollutants to benign compounds than the zeolite often used in catalytic converters for trucks. Image: Daniel Schwalbe-Koda, MIT

but a combination of the two in a single solid. "The result blends two different structures together in a way that the final result is better than the sum of its parts," says Schwalbe-Koda. "The catalyst is like the one used in catalytic converters in today's trucks—only better." It's more efficient in converting nitrogen oxides to harmless nitrogen gases and water, and—because of the two different pore sizes and the aluminosilicate composition—it works well on exhaust that's fairly hot, as during normal operation, and also on exhaust that's fairly cool, as during startup.

Putting the work into practice

As with all materials, the commercial viability of a zeolite will depend in part on the cost of making it. The researchers' technique can identify promising templating molecules, but some of them may be difficult to synthesize in the lab. As a result, the overall cost of that molecule-zeolite combination may be too high to be competitive.

Gómez-Bombarelli and his team therefore include in their assessment process a calculation of cost for synthesizing each templating molecule they identified—generally the most expensive part of making a given zeolite. They use a publicly available model devised in 2018 by Connor Coley PhD '19, now the Henri Slezynger (1957) Career Development Assistant Professor of Chemical Engineering at MIT. The model takes into account all the starting materials and the step-by-step chemical reactions needed to produce the targeted templating molecule.

However, commercialization decisions aren't based solely on cost. Sometimes there's a trade-off between cost and performance. "For instance, given our chabazite findings, would customers or the community trade a little bit of activity for a 100-fold decrease in the cost of the templating molecule?" says Gómez-Bombarelli. "The answer is likely yes. So we've made a tool that can help them navigate that trade-off." And there are other factors to consider. For example, is this templating molecule truly novel, or have others already studied it—or perhaps even hold a patent on it?

"While an algorithm can guide development of templating molecules and quantify specific molecule-zeolite matches, other types of assessments are best left to expert judgment," notes Schwalbe-Koda. "We need a partnership between computational analysis and human intuition and experience."

To that end, the MIT researchers and their colleagues decided to share their techniques and findings with other zeolite researchers. Led by Schwalbe-Koda, they created an online database that they made publicly accessible and easy to use—an unusual step, given the competitive industries that rely on zeolites. The interactive website—zeodb.mit.edu—contains the researchers' final metrics for templating molecule-zeolite pairs resulting from hundreds of thousands of simulations; all the identified journal articles, along with which molecules and zeolites were examined and what synthesis conditions were used; and many more details. Users are free to search and organize the data in any way that suits them.

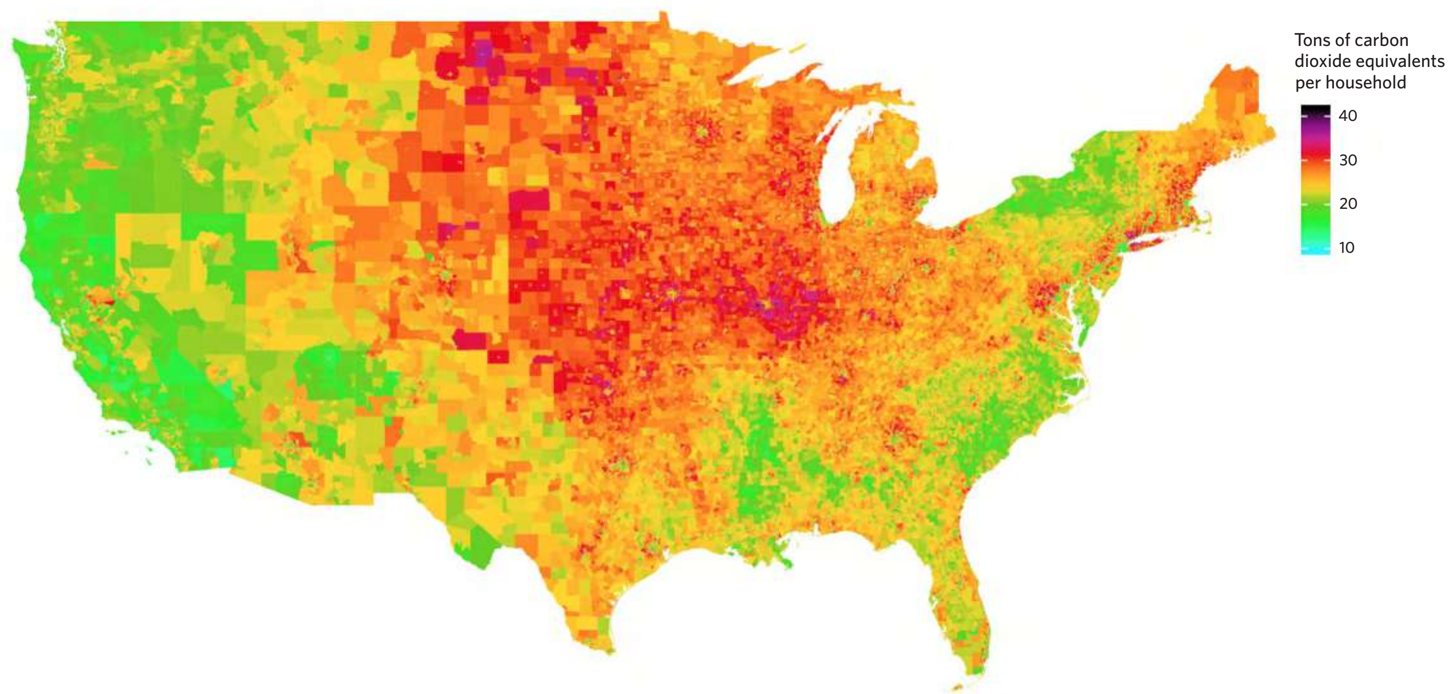
Gómez-Bombarelli, Schwalbe-Koda, and their colleagues hope that their techniques and the interactive website will help other researchers explore and discover promising new templating molecules and zeolites, some of which could have profound impacts on efforts to decarbonize energy and tackle climate change.

NOTES

This research involved a team of collaborators at MIT, the Instituto de Tecnologia Química (UPV-CSIC), and Stockholm University. The work was supported in part by the MIT Energy Initiative Seed Fund Program and by seed funds from the MIT International Science and Technology Initiative. Daniel Schwalbe-Koda was supported by an ExxonMobil-MIT Energy Fellowship in 2020–2021. More information about the research can be found in:

D. Schwalbe-Koda, S. Kwon, C. Paris, E. Bello-Jurado, Z. Jensen, E. Olivetti, T. Willhammar, A. Corma, Y. Román-Leshkov, M. Moliner, and R. Gómez-Bombarelli. "A priori control of zeolite phase competition and intergrowth with high-throughput simulations." *Science*, vol. 374, 2021. Online: doi.org/10.1126/science.abh3350.

Policies to cut carbon emissions: Designing an equitable option



Average household carbon footprints across the continental United States. An analysis by MIT Professor Christopher Knittel and Tomas Green SM '20 shows that households with high carbon footprints—shown here in red to purple—tend to fall in the middle of the country, while households with low carbon footprints—shown in green to blue—are more likely to be on the coasts. Therefore, if carbon emissions are taxed across the board and the revenue distributed equally to every U.S. household, households in certain geographical regions will pay more than others. The MIT researchers suggest a way to correct for such unintended consequences of a carbon tax.

IN BRIEF

MIT researchers have developed a way to determine which U.S. households win and lose financially under policies designed to reduce carbon emissions. Using census data and machine learning, they estimate average impacts on household budgets of specific policies at fine resolution across the continental United States. Results show that taxing carbon emissions and redistributing the collected revenues—the policy touted as most efficient at bringing about change—protects vulnerable low-income households but ends up squeezing the budgets of those in the middle of the country and in rural areas. The analyses show that slightly adjusting the refunds can correct those unintended consequences. The researchers determined that fuel economy and clean energy standards are policies that would also be inequitable and provide no revenue with which to make corrections. Already, policy makers have requested special MIT analyses to help them better understand the potential impacts of climate policies under discussion.

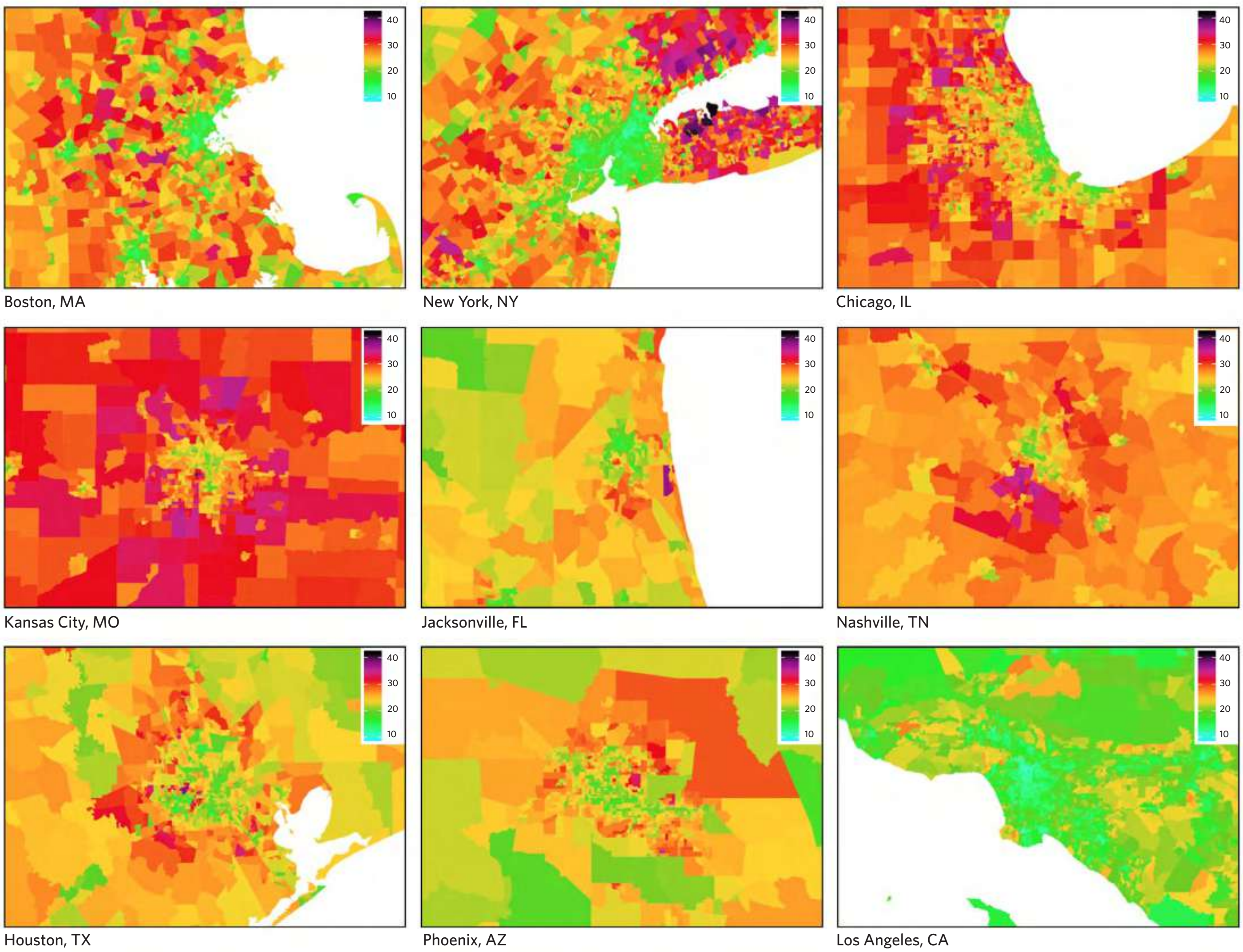
The growing urgency of today's climate challenge is intensifying discussions of policy measures that could enable the United States to achieve net-zero carbon emissions by 2050. Leading economists support policies that tax carbon emissions as the approach that will bring the needed change most quickly and at lowest cost. But there are serious questions about the possible inequity of that approach. All policies lead to unintended consequences, including transferring money from one household to another. If a carbon tax is imposed, will certain groups bear more of the burden than others?

The burden imposed will depend—directly or indirectly—on the level of carbon-emitting goods and services that various groups consume. The first step in addressing the equity question is therefore to establish the "carbon footprint" of households across the country. "The ideal would be to know the carbon footprint of every household in the United States, but that's not feasible," says Christopher Knittel, the George P. Shultz Professor of Energy Economics at the MIT Sloan School of Management, deputy director for policy at the MIT Energy Initiative, and director of the MIT Center for Energy and Environmental Policy Research.

Instead, Knittel and Tomas Green SM '20, now a fellow at the U.S. Department of Energy, set their sights on determining the carbon footprint down to the level of a census tract. There are more than 74,000 census tracts in the United States, each including about 4,000 households. The researchers' goal was to calculate the average carbon footprint of the 4,000 households in each census tract.

No data are available on the consumption of electricity, natural gas, gasoline, or other sources of carbon emissions at the census tract level. "But we do have such data for a representative sample of Americans—along with their age, income, a variety of other demographics, and maybe what state they live in," says Knittel. "That's where the machine learning comes in."

By analyzing those data, a machine learning model that the team developed



Average household carbon footprints for a sampling of U.S. cities (in tons of carbon dioxide equivalents per household). As shown in the maps above, in many cities—for example, Chicago, Kansas City, and Los Angeles—average household carbon footprints are higher in the suburbs than in the city center. As a result, under a carbon tax policy, suburban dwellers would likely bear more of the burden than residents in the city center.

determines the relationship between the variables about those people and their consumption of, for example, electricity. Once that relationship is known, the model can apply it to data on age, income, and other variables for a given census tract and estimate average electricity consumption. "Then we do that for all the things that produce carbon and add it all up for that census tract," explains Knittel. "Now we have the average carbon footprint for all households at the census tract level." Ultimately, Knittel and Green were able to estimate average household carbon footprints for 72,538 of the 74,134 census tracts in the United States.

What the carbon footprints tell us

Knittel finds the carbon footprints striking. "There are three broad lessons that we learn from the carbon footprints," he says, emphasizing that all three should be taken into account during the policy-making process.

The first broad lesson is that carbon footprints increase with income. In other words, wealthy people produce more carbon.

The second is that carbon footprints are higher in the middle of the continental United States and lower on the West Coast and along the mid to south Atlantic Coast.

The third is that carbon footprints are lower in cities than in rural and suburban areas.

To convey those findings, Knittel and Green use maps with colors that represent average household carbon footprints at the census tract level. For example, the map on page 11 shows household carbon footprints for the continental United States. The key at the right defines the carbon footprints in terms of tons of carbon dioxide equivalents, a measure that puts emissions of all greenhouse gases on a common scale. The colors provide visual evidence of the second broad lesson. The red in the middle of the country indicates that carbon footprints are high in that region, as they are in certain areas of the Northeast due to cold winters and high consumption of heating oil. The West Coast and lower Atlantic Seaboard are among the areas dominated by green, indicating low carbon footprints.

The maps on page 12 show carbon footprints in various cities. In most cases, they demonstrate the third broad lesson—that carbon footprints are lower in urban areas than in the suburbs. Chicago and Kansas City are good examples: They are green in the center and become more yellow and then red moving outward. At a glance, Los Angeles looks green; on closer inspection, one can see blue sections in the city center, indicating the very lowest carbon footprints on the scale.

The figure on page 14 provides a quantitative look at both the impact of wealth on carbon footprints—the first broad lesson—and how that impact changes depending on how urban or rural an area is—the third broad lesson. The chart divides the total households in the United States into five income groups, or "quintiles," of equal size—an approach often used in economic analysis. (As an example, if there were 100 households, they could be ordered based on income and then placed into five income quintiles with 20 households in each one.) In the figure, income increases from left to right. The quintiles are further divided into three rows—urban, suburban, and rural, from top to bottom. Each of the 15 plots shows the distribution of household carbon footprints in that group. Carbon footprint is on the x-axis and fraction of households on the y-axis. The vertical dashed lines show the U.S. average household carbon footprint.

Looking across the top row from left to right—which shows urban areas from the lowest to the highest income quintile—the shaded area representing the carbon footprint distribution shifts from left to right. So, as households become wealthier, their carbon footprints increase.

The trend also changes depending on where the household is located. Looking from top to bottom within the same income quintile, the carbon footprint distribution shifts to the right. So, for a given income group, carbon footprints are generally higher for households in suburban areas than in urban areas and still higher for households in rural areas. That change serves to quantify the researchers' third broad lesson—that people in more rural areas have higher carbon footprints than those in cities.

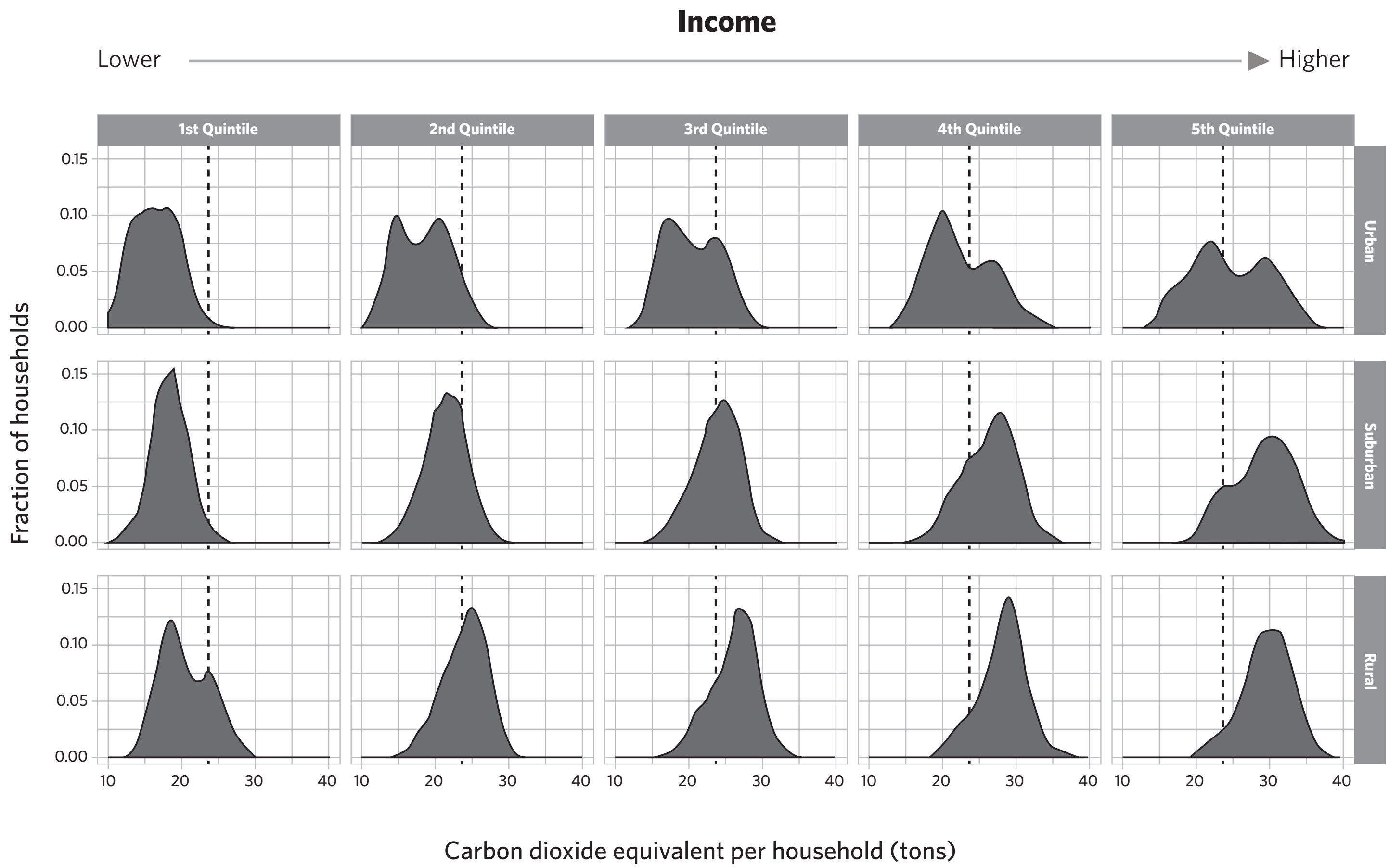
"We find that any policy supporting decarbonization is likely to be tougher on the middle of the U.S. and tougher on rural and suburban areas," says Knittel. "That's not usually a recipe for success in Washington, D.C."

How equitable are carbon tax policies?

Armed with estimates of average household carbon footprints across the United States, Knittel and Green were ready to model various versions of a carbon tax policy to estimate the annual cost and benefit for the average household at the census tract level. The policy that's most often discussed is a "tax-and-dividend plan" that taxes carbon, collects the revenues, and redistributes the collected money equally across households, so every household receives the same check. In light of the researchers' broad lessons concerning carbon footprints, they asked: Is that system fair for everyone?

The fact that wealthy people consume more carbon is good for the equity of the plan because it means that wealthier households would pay more. Indeed, the researchers found that, on average, low-income households would actually receive a larger dividend check than what they would pay in increased prices due to carbon taxes. Thus, the policy is not regressive, but rather progressive; it benefits people with lower incomes.

However, the other two broad lessons lead to inequitable outcomes from this simple tax-and-dividend plan, the researchers say. With carbon footprints generally higher in Middle America and lower on the coasts, the former regions would pay more than the latter. In essence, there would be a transfer of money from Middle America to the coasts. And with carbon footprints higher in rural and suburban areas than in cities, there would be a transfer of money from rural and suburban households to urban households. Both of those outcomes mean that the



Total household carbon footprints across income quintiles and urbanicity compared to the U.S. average. This chart divides U.S. households into five equal-sized income groups ("quintiles"), with income increasing from the left column to the right. The three rows from top to bottom show results for urban, suburban, and rural areas. Within each quintile, the shaded area represents the distribution of household carbon footprints compared to the U.S. average, which is indicated by the dashed line. Overall, household carbon footprints tend to increase with wealth and in more rural locations. In addition, there can be a wide and sometimes bimodal distribution within each grouping. The bimodal feature occurs when people living in middle of the country have the same income as those living on the coasts but have a higher carbon footprint because their power grid is dirtier.

simple carbon tax-and-dividend plan is inequitable: Households in Middle America and in rural and (to some extent) suburban areas would carry more of the overall burden of the tax than others.

But there's a way to design a tax-and-dividend policy to keep those two negative outcomes from occurring: Send different dividend checks to different households. Using their model, the researchers examined the impacts of carbon tax-and-dividend policies with the same per-ton carbon fee but with differing dividends based on geographic location in the country or in urban, suburban, or rural locations. Their results showed that a small adjustment in the dividend checks—as little as 8%—would solve the inequity problem.

Inequity in other proposed policies

For Knittel, a final takeaway from the study is that alternatives to a carbon tax "don't look great at all." For example, both clean energy standards and renewable portfolio standards—common policies designed to reduce emissions—focus on decarbonizing the electric grid (the latter excludes nuclear power). But the middle of the United States relies on a particularly dirty grid, so those policies will again be more costly for people in the middle of the country than for those on the coasts. Fuel economy standards focus on vehicles, and people in the middle of the country and in rural areas tend to drive more miles and have less fuel-efficient cars, so such policies will place them at an economic disadvantage.

But perhaps the biggest drawback of such regulations is that—unlike a carbon tax—they don't generate revenue.

"So there's no way to undo the negative impacts," says Knittel. Unless policy makers can find another source of revenue, they have no flexibility to protect certain groups.

Practical implications

What is the message for policy makers? A policy that taxes carbon emissions is more efficient and less costly overall than other frequently proposed policies. "But it's critical to design any carbon tax-and-dividend policy carefully and intelligently to avoid some of the inequities that may arise and the political pitfalls that can result," says Knittel.

In terms of how to design the refund checks, he has a suggestion. There are 10 census divisions in the United States, and he proposes sending different checks to households based on those divisions, with bigger checks going to those in the middle of the United States and to rural and suburban areas.

But he stresses that the decision is up to policy makers. "My goal is to give policy makers data with which they can make informed decisions in the interest of their constituents," he says. And his analytical techniques are available to help decision makers assess the implications of specific policies being considered.

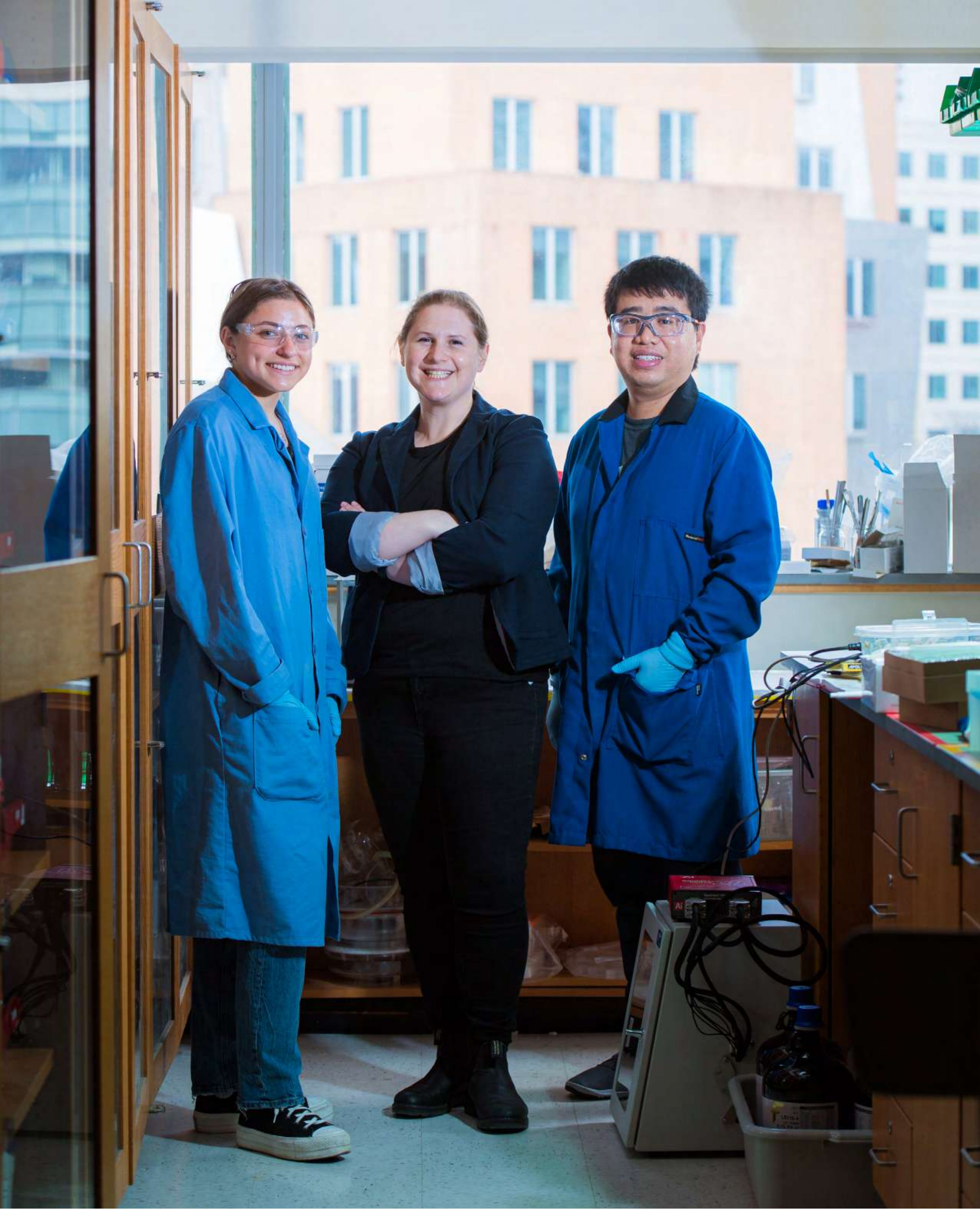
As an example, he describes an experience in December 2021. At that time, there was considerable discussion about a federal budget reconciliation package, and for a while, a carbon tax seemed to be on the table, including a version that exempted gasoline from such a tax. "I began receiving requests from policy makers and staffers in D.C. to generate new maps for them so they could see what different carbon tax proposals would look like," he recalls. Did he and his team do so? His response: "Of course we did! We were generating multiple maps on a daily basis." As the debate unfolded, policy makers could see in detail the impacts of specific climate-motivated policies on different populations, including their own constituents.

The researchers conclude that—done well—a carbon tax-and-dividend policy could serve as a good, bipartisan, "win-win" option that would benefit constituents in progressive and conservative districts alike.

NOTES

This research was funded by the Emerson Collective through the Roosevelt Project, under the MIT Center for Energy and Environmental Policy Research. The goal of the Roosevelt Project is to provide an analytical basis for charting a path to a low-carbon economy in a way that promotes high-quality job growth, minimizes worker and community dislocation, and harnesses the benefits of energy technologies for regional economic development. Read more at ceepr.mit.edu/roosevelt-project/about-the-project. This *Energy Futures* article is based on the following special report published by the Roosevelt Project:

T.W. Green and C.R. Knittel. "Distributed effects of climate policy: A machine learning approach." MIT Center for Energy and Environmental Policy Research, The Roosevelt Project Special Working Paper Series, 2020. Online: ceepr.mit.edu/roosevelt-project/publications.



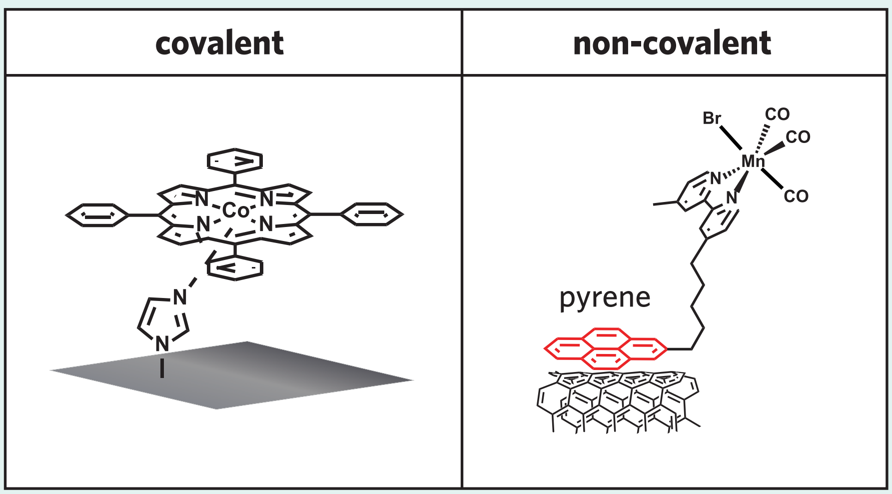
Turning carbon dioxide into valuable products: DNA can help guide the process

IN BRIEF

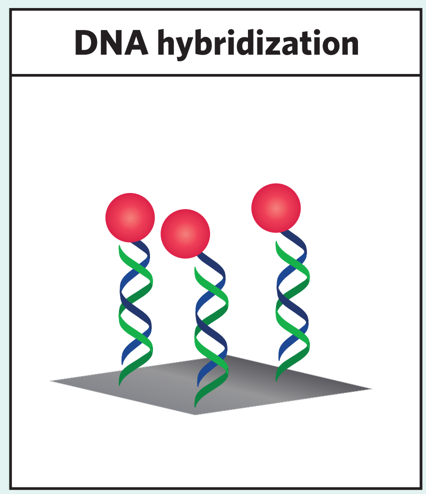
MIT chemical engineers have found a way to speed up a chemical reaction that is key to converting captured carbon dioxide emissions into useful, valuable products. To prepare, they add a bit of DNA to a commonly used catalyst. They then rely on the natural behavior of DNA to situate the catalyst where it's needed on an electrode inside an electrochemical device. The DNA-linked catalyst plus a jolt of voltage provides the encouragement needed to make the reluctant reaction happen. The team found that the modified catalyst is more stable under typical operating conditions, and it significantly improves the conversion efficiency. The researchers believe that their approach can be used with other classes of catalysts to encourage a wide range of reluctant electrochemical reactions.

Carbon dioxide (CO_2) is a major contributor to climate change and a significant product of many human activities, notably industrial manufacturing. A major goal in the energy field has been to chemically convert emitted CO_2 into valuable chemicals or fuels. But while CO_2 is available in abundance, it has not yet been widely used to generate value-added products. Why not?

The reason is that CO_2 molecules are highly stable and therefore not prone to being chemically converted to a different form. Researchers have sought materials

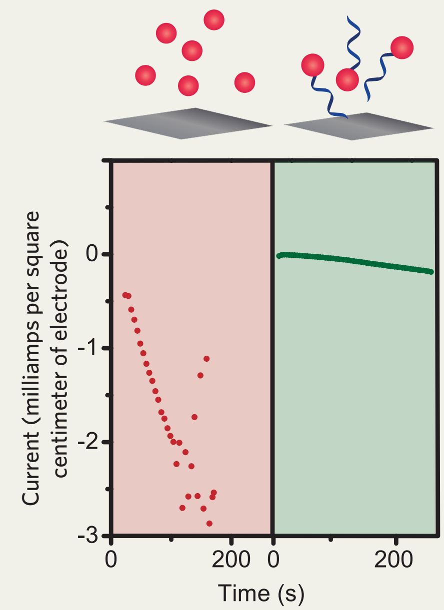


Two common approaches to immobilizing small-molecule catalysts on electrodes. In the left-hand drawing, the catalyst at the top is connected to a glassy carbon electrode by a nitrogen-based ring; the two structures share electrons, forming a covalent bond that is essentially permanent. In the right-hand drawing, the catalyst is connected to an electrode of carbon nanotubes by a pyrene molecule; because the pyrene and carbon nanotubes don't share electrons, they are attached non-covalently and can be separated easily.



Using DNA to attach the catalyst to the electrode. In the researchers' approach, the catalyst—represented above by the red sphere—is connected to a carbon electrode by strands of DNA. Initially, one strand of DNA is deposited on the electrode, and the other is in solution with the catalyst attached. When the two strands meet up, they lock together, as shown here. The green strand that is attached to the electrode and the blue strand that is carrying the catalyst are now connected, so the catalyst is firmly linked to the electrode. Over time, the catalyst will become inactive. Raising the temperature will release the DNA strand with the spent catalyst so fresh catalyst can be attached.

Facing page: Professor Ariel Furst (center), undergrad Rachel Ahlmark (left), postdoc Gang Fan (right), and their colleagues are employing biological materials, including DNA, to achieve the conversion of carbon dioxide to valuable products. Photo: Gretchen Ertl



Improving catalyst stability by adding single DNA strands to a catalyst in solution. The stability of a catalyst can be tested by inputting a voltage onto an electrode inside an electrochemical device and monitoring the resulting current that flows. Left panel: When a voltage of practical interest was applied to a test device containing unmodified catalyst in solution, the measured current rapidly dropped over time, indicating that the free-floating catalyst was degrading—a major problem in an electrochemical system. Right panel: When the floating catalyst had DNA strands attached, that rapid decline in the measured current did not occur.

and device designs that could help spur that conversion, but nothing has worked well enough to yield an efficient, cost-effective system.

Two years ago, Ariel Furst, the Raymond (1921) and Helen St. Laurent Career Development Professor of Chemical Engineering at MIT, decided to try using something different—a material that gets more attention in discussions of biology than of chemical engineering. Already, results from work in her lab suggest that her unusual approach is paying off.

The stumbling block

The challenge begins with the first step in the CO_2 conversion process. Before being transformed into a useful product, CO_2 must be chemically converted into carbon monoxide (CO). That conversion can be encouraged using electrochemistry, a process in which input voltage provides the extra energy needed to make the stable CO_2 molecules react. The problem is that achieving the CO_2-to-CO conversion requires large energy inputs—and even then, CO makes up only a small fraction of the products that are formed.

To explore opportunities for improving this process, Furst and her research group focused on the electrocatalyst, a material that enhances the rate of a chemical reaction without being consumed in the process. The catalyst is key to successful operation. Inside an electrochemical device, the catalyst is often suspended in an aqueous (water-based) solution. When an electric potential (essentially a voltage) is applied to a submerged electrode, dissolved CO_2 will—helped by the catalyst—be converted to CO.

But there's one stumbling block: The catalyst and the CO_2 must meet on the surface of the electrode for the reaction to occur. In some studies, the catalyst is dispersed in the solution, but that approach requires more catalyst and isn't very efficient, according to Furst. "You have to both wait for the diffusion of CO_2 to the catalyst and for the catalyst to reach the electrode before the reaction can occur," she explains. As a result, researchers worldwide have been exploring different methods of "immobilizing" the catalyst on the electrode.

Connecting the catalyst and the electrode

Before Furst could delve into that challenge, she needed to decide which of the two types of CO_2 conversion catalysts to work with: the traditional solid-state catalyst or a catalyst made up of small molecules. In examining the literature, she concluded that small-molecule catalysts held the most promise. While their conversion efficiency tends to be lower than that of solid-state versions, molecular catalysts offer one important advantage: They can be tuned to emphasize reactions and products of interest.

The left figure on page 17 illustrates two common approaches to immobilizing small-molecule catalysts on an electrode. In the left-hand drawing, the metal center of the catalyst at the top (here, cobalt) is linked by a nitrogen-based ring to a glassy carbon electrode (the gray square) by strong covalent bonds—a type of bond in which atoms share electrons; the result is a strong, essentially permanent connection. In the right-hand drawing, a molecule (in this case, pyrene) sets up a non-covalent attachment between the manganese-based catalyst at the top and an electrode made of carbon materials (in this case, nanotubes); unlike a covalent bond, this connection can easily be broken.

Neither approach is ideal. In the former case, the catalyst and electrode are firmly attached, ensuring efficient reactions; but when the activity of the catalyst degrades over time (which it will), the electrode can no longer be accessed. In the latter case, a degraded catalyst can be removed; but the exact placement of the small molecules of the catalyst on the electrode can't be controlled, leading to an inconsistent, often decreasing, catalytic efficiency—and simply increasing the amount of catalyst on the electrode surface without concern for where the molecules are placed doesn't solve the problem.

What was needed was a way to position the small-molecule catalyst firmly and accurately on the electrode and then release it when it degrades. For that task, Furst turned to what she and her team regard as a kind of "programmable molecular Velcro": deoxyribonucleic acid, or DNA.

Adding DNA to the mix

Mention DNA to most people, and they think of biological functions in living things. But the members of Furst's lab view DNA as more than just genetic code. "DNA has these really cool physical properties as a biomaterial that people don't often think about," she says. "DNA can be used as a molecular Velcro that can stick things together with very high precision."

Furst knew that DNA sequences had previously been used to immobilize molecules on surfaces for other purposes. So she devised a plan to use DNA to direct the immobilization of catalysts for CO_2 conversion.

Her approach depends on a well-understood behavior of DNA called hybridization. The familiar DNA structure is a double helix that forms when two complementary strands connect. When the sequence of bases (the four building blocks of DNA) in the individual strands match up, hydrogen bonds form between complementary bases, firmly linking the strands together.

Using that behavior for catalyst immobilization involves two steps. First, the researchers attach a single strand of DNA to the electrode. Then they attach a complementary strand to the catalyst that is floating in the aqueous solution. When the latter strand gets near the former, the two strands hybridize; they become linked by multiple hydrogen bonds between properly paired bases. The result is shown in the right-hand figure on page 17. The catalyst (shown as a red sphere) is firmly affixed to the electrode by means of two interlocked, self-assembled DNA strands (the wavy lines), one connected to the electrode (shown in green) and the other to the catalyst (shown in blue).

Better still, the two strands can be detached from one another. "The connection is stable, but if we heat it up, we can remove the secondary strand that has the catalyst on it," says Furst. "So we can de-hybridize it. That allows us to recycle our electrode surfaces—without having to disassemble the device or do any harsh chemical steps."

Experimental investigation

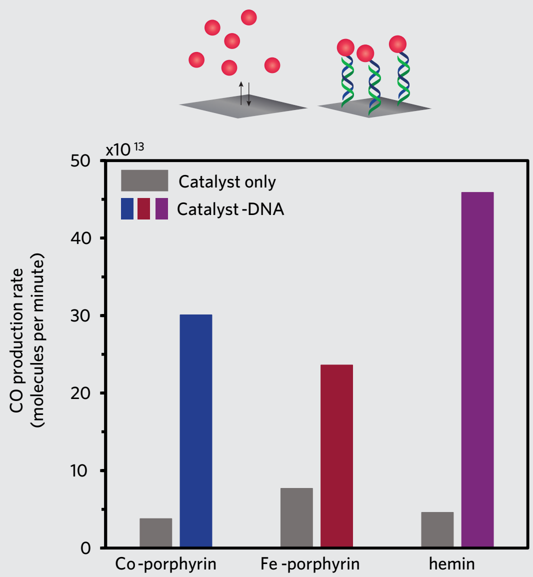
To explore that idea, Furst and her team—postdoctoral researchers Gang Fan and Thomas Gill, former graduate student Nathan Corbin PhD '21, and former postdoc Amruta Karbelkar—performed a series of experiments using three small-molecule catalysts based on porphyrins, a group of compounds that are biologically important for processes ranging from enzyme activity to oxygen transport. Two of the catalysts involve a synthetic porphyrin plus a metal center of either cobalt or iron. The third catalyst is hemin, a natural porphyrin compound used to treat porphyria, a set of disorders that can affect the nervous system. "So even the small-molecule catalysts we chose are kind of inspired by nature," comments Furst.

In their experiments, the researchers first needed to modify single strands of DNA and deposit them on one of the electrodes submerged in the solution inside their electrochemical cell. Though this sounds straightforward, it did require some new chemistry. Led by Karbelkar and undergraduate researcher Rachel Ahlmark '24, the team developed a fast, easy way to attach DNA to electrodes. For this work, the researchers' focus was on attaching DNA, but the "tethering" chemistry they developed can also be used to attach enzymes (protein catalysts), and Furst believes it will be highly useful as a general strategy for modifying carbon electrodes.

Once the single strands of DNA were deposited on the electrode, the researchers synthesized complementary strands and attached to them one of the three catalysts. When the DNA strands with the catalyst were added to the solution in the electrochemical cell, they readily hybridized with the DNA strands on the electrode. After half an hour, the researchers applied a voltage to the electrode to chemically convert CO_2 dissolved in the solution and used a gas chromatograph to analyze the makeup of the gases produced by the conversion.

The team found that when the DNA-linked catalysts were freely dispersed in the solution, they were highly soluble—even when they included small-molecule catalysts that don't dissolve in water on their own. Indeed, while porphyrin-based

The researchers test and compare the performance of their catalysts using this sealed electrochemical cell. Here, an electrode modified with the catalyst is readied for testing. Once the electrochemical reaction begins, the generated gases will collect in the space above the solution, where they can be sampled and analyzed. Photo: Gretchen Ertl



Impact on CO generation of immobilizing catalysts with DNA. In this figure, each pair of bars presents results with one of the three catalysts tested. The left-hand bar shows CO generated per minute with the unmodified catalyst in solution. The right-hand bar shows CO generated per minute with the same catalyst modified with DNA and immobilized on the electrode. Immobilization significantly increases the rate of CO output, regardless of the molecule used as the catalyst.

catalysts in solution often stick together, once the DNA strands were attached, that counterproductive behavior was no longer evident.

The DNA-linked catalysts in solution were also more stable than their unmodified counterparts. They didn't degrade at voltages that caused the unmodified catalysts to degrade. "So just attaching that single strand of DNA to the catalyst in solution makes those catalysts more stable," says Furst. "We don't even have to put them on the electrode surface to see improved stability." When converting CO_2 in this way, a stable catalyst will give a steady current over time. Experimental results presented in the figure on page 18 show that adding the DNA prevented the catalyst from degrading at voltages of interest for practical devices. Moreover, with all three catalysts in solution, the DNA modification significantly increased the production of CO per minute.

Allowing the DNA-linked catalyst to hybridize with the DNA connected to the electrode brought further improvements, even compared to the same DNA-linked catalyst in solution. For example, as a result of the DNA-directed assembly, the catalyst ended up firmly attached to the electrode, and the catalyst stability was further enhanced. Despite being highly soluble in aqueous solutions, the DNA-linked catalyst molecules remained hybridized at the surface of the electrode, even under harsh experimental conditions.

Immobilizing the DNA-linked catalyst on the electrode also significantly increased the rate of CO production. The figure above shows the CO production rate with each of the team's catalysts in solution without attached DNA strands—the conventional setup—and then with them immobilized by DNA on the electrode. With all three catalysts, the amount of CO generated per minute was far higher when the DNA-linked catalyst was immobilized on the electrode.

In addition, immobilizing the DNA-linked catalyst on the electrode greatly increased the "selectivity" in terms of the products. One persistent challenge in using CO_2 to generate CO in aqueous solutions is that there is an inevitable competition between the formation of CO and the formation of hydrogen. That tendency was eased by adding DNA to the catalyst in solution—and even more so when the catalyst was immobilized on the electrode using DNA. For both the cobalt-porphyrin catalyst and the hemin-based catalyst, the formation of CO relative to hydrogen was significantly higher with the DNA-linked catalyst on the electrode than in solution. With the iron-porphyrin catalyst they were about the same. "With the iron, it doesn't matter whether it's in solution or on the electrode," Furst explains. "Both of them have selectivity for CO, so that's good, too."

Progress and plans

Furst and her team have now demonstrated that their DNA-based approach combines the advantages of the traditional solid-state catalysts and the newer small-molecule ones. In their experiments, they achieved the highly efficient chemical conversion of CO_2 to CO and also were able to control the mix of products formed. And they believe that their technique should prove scalable: DNA is inexpensive and widely available, and the amount of catalyst required is several orders of magnitude lower when it's immobilized using DNA.

Based on her work thus far, Furst hypothesizes that the structure and spacing of the small molecules on the electrode may directly impact both catalytic efficiency and product selectivity. Using DNA to control the precise positioning of her small-molecule catalysts, she plans to evaluate those impacts and then extrapolate design parameters that can be applied to other classes of energy-conversion catalysts. Ultimately, she hopes to develop a predictive algorithm that researchers can use as they design electrocatalytic systems for a wide variety of applications.

NOTES

This research was supported by a grant from the MIT Energy Initiative Seed Fund. Further information can be found in:

G. Fan, N. Corbin, T. Gill, A. Karbelkar, and A. Furst. "DNA-based immobilization for improved electrochemical carbon dioxide reduction." *ChemRxiv*, Cambridge Open Engage, 2022. Online: doi.org/10.26434/chemrxiv-2022-qll2k.

MIT announces five flagship projects in first-ever Climate Grand Challenges competition

The winners of the first-ever Climate Grand Challenges will become multiyear flagship research projects, helping define a new research agenda focused on addressing complex unsolved climate problems and bringing high-impact solutions to the world on an accelerated basis.
Photo: Bearwalk Cinema

On April 11, 2022, MIT announced the five flagship projects selected in its first-ever Climate Grand Challenges competition. These multiyear projects will define a dynamic research agenda focused on unraveling some of the toughest unsolved climate problems and bringing high-impact, science-based solutions to the world on an accelerated basis.

Representing the most promising concepts to emerge from the two-year competition, the five flagship projects will receive additional funding and resources from MIT and others to develop their ideas and swiftly transform them into practical solutions at scale.

"Climate Grand Challenges represents a whole-of-MIT drive to develop game-changing advances to confront the escalating climate crisis, in time to make a difference," says MIT President L. Rafael Reif. "We are inspired by the creativity and boldness of the flagship ideas and by their potential to make a significant contribution to the global climate response. But given the planet-wide scale of the challenge, success depends on partnership. We are eager to work with visionary leaders in every sector to accelerate this impact-oriented research, implement serious solutions at scale, and inspire others to join us in confronting this urgent challenge for humankind."

Brief descriptions of the five Climate Grand Challenges flagship projects are provided below.

Bringing computation to the climate challenge

This project leverages advances in artificial intelligence, machine learning, and data sciences to improve the accuracy of climate models and make them more useful to a variety of stakeholders—from communities to industry. The team is developing a digital twin of the Earth that harnesses more data than ever before to reduce and quantify uncertainties in climate projections.

Research leads: Raffaele Ferrari, the Cecil and Ida Green Professor of Oceanography in the Department of Earth, Atmospheric and Planetary Sciences, and director of the Program in Atmospheres, Oceans, and Climate; and Noelle Eckley Selin, director of the Technology and Policy Program and professor with a joint appointment in the Institute for Data, Systems, and Society and the Department of Earth, Atmospheric and Planetary Sciences

Center for Electrification and Decarbonization of Industry

This project seeks to reinvent and electrify the processes and materials behind hard-to-decarbonize industries such as steel, cement, ammonia, and ethylene production. A new innovation hub will perform targeted fundamental research and engineering with urgency, pushing the technological envelope on electricity-driven chemical transformations.

Research leads: Yet-Ming Chiang, the Kyocera Professor of Materials Science and Engineering, and Bilge Yildiz, the Breene M. Kerr Professor in the Department of Nuclear Science and Engineering and professor in the Department of Materials Science and Engineering

Preparing for a new world of weather and climate extremes

This project addresses key gaps in knowledge about intensifying extreme events such as floods, hurricanes, and heat waves, and quantifies their long-term risk in a changing climate. The team is developing a scalable climate-change adaptation toolkit to help vulnerable communities and low-carbon energy providers prepare for these extreme weather events.

Research leads: Kerry Emanuel, the Cecil and Ida Green Professor of Atmospheric Science in the Department of Earth, Atmospheric and Planetary

At the Climate Grand Challenges showcase event on April 21, 2022, U.S. Special Presidential Envoy for Climate John Kerry (left) and MIT President L. Rafael Reif discuss strategies to help the world avert the worst consequences of climate change and make the United States a leader again in bringing technology into commercial use. Read more about the event at bit.ly/CGC-event. Photo: Gretchen Ertl

Sciences and co-director of the MIT Lorenz Center; Miho Mazereeuw, associate professor of architecture and urbanism in the Department of Architecture and director of the Urban Risk Lab; and Paul O'Gorman, professor in the Program in Atmospheres, Oceans, and Climate in the Department of Earth, Atmospheric and Planetary Sciences

The Climate Resilience Early Warning System

The CREWSnet project seeks to reinvent climate change adaptation with a novel forecasting system that empowers underserved communities to interpret local climate risk, proactively plan for their futures by incorporating resilience strategies, and minimize losses. CREWSnet will initially be demonstrated in southwestern Bangladesh, serving as a model for similarly threatened regions around the world.

Research leads: John Aldridge, assistant leader of the Humanitarian Assistance and Disaster Relief Systems Group at MIT Lincoln Laboratory, and Elfatih Eltahir, the H.M. King Bhumibol Professor of Hydrology and Climate in the Department of Civil and Environmental Engineering

Revolutionizing agriculture with low-emissions, resilient crops

This project works to revolutionize the agricultural sector with climate-resilient crops and fertilizers that have the ability to dramatically reduce greenhouse gas emissions from food production.

Research lead: Christopher Voigt, the Daniel I.C. Wang Professor in the Department of Biological Engineering

"As one of the world's leading institutions of research and innovation, it is incumbent upon MIT to draw on our depth of knowledge, ingenuity, and ambition to tackle the hard climate problems now confronting the world," says Richard Lester, MIT associate provost for international activities. "Together with collaborators across industry, finance, community, and government, the Climate Grand Challenges teams are looking to develop and implement high-impact, path-breaking climate solutions rapidly and at a grand scale."

The initial call for ideas in 2020 yielded nearly 100 letters of interest from almost 400 faculty members and senior researchers, representing 90% of MIT departments. After an extensive evaluation, 27 finalist teams received a total of $2.7 million to develop comprehensive research and innovation plans. The projects address four broad research themes:

- Building equity and fairness into climate solutions
- Decarbonizing complex industries and processes
- Removing, managing, and storing greenhouse gases
- Using data and science to forecast climate-related risk

To select the winning projects, research plans were reviewed by panels of international experts representing relevant scientific and technical domains as well as experts in processes and policies for innovation and scalability.

"In response to climate change, the world really needs to do two things quickly: deploy the solutions we already have much more widely, and develop new solutions that are urgently needed to tackle this intensifying threat," says Maria Zuber, MIT vice president for research. "These five flagship projects exemplify MIT's strong determination to bring its knowledge and expertise to bear in generating new ideas and solutions that will help solve the climate problem."

"The Climate Grand Challenges flagship projects set a new standard for inclusive climate solutions that can be adapted and implemented across the globe," says MIT Chancellor Melissa Nobles. "This competition propels the entire MIT research community—faculty, students, postdocs, and staff—to act with urgency around a worsening climate crisis, and I look forward to seeing the difference these projects can make."

"MIT's efforts on climate research amid the climate crisis was a primary reason that I chose to attend MIT, and remains a reason that I view the Institute favorably. MIT has a clear opportunity to be a thought leader in the climate space in our own MIT way, which is why CGC fits in so well," says Megan Xu '22, who served on the Climate Grand Challenges student committee and is studying ways to make the food system more sustainable.

The Climate Grand Challenges competition is a key initiative of "Fast Forward: MIT's Climate Action Plan for the Decade," which the Institute published in May 2021. Fast Forward outlines MIT's comprehensive plan for helping the world address the climate crisis. It consists of five broad areas of action: sparking innovation, educating future generations, informing and leveraging government action, reducing MIT's own climate impact, and uniting and coordinating all of MIT's climate efforts.

MIT News Office

Center for Electrification and Decarbonization of Industry: Uniting MIT climate researchers to create scalable clean energy solutions under one roof

On April 11, 2022, MIT announced five multiyear flagship projects in the first-ever Climate Grand Challenges competition (see the article on page 21). Subsequently, MIT News published articles focusing on each of the flagship projects and the interdisciplinary research teams behind them. All of the flagship projects highlight MIT's commitment to combat climate change. We're republishing the story about the flagship project devoted to the decarbonization of industry. Decarbonization of industry is a key focus of research at the MIT Energy Initiative (MITEI), and this flagship effort is led by two faculty members who are deeply engaged at MITEI.

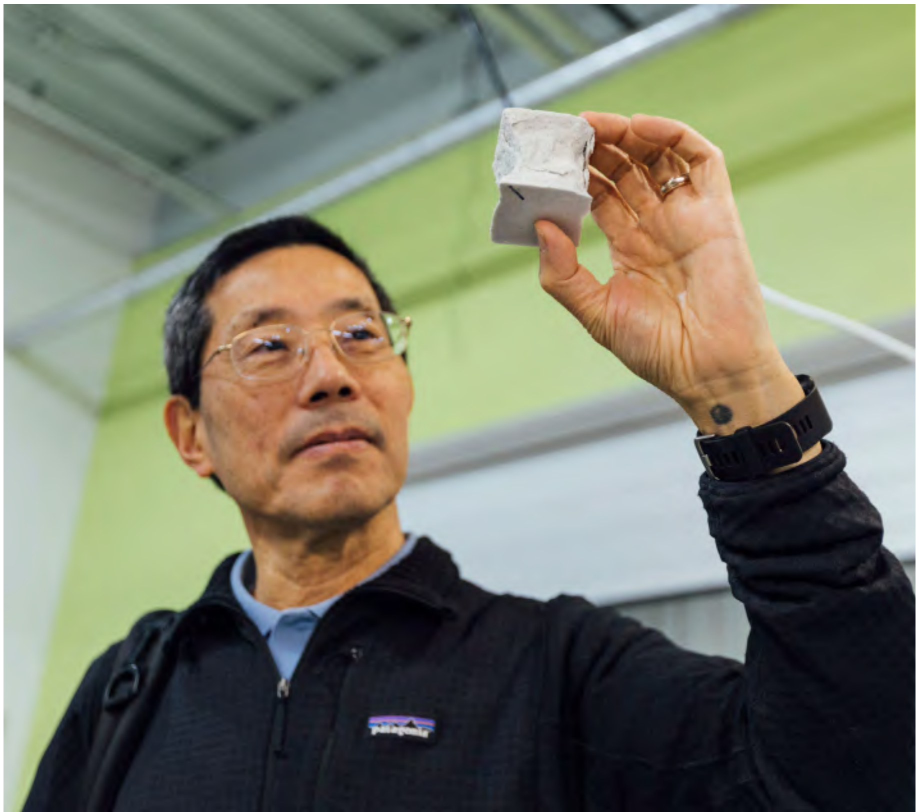
One of the biggest leaps that humankind could take to drastically lower greenhouse gas emissions globally would be the complete decarbonization of industry. But without finding low-cost, environmentally friendly substitutes for industrial materials, the traditional production of steel, cement, ammonia, and ethylene will continue pumping out billions of tons of carbon annually; these sectors alone are responsible for at least one-third of society's global greenhouse gas emissions.

A major problem is that industrial manufacturers, whose success depends on reliable, cost-efficient, and large-scale production methods, are too heavily invested in processes that have historically been powered by fossil fuels to quickly switch to new alternatives. It's a machine that kicked on more than 100 years ago, and which MIT electrochemical engineer Yet-Ming Chiang says we can't shut off without major disruptions to the world's massive supply chain of these materials. What's needed, Chiang says, is a broader, collaborative clean energy effort that takes "targeted fundamental research all the way through to pilot demonstrations that greatly lower the risk for adoption of new technology by industry."

This would be a new approach to decarbonization of industrial materials production that relies on largely unexplored but cleaner electrochemical processes. New production methods could be optimized and integrated into the industrial machine to make it run on low-cost, renewable electricity in place of fossil fuels.

Recognizing this, Chiang, the Kyocera Professor in the Department of Materials Science and Engineering, teamed with research collaborator Bilge Yildiz, the Breene M. Kerr Professor of Nuclear Science and Engineering and professor of materials science and engineering, with key input from Karthish Manthiram, visiting professor in the Department of Chemical Engineering, to submit a project proposal to the MIT Climate Grand Challenges. Their plan: to create an innovation hub on campus that would bring together MIT researchers individually investigating decarbonization of steel, cement, ammonia, and ethylene under one roof, combining research equipment and directly collaborating on new methods to produce these four key materials.

Many researchers across MIT have already signed on to join the effort, including Antoine Allanore, associate professor of metallurgy, who specializes in the development of sustainable materials and manufacturing processes, and Elsa Olivetti, the Esther and Harold E. Edgerton Associate Professor in the Department of Materials Science and Engineering, who is an expert in materials economics and sustainability. Other MIT faculty currently involved include Fikile Brushett, Betar Gallant, Ahmed Ghoniem, William Green, Jeffrey Grossman, Ju Li, Yuriy Román-Leshkov, Yang Shao-Horn, Robert Stoner, Yogesh Surendranath, Timothy Swager, and Kripa Varanasi.



Professor Yet-Ming Chiang holds a mechanical test specimen of decarbonized cement. Photo: Bearwalk Cinema

"The team we brought together has the expertise needed to tackle these challenges, including electrochemistry—using electricity to decarbonize these chemical processes—and materials science and engineering, process design and scale-up techno-economic analysis, and system integration, which is all needed for this to go out from our labs to the field," says Yildiz.

Selected from a field of more than 100 proposals, their Center for Electrification and Decarbonization of Industry (CEDI) will be the first such institute worldwide dedicated to testing and scaling the most innovative and promising technologies in sustainable chemicals and materials. CEDI will work to facilitate rapid translation of lab discoveries into affordable, scalable industry solutions, with the potential to offset as much as 15% of greenhouse gas emissions. The team estimates that some CEDI projects already underway could be commercialized within three years.

"The real timeline is as soon as possible," says Chiang.

To achieve CEDI's ambitious goals, a physical location is key, staffed with permanent faculty as well as undergraduates, graduate students, and postdocs. Yildiz says the center's success will depend on engaging student researchers to carry forward with research addressing the biggest ongoing challenges to decarbonization of industry.

"We are training young scientists, students, on the learned urgency of the problem," says Yildiz. "We empower them with the skills needed, and even if an individual project does not find the implementation in the field right away, at least we would have trained the next generation that will continue to go after them in the field."

Chiang's background in electrochemistry showed him how the efficiency of cement production could benefit from adopting clean electricity sources, and Yildiz's work on ethylene, the source of plastic and one of industry's most valued chemicals, has revealed overlooked cost benefits to switching to electrochemical processes with less expensive starting materials.

Professor Bilge Yildiz (left) in conversation with her PhD students Filip Grajkowski (middle) and Sophie Wallant (right) in her laboratory. Photo: Bearwalk Cinema

With industry partners, they hope to continue these lines of fundamental research along with Allanore, who is focused on electrifying steel production, and Manthiram, who is developing new processes for ammonia. Olivetti will focus on understanding risks and barriers to implementation. This multilateral approach aims to speed up the timeline to industry adoption of new technologies at the scale needed for global impact.

"One of the points of emphasis in this whole center is going to be applying techno-economic analysis of what it takes to be successful at a technical and economic level, as early in the process as possible," says Chiang.

The impact of large-scale industry adoption of clean energy sources in the four key areas that CEDI plans to target first would be profound, as these sectors are currently responsible for 7.5 billion tons of emissions annually. There is the potential for even greater impact on emissions as new knowledge is applied to other industrial products beyond the initial four targets of steel, cement, ammonia, and ethylene. Meanwhile, the center will stand as a hub to attract new industry, government stakeholders, and research partners to collaborate on urgently needed solutions, both newly arising and long overdue.

When Chiang and Yildiz first met to discuss ideas for MIT Climate Grand Challenges, they decided they wanted to build a climate research center that functioned unlike any other to help pivot large industry toward decarbonization. Beyond considering how new solutions will impact industry's bottom line, CEDI will also investigate unique synergies that could arise from the electrification of industry, such as processes that would create new byproducts that could be the feedstock to other industry processes, reducing waste and increasing efficiencies in the larger system. And because industry is so good at scaling, those added benefits would be widespread, finally replacing century-old technologies with critical updates designed to improve production and markedly reduce industry's carbon footprint sooner rather than later.

"Everything we do, we're going to try to do with urgency," Chiang says. "The fundamental research will be done with urgency, and the transition to commercialization, we're going to do with urgency."

Ashley Belanger, MIT School of Engineering

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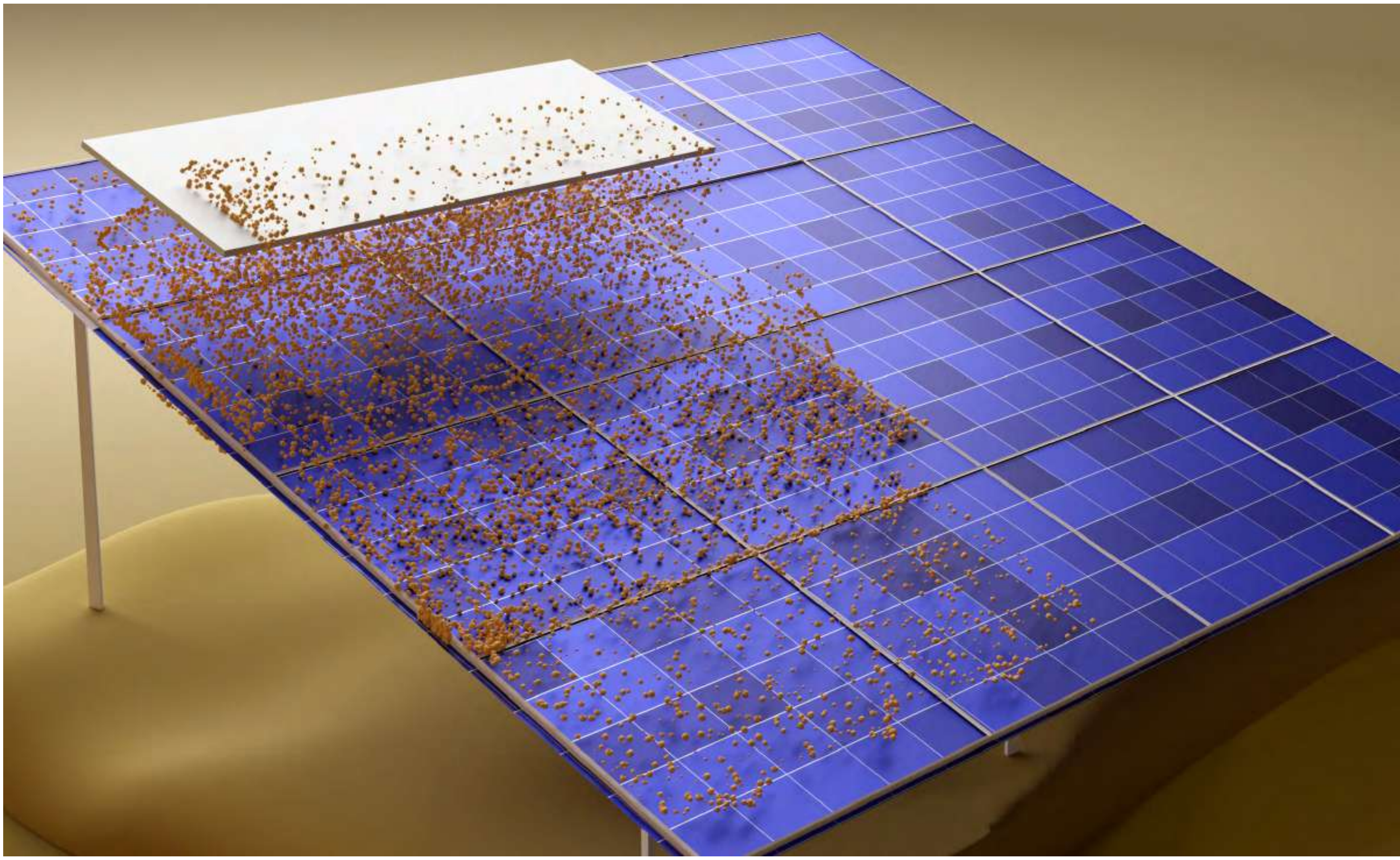
How to remove dust on solar panels without using water, improving overall efficiency

Solar power is expected to reach 10% of global power generation by the year 2030, and much of that is likely to be located in desert areas, where sunlight is abundant. But the accumulation of dust on solar panels or mirrors is already a significant issue—it can reduce the output of photovoltaic panels by as much as 30% in just one month—so regular cleaning is essential for such installations.

But cleaning solar panels currently is estimated to use about 10 billion gallons of water per year—enough to supply drinking water for up to 2 million people. Attempts at waterless cleaning are labor-intensive and tend to cause irreversible scratching of the surfaces, which also reduces efficiency. Now, a team of researchers at MIT has devised a way of automatically cleaning solar panels, or the mirrors of solar thermal plants, in a waterless, no-contact system that could significantly reduce the dust problem, they say.

The new system uses electrostatic repulsion to cause dust particles to detach and virtually leap off the panel's surface, without the need for water or brushes. To activate the system, a simple electrode passes just above the solar panel's surface, imparting an electrical charge to the dust particles, which are then repelled by a charge applied to the panel itself. The system can be operated automatically using a simple electric motor and guide rails along the side of the panel. The research is described in a paper in *Science Advances* by MIT graduate student Sreedath Panat and professor of mechanical engineering Kripa Varanasi.

Despite concerted efforts worldwide to develop ever more efficient solar panels, Varanasi says, "a mundane problem like dust can actually put a serious dent in the whole thing." Lab tests conducted by Panat and Varanasi showed that the dropoff of energy output from the panels happens steeply at the very beginning of the process of dust accumulation and can easily reach 30% reduction after just one month without cleaning. Even a 1% reduction in power, for a 150-megawatt solar installation, they calculated, could result in a $200,000 loss in annual



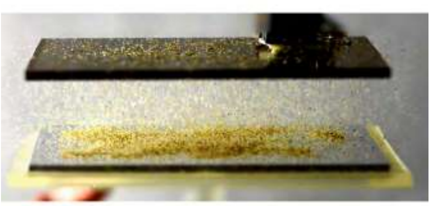
Dust that accumulates on solar panels is a major problem, but washing the panels uses huge amounts of water. MIT engineers have now developed a waterless cleaning method to remove dust on solar installations in water-limited regions, improving overall efficiency. Image courtesy of the researchers revenue. The researchers say that globally, a 3% to 4% reduction in power output from solar plants would amount to a loss of between $3.3 billion and $5.5 billion.

"There is so much work going on in solar materials," Varanasi says. "They're pushing the boundaries, trying to gain a few percent here and there in improving the efficiency, and here you have something that can obliterate all of that right away."

Many of the largest solar power installations in the world, including ones in China, India, the United Arab Emirates, and the United States, are located in desert regions. The water used for cleaning these solar panels using pressurized water jets has to be trucked in from a distance, and it has to be very pure to avoid leaving behind deposits on the surfaces. Dry scrubbing is sometimes used but is less effective at cleaning the surfaces and can cause permanent scratching that also reduces light transmission.

The new system uses electrostatic repulsion to cause dust particles to detach and virtually leap off the panel's surface, without the need for water or brushes.
Image courtesy of the researchers

Voltage off



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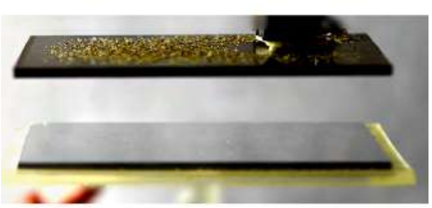

Voltage off

Water cleaning makes up about 10% of the operating costs of solar installations. The new system could potentially reduce these costs while improving the overall power output by allowing for more frequent automated cleanings, the researchers say.

"The water footprint of the solar industry is mind-boggling," Varanasi says, and it will be increasing as these installations continue to expand worldwide. "So, the industry has to be very careful and thoughtful about how to make this a sustainable solution."

Other groups have tried to develop electrostatic-based solutions, but these have relied on a layer called an electrodynamic screen, using interdigitated electrodes. These screens can have defects that allow moisture in and cause them to fail, Varanasi says. While they might be useful on a place like Mars, he says, where moisture is not an issue, even in desert environments on Earth this can be a serious problem.

The new system they developed only requires an electrode, which can be a simple metal bar, to pass over the panel, producing an electric field that imparts a charge to the dust particles as it goes. An opposite charge applied to a transparent conductive layer just a few nanometers thick deposited on the glass covering of the solar panel then repels the particles, and by calculating the right voltage to apply, the researchers were able to find a voltage range sufficient to overcome the pull of gravity and adhesion forces, and cause the dust to lift away.

Using specially prepared laboratory samples of dust with a range of particle sizes, experiments proved that the process works effectively on a laboratory-scale test installation, Panat says. The tests showed that humidity in the air provided a thin coating of water on the particles, which turned out to be crucial to making the effect work. "We performed experiments at varying humidities from 5% to 95%," Panat says. "As long as the ambient humidity is greater than 30%, you can remove almost all of the particles from the surface, but as humidity decreases, it becomes harder."

Varanasi says that "the good news is that when you get to 30% humidity, most deserts actually fall in this regime." And even those that are typically drier than that tend to have higher humidity in the early morning hours, leading to dew formation, so the cleaning could be timed accordingly.

"Moreover, unlike some of the prior work on electrodynamic screens, which actually do not work at high or even moderate humidity, our system can work at humidity even as high as 95%, indefinitely," Panat says.

In practice, at scale, each solar panel could be fitted with railings on each side, with an electrode spanning across the panel. A small electric motor, perhaps using a tiny portion of the output from the panel itself, would drive a belt system to move the electrode from one end of the panel to the other, causing all the dust to fall away. The whole process could be automated or controlled remotely. Alternatively, thin strips of conductive transparent material could be permanently arranged above the panel, eliminating the need for moving parts.

By eliminating the dependency on trucked-in water, by eliminating the buildup of dust that can contain corrosive compounds, and by lowering the overall operational costs, such systems have the potential to significantly improve the overall efficiency and reliability of solar installations, Varanasi says.

This research was supported by Italian energy firm Eni S.p.A. through the MIT Energy Initiative. The paper, "Electrostatic dust removal using adsorbed moisture-assisted charge induction for sustainable operation of solar panels," by Sreedath Panat and Kripa K. Varanasi, appeared in the March 11, 2022, issue of *Science Advances* and is available online at doi.org/10.1126/sciadv.abm0078.

David L. Chandler, MIT News Office

What choices does the world need to make to keep global warming below two degrees Celsius?

Using a unique modeling strategy, researchers at the MIT Joint Program on the Science and Policy of Global Change find several possible patterns of energy and technology development under a specified long-term climate target or economic outcome. Photo: Ron Gilbert/Flickr

When the 2015 Paris Agreement set a long-term goal of keeping global warming "well below two degrees Celsius, compared to pre-industrial levels" to avoid the worst impacts of climate change, it did not specify how its nearly 200 signatory nations could collectively achieve that goal. Each nation was left to its own devices to reduce greenhouse gas emissions in alignment with the 2°C target. Now a new modeling strategy developed at the MIT Joint Program on the Science and Policy of Global Change that explores hundreds of potential future development pathways provides new insights on the energy and technology choices needed for the world to meet that target.

Described in a study appearing in the journal *Earth's Future*, the new strategy combines two well-known computer modeling techniques to scope out the energy and technology choices needed over the coming decades to reduce emissions sufficiently to achieve the Paris goal.

The first technique, Monte Carlo analysis, quantifies uncertainty levels for dozens of energy and economic indicators including fossil fuel availability, advanced energy technology costs, and population and economic growth; feeds that information into a multi-region, multi-economic-sector model of the world economy that captures the cross-sectoral impacts of energy transitions; and runs that model hundreds of times to estimate the likelihood of different outcomes. The MIT study focuses on projections through the year 2100 of economic growth and emissions for different sectors of the global economy, as well as energy and technology use.

The second technique, scenario discovery, uses machine learning tools to screen databases of model simulations in order to identify outcomes of interest and their conditions for occurring. The MIT study applies these tools in a unique way by combining them with the Monte Carlo analysis to explore how different outcomes are related to one another (e.g., do low-emission outcomes necessarily involve large shares of renewable electricity?). This approach can also identify individual scenarios, out of the hundreds explored, that result in specific combinations of outcomes of interest (e.g., scenarios with low emissions, high GDP growth, and limited impact on electricity prices), and also provide insight into the conditions needed for that combination of outcomes.

Using this unique approach, the MIT Joint Program researchers find several possible patterns of energy and technology development under a specified long-term climate target or economic outcome.

"This approach shows that there are many pathways to a successful energy transition that can be a win-win for the environment and economy," says Jennifer Morris SM '09, PhD '13, a research scientist in the MIT Joint Program and the MIT Energy Initiative and the study's lead author. "Toward that end, it can be used to guide decision makers in government and industry to make sound energy and technology choices and avoid biases in perceptions of what 'needs' to happen to achieve certain outcomes."

For example, while achieving the 2°C goal, the global level of combined wind and solar electricity generation by 2050 could be less than three times or more than 12 times the current level (which is just over 2,000 terawatt hours). These are very different energy pathways, but both can be consistent with the 2°C goal. Similarly, there are many different energy mixes that can be consistent with maintaining high GDP growth in the United States while also achieving the 2°C goal, with different possible roles for renewables, natural gas, carbon capture and storage, and bioenergy. The study finds renewables to be the most robust electricity investment option, with sizable growth projected under each of the long-term temperature targets explored.

The researchers also find that long-term climate targets have little impact on economic output for most economic sectors through 2050, but do require each sector to significantly accelerate reduction of its greenhouse gas emissions intensity (emissions per unit of economic output) so as to reach near-zero levels by midcentury.

"Given the range of development pathways that can be consistent with meeting a 2°C goal, policies that target only specific sectors or technologies can unnecessarily narrow the solution space, leading to higher costs," says former MIT Joint Program Co-Director John Reilly, a senior lecturer in the MIT Sloan School of Management and a co-author of the study. "Our findings suggest that policies designed to encourage a portfolio of technologies and sectoral actions can be a wise strategy that hedges against risks."

This research was supported by the U.S. Department of Energy Office of Science. The paper, "Representing socio-economic uncertainty in human system models," by Jennifer Morris, John Reilly, Sergey Paltsev, Andrei Sokolov, and Kenneth Cox, appeared in *Earth's Future*, volume 10, number 4, 2022; it is available online at doi.org/10.1029/2021EF002239.

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

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New class explores paths to reducing transportation emissions

Transportation is responsible for nearly a quarter of all energy-related carbon dioxide (CO_2) emissions worldwide, making decarbonizing the sector critical to reducing carbon emissions and addressing climate change. Last fall, MIT unveiled a new course—11.149/11.449 Decarbonizing Urban Mobility—to introduce students to the factors involved in addressing this complex challenge.

"We want people to be grounded in reality so they can make good decisions about what it takes to get to zero carbon emissions," says Andrew Salzberg, a lecturer in MIT's Department of Urban Studies and Planning. The former head of transportation policy at Uber, Salzberg taught the class together with Jinhua Zhao, the Edward and Joyce Linde Associate Professor of City and Transportation Planning and director of the MIT Mobility Initiative.

"This course, the first of its kind at MIT, works to place transportation in the context of broader decarbonization efforts while also situating the decarbonization challenge in the specific landscape of transportation planning," Zhao says. "Transportation is now the leading source of carbon pollution in the United States. This is a unique moment that calls for a course specifically and narrowly focused on decarbonization in urban mobility."

Urban mobility is an important focus because cities are at the epicenter of the technology revolution taking place in mobility—with new options such as ride sharing, autonomous vehicles, and passenger drones. Nevertheless, transportation has proved stubbornly difficult to decarbonize—making the sector ripe for further study, Zhao says.

Transportation presents a special challenge because it involves just about everyone, Salzberg adds. "We're talking about hundreds of millions of vehicles, almost all burning fossil fuels. So, there are a great many decision makers who are choosing how they want to get around," he says. "You have to win a lot of hearts and minds. So, that makes it hard."

The complexity of the topic came as a surprise to Purvaja Balaji '24, a computer science and engineering major who took the inaugural class in fall 2021. "I thought if everyone just adopted electric vehicles and took public transportation, we'd be good," she says. Instead, Balaji learned that many factors contribute to the problem, including how far people need to travel, the fuel efficiency of vehicles, and the amount of carbon emitted to power vehicles—even electric cars, which can draw power from either renewable or fossil-fueled sources.

There are also myriad possible solutions—including not only the adoption of more energy-efficient modes of transportation but also policy approaches such as establishing low emission zones or imposing carbon taxes.

"When you talk about decarbonizing transportation, two main themes are to approach it with technology—electric cars, clean energy, et cetera—or through the policy side. We tried to emphasize to students that just one or the other was not going to be a sufficient approach given the scale of the problem," says Nicholas Caros, a PhD student in civil and environmental engineering who served as the teaching assistant for the class. "Hopefully this expanded their thinking."

"Decarbonizing transportation is a hot topic, so there's a lot of information out there, but it's hard to understand what you should prioritize," says Naroa Coretti Sánchez, a PhD student in the Media Lab who took the class, which was open to both undergraduate and graduate students. "They don't give you the answers, of course, but it's a very good class in the sense that you start to understand that these are the tools that we have, these are the potential impacts, and these are the challenges."

Cutting carbon emissions from transportation in cities is an essential feature of any strategy to address climate change. During an MIT course first offered in fall 2021, students learned the challenges involved in designing an effective strategy for decarbonizing urban mobility, given the many technology and policy options available. Image: Panimoni/Shutterstock

Quantitative approach

To help students assess decarbonizing options, the faculty began by introducing a mathematical construct known as the Kaya identity, which uses factors such as population, gross domestic product, and energy consumption data to quantify how much human sources contribute to carbon emissions. "It's MIT, so it helps to be quantitative when we can," Salzberg says.

Caros explains that transportation emissions are also broken down into contributing factors, with each providing a lever for control. The components of a commute by car, for example, would include how energy-efficient the vehicle is but also the distance traveled. So, while technology can make the vehicle more energy-efficient, working from home could reduce emissions even further—which was a key takeaway for Coretti. "One of the biggest lessons from the class is the importance of reducing the vehicle miles traveled," she says.

Similarly, while public transportation can often be a better choice in terms of emissions, that's not invariably the case. "If you're the only person on the bus, taking it might be a worse decision than driving by yourself," Caros says.

To illustrate such trade-offs, in one assignment the instructors gave students a simple spreadsheet tool and asked them to design their own pathways to reducing Boston's carbon emissions. It was a sobering exercise, Salzberg says, because even in a city like Boston with fairly robust public transportation options, it's hard to find alternatives to driving for long distances.

Students were also assigned to debate decarbonization solutions. They could choose either to reduce vehicle miles traveled or to "electrify everything"—but after choosing their topics, Salzberg had the students argue the opposing point of view. "That was a very good experience," Coretti says. "I was going to argue for reducing vehicle miles traveled. Then I switched to electrification and learned that there are also very valid arguments for that option."

Learning from experts

Over the course of the semester, students heard from more than a dozen guest speakers on topics ranging from city planning to the power generation needs of electric vehicles. "We've never decarbonized transportation, so you can't look back to get those lessons. We're trying to learn from people who are doing it as we speak," Salzberg says.

Reid Ewing, a professor of city and metropolitan planning at the University of Utah, explained that city design directly impacts transportation emissions since people in dense cities, such as New York or Boston, don't have to travel as far for everyday activities as do residents of sprawling cities such as Houston.

Nathaniel Horadam, a managing consultant at the nonprofit Center for Transportation and the Environment, illuminated the challenges of switching to battery-powered electric buses. "They don't work very well in the cold, the batteries don't perform as well, and you have to heat the bus," Caros says.

Balaji says she most enjoyed the talk by Greg Rogers from Nuro, a robotics company that makes autonomous, zero-emission delivery vehicles. "It was interesting to hear his perspective on how that kind of transportation will impact climate change," she says.

A variety of solutions

For the final assignment, Salzberg and Zhao asked students to lay out a strategy for reducing emissions in a city of their choice. Proposed solutions varied from electrifying New York City's taxi fleet to revamping the parking requirements for new buildings in San Diego. Balaji, for example, focused on the advantages of electrifying Boston's bus fleet. Coretti—who is working on autonomous bicycles for her PhD research—examined the impact on emissions of enabling shared bicycles to relocate themselves to spots where they are most needed; currently trucks are often used for this job.

"We gave them no constraints," Salzberg says. "The range of projects—from parking standards to bike lane design—felt like a real endorsement of the whole idea of the course, which is that there is a wide range of solutions that we should be talking about together."

For Coretti, the assignment underscored her main takeaway from the class: "You have to do a lot of everything to meet the climate target."

Salzberg and Zhao note that 11.149/11.449 Decarbonizing Urban Mobility will be held again in fall 2022. Down the line, the class will also be publicly available to online audiences via MITx thanks to a project supported by the MIT Energy Initiative and underwritten in part by a grant from the UN Habitat Programme.

Kathryn M. O'Neill, MITEI correspondent

Lessons from energy leaders: IAP course connects MIT and global learners with practitioners and experts

MIT engineers and scientists are at the vanguard of developing new technologies to achieve the goal of net-zero carbon emissions by 2050. But there is more that the MIT community could be contributing, believes Angeliki Diane Rigos PhD ’85, associate director of graduate programs for the MIT Energy Initiative (MITEI) and program manager for the MIT Center for Enhanced Nanofluidic Transport.

“We need to think of ourselves as leading the energy transition, not just participating in it,” she says. “We tend to be siloed at MIT and don’t talk enough to people in the real world.”

To address this shortcoming, Rigos designed the course “Leading the Energy Transition” for January’s Independent Activities Period (IAP) featuring guest instructors with expertise in addressing the complex challenges that arise when low-carbon mandates meet social, political, and economic realities.

“Leading change is difficult, requiring different strategies for different situations and the capacity to adjust to new problems,” says Rigos, whose varied career includes stints as a research scientist, professor, industry consultant, and mentor to clean technology entrepreneurs.

Among the speakers for this virtual IAP class were current and former heads of federal and state government agencies, corporate energy representatives, and MITEI policy and technology experts. “By sharing their individual and organizational perspectives on advancing the energy transition, I hoped to inspire our students to believe they could lead their own initiatives,” says Rigos.

Where the gears are turning

As an economist whose research falls at the intersection of energy, climate, and poverty alleviation, Andrea Cristina Ruiz signed up for the IAP class “to get a survey understanding of the different lenses that could be applied to understand the energy transition,” she says. A manager of the Energy, Environment, and Climate Change Sector at the Abdul Latif Jameel Poverty Action Lab (J-PAL) at the time of the course, Ruiz was charged with advancing the use of evidence and promoting evidence-based policy making toward equitable and cost-effective climate change policies and interventions.

“I wanted to see where the gears are turning in scientific, technological, and other communities which are all part of the solution, to understand how I fit in,” says Ruiz, who is now an economist at the Eastern Research Group, an environmental consulting firm. “The course gave me an interdisciplinary, nuanced, and holistic take on key challenges in the energy transition—a transition that is essential if we want to avert the worst impacts of climate change,” she says.

Image: Jenn Schlick, MITEI

Some of the insights she found particularly useful came from Emre Gençer, a MITEI research scientist who weighs the costs and benefits of new, carbon-reducing technologies based on cradle-to-grave emissions. In his presentation, Gençer outlined the importance of moving as swiftly as possible to an all-electric vehicle fleet.

“We must immediately cut emissions, but how we get there is very important,” he said. “Instead of waiting until we have widespread electric charging infrastructure, we can switch from internal combustion engine vehicles (ICEVs) to plug-in hybrids or hybrids immediately.” He also proposed banning ICEVs.

In another session, Christopher Knittel, the George P. Shultz Professor of Energy Economics at the MIT Sloan School of Management and deputy director for policy at MITEI, discussed policy options for driving the energy transition. “Climate change represents a case where markets don’t work well,” he noted, pointing to persistent resistance to the idea of a carbon tax.

Saving the planet will mean paying more for clean energy, so distributing this burden equitably will be central to any successful policy, Knittel suggested. "I care deeply not just about efficiency but about the winners and losers associated with climate change policy," Knittel said. He shared research demonstrating that a small carbon tax, whose dividends are distributed to the most economically vulnerable in society, could have an outsized and rapid impact on emissions.

These presentations "made the dimensions of the climate change problem more accessible," says Ruiz. "I'm not an expert on decarbonization or electrification, but knowing what policies exist and what economic models can be used will help me ask the right questions," she says.

Finding a balance

"Leading the Energy Transition" drew several hundred participants over the duration of the course—from current MIT students and MIT alumni to globally based students and professionals eager to glean ideas for their studies and careers. In course entry surveys, many noted their desire to accelerate the energy transition and identified specific interests in economically and politically feasible paths for decarbonizing the electric grid, commercializing nuclear fusion, and achieving climate justice.

Some students sought a sense of the speakers' personal experiences managing their day-to-day responsibilities and expectations. "What tactics do you find to balance pragmatism about the timelines of technological development with excitement over opportunities for shorter-term impacts?" asked Katherine Papageorge, a fellow in the MIT System Design and Management master's program.

"You can be scared of the scale of the challenge, but finding solutions for the future is really the opportunity of a lifetime," said Lene Hviid, the global key account manager–metals at Shell Energy. "When people come to tell me all the reasons something can't work, I tell them I want to hear *how* we make it work." Hviid also noted that "a lot of technology moves fast, and what we thought we couldn't do two years ago is happening today."

The next generation of leaders in the energy transition must cultivate a unique set of skills, including "a significant amount of patience because no solution is perfect," said Joanna Troy, the director of energy policy and planning at the Commonwealth of Massachusetts. Her job, which involves expanding clean energy across the state and region, requires listening to stakeholders with competing demands.

"The roadmap is always changing, and you need to maintain a certain internal calm, focusing on making decisions with the evidence you have in front of you, and then evaluating and restarting the problem multiple times," she said.

Course participants had ample class time to question practitioners such as Troy and Robert Ethier, the vice president of system planning at ISO New England, not just on the specifics of their jobs but for a glimpse of the future—whether widespread adoption of electric heat pumps, generation of green hydrogen, or a massive buildout of new transmission lines.

What does history teach us?

But instructors also cautioned participants that technological fixes for the future cannot in themselves deliver net-zero carbon results, and even good policy can get sidetracked. Emeritus Institute Professor John M. Deutch, who served as director of the Central Intelligence Agency and in a number of positions for the U.S. Department of Energy—including director of energy research, acting assistant secretary for energy technology, and undersecretary of the department—offered "good and bad lessons from the past 50 years on the country's judgment and pursuit of policies around promising energy technologies."

The Clean Air Act, first passed by Congress in 1963 and then amended in 1970, can be marked a success, he said, since the monetary benefits of reducing pollution were much greater than the expense. But Deutch added that the constant turmoil of American politics, not to mention the threat of wars and economic disruptions, makes it generally more difficult "to organize ourselves to go after big technological changes," he said. "Without harmony, it's hard to solve problems, and in the U.S. currently, we don't have much harmony."

Students pressed Deutch on his apparently gloomy take on the likelihood of securing society's carbon reduction goals. Chumani Mokoena, a master's student in the Department of Nuclear Science and Engineering, asked whether fusion energy and conventional nuclear energy, along with renewables, might "achieve a clean and sustainable economy in three to five decades." Deutch counseled those in the class to "be careful about silver bullets" and that society must "have good public participation to understand and support such efforts."

To Chinenye Nwosu, who works in the energy industry in Nigeria, this was a clear call to leadership: "In countries where the mix of power-generation structures is not improving as quickly as we would like, we need to educate people," she said. "It will be a lot of work, but we must organize to demand concrete action from [both] campaigning and elected politicians toward achieving net zero."

Leda Zimmerman, MITEI correspondent

Joy Dunn '08: Bridging careers in aerospace manufacturing and fusion energy with a focus on intentional inclusion

Joy Dunn '08 spent a decade working in aerospace manufacturing before joining Commonwealth Fusion Systems, where she plays a key role in developing a commercially viable fusion power plant. A consistent theme running through her career has been a commitment to equity and inclusion.
Photo courtesy of Commonwealth Fusion Systems

"A big theme of my life has been focusing on intentional inclusion and how I can create environments where people can really bring their whole authentic selves to work," says Joy Dunn '08. As the head of operations at Commonwealth Fusion Systems, an MIT spinout working to achieve commercial fusion energy, Dunn looks for solutions to the world's greatest climate challenges—while creating an open and equitable work environment where everyone can succeed.

This theme has been cultivated throughout her professional and personal life, including as a Young Global Leader at the World Economic Forum and as a board member at Out for Undergrad, an organization that works with LGBTQ+ college students to help them achieve their personal and professional goals. Through her careers both in aerospace and energy, Dunn has strived to instill a sense of equity and inclusion from the inside out.

Developing a love for space

Dunn's childhood was shaped by space. "I was really inspired as a kid to be an astronaut," she says, "and for me that never stopped." Dunn's parents—both of whom had careers in the aerospace industry—encouraged her from an early age to pursue her interests, from building model rockets to visiting the National Air and Space Museum to attending space camp. A large inspiration for this passion arose when she received a signed photo from Sally Ride—the first American woman in space—that read, "To Joy, reach for the stars."

As her interests continued to grow in middle school, she and her mom looked to see what it would take to become an astronaut, asking questions such as "what are the common career paths?" and "what schools did astronauts typically go to?" They quickly found that MIT was at the top of that list, and by seventh grade, Dunn had set her sights on the Institute.

After years of hard work, Dunn entered MIT in the fall of 2004 with a major in aerospace, aeronautical, and astronautical engineering (AeroAstro). At MIT, she remained fully committed to her passion while also expanding into other activities such as varsity softball, the MIT Undergraduate Association, and the Alpha Chi Omega sorority.

One of the highlights of Dunn's college career was Unified Engineering (Course 16), a year-long course required for all AeroAstro majors that provides a foundational knowledge of aerospace engineering—culminating in a team competition where students design and build remote-controlled planes to be pitted against each other. "My team actually got first place, which was very exciting. And I honestly give a lot of that credit to our pilot. He did a very good job of not crashing!" In fact, that pilot was Warren Hoburg '08, a former assistant professor in AeroAstro and current NASA astronaut training for a mission on the International Space Station.

As Dunn was growing up, her parents supported her interest in space and space exploration. Here she is at space camp, where she learned what it takes to be an astronaut and had fun building and launching model rockets.
Photo courtesy of Joy Dunn

Pursuing her passion at SpaceX

Dunn's undergraduate experience culminated with an internship at the aerospace manufacturing company SpaceX in the summer of 2008. "It was by far my favorite internship of the ones that I had in college. I got to work on really hands-on projects and had the same amount of responsibility as a full-time employee."

By the end of the internship, she was hired as a propulsion development engineer for the Dragon spacecraft where she helped to build the thrusters for the first Dragon mission. Eventually, she transferred to the role of manufacturing engineer. "A lot of what I've done in my life is building things and looking for process improvements," so it was a natural fit. From there, she rose through the ranks, eventually becoming the senior manager of spacecraft manufacturing engineering where she oversaw all the manufacturing, test, and integration engineers working on Dragon. "It was pretty incredible to go from building thrusters to building the whole vehicle," she says.

During her tenure, Dunn also co-founded SpaceX's Women's Network and its LGBT affinity group, Out and Allied. "It was about providing spaces for employees to get together and provide a sense of community," she says. Through these groups, she helped start mentorship and community outreach programs, as well as helped grow the pipeline of women in leadership roles for the company.

An MIT internship at SpaceX led to Dunn's being hired as a propulsion development engineer at the company, where she helped build the thrusters for the Dragon spacecraft. After several promotions, she became the senior manager responsible for building the whole vehicle. Photo courtesy of Joy Dunn

In spite of all her successes at SpaceX, she couldn't help but think about what came next. "I had been at SpaceX for almost a decade and had these thoughts of, 'do I want to do another tour of duty or look at doing something else?' The main criteria I set for myself was to do something that is equally or more world-changing than SpaceX."

A pivot to fusion

It was at this time in 2018 that Dunn received an email from a former mentor asking if she had heard about a fusion energy startup called Commonwealth Fusion Systems (CFS) that worked with the MIT Plasma Science and Fusion Center. "I didn't know much about fusion at all. I had heard about it as a science project that was still many, many years away as a viable energy source."

After learning more about the technology and company, "I was just like 'holy cow, this has the potential to be even more world-changing than what SpaceX is doing.'" She adds, "I decided that I wanted to spend my time and brainpower focusing on cleaning up the planet instead of getting off it."

After connecting with CFS CEO Bob Mumgaard SM '15, PhD '15, Dunn joined the company and returned to Cambridge as the head of manufacturing. While moving from the aerospace industry to fusion energy was a large shift, she said her first project—building a fusion-relevant, high-temperature superconducting magnet capable of achieving 20 tesla—tied back into her life of being a builder who likes to get her hands on things.

Over the course of two years, she oversaw the production and scaling of the magnet manufacturing process. When she first came in, the magnets were being constructed in a time-consuming and manual way. "One of the things I'm most proud of

Dunn inspects progress on the construction of the new CFS campus in Devens, Massachusetts, where facilities will house the company's manufacturing operations and its SPARC fusion device. Dunn is now head of operations, responsible for manufacturing, facilities and construction, safety, and quality. Photo courtesy of Commonwealth Fusion Systems

from this project is teaching MIT research scientists how to think like manufacturing engineers," she says. "It was a great symbiotic relationship. The MIT folks taught us the physics and science behind the magnets, and we came in to figure out how to make them into a more manufacturable product."

In September 2021, CFS tested this high-temperature superconducting magnet and achieved its goal of 20 tesla. This was a pivotal moment for the company that brought it one step closer to achieving its goal of producing net-positive fusion power. Now, CFS has begun work on a new campus in Devens, Massachusetts, to house their manufacturing operations and SPARC fusion device. Dunn plays a pivotal role in this expansion as well. In March 2021, she was promoted to the head of operations, which expanded her responsibilities beyond managing manufacturing to include facilities, construction, safety, and quality. "It's been incredible to watch the campus grow from a pile of dirt…into full buildings."

In addition to the groundbreaking work, Dunn highlights the culture of inclusiveness as something that makes CFS stand apart to her. "One of the main reasons that drew me to CFS was hearing from the company founders about their thoughts on diversity, equity, and inclusion, and how they wanted to make that a key focus for their company. That's been so important in my career, and I'm really excited to see how much that's valued at CFS." The company has carried this out through programs such as Fusion Inclusion, an initiative that aims to build a strong and inclusive community from the inside out.

Dunn stresses "the impact that fusion can have on our world and for addressing issues of environmental injustice through an equitable distribution of power and electricity." Adding, "That's a huge lever that we have. I'm excited to watch CFS grow and for us to make a really positive impact on the world in that way."

Turner Jackson, MITEI

Recent energy graduates reflect on their time at MIT

Ana Cristina Fiallo: Courtesy of Ana Cristina Fiallo

Ana Cristina Fiallo '22

"I was first inspired to commit to a future in sustainable energy after the Category 4 Hurricane María took its course across my island home of Puerto Rico on September 20, 2017, in the midst of working on my college application to MIT," says Ana Cristina Fiallo '22, a recent computer science and urban science and planning graduate who minored in energy studies. The destruction to the island and its electricity grid opened her eyes to the fundamental importance of energy infrastructure and the "just transition to renewable, reliable energy sources in the face of climate change." This passion has permeated all of her experiences at MIT, from the classroom to internships, Undergraduate Research Opportunity Program (UROP) appointments, student organizations, and beyond.

Fiallo engaged in several UROPs during her time at MIT, including projects that explored the implementation of sustainable energy technologies such as solar and battery storage within informal settlements; the use of satellite imagery and deep learning algorithms to assess damage from extreme weather events; and the role that machine learning can play in analyzing urban air pollution. Further, she participated in internships at the electric vehicle manufacturer Tesla and at GreenWatch, an organization dedicated to combatting greenwashing using artificial intelligence. Two highlights of Fiallo's undergraduate energy experience were 11.165 Urban Energy Systems and Policy and 1.C01 Machine Learning for Sustainable Systems. These classes helped to lay the practical foundations for her understanding of the technical and socio-political aspects of the climate crisis.

Beyond the classroom and lab, Fiallo was active in many student groups, such as the Society of Hispanic Professional Engineers, DanceTroupe, MIT CodeIt, the Association of Puerto Rican students, and—especially—the Number Six Club, MIT's chapter of the Delta Psi co-ed literary fraternity, "which has become my family at MIT from which I have learned so much." Additionally, with the MIT Climate and Energy Club, she helped organize the MIT Energy Night for two years.

In fall 2022, Fiallo plans to continue her studies at MIT by pursuing a master's in engineering in the Department of Civil and Environmental Engineering with a focus on climate, environment, and sustainability. "This passion and interest in resilient energy development has continued with me from my first steps on MIT's campus and into the MIT Energy Commons, to my last steps as an undergraduate senior, and beyond," she says.

Kara Rodby: Volta Energy Technologies

Kara Rodby PhD '22

"I always had an interest in sustainability. I think it stemmed from being very efficiency-minded my whole life," says Kara Rodby PhD '22. "My mom was very poor growing up, so she was always frugal. Even though we were much more privileged when I was growing up, she still exemplified efficiency." Therefore, to Rodby, "being efficient—whether it's with time, money, or resources—just makes sense, and certainly so in addressing climate change." Before coming to MIT, Rodby studied environmental engineering at Northwestern University as an undergraduate, which helped to confirm her interest in energy storage technologies—but did not provide her with the complete toolset that she needed. This expanding interest is what pushed her to pursue a PhD in chemical engineering from MIT.

Rodby's PhD research focused on redox flow batteries (RFBs), a type of electrochemical energy storage device that is attractive because it decouples energy and power by physically separating the energy storage capacity from the power components. While this advantage can make RFBs cost-competitive with other, more common batteries—such as lithium-ion—RFBs have seen minimal adoption. In particular, Rodby sought to explore the economic, political, and social determinants that have minimized RFBs' use at scale and to address these barriers using techno-economic modeling. Rodby also played an important role in the second chapter of MITEI's recent *Future of Energy Storage* report where she provided techno-economic and qualitative analyses on RFBs.

Outside of the lab, Rodby was deeply involved with student activism, addressing inequity and discrimination in academia and at MIT. Having experienced these issues firsthand, Rodby was inspired to meet with other students and to participate in working groups and committees to find lasting solutions. During her last two years, Rodby became strongly involved in the Graduate Student Union. She says, "Winning our student union just prior to my graduation was by far the most rewarding and meaningful thing I've been a part of in my life. It demonstrated that if we come together and work hard, we can truly do anything."

Currently, Rodby is working for Volta Energy Technologies as a technical analyst. Volta is a venture capital firm that raises funds to invest in hard-tech energy storage startups. In this position, she analyzes the technologies of incoming companies to help Volta determine whether to invest in them. Pursuing an education and career in renewable energy harkens back to her appreciation for efficiency. "To me, it feels like addressing climate change by developing sustainable energy is also simultaneously building the most efficient and sensible energy system."

Turner Jackson, MITEI

Building consensus on concessions: MITEI leaders help push the conversation on ending energy poverty at online conference

On the entire continent of Africa, there is only one financially solvent utility company, says Robert Stoner, deputy director for science and technology at the MIT Energy Initiative (MITEI).

The utility, UMEME—a private company—operates in Uganda under a "concession" granted by the government. In utility concession agreements, private operators typically manage key activities—such as investing in new infrastructure, operating and maintaining existing assets to improve quality of service, and establishing more robust billing and collection systems—for a prescribed period of time, in exchange for an attractive remuneration from the beneficiaries of the service via regulated tariffs.

Although utility concessions have been attempted with mixed levels of success in developing countries around the world, Stoner and other MITEI leaders see them as a promising tool to help end energy poverty.

"You're bringing money and sound management from investors improving the quality of the system," Stoner says. "UMEME has been a success, overall. But the remuneration is now perceived as excessive, and it was not meant to increase rural electrification in a country with a low access rate. Despite the moderate cost impact, UMEME has turned into a political problem, and the government may not renew that concession."

Stoner co-leads the MIT-Comillas Universal Energy Access lab, a collaborative research group on power systems in developing countries. The other co-leader of the group is Ignacio Pérez-Arriaga, a visiting professor at MIT and professor at the Universidad Pontificia Comillas in Madrid, Spain. Both Stoner and Pérez-Arriaga also have leadership roles on the Global Commission to End Energy Poverty.

In March, Pérez-Arriaga took the lead in organizing the online "International Conference on Concessions in the Power Sector." The event, hosted by the government of Ghana, brought together more than 50 speakers—and more than 300 participants—from the African School of

Sub-Saharan Africa has more than 600 million people without electricity. A recent conference brought together a global audience to discuss how utility concessions can be a promising tool to help end energy poverty in developing countries around the world. Photo: Social Income/Unsplash

Regulation, the World Bank, and the Rockefeller Foundation, along with MITEI and the Global Commission to End Energy Poverty.

"Sub-Saharan Africa has more than 600 million people without electricity," Pérez-Arriaga notes. "Energy poverty is a huge problem, so with the conference we are trying to draw attention to the instrument of concessions as an approach that combines business, regulatory, and financial aspects in a way that can improve the performance of utilities and attract private investment. Concessions have frequently been ignored in the current policy debate, and we wanted to reverse that trend."

Confronting challenges

In most countries with significant levels of energy poverty, Stoner says, the major problems lie not in generation or transmission of electricity, but rather in distribution. Often, distribution utilities fail to provide reliable service, which discourages customers from connecting to the grid. Many who do connect do so illegally, drawing power without paying for it, which drives up costs for paying customers. Also, distributing electricity to rural areas is typically a losing proposition from a financial perspective, making it difficult for governments or private operators to build viable systems that provide universal access.

"The distribution system is where the rubber meets the road," Stoner says. "It's where all the hardware of the electrical system comes into contact with the customers."

To solve these problems, Stoner says, governments would benefit from designing concessions in new ways. For instance, concessions can be designed with viable business models for off-grid solutions like minigrids and standalone systems, based on affordable tariffs—along with subsidies to developers. Sub-franchises can be created that carve out territories within presently unviable distribution companies, where suitable combinations of diverse customers can make possible viable business models.

Santos José Díaz Pastor, a member of the Universal Energy Access Lab, helped to organize the conference. While the ideas behind utility concessions are sound, he says, it is challenging to apply those ideas to dozens of different countries that all have their own specific features.

"There's no framework that works everywhere," he says. "When you analyze concessions, there are so many things you can adapt to each country. The major problem is getting the capital to make all the investments that are needed. But implementation is where the plans usually fail. You have to design business models with financing schemes that are sustainable over the long term."

Learning from the past

Pérez-Arriaga says that governments and private operators are already applying lessons learned from previous concession agreements. For instance, he points to a concession in a flood-prone area of India. After the area was hit by a cyclone, the government held the private operator responsible for repairing the damage—only to see the company go broke and abandon the area. But in a more recent concession agreement in the same region, Pérez-Arriaga says, the government stepped in to provide funding after a natural disaster, allowing the private operator to restore service to most areas within 24 or 48 hours.

"The company has the confidence that they are supported by the government, and so they will do everything that is needed to provide good service," he says.

Another important lesson: Governments and private operators must collaborate and ensure that their agreements will be financially viable for all parties. In one concession agreement in Senegal, Pérez-Arriaga says, the government maintained control of the more economically viable urban distribution systems, while giving over control of unprofitable rural distribution systems to a private operator, with unsatisfactory results.

"The regulated tariffs were unable to cover the cost of the service, and there were no subsidies," Pérez-Arriaga says. "You have to create a concession business model that is viable and sustainable, and that typically requires cross-subsidization among urban and rural areas. Also, people have to learn to write sound contracts—for instance, with clear termination clauses. There are silly mistakes that people have made, because they were not thinking of the many things that could go wrong."

Looking ahead

Grégoire Jacquot, who was a MITEI research fellow while helping organize the conference, says organizers had three main goals for the event. First, they wanted to create a platform for in-depth discussions about how utility concessions should be structured and financed. Second, they wanted to build a network of senior practitioners who could advise one another on the topic. And, finally, they wanted to pave the way for a larger, in-person conference later in the year.

"The experts were eager to share," Jacquot says. "I could feel the enthusiasm. For the first time, they had an opportunity to talk in a structured way about their experiences."

"We don't want to only talk about concessions and energy poverty once a crisis appears, or when a development bank has money for a project," Jacquot adds. "Our vision is to use concessions at a large scale and back these concessions with strong, quantified plans to reform the power sector."

Pérez-Arriaga calls the event an "appetizer" for the work to come on concessions in the energy sector. "What we are trying to do is mobilize the governments, the development partners, the big institutions, to address the problem of access to electricity," he says. "We are trying to mobilize billions of dollars. This is a marathon."

Calvin Hennick, MITEI correspondent

Investors awake to the risks of climate change, says finance executive Poppy Allonby at MITEI colloquium

Poppy Allonby is a senior financial executive who has spent more than two decades analyzing the link between climate change and investing. Photo: Kelley Travers, MITEI

Poppy Allonby, a senior financial executive and the former managing director of BlackRock, has been analyzing the link between climate change and investing for more than two decades. "For a lot of that, it was quite lonely," Allonby said during her December 2021 address at the MIT Energy Initiative Fall Colloquium. "There weren't that many other people looking at this field. And over the last three or four years, that's completely changed."

Increasingly, Allonby said, investors are opening their eyes to the long-term risks of climate change—risks that threaten not only the planet but also their portfolios. And as more institutional investors come to see climate change as a threat to their beneficiaries, they are taking action to fight it. Still, she cautioned that much more work remains to be done.

"Various investors are at very different stages in considering climate change," Allonby said. "Once they realize this is something they need to think about … they need to do a risk assessment, then develop a strategy."

"When you look at different institutions," she said, "some are just at the very beginning of this journey."

A changing landscape

Although there is a compelling moral case to be made for taking steps to mitigate climate change, Allonby noted that institutional investors such as pension funds are bound by a fiduciary duty to their beneficiaries. That is to say, they are obligated to put their client or member interests ahead of their own.

"I talk about fiduciary duty, because one of the things that has really changed in the investment space is that more and more investors are beginning to see climate change and climate risk as [impacting] their fiduciary duty," said Allonby. "That has been a shift. In my mind, it makes total sense. If you're a long-term investor … and you're thinking about beneficiaries that need assets over the next 10 or 20 years, and thinking about risks that might materialize—and climate change, in particular—then that makes a lot of sense. But that is not where we were five or 10 years ago."

Allonby spent more than 20 years at the multinational investment management corporation BlackRock. For 17 of those years, she was a senior portfolio manager responsible for managing multibillion-dollar funds investing globally in companies across the traditional energy sector, and also those involved in sustainable energy and mitigating climate change. Most recently, she was head of the corporation's Global Product Group on several continents, where she provided oversight for nearly $1 trillion in assets and played a critical role in developing BlackRock's sustainable product strategy.

"Where I like to think the finance industry is heading is integration," she said. "This means thinking holistically about pretty much every decision you make as an investor, and thinking about how climate risk is going to impact that investment. That is a sea change in the mentality around how people invest."

Divestment versus engagement

For many years, activists have pushed for institutions—including MIT—to divest from fossil fuel companies. By keeping fossil fuel companies out of their portfolios, these activists argue, institutions and individuals can exert social, political, and economic pressure on these corporations and help to accelerate the shift to renewable energy.

However, Allonby argued instead for ongoing engagement with fossil fuel companies, reasoning that this better positions investors to push for change. "My personal view with divesting from oil and gas companies is, that's not very effective," Allonby said. "I think there might be examples where you have very specific companies which you don't think will be involved in the transition [to net zero], and [divestment] might make sense. Or if you've got an institutional investor where it is imperative that their investment is entirely aligned with their values—so, certain charities—it might make sense. But if you really care about change, I think you need to keep a seat at the table."

In a way, Allonby said, divesting from fossil fuel companies lets leaders at those organizations off the hook, reducing the pressure on them to make meaningful changes to their operations. "Imagine a company that is incredibly polluting and not sustainable, and they have shareholders that are not happy, but they don't do anything, and those shareholders decide to divest," she said. "What happens as a result of that, potentially, is the company goes, 'Oh, that was easy!

I didn't have to do anything, and [the activists] have gone away.' And potentially, those assets end up being owned by people who care less. So that is a risk, when you think about divestment."

Challenges and opportunities

Allonby outlined several challenges with climate-focused investing, but also noted a number of opportunities—both for investors looking to make money, and those looking to make a change.

Among the challenges: For one, some investors simply still need to be convinced that climate change is a problem they should be working to solve. Also, Allonby said, there is a lack both of a formalized methodology and of specialized investment products for climate-focused investing, although she noted that both of these areas are improving. Finally, she said, it remains a challenge to encourage investors to direct capital toward clean-energy projects in developing countries.

Investors can both set themselves up for financial success and mitigate climate change, Allonby said, through savvy investments in either distressed or underpriced assets. "If you can buy assets that are discounted or cheaper because people have real concerns about their environmental footprint, then you can work with those companies to improve it and therefore reduce the risk and improve the valuation," she said.

Allonby, pointing to the high cost of waterfront property in areas that are vulnerable to rising sea levels, also suggested that the long-term risks of climate change have not been fully priced into many assets. "My view is that we haven't really gotten our arms around that," she said. "From a purely investment perspective, that's also an opportunity."

Additionally, Allonby noted the recent rise of ESG funds, which invest with environmental, social, and corporate governance guidelines in mind. Some of these funds, she noted, have outperformed the larger market over the past several years.

"When we talk about climate change, one has a range of emotions," Allonby said. "Sometimes it can feel like we're not making enough progress. And one of the nice things about being here at MIT is that whenever I'm here, I always feel hopeful about the future, and quite hopeful about all of the technologies and work that you are doing to transition energy systems and move things forward. When you look at what's happening in the financial services sector, there's still a huge amount to do, but it's also quite a hopeful story."

Calvin Hennick, MITEI correspondent

Following her presentation, Poppy Allonby (right) sat with MITEI Director Robert C. Armstrong (left) to address questions from the audience.
Photo: Kelley Travers, MITEI

MIT spinoff Takachar processes waste biomass to reduce airborne emissions

To prepare fields for planting, farmers the world over often burn corn stalks, rice husks, hay, straw, and other waste left behind from the previous harvest. In many places, the practice creates huge seasonal clouds of smog, contributing to air pollution that kills 7 million people globally a year, according to the World Health Organization.

Annually, $120 billion worth of crop and forest residues are burned in the open worldwide—a major waste of resources in an energy-starved world, says Kevin Kung SM '13, PhD '17. Kung is working to transform this waste biomass into marketable products—and capitalize on a billion-dollar global market—through his MIT spinoff company, Takachar.

Founded in 2015, Takachar develops small-scale, low-cost, portable equipment to convert waste biomass into solid fuel using a variety of thermochemical treatments, including one known as oxygen-lean torrefaction. The technology emerged from Kung's PhD project in the lab of Ahmed Ghoniem, the Ronald C. Crane (1972) Professor of Mechanical Engineering.

Biomass fuels, including wood, peat, and animal dung, are a major source of carbon emissions—but billions of people rely on such fuels for cooking, heating, and other household needs. "Currently, burning biomass generates 10% of the primary energy used worldwide, and the process is used largely in rural, energy-poor communities. We're not going to change that overnight. There are places with no other sources of energy," Ghoniem says.

Takachar co-founders Vidyut Mohan (left) and Kevin Kung SM '13, PhD '17.
Photo: Echoing Green Foundation

What Takachar's technology provides is a way to use biomass more cleanly and efficiently by concentrating the fuel and eliminating contaminants such as moisture and dirt, thus creating a "clean-burning" fuel—one that generates less smoke. "In rural communities where biomass is used extensively as a primary energy source, torrefaction will address air pollution head-on," Ghoniem says.

Thermochemical treatment densifies biomass at elevated temperatures, converting plant materials that are typically loose, wet, and bulky into compact charcoal. Centralized processing plants exist, but collection and transportation present major barriers to utilization, Kung says. Takachar's solution moves processing into the field: To date, Takachar has worked with about 5,500 farmers to process 9,000 metric tons of crops.

Takachar estimates its technology has the potential to reduce carbon dioxide equivalent emissions by gigatons per year at scale. ("Carbon dioxide equivalent" is a measure used to gauge global warming potential.) In recognition, in 2021 Takachar won the first-ever Earthshot Prize in the clean air category, a £1 million prize funded by Prince William and Princess Kate's Royal Foundation.

Roots in Kenya

As Kung tells the story, Takachar emerged from a class project that took him to Kenya—which explains the company's name, a combination of *takataka*, which mean "trash" in Swahili, and *char*, for the charcoal end product.

It was 2011, and Kung was at MIT as a biological engineering grad student focused on cancer research. But "MIT gives students big latitude for exploration, and I took courses outside my department," he says. In spring 2011, he signed up for a class known as 15.966 Global Health Delivery Lab in the MIT Sloan School of Management. The class brought Kung to Kenya to work with a nongovernmental organization in Nairobi's Kibera, the largest urban slum in Africa.

"We interviewed slum households for their views on health, and that's when I noticed the charcoal problem," Kung says. The problem, as Kung describes it, was that charcoal was everywhere in Kibera—piled up outside, traded by the road, and used as the primary fuel, even indoors. Its creation contributed to deforestation, and its smoke presented a serious health hazard.

Eager to address this challenge, Kung secured fellowship support from the MIT International Development Initiative and the Priscilla King Gray Public Service Center to conduct more research in Kenya. In 2012, he formed Takachar as a team and received seed money from the MIT IDEAS Global Challenge, MIT Legatum Center, and D-Lab to produce charcoal from household organic waste. (This work also led to a fertilizer company, Safi Organics, that Kung founded in 2016 with the help of MIT IDEAS. But that is another story.)

Meanwhile, Kung had another top priority: finding a topic for his PhD dissertation. Back at MIT, he met Alexander Slocum, the Walter M. May and A. Hazel May Professor of Mechanical Engineering, who on a long walk-and-talk along the Charles River suggested he turn his Kenya work into a thesis. Slocum connected him with Robert Stoner, deputy director for science and technology at the MIT Energy Initiative (MITEI) and founding director of MITEI's Tata Center for Technology

After harvest, farmers worldwide generally burn the waste that remains, creating dangerous levels of toxic haze and wasting potentially valuable resources. The MIT spinoff company Takachar is providing technology that can be used in the field to convert that agricultural waste into a solid, clean-burning fuel. Photo: Kevin Kung

and Design. Stoner in turn introduced Kung to Ghoniem, who became his PhD advisor, while Slocum and Stoner joined his doctoral committee.

Roots in MIT lab

Ghoniem's telling of the Takachar story begins, not surprisingly, in the lab. Back in 2010, he had a master's student interested in renewable energy, and he suggested the student investigate biomass. That student, Richard Bates '10, SM '12, PhD '16, began exploring the science of converting biomass to more clean-burning charcoal through torrefaction.

Most torrefaction (also known as low-temperature pyrolysis) systems use external heating sources, but the lab's goal, Ghoniem explains, was to develop an efficient, self-sustained reactor that would generate fewer emissions. "We needed to understand the chemistry and physics of the process, and develop fundamental scaling models, before going to the lab to build the device," he says.

By the time Kung joined the lab in 2013, Ghoniem was working with the Tata Center to identify technology suitable for developing countries and largely based on renewable energy. Kung was able to secure a Tata Fellowship and—building on Bates' research—develop the small-scale, practical device for biomass thermochemical conversion in the field that launched Takachar.

This device, which was patented by MIT with inventors Kung, Ghoniem, Stoner, MIT research scientist Santosh Shanbhogue, and Slocum, is self-contained and scalable. It burns a little of the biomass to generate heat; this heat bakes the rest of the biomass, releasing gases; the system then introduces air to enable these gases to combust, which burns off the volatiles and generates more heat, keeping the thermochemical reaction going.

"The trick is how to introduce the right amount of air at the right location to sustain the process," Ghoniem explains. "If you put in more air, that will burn the biomass. If you put in less, there won't be enough heat to produce the charcoal. That will stop the reaction."

About 10% of the biomass is used as fuel to support the reaction, Kung says, adding that "ninety percent is densified into a form that's easier to handle and utilize." He notes that the research received financial support from the Abdul Latif Jameel Water and Food Systems Lab and the Deshpande Center for Technological Innovation, both at MIT. Sonal Thengane, another postdoc in Ghoniem's lab, participated in the effort to scale up the technology at the MIT Bates Lab (no relation to Richard Bates).

The charcoal produced is more valuable per ton and easier to transport and sell than biomass, reducing transportation costs by two-thirds and giving farmers an additional income opportunity—and an incentive not to burn agricultural waste, Kung says. "There's more income for farmers, and you get better air quality."

Roots in India

When Kung became a Tata Fellow, he joined a program founded to take on the biggest challenges of the developing world, with a focus on India. According to Stoner, Tata Fellows, including Kung, typically visit India twice a year and spend six to eight weeks meeting stakeholders in industry, the government, and in communities to gain perspective on their areas of study.

"A unique part of Tata is that you're considering the ecosystem as a whole," says Kung, who interviewed hundreds of smallholder farmers, met with truck drivers, and visited existing biomass processing plants during his Tata trips to India. (Along the way, he also connected with Indian engineer Vidyut Mohan, who became Takachar's co-founder.)

"It was very important for Kevin to be there walking about, experimenting, and interviewing farmers," Stoner says. "He learned about the lives of farmers."

These experiences helped instill in Kung an appreciation for small farmers that still drives him today as Takachar rolls out its first pilot programs, tinkers with the technology, grows its team (now up to 10), and endeavors to build a revenue stream. So, while Takachar has gotten a lot of attention and accolades—from the IDEAS award to the Earthshot Prize—Kung says what motivates him is the prospect of improving people's lives.

The dream, he says, is to empower communities to help both the planet and themselves. "We're excited about the environmental justice perspective," he says. "Our work brings production and carbon removal or avoidance to rural communities—providing them with a way to convert waste, make money, and reduce air pollution."

Kathryn M. O'Neill, MITEI correspondent

3 Questions: Emre Gençer on the role of blue hydrogen in decarbonizing the world's energy systems

In the past several years, hydrogen energy has increasingly become a more central aspect of the clean energy transition. Hydrogen can produce clean, on-demand energy that could complement variable renewable energy sources such as wind and solar power. That being said, pathways for deploying hydrogen at scale have yet to be fully explored. In particular, the optimal form of hydrogen production remains in question.

This past fall, MIT Energy Initiative Research Scientist Emre Gençer and researchers from a wide range of global academic and research institutions published "On the climate impacts of blue hydrogen production" in the journal Sustainable Energy & Fuels *(doi.org/10.1039/D1SE01508G). The article presents a comprehensive life cycle assessment (LCA) analysis of blue hydrogen. Here, Gençer discusses the findings of the study and the role that hydrogen will play more broadly in decarbonizing the world's energy systems.*

Q What are the differences between gray, green, and blue hydrogen?

A Though hydrogen does not generate any emissions directly when it is used, hydrogen production can have a huge environmental impact. Colors of hydrogen are increasingly used to distinguish different production methods and as a proxy to represent the associated environmental impact. Today, close to 95% of hydrogen production comes from fossil resources. As a result, the carbon dioxide (CO_2) emissions from hydrogen production are quite high. Gray, black, and brown hydrogen refer to fossil-based production. Gray is the most common form of production and comes from natural gas, or methane, using steam methane reformation but without capturing CO_2. There are two ways to move toward cleaner hydrogen production. One is applying carbon capture and storage to the fossil fuel–based hydrogen production processes. Natural gas–based hydrogen production with carbon capture and storage is referred to as blue hydrogen. If substantial amounts of CO_2 from natural gas reforming are captured and permanently stored, such hydrogen could be a low-carbon energy carrier. The second way to produce cleaner hydrogen

Image: akitada31/Pixabay

is by using electricity to produce hydrogen via electrolysis. In this case, the source of the electricity determines the environmental impact of the hydrogen, with the lowest impact being achieved when electricity is generated from renewable sources, such as wind and solar. This is known as green hydrogen.

Q What insights does an LCA approach give us when analyzing blue hydrogen and other low-carbon energy systems?

A Mitigating climate change requires significant decarbonization of the global economy. Accurate estimation of cumulative greenhouse gas (GHG) emissions and its reduction pathways is critical irrespective of the source of emissions. An LCA approach allows the quantification of the environmental life cycle of a commercial product, process, or service impact with all the stages (cradle-to-grave). The LCA-based comparison of alternative energy pathways, fuel options, etc., provides an apples-to-apples comparison of low-carbon energy choices.

In the context of low-carbon hydrogen, it is essential to understand the GHG impact of supply chain options. Depending on the production method, contribution of life cycle stages to the total emissions might vary. For example, with natural gas–based hydrogen production, emissions associated with production and transport of natural gas might be a significant contributor based on its leakage and flaring rates. If these rates are not precisely accounted for, the environmental impact of blue hydrogen can be underestimated. However, the same rationale is also true for electricity-based hydrogen production. If the electricity is not supplied from low-carbon sources such as wind, solar, or nuclear, the carbon intensity of hydrogen can be significantly underestimated. In the case of nuclear, there are also other environmental impact considerations. An LCA approach—if performed with consistent system boundaries—can provide an accurate environmental impact comparison. It should also be noted that these estimations can only be as good as the assumptions and correlations used unless they are supported by measurements.

Q What conditions are needed to make blue hydrogen production most effective, and how can it complement other decarbonization pathways?

A Hydrogen is considered one of the key vectors for the decarbonization of hard-to-abate sectors such as heavy-duty transportation. Currently, more than 95% of global hydrogen production is fossil-fuel based. In the next decade, massive amounts of hydrogen must be produced to meet this anticipated demand. It is very hard, if not impossible, to meet this demand without leveraging existing production assets. The immediate and relatively cost-effective option is to retrofit existing plants with carbon capture and storage (blue hydrogen). The environmental impact of blue hydrogen may vary over large ranges but depends on only a few key parameters: the methane emission rate of the natural gas supply chain, the CO_2 removal rate at the hydrogen production plant, and the global warming metric applied. State-of-the-art reforming with high CO_2 capture rates combined with natural gas supply featuring low methane emissions substantially reduces GHG emissions compared to conventional natural gas reforming. Under these conditions, blue hydrogen is compatible with low-carbon economies and exhibits climate change impacts at the upper end of the range of those caused by hydrogen production from renewable-based electricity. However, neither current blue nor green hydrogen production pathways render fully "net-zero" hydrogen without additional CO_2 removal.

Turner Jackson, MITEI

NOTE

The study was conducted in collaboration with researchers from the Paul Scherrer Institute, ETH Zurich, University of Calgary, Utrecht University, University of Sheffield, University of Aberdeen, Potsdam Institute for Climate Impact Research, University of Texas, Politecnico di Milano, TNO Innovation for Life, and Heriot-Watt University.

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MITEI Startup Member Commonwealth Fusion Systems in new pact with PSFC

MIT's Plasma Science and Fusion Center (PSFC) will substantially expand its fusion energy research and education activities under a new five-year agreement with Institute spinout Commonwealth Fusion Systems (CFS).

"This expanded relationship puts MIT and PSFC in a prime position to be an even stronger academic leader that can help deliver the research and education needs of the burgeoning fusion energy industry, in part by utilizing the world's first burning plasma and net energy fusion machine, SPARC," says PSFC director Dennis Whyte. "CFS will build SPARC and develop a commercial fusion product, while MIT PSFC will focus on its core mission of cutting-edge research and education."

Commercial fusion energy has the potential to play a significant role in combating climate change, and there is a concurrent increase in interest from the energy sector, governments, and foundations. The new agreement, administered by the MIT Energy Initiative (MITEI) where CFS is a Startup Member, will help PSFC expand its fusion technology efforts with a wider variety of sponsors. The collaboration enables rapid execution at scale and technology transfer into the commercial sector as soon as possible.

This new agreement doubles CFS's financial commitment to PSFC, enabling greater recruitment and support of students, staff, and faculty. It extends the collaboration between PSFC and CFS that resulted in numerous advances toward fusion power plants, including last fall's demonstration of a high-temperature superconducting fusion electromagnet with a record-setting field strength of 20 tesla.

"This has been an incredibly effective collaboration that has resulted in a major breakthrough for commercial fusion with the successful demonstration of revolutionary fusion magnet technology that will enable the world's first commercially relevant net energy fusion device, SPARC, currently under construction," says Bob Mumgaard SM '15, PhD '15, CEO of Commonwealth Fusion Systems.

"Our goal from the beginning was to create a membership model that would allow startups that have specific research challenges to leverage the MITEI ecosystem, including MIT faculty, students, and other MITEI Members," says MITEI Director Robert Armstrong. "The team at the PSFC and MITEI has worked seamlessly to support CFS, and we are excited for this next phase of the relationship."

MIT Plasma Science and Fusion Center

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MIT researchers enlist DNA to help turn carbon dioxide into useful products

Professor Ariel Furst (center), undergrad Rachel Ahlmark (left), postdoc Gang Fan (right), and their colleagues have demonstrated a promising new approach to a challenging problem: turning carbon dioxide—a major contributor to climate change—into valuable products. Their approach is based on standard electrochemistry: A catalyst plus a jolt of voltage causes a chemical reaction to occur. In an unusual twist, they add strands of DNA to their catalyst and then rely on the natural behavior of DNA to hook the catalyst directly to the electrode that delivers the voltage. A series of experimental measurements confirmed that their approach significantly increases the rate at which carbon dioxide conversion progresses. Read more on page 16. Photo: Gretchen Ertl