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Energy Futures

SPRING 2023

MIT
ENERGY
INITIATIVE

Retrofitting buildings to reduce urban carbon emissions: Is it enough? p. 4

From biomass to aviation fuel: MIT finds a way p. 10

Straight from the cow's mouth: MIT researcher aims to capture methane before it warms the climate p. 25

MITEI researcher races from Cambridge to Kiev to help funnel aid to the front line p. 27

Energy Reads is a podcast from the MIT Energy Initiative featuring 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?

"Flow batteries for grid-scale energy storage," by Nancy W. Stauffer
A modeling framework by MIT researchers can help speed the development of flow batteries for large-scale, long-duration electricity storage on the future grid.

"To decarbonize the chemical industry, electrify it," by Kelley Travers*
The chemical industry is the world's largest industrial energy consumer and the third largest source of industrial emissions; and yet, the chemical industry has been largely untouched when it comes to decarbonization. In a new paper, researchers from MIT and DC-MUSE urge industry and the research community to explore electrification pathways to reduce chemical industry emissions.

"Shrinky Dinks, nail polish, and smelly bacteria," by Deborah Halber
With the help of a children's toy called Shrinky Dinks, carbon-based materials, nail polish, and a certain smelly bacterium, high school students spent the summer in an MIT lab creating electrodes for low-cost microbial fuel cells.

…and more

* You can also read this article on page 15 of this issue of *Energy Futures*!

On the cover
To reduce energy use and carbon emissions, many cities have adopted policies aimed at encouraging building retrofits such as upgrading appliances and installing rooftop solar panels. Professor Christoph Reinhart (right), PhD candidate Zachary Berzolla SM '21 (left), and their colleagues in the MIT Sustainable Design Laboratory have launched online simulation tools that enable urban decision makers to determine the impacts of their policies on their cities' future carbon emissions. Analyses performed in collaboration with representatives from eight cities worldwide showed that meeting their targeted reductions in carbon emissions will require more ambitious retrofitting plans plus steps to decarbonize the local electricity grid. To read more, turn to page 4. Photo: Gretchen Ertl

Energy Futures

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Spring 2023

MITei
MIT Energy Initiative

Massachusetts Institute of Technology

A letter from the director

Dear friends,

It has been my great pleasure to welcome you to *Energy Futures* throughout my time as director of the MIT Energy Initiative. After 50 years on the MIT faculty and the past decade as MITEI director, I am retiring this summer. As I scale back my activities, I do so with great pride and confidence in the ongoing work of MITEI and so many outstanding MIT students, professors, researchers, and staff, who are transforming the world's energy systems to address climate change and meet the energy needs of the world.

Our cover story focuses on an important area of decarbonization—the built environment. A team in the MIT Sustainable Design Laboratory has developed a website providing simulation tools that city policy makers can use to analyze the effectiveness of building retrofit incentives in reducing carbon emissions (page 4). Analyses performed with eight cities around the globe showed the limits of their current retrofitting incentives and helped to motivate policy changes to speed the path to net zero.

This edition of *Energy Futures* is full of reporting on promising energy research. On page 10, read about an exciting effort to make fuel from biomass for aviation—one of the most difficult to decarbonize industries. As the biomass source, the chemical engineers use lignin, a plant material typically rejected as waste during biofuel production. The new processing technique may finally make possible an aviation fuel made from 100% renewable material.

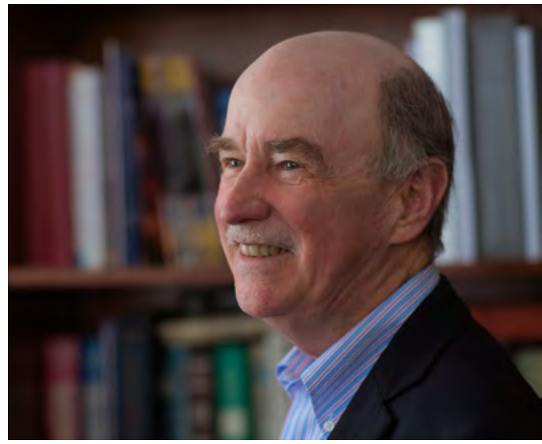
Other research articles include a focus on electrification from low-carbon sources as a pathway for decarbonization of the chemical industry (page 15); a study that finds dramatic health benefits from prioritizing powering down the most polluting fossil fuel power plants when wind energy is available (page 17); and the development of ultralight solar cells—thinner than human hair—that can turn almost any surface into a power source (page 21). And there are more research stories to explore.

On page 25, meet Associate Professor of Civil and Environmental Engineering Desirée Plata, who directs the MIT Methane Network, dedicated to reducing methane emissions. Plata's lab has developed a technique using a clay-like material called zeolite to capture and convert methane—an approach that could have a fast, beneficial impact on climate warming.

This issue also shares the story of a remarkable MIT alum, Ian Miller SM '19 (page 27). The suffering of the people of Ukraine has touched many people. But not many have responded as Miller has. Within hours of the Russian attack on Ukraine in February 2022, Miller, then a MITEI project manager, was jetting to Poland and the Polish-Ukraine border, to help. He has now co-founded a nonprofit that is delivering aid to Ukraine and her people.

The start of a fusion energy industry will require a steady infusion of skilled talent. A new program at the MIT Plasma Science and Fusion Center is addressing that need—by making meaningful fusion energy research accessible to undergraduates. On page 34, read about FUSars—fusion undergraduate scholars—and the inaugural cohort of 10 students who began this winter.

As always, our events team at MITEI is busy. Our spring symposium focused on the role of offshore wind in decarbonizing the electric power system. It drew academics, energy analysts, government officials, and utility executives, who discussed threats to the rapid rollout of offshore wind and explored paths for overcoming gridlock (page 37). At MITEI's Earth Day Colloquium, Massachusetts State Senator Mike Barrett discussed roadblocks in the way of development of an offshore wind industry in the state and yet expressed optimism in achieving Massachusetts' decarbonization goals (page 40).



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

Finally, don't miss our article about the MIT spinoff, Waya Energy, on page 42. Using a set of modeling and visualization tools developed at MITEI, the Waya team has helped governments develop electrification plans in 22 countries on almost every continent.

As you explore this edition of *Energy Futures*, I thank you again for your support of MITEI and our work. I will remain engaged with MITEI, and I hope you will, too.

Gratefully,

Robert C Armstrong

Professor Robert C. Armstrong
MITEI Director
May 2023

MIT Energy Initiative director announces retirement

After 50 years on the MIT faculty, Robert Armstrong will retire at the end of June 2023.

Robert C. Armstrong, the Chevron Professor of Chemical Engineering who has been the director of the MIT Energy Initiative (MITEI) since 2013 and part of MITEI's leadership team since its inception in 2007, has announced that he will retire effective June 30, 2023. At that time, he will have completed 50 years on the MIT faculty.

Armstrong plans to continue to work at 10% capacity, focusing on research projects on which he serves as principal investigator and also advising a number of graduate students.

"Working at MIT has been a great honor and privilege for me," says Armstrong. "Nowhere else can I imagine having had the opportunity to work with such exceptional students and colleagues and to have a 'job' that makes me want to get up every day to see what I can do to help humanity with its great challenges."

Armstrong joined the founding MITEI leadership team with Ernest Moniz, now the Cecil and Ida Green Professor of Physics and Engineering Systems emeritus and special advisor to the MIT President. When Moniz left MIT in 2013 to become U.S. Secretary of Energy, Armstrong was named MITEI director.

"MITEI has enabled us to leverage MIT's great talent base to make significant advances in energy research, education, and outreach," says Armstrong. "This is an incredibly important and exciting time in energy, and there is much to be done in envisioning and implementing an energy transition that mitigates the worst impacts of climate change, provides energy justly and equitably to those around the world without access or with inadequate access, and improves security of energy supply. I have been honored to do this work with amazing colleagues at MITEI and throughout MIT, and I will be cheering that team on, as it races to reach net-zero greenhouse gas emissions by 2050."

MIT Vice President for Research Maria Zuber will form a search committee to select the new MITEI director. Zuber has worked closely with Armstrong since she became vice president for research in 2012.

"Anyone who knows Bob knows that he is soft-spoken, but a person of deep conviction," says Zuber. "He is a master of complexity, an admired educator, a respected leader, and a terrific colleague. During his decade as director, Bob has focused the MIT Energy Initiative on the urgent, daunting challenge of transforming the global energy system to respond to the climate crisis. In the last couple of years, Bob led the creation of MITEI's Future Energy Systems Center, reflecting his keen understanding that an effective climate response requires integrated analysis and a systems approach—there is no one-fix-all solution. I congratulate Bob on a remarkable career, and I thank him for his half century of dedicated service to MIT."

Armstrong joined the MIT faculty in 1973 after earning his doctorate in chemical engineering from the University of Wisconsin, Madison. A native of Louisiana, he earned his undergraduate degree in chemical engineering from the Georgia Institute of Technology. He served as chair of the MIT Department of Chemical Engineering from 1996 until joining MITEI in 2007.

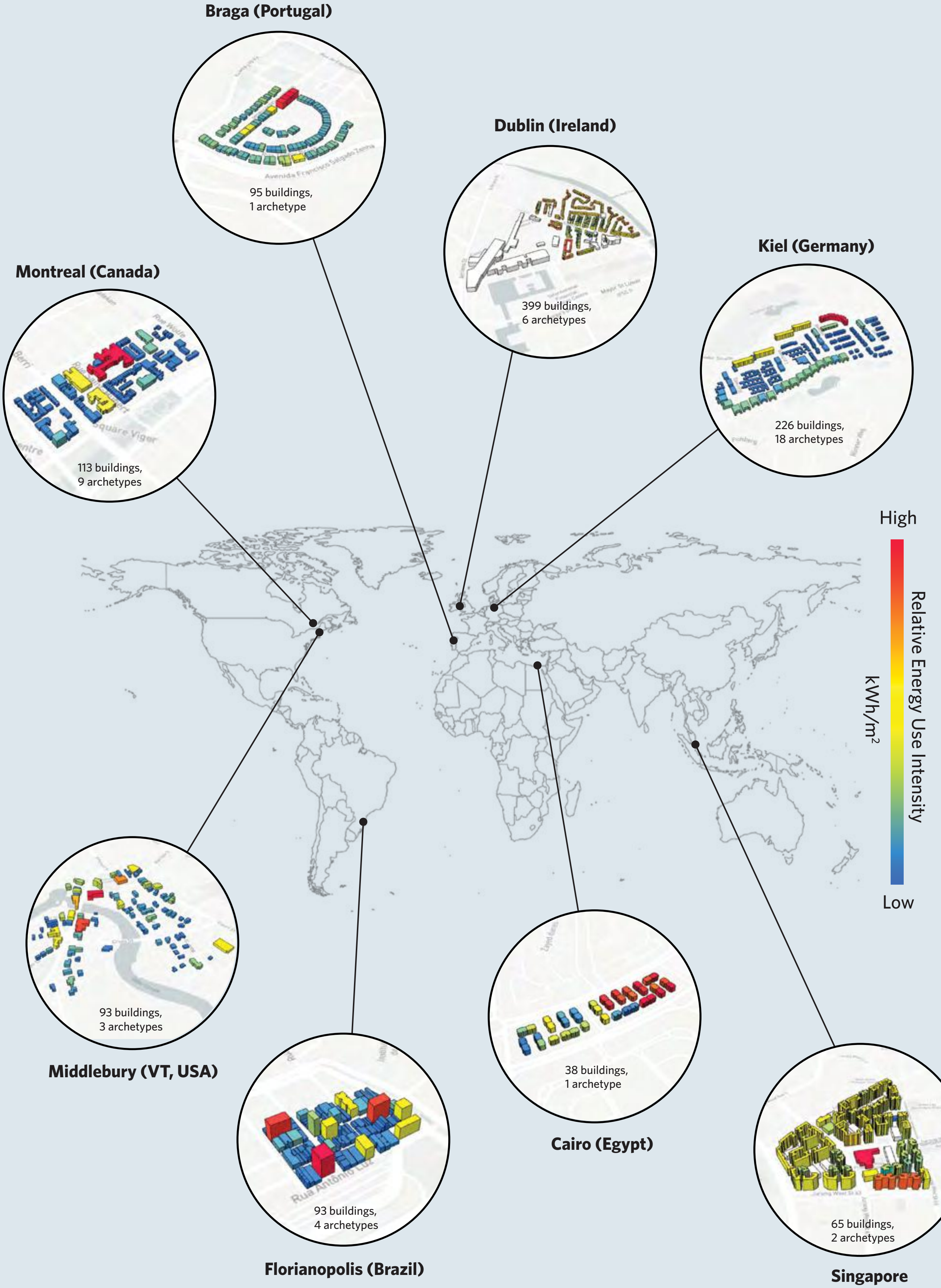
"In his fifty years at MIT, Bob has been a truly dedicated educator, researcher, and leader in our department, the Institute, and the field of chemical engineering," says Paula T. Hammond, Institute Professor and the head of the MIT Department of Chemical Engineering—a successor to Armstrong in that role. "During his time as head, he expertly expanded the breadth and depth of the department's research and academics while maintaining its high level of excellence. He has served as a thoughtful and proactive mentor to so many of our faculty members, as well as a dedicated teacher and advocate for modernizing chemical engineering curriculum. We are extremely fortunate to have profited from his scholarship and leadership over the past several decades and will continue to benefit thanks to his vision and work toward the future of chemical engineering and energy."

MITEI Director Robert C. Armstrong (seated) is applauded by colleagues at MITEI's spring symposium on March 22, 2023. Photo: Gretchen Ertl

In 2008, Armstrong was elected a member of the National Academy of Engineering, based on his research into non-Newtonian fluid mechanics, his leadership in chemical engineering education, and his co-authoring of seminal chemical engineering textbooks. He became a fellow of the American Academy of Arts and Sciences in 2020.

He received the 2006 Bingham Medal from The Society of Rheology, which is devoted to the study of the science of deformation and flow of matter, as well as the Founders Award (2020), the Warren K. Lewis Award (2006), and the Professional Progress Award (1992), all from the American Institute of Chemical Engineers.

Tom Melville, MITEI


Braga (Portugal)
95 buildings,
1 archetype
Dublin (Ireland)
399 buildings,
6 archetypes
Kiel (Germany)
226 buildings,
18 archetypes
Montreal (Canada)
113 buildings,
9 archetypes
Middlebury (VT, USA)
93 buildings,
3 archetypes
Florianopolis (Brazil)
93 buildings,
4 archetypes
Cairo (Egypt)
38 buildings,
1 archetype
Singapore
65 buildings,
2 archetypes
High
Relative Energy Use Intensity
kWh/m²
Low

Cutting urban carbon emissions by retrofitting buildings

MIT study shows that cities' plans often won't achieve their goals; decarbonizing the local grid could make the difference.

IN BRIEF

To reduce their energy use and carbon emissions, cities have been adopting policies and incentive programs to encourage building retrofits, from upgrading appliances to installing rooftop solar panels. Analyses performed by an MIT team with policy makers from eight cities yielded discouraging results: Even if the retrofits targeted by their policies are accomplished, many cities won't meet their emission-reduction goals. Further analyses showed that also decarbonizing the surrounding electric grid is the key to success. In response, most of the policy makers have now performed further analyses and enacted new incentive programs. The MIT researchers have posted a website presenting the simulation tools and step-by-step instructions so that all cities worldwide can perform analyses based on their own urban datasets and current retrofit plans. In further work, the researchers extended their modeling framework to explore the rate at which specific incentives will prompt retrofits in households with varying income levels, providing guidance for equitable and effective policy design.

To support the worldwide struggle to reduce carbon emissions, many cities have made public pledges to cut their carbon emissions in half by 2030, and some have promised to be carbon neutral by 2050. Buildings can be responsible for more than half a municipality's carbon emissions. Today, new buildings are typically designed in ways that minimize energy use and carbon emissions. So attention focuses on cleaning up existing buildings.

A decade ago, leaders in some cities took the first step in that process: They quantified their problem. Based on data from their utilities on natural gas and electricity consumption and standard pollutant-emission rates, they calculated how much carbon came from their buildings. They then adopted policies to encourage retrofits, such as adding insulation, switching to double-glazed windows, or installing rooftop solar panels. But will those steps be enough to meet their pledges?

"In nearly all cases, cities have no clear plan for how they're going to reach their goal," says Christoph Reinhart, a professor in the Department of Architecture and director of the Building Technology Program. "That's where our work comes in. We aim to help them perform analyses so they can say, 'If we, as a community, do A, B, and C to buildings of a certain type within our jurisdiction, then we are going to get there.'"

To support those analyses, Reinhart and a team in the MIT Sustainable Design Laboratory (SDL)—PhD candidate Zachary M. Berzolla SM '21; former doctoral student Yu Qian Ang PhD '22, now a research collaborator at the SDL; and former postdoc Samuel Letellier-Duchesne, now a senior building performance analyst at the international building engineering and consulting firm Introba—launched a publicly accessible website providing a series of simulation tools and a process for using them to determine the impacts of planned steps on a specific building stock. Says Reinhart: "The takeaway can be a clear technology pathway—a combination of building upgrades, renewable energy deployments, and other measures that will enable a community to reach its carbon-reduction goals for their built environment."

Analyses performed in collaboration with policy makers from selected cities around the world yielded insights demonstrating that reaching current goals will require more effort than city representatives and—in a few cases—even the research team had anticipated.

Exploring carbon-reduction pathways

The researchers' approach builds on a physics-based "building energy model," or BEM, akin to those that architects use to design high-performance green buildings. In 2013, Reinhart and his team developed a method of extending that concept to analyze a cluster of buildings. Based on publicly available geographic information system (GIS) data, including each building's type, footprint, and year of construction, the method defines the neighborhood—including trees, parks, and so on—and then, using meteorological data, how the buildings will interact, the airflows among them, and their energy use. The result is an "urban building energy model," or UBEM, for a neighborhood or a whole city.

Facing page: Effectiveness of current urban policies aimed at reducing carbon emissions. MIT researchers have developed a methodology that enables urban policy makers to determine the impacts of planned building retrofits on energy use and carbon emissions in their cities or neighborhoods. To test and demonstrate their approach, the MIT team worked with representatives from the eight cities shown here. The notes show how many buildings and archetypes (groupings of buildings with similar physical characteristics and properties) were used to represent typical neighborhoods in each city. The colors indicate energy use intensity (in kilowatt-hours per square meter) relative to other buildings in the model.

Professor Christoph Reinhart (right), PhD candidate Zachary Berzolla SM '21 (left), and others in the MIT Sustainable Design Laboratory have developed simulation tools that can help urban decision makers achieve energy-saving building retrofits and other measures needed to meet their carbon-reduction goals for the future. Here, the MIT researchers pose in front of the Metropolitan Storage Warehouse, an iconic Cambridge building that opened in 1895 as a storage facility and is now being renovated to house MIT's School of Architecture and Planning and related groups and activities. Photo: Gretchen Ertl

The website developed by the MIT team enables neighborhoods and cities to develop their own UBEM and to use it to calculate their current building energy use and resulting carbon emissions and then how those outcomes would change assuming different retrofit programs or other measures being implemented or considered. "The website—UBEM.io—provides step-by-step instructions and all the simulation tools that a team will need to perform an analysis," says Reinhart.

The website starts by describing three roles required to perform an analysis: a local sustainability champion who is familiar with the municipality's carbon-reduction efforts; a GIS manager who has access to the municipality's urban datasets and maintains a digital model of the built environment; and an energy modeler—typically a hired consultant—who has a background in green building consulting and individual building energy modeling.

The team begins by defining "shallow" and "deep" building retrofit scenarios. To explain, Reinhart offers some examples: "'Shallow' refers to things that just happen, like when you replace your old, failing appliances with new, energy-efficient ones, or you install LED light bulbs and weatherstripping everywhere," he says. "'Deep' adds to that list things you might do only every 20 years, such as ripping out walls and putting in insulation or replacing your gas furnace with an electric heat pump."

Once those scenarios are defined, the GIS manager uploads to UBEM.io a data set of information about the city's buildings, including their locations and attributes such as geometry, height, age, and use (e.g., commercial, retail, residential). The energy modeler then builds a UBEM to calculate the energy use and carbon emissions of the existing building stock. Once that baseline is established, the energy modeler can calculate how specific retrofit measures will change the outcomes.

Workshop to test-drive the method

Two years ago, the MIT team set up a three-day workshop to test the website with sample users. Participants included policy makers from eight cities and municipalities around the world, namely, Braga (Portugal), Cairo (Egypt), Dublin (Ireland), Florianopolis (Brazil), Kiel (Germany), Middlebury (Vermont, United States), Montreal (Canada), and Singapore (see page 4). Taken together, the cities represent a wide range of climates, socioeconomic demographics, cultures, governing structures, and sizes.

Working with the MIT team, the participants presented their goals, defined shallow- and deep-retrofit scenarios for their city, and selected a limited but representative area for analysis—an approach that would speed up analyses of different options while also generating results valid for the city as a whole.

They then performed analyses to quantify the impacts of their retrofit scenarios. Finally, they learned how best to present their findings—a critical part of the exercise. "When you do this analysis and bring it back to the people, you can say, 'This is our homework over the next 30 years. If we do this, we're going to get there,'" says Reinhart. "That makes you part of the community, so it's a joint goal."

Sample results

After the close of the workshop, Reinhart and his team confirmed their findings for each city and then added one more factor to the analyses: the state of the city's electric grid. Several cities in the study had pledged to make their grid carbon-neutral by 2050. Including the grid in the analysis was therefore critical: If a building becomes all electric and purchases its electricity from a carbon-free grid, then that building will be carbon neutral—even with no on-site energy-saving retrofits.

The figure on page 9 presents results for three of the eight cities. In each case, the tops of the bars indicate the total kilograms of carbon dioxide equivalent emitted per square meter of floor space. The horizontal red lines indicate any reductions that the city leaders targeted or pledged. From left to right, the bars show the calculated total assuming the following scenarios: the baseline; shallow retrofit only; shallow retrofit plus a clean electricity grid; deep retrofit only; deep retrofit plus rooftop photovoltaic (PV) solar panels; and deep retrofit plus a clean grid. Note that "rooftop PVs" means that decarbonized electricity comes only from the rooftop PVs, and that the "clean grid" is based on the area's most ambitious decarbonization target for their power grid. For Middlebury and Dublin, that target is net zero. For Singapore, the target is slightly less ambitious.

The following paragraphs summarize each city's setting, emission-reduction goals, current and proposed measures, and calculations of how implementation of those measures would affect their energy use and carbon emissions.

Singapore

Singapore is generally hot and humid, and its building energy use is largely in the form of electricity for cooling. The city is dominated by high-rise buildings, so there's not much space for roof-top solar installations to generate the needed electricity. Therefore, plans for decarbonizing the current building stock must involve retrofits. The shallow-retrofit scenario focuses on installing energy-efficient lighting and appliances. To those steps, the deep-retrofit scenario adds adopting a district cooling system. As indicated by the horizontal red lines, Singapore's stated goals are to cut the baseline carbon emissions by about a third by 2030 and to cut it in half by 2050.

The figure shows that, with just the shallow retrofits, Singapore won't achieve its 2030 goal. But with the deep retrofits, it should come close. Notably, decarbonizing the electric grid would enable Singapore to meet and substantially exceed its 2050 target assuming either retrofit scenario.

Dublin

Dublin has a mild climate with relatively comfortable summers but cold, humid winters. As a result, the city's energy use is dominated by fossil fuels (the dark gray bars), in particular, natural gas for space heating and domestic hot water. The city presented just one target—a 40% reduction by 2030.

Dublin has many neighborhoods made up of Georgian row houses, and, at the time of the workshop, the city already had a program in place encouraging groups of owners to insulate their walls. The shallow-retrofit scenario therefore focuses on weatherization upgrades (adding weatherstripping to windows and doors, insulating crawlspaces, and so on). To that list, the deep-retrofit scenario adds insulating walls and installing upgraded windows. The participants didn't include electric heat pumps as the city was then assessing the feasibility of expanding the existing district heating system.

Results of the analyses show that implementing the shallow-retrofit scenario won't enable Dublin to meet its 2030 target. But the deep-retrofit scenario will. However, like Singapore, Dublin could make major gains by decarbonizing its electric grid. The analysis shows that a decarbonized grid—with or without the addition of rooftop solar panels where possible—could more than halve the carbon emissions that remain in the deep-retrofit scenario. Indeed, a decarbonized grid plus electrification of the heating system by incorporating heat pumps could enable Dublin to meet a future net-zero target.

Middlebury

Middlebury, Vermont, has warm, wet summers and frigid winters. Like Dublin, its energy demand is dominated by natural gas for heating. But unlike Dublin, it already has a largely decarbonized electric grid with a high penetration of renewables.

For the analysis, the Middlebury team chose to focus on an aging residential neighborhood similar to many that surround the city core. The shallow-retrofit scenario calls for installing heat pumps for space heating, and the deep-retrofit scenario adds improvements in building envelopes (the façade, roof, and windows). The town's targets are a 40% reduction from the baseline by 2030 and net-zero carbon by 2050.

Results of the analyses showed that implementing the shallow-retrofit scenario won't achieve the 2030 target. The deep-retrofit scenario would get the city to the 2030 target but not to the 2050 target. Indeed, even with the deep retrofits, fossil fuel use remains high. The explanation? While both retrofit scenarios call for installing heat pumps for space heating, the city would continue to use natural gas to heat its hot water.

Lessons learned

For several policy makers, seeing the results of their analyses was a wake-up call. They learned that the strategies they had planned might not be sufficient to meet their stated goals—an outcome that could prove publicly embarrassing for them in the future.

Like the policy makers, the researchers learned from the experience. Reinhart notes three main take-aways.

First, he and his team were surprised to find how much of a building's energy use and carbon emissions can be traced to domestic hot water. With Middlebury, for example, even switching from natural gas to heat pumps for space heating didn't yield the expected effect: The gray bars representing carbon from fossil fuel use remained. As Reinhart recalls, "I kept saying, 'What's all this gray?'" While the policy makers talked about using heat pumps, they were still going to use natural gas to heat their hot water. "It's just stunning that hot water is such a big ticket item. It's huge," says Reinhart.

Second, the results demonstrate the importance of including the state of the local electric grid in this type of analysis. "Looking at the bar graphs, it's clear that if we want to have a successful energy transition, the building sector and the electric grid sector both have to do their homework," notes Reinhart. Moreover, in many cases, reaching carbon neutrality by 2050 would require not only a carbon-free grid but also all-electric buildings.

Third, Reinhart was struck by how different the graphs for the eight cities look. "This really celebrates the uniqueness of different parts of the world," he says. "The physics used in the analysis is the same everywhere, but differences in the climate, the building stock, construction practices, electric grids, and other factors make the consequences of making the same change vary widely."

In addition, says Reinhart, "there are sometimes deeply engrained conflicts of interest and cultural norms, which is why you cannot just say everybody should do this and do this." For instance, in one case, the city owned both the utility and the natural gas it burned. As a result, the policy makers didn't consider putting in heat pumps because "the natural gas was a significant source of municipal income, and they didn't want to give that up," explains Reinhart.

Finally, the analyses quantified two other important measures: energy use and "peak load," which is the maximum electricity demanded from the grid over a specific time period. Reinhart says that energy use "is probably mostly a plausibility check. Does this make sense?" And peak load is important because the utilities need to keep a stable grid.

Middlebury's analysis provides an interesting look at how certain measures could influence peak electricity demand. There, the introduction of electric heat pumps for space heating more than doubles the peak demand from buildings, suggesting that substantial additional capacity would have to be added to the grid in that region. But when heat pumps are combined with other retrofitting measures, the peak demand drops to levels lower than the starting baseline.

The aftermath: An update

Reinhart stresses that the specific results from the workshop provide just a snapshot in time, that is, where the cities were at the time of the workshop. "This is not the fate of the city," he says. "If we were to do the same exercise today, we'd no doubt see a change in thinking, and the outcomes would be different."

For example, heat pumps are now familiar technology and have demonstrated their ability to handle even bitterly cold climates. And in some regions, they've become economically attractive, as the war in Ukraine has made natural gas both scarce and expensive. Also, there's now awareness of the need to deal with hot water production.

Reinhart notes that performing the analyses at the workshop did have the intended impact: It brought about change. Two years after the project had ended, most of the cities reported that they had implemented new policy measures or had expanded their analysis across their entire building stock. "That's exactly what we want," comments Reinhart. "This is not an academic exercise. It's meant to change what people focus on and what they do."

Designing policies with socioeconomics in mind

Reinhart notes a key limitation of the UBEM.io approach: It looks only at technical feasibility. But will the building owners be willing and able to make the energy-saving retrofits? Data show that—even with today's incentive programs and subsidies—current adoption rates are only about 1%. "That's way too low to enable a city to achieve its emission-reduction goals in 30 years," says Reinhart. "We need to take into account the socioeconomic realities of the residents to design policies that are both effective and equitable."

To that end, the MIT team extended their UBEM.io approach to create a socio-techno-economic analysis framework that can predict the rate of retrofit adoption throughout a city. Based on Census data, the framework creates a UBEM that includes demographics for the specific types of buildings in a city. Accounting for the cost of making a specific retrofit plus financial benefits from policy incentives and future energy savings, the model determines the economic viability of the retrofit package for representative households.

Sample analyses for two Boston neighborhoods suggest that high-income households are largely ineligible for need-based incentives or the incentives are insufficient to prompt action. Lower-income households are eligible and could benefit financially over time, but they don't act, perhaps due to limited access to information, a lack of time or capital, or a variety of other reasons.

Reinhart notes that their work thus far "is mainly looking at technical feasibility. Next steps are to better understand occupants' willingness to pay and then to determine what set of federal and local incentive programs will trigger households across the demographic spectrum to retrofit their apartments and houses, helping the worldwide effort to reduce carbon emissions."

Nancy W. Stauffer, MITEI

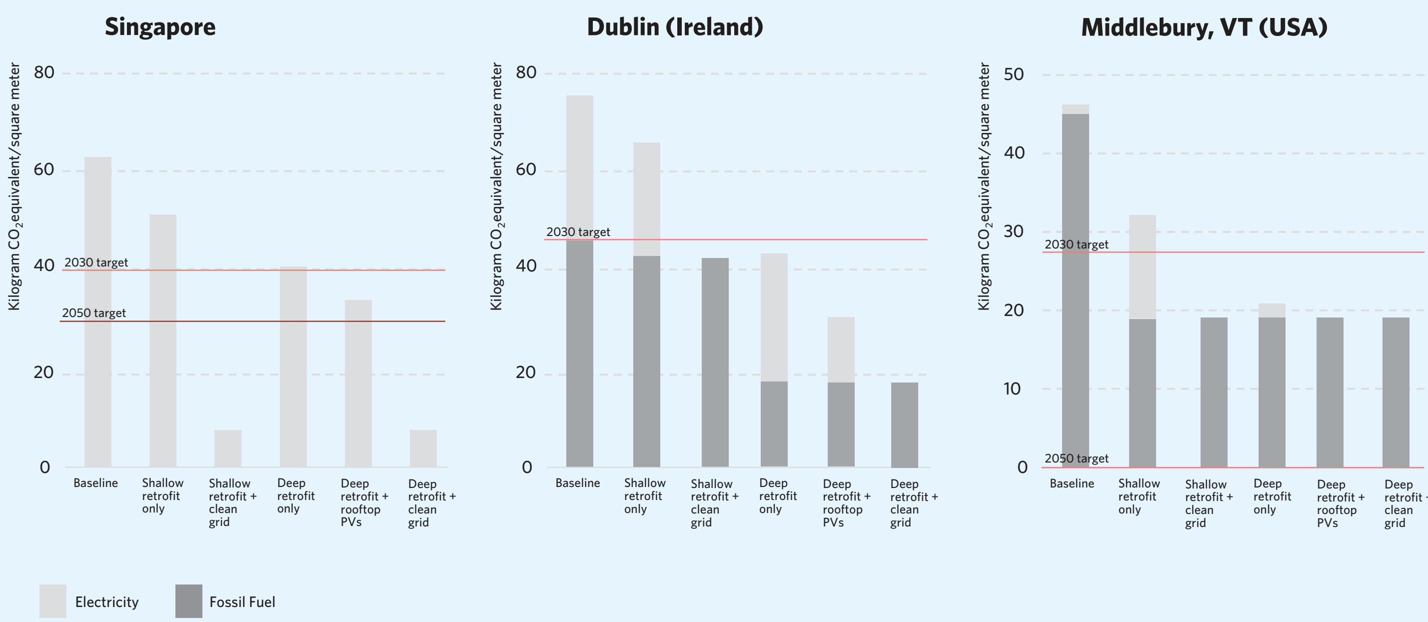
NOTES

This work was supported by Shell under the MIT Energy Initiative. Zachary Berzolla was supported by the U.S. National Science Foundation Graduate Research Fellowship. Samuel Letellier-Duchesne was supported by the Postdoctoral Fellowship of the Natural Sciences and Engineering Research Council of Canada. Further information about the research can be found in:

Y.Q. Ang, Z.M. Berzolla, S. Letellier-Duchesne, and C.F. Reinhart. "Carbon reduction technology pathways for existing buildings in eight cities." *Nature Communications*, April 4, 2023. Online: doi.org/10.1038/s41467-023-37131-6.

Y.Q. Ang, Z.M. Berzolla, S. Letellier-Duchesne, V. Jusiega, and C.F. Reinhart. "UBEM.io: A web-based framework to rapidly generate urban building energy models for carbon reduction technology pathways." *Sustainable Cities and Society*, February 2022. Online: doi.org/10.1016/j.scs.2021.103534.

Y. Nidam, A. Irani, J. Bemis, and C. Reinhart. "Census-based urban building energy modeling to evaluate the effectiveness of retrofit programs." *Environment and Planning B: Urban Analytics and City Science*, 2023. Online: doi.org/10.1177/23998083231154576.



Effectiveness of current urban policies aimed at reducing carbon emissions. The bars shown here represent annual carbon emissions in kilograms of carbon dioxide equivalent per square meter for each city's baseline and for their specified scenarios. Thus, the bars show the impacts of their shallow- and deep-retrofit measures on their own, when they're combined with cleanup of the local electricity grid, and—for the deep-retrofit scenario—when they're combined with installation of rooftop photovoltaic (PV) solar panels. Note that the calculations for "clean grid" are based on the area's most ambitious grid-decarbonization target. The red horizontal lines show the city's carbon emissions reduction targets. For all three cities, reducing carbon emissions from the grid plays an important role in meeting their carbon-reduction targets.

Making aviation fuel from biomass

A new MIT technique could be the key.

IN BRIEF

Jet fuel is a highly regulated mixture of different hydrocarbons. Today, there are approved commercial methods for making roughly three quarters of that mixture from renewable sources such as biomass. But despite extensive research, the other quarter still must come from fossil fuels. Now, an MIT-led team has demonstrated a technique that may make it possible to get that last quarter from biomass, in particular, from lignin, a component of plant material that is typically discarded as waste during biofuel production. The technique calls for reacting the biomass over a carefully selected catalyst to extract the lignin and break it down into a stable oil. Then, inside a custom-built reactor, the oil comes into contact with a different catalyst. The product that forms displays the same behavior and properties as the fossil fuel–derived hydrocarbons that now make up the last quarter of the jet fuel mixture. If this product passes some final rigorous tests for jet-fuel certification, the result could be—at last—an aviation fuel that's 100% sustainable.

In 2021, nearly a quarter of the world's carbon dioxide emissions came from the transportation sector, with aviation being a significant contributor. While the growing use of electric vehicles is helping to clean up ground transportation, today's batteries can't compete with fossil fuel–derived liquid hydrocarbons in terms of energy delivered per pound of weight—a major concern when it comes to flying. Meanwhile, based on projected growth in travel demand, consumption of jet fuel is projected to double between now and 2050—the year by which the international aviation industry has pledged to be carbon neutral.

Many groups have targeted a 100% sustainable hydrocarbon fuel for aircraft, but without much success. Part of the challenge is that aviation fuels are so tightly regulated. "This is a subclass of fuels that has very specific requirements in terms of the chemistry and the physical properties of the fuel because you can't risk something going wrong in an airplane engine," says Yuriy Román-Leshkov, the Robert T. Haslam (1911) Professor of Chemical Engineering. "If you're flying at 30,000 feet, it's very cold outside, and you don't want the fuel to thicken or freeze. That's why the formulation is very specific."

Aviation fuel is a combination of two large classes of chemical compounds. Some 75% to 90% of it is made up of "aliphatic" molecules, which consist of long chains of carbon atoms linked together. "This is similar to what we would find in diesel fuels, so it's a classic hydrocarbon that is out there," explains Román-Leshkov. The remaining 10% to 25% consists of "aromatic" molecules, each of which includes at least one ring made up of six connected carbon atoms.

In most transportation fuels, aromatic hydrocarbons are viewed as a source of pollution, so they're removed as much as possible. However, in aviation fuels, some aromatic molecules must remain because they set the necessary physical and combustion properties of the overall mixture. They also perform one more critical task: They ensure that seals between various components in the aircraft's fuel system are tight. "The aromatics get absorbed by the plastic seals and make them swell," explains Román-Leshkov. "If for some reason the fuel changes, so can the seals, and that's very dangerous."

As a result, aromatics are a necessary component—but they're also a stumbling block in the move to create sustainable aviation fuels, or SAFs. Companies know how to make the aliphatic fraction from inedible parts of plants and other renewables, but they haven't yet developed an approved method of generating the aromatic fraction from sustainable sources. As a result, there's a "blending wall," explains Román-Leshkov. "Since we need that aromatic content—regardless of its source—there will always be a limit on how much of the sustainable aliphatic hydrocarbons we can use without changing the properties of the mixture." He notes a similar blending wall with gasoline. "We have a lot of ethanol, but we can't add more than 10% without changing the properties of the gasoline. In fact, current engines can't handle even 15% ethanol without modification."

No shortage of renewable source material—or attempts to convert it

For the past five years, understanding and solving the SAF problem has been the goal of research by Román-Leshkov and his MIT team—Michael L. Stone PhD '21, Matthew S. Webber, and others—as well as their collaborators at Washington State University, the National Renewable

Facing page: Professor Yuriy Román-Leshkov and collaborators in his MIT group and elsewhere have demonstrated a new way to produce a critical component of aviation fuel from lignin, a plant material that's generally discarded as waste during biomass processing. If samples of the new product pass a final test for jet-fuel certification, the result could be aviation fuel that's made entirely from sustainable sources. Photo: Gretchen Ertl

Energy Laboratory (NREL), and the Pacific Northwest National Laboratory. Their work has focused on lignin, a tough material that gives plants structural support and protection against microbes and fungi. About 30% of the carbon in biomass is in lignin, yet when ethanol is generated from biomass, the lignin is left behind as a waste product.

Despite valiant efforts, no one has found an economically viable, scalable way to turn lignin into useful products, including the aromatic molecules needed to make jet fuel 100% sustainable. Why not? As Román-Leshkov says, "It's because of its chemical recalcitrance." It's difficult to make it chemically react in useful ways. As a result, every year millions of tons of waste lignin are burned as a low-grade fuel, used as fertilizer, or simply thrown away.

Understanding the problem requires understanding what's happening at the atomic level. The left-hand diagram in the figure below shows the chemical structure of a single lignin molecule—the starting point of the challenge. This big "macro-molecule" is made up of a network of many aromatic rings connected by oxygen (O) and hydrogen (H) atoms. (Unlabeled corners indicate carbon atoms, and the aromatic rings are recognizable by their hexagonal shape with three short lines inside.) Put simply, the key to converting lignin into the aromatic fraction of SAF is to break that macromolecule into smaller pieces while in the process getting rid of all of the oxygen atoms.

In general, most industrial processes begin with a chemical reaction that prevents the subsequent upgrading of lignin: As the lignin is extracted from the biomass, the aromatic molecules in it react with one another, linking together to form strong networks that won't react further. As a result, the lignin is no longer useful for making aviation fuels.

To avoid that outcome, Román-Leshkov and his team utilize another approach: They use a catalyst to induce a chemical reaction that wouldn't normally occur during extraction. By reacting the biomass in the presence of a ruthenium-based catalyst, they are able to remove the lignin from the biomass and produce a black liquid called lignin oil. That product is chemically stable, meaning that the aromatic molecules in it will no longer react with one another.

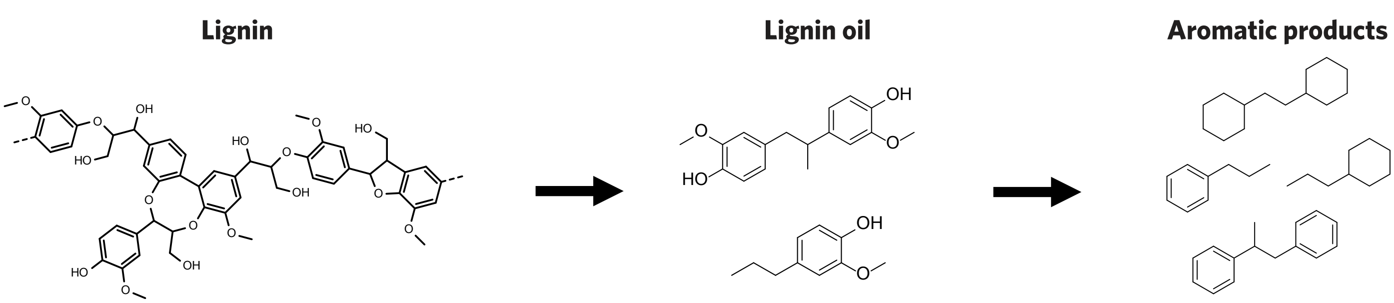
As shown in the middle diagram below, they've now successfully broken the original lignin macromolecule into fragments that contain just one or two aromatic rings each. However, while the isolated fragments don't chemically react, they still contain oxygen atoms. Therefore, one task remains: finding a way to remove the oxygen atoms.

In fact, says Román-Leshkov, getting from the molecules in the middle diagram to the targeted molecules such as those shown in the right-hand diagram required them to accomplish three things in a single step: They needed to selectively break the carbon-oxygen bonds to free the oxygen atoms; they needed to avoid incorporating non-carbon atoms into the aromatic rings (for example, atoms from the hydrogen gas that must be present for all of the chemical transformations to occur); and they needed to preserve the carbon backbone of the molecule, that is, the series of linked carbon atoms that connect the aromatic rings that remain.

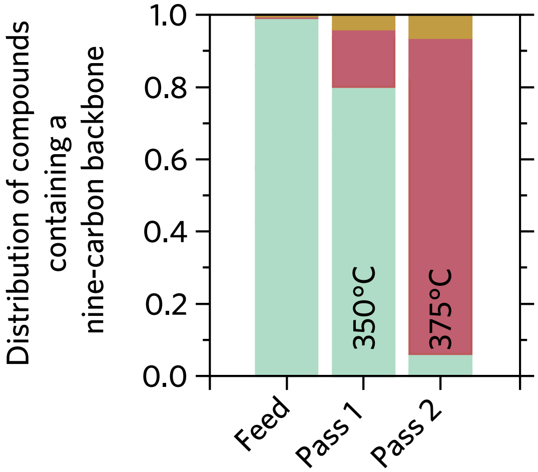
Ultimately, Román-Leshkov and his team found a special ingredient that would do the trick: a molybdenum carbide catalyst. "It's actually a really amazing catalyst because it can perform those three actions very well," says Román-Leshkov. "In addition to that, it's extremely resistant to poisons. Plants can contain a lot of components like proteins, salts, and sulfur, which often poison catalysts so they don't work anymore. But molybdenum carbide is very robust and isn't strongly influenced by such impurities."

Trying it out on lignin from poplar trees

To test their approach in the lab, the researchers first designed and built a specialized "trickle-bed" reactor, a type of chemical reactor in which both liquids



Converting molecules in waste biomass to aromatic molecules for sustainable aviation fuel. The left-hand diagram above shows an example of the type of large molecule that makes up lignin, a material typically discarded as waste during biomass processing. The first step in the MIT conversion technique breaks that large molecule into small fragments, as shown in the center diagram. The next two-step procedure removes the oxygen atoms while retaining the aromatic rings and the carbon "backbone" that links them together. The result is a mixture of aromatic molecules such as those that appear in the right-hand diagram—the material now needed to make aviation fuel fully sustainable.



Converting lignin oil from poplar biomass into products. To generate the aromatics needed for fully sustainable aviation fuel, the researchers ran the lignin oil formed during the first step of their process twice through particles of a molybdenum carbide catalyst. To analyze their results, they tracked compounds containing nine-carbon backbones—the most abundant compounds in the starting oil due to the inherent structure of lignin. This chart shows the distribution of those compounds in the oil and then how that distribution changes as a result of two sequential passes at the temperatures indicated. **Green** represents oxygen-containing molecules such as those shown in the center panel of the figure on page 12. **Red** represents the targeted aromatic products, while **gold** indicates other jet-fuel aliphatic molecules that form. The temperatures used in this example—350°C for the first pass and 375°C for the second—produced the best outcome, generating stable carbon yields higher than had been seen before.

and gases flow downward through a packed bed of catalyst particles. They then obtained biomass from a poplar, a type of tree known as an "energy crop" because it grows quickly and doesn't require a lot of fertilizer.

To begin, they reacted the poplar biomass in the presence of their ruthenium-based catalyst to extract the lignin and produce the lignin oil. They then flowed the oil through their trickle-bed reactor containing the molybdenum carbide catalyst. The mixture that formed contained some of the targeted product but also a lot of others that still contained oxygen atoms.

Román-Leshkov notes that in a trickle-bed reactor, the time during which the lignin oil is exposed to the catalyst depends entirely on how quickly it drips down through the packed bed. To increase the exposure time, they tried passing the oil through the same catalyst twice. However, the distribution of products that formed in the second pass wasn't as they had predicted based on the outcome of the first pass.

With further investigation, they figured out why. The first time the lignin oil drips through the reactor, it deposits oxygen onto the catalyst. The deposition of the oxygen changes the behavior of the catalyst such that certain products appear or disappear—with the temperature being critical. "The temperature and oxygen content set the condition of the catalyst in the first pass," says Román-Leshkov. "Then, on the second pass, the oxygen content in the flow is lower, and the catalyst can fully break the remaining carbon-oxygen bonds." The process can thus operate continuously: Two separate reactors containing independent catalyst beds would be connected in series, with the first pretreating the lignin oil and the second removing any oxygen that remains.

The bar chart above presents results from an experiment involving lignin oil from poplar biomass running under optimized conditions: 350°C in the first step and 375°C in the second step. The distributions of different chemical compounds are indicated by color. Red represents the desired product—aromatic hydrocarbons such as those shown in the right-hand panel of the figure on page 12. Green represents oxygen-containing molecules such as those shown in the center panel of the same figure. Gold shows other aliphatic jet-fuel molecules that form. Under those optimized conditions, the catalyst remains stable while generating more than 87% (by weight) of aromatic molecules.

"When we do our chemistry with the molybdenum carbide catalyst, our total carbon yields are nearly 85% of the theoretical carbon yield," says Román-Leshkov. "In most lignin-conversion processes, the carbon yields are very low, on the order of 10%.

The two vials shown above contain products from key steps in the MIT procedure. The brown lignin oil in the left-hand vial formed when the biomass was exposed to the first catalyst. The clear liquid in the right-hand vial—here displayed by Professor Román-Leshkov—formed when the lignin oil passed though the trickle-bed reactor for the second time. Now free of oxygen molecules, it is the aromatic fraction needed to make today's aviation fuel 100% sustainable. Photos: Gretchen Ertl

That's why the catalysis community got very excited about our results—because people had not seen carbon yields as high as the ones we generated with this catalyst."

There remains one key question: Does the mixture of components that forms have the properties required for aviation fuel? "When we work with these new substrates to make new fuels, the blend that we create is different from standard jet fuel," says Román-Leshkov. "Unless it has the exact properties required, it will not qualify for certification as jet fuel."

To check their products, Román-Leshkov and his team send samples to Washington State University, where a team operates a combustion lab devoted to testing fuels. Results from initial testing of the composition and properties of the samples have been encouraging. Based on the composition and published prescreening tools and procedures, the researchers have made initial property predictions for their samples, and they looked good. For example, the freezing point, viscosity, and threshold sooting index are predicted to be lower than the values for conventional aviation aromatics. (In other words, their material should flow more easily and be less likely to freeze than conventional aromatics while also generating less soot in the atmosphere when they burn.) Overall, the predicted properties are near to or more favorable than those of conventional fuel aromatics.

Next steps

The researchers are continuing to study how their sample blends behave at different temperatures and, in particular, how well they perform that key task: soaking into and swelling the seals inside jet engines. "These molecules are not the typical aromatic molecules that you use in jet fuel," says Román-Leshkov. "Preliminary tests with sample seals show that there's no difference in how our lignin-derived aromatics swell the seals, but we need to confirm that. There's no room for error."

In addition, he and his team are working with their NREL collaborators to scale up their methods. NREL has much larger reactors and other infrastructure needed to produce large quantities of the new sustainable blend. Based on the promising results thus far, the team wants to be prepared for the further testing required for the certification of jet fuels. In addition to testing samples of the fuel, the full certification procedure calls for demonstrating its behavior in an operating engine—"not while flying, but in a lab," clarifies Román-Leshkov. In addition to requiring large samples, that demonstration is both time-consuming and expensive—which is why it's the very last step in the strict testing required for a new sustainable aviation fuel to be approved.

Román-Leshkov and his colleagues are now exploring the use of their approach with other types of biomass, including pine, switchgrass, and corn stover (the leaves, stalks, and cobs left after corn is harvested). But their results with poplar biomass are promising. If further testing confirms that their aromatic products can replace the aromatics now in jet fuel, "the blending wall could disappear," says Román-Leshkov. "We'll have a means of producing all the components in aviation fuel from renewable material, potentially leading to aircraft fuel that's 100% sustainable."

Nancy W. Stauffer, MITEI

NOTES

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M.L. Stone, M.S. Webber, W.P. Mounfield III, D.C. Bell, E. Christensen, A.R.C. Morais, Y. Li, E.M. Anderson, J.S. Heyne, G.T. Beckham, and Y. Román-Leshkov. "Continuous hydrodeoxygenation of lignin to jet-range aromatic hydrocarbons." *Joule*, October 2022. Online: doi.org/10.1016/j.joule.2022.08.005.

Postdoc Jamison Watson joined the Román Lab in January 2021 to focus on the catalytic upgrading and conversion of lignin into the aromatic fraction needed to make aviation fuel fully sustainable. Here, he adjusts the trickle-bed reactor to optimize its performance. In related research, he is working to further improve product yields by breaking apart molecules in the mixture that are still too large for use in sustainable aviation fuels. Photo: Gretchen Ertl

To decarbonize the chemical industry, electrify it

Researchers urge industry and the research community to explore electrification pathways to reduce chemical industry emissions.

Electrification powered by low-carbon sources should be considered more broadly as a viable decarbonization pathway for the chemical industry, argue researchers. Photo: David Arrowsmith/Unsplash

The chemical industry is the world's largest industrial energy consumer and the third largest source of industrial emissions, according to the International Energy Agency. In 2019, the industrial sector as a whole was responsible for 24% of global greenhouse gas emissions. And yet, as the world races to find pathways to decarbonization, the chemical industry has been largely untouched.

"When it comes to climate action and dealing with the emissions that come from the chemical sector, the slow pace of progress is partly technical and partly driven by the hesitation on behalf of policy makers to overly impact the economic competitiveness of the sector," says Dharik Mallapragada, a principal research scientist at the MIT Energy Initiative.

With so many of the items we interact with in our daily lives—from soap to baking soda to fertilizer—deriving from products of the chemical industry, the sector has become a major source of economic activity and employment for many nations, including the United States and China. But as the global demand for chemical products continues to grow, so do the industry's emissions.

New sustainable chemical production methods need to be developed and deployed, and current emission-intensive chemical production technologies need to be reconsidered, urge the authors of a paper published in *Joule*. Researchers from DC-MUSE, a multi-institution research initiative, argue that electrification powered by low-carbon sources should be viewed more broadly as a viable decarbonization pathway for the chemical industry. In this paper, they shine a light on different potential methods to do just that.

"Generally, the perception is that electrification can play a role in this sector—in a very narrow sense—in that it can replace fossil fuel combustion by providing the heat that the combustion is providing," says Mallapragada, a member of DC-MUSE. "What we argue is that electrification could be much more than that."

The researchers outline four technological pathways—ranging from more mature, near-term options to less technologically mature options in need of research investment—and present the opportunities and challenges associated with each.

The first two pathways directly substitute fossil fuel–produced heat (which facilitates the reactions inherent in chemical production) with electricity or electrochemically generated hydrogen. The researchers suggest that both options could be deployed now and potentially be used to retrofit existing facilities. Electrolytic hydrogen is also highlighted as an opportunity to replace fossil fuel–produced hydrogen (a process that emits carbon dioxide) as a critical chemical feedstock. In 2020, fossil-based hydrogen supplied nearly all hydrogen demand (90 megatons) in the chemical and refining industries—hydrogen's largest consumers.

The researchers note that increasing the role of electricity in decarbonizing the chemical industry will directly affect the decarbonization of the power grid. They stress that to successfully implement these technologies, their operation must coordinate with the power grid in a mutually beneficial manner to avoid overburdening it. "If we're going to be serious about decarbonizing the sector and relying on electricity for that, we have to be creative in how we use it," says Mallapragada. "Otherwise we run the risk of having addressed one problem, while creating a massive problem for the grid in the process."

Electrified processes have the potential to be much more flexible than conventional fossil fuel–driven processes. This can reduce the cost of chemical production by allowing producers to shift electricity consumption to times when the cost of electricity is low. "Process flexibility is particularly impactful during stressed power grid conditions and can help better accommodate renewable generation resources, which are intermittent and are often poorly correlated with daily power grid cycles," says Yury Dvorkin, an associate research professor at the Johns Hopkins Ralph O'Connor Sustainable Energy Institute. "It's beneficial for potential adopters because it can help them avoid consuming electricity during high-price periods."

Dvorkin adds that some intermediate energy carriers, such as hydrogen, can potentially be used as highly efficient energy storage for day-to-day operations and as long-term energy storage. This would help support the power grid during extreme events when traditional and renewable generators may be unavailable. "The application of long-duration storage is of particular interest as this is a key enabler of a low-emissions society, yet not widespread beyond pumped hydro units," he says. "However, as we envision electrified chemical manufacturing, it is important to ensure that the supplied electricity is sourced from low-emission generators to prevent emissions leakages from the chemical to the power sector."

The next two pathways introduced—utilizing electrochemistry and plasma—are less technologically mature but have the potential to replace energy- and carbon-intensive thermochemical processes currently used in the industry. By adopting electrochemical processes or plasma-driven reactions instead, chemical transformations can occur at lower temperatures and pressures, potentially enhancing efficiency. "These reaction pathways also have the potential to enable more flexible, grid-responsive plants and the deployment of modular manufacturing plants that leverage distributed chemical feedstocks such as biomass waste—further enhancing sustainability in chemical manufacturing," says Miguel Modestino, the director of the Sustainable Engineering Initiative at the New York University Tandon School of Engineering.

A large barrier to deep decarbonization of chemical manufacturing relates to its complex, multi-product nature. But, according to the researchers, each of these electricity-driven pathways supports chemical industry decarbonization for various feedstock choices and end-of-life disposal decisions. Each should be evaluated in comprehensive techno-economic and environmental life cycle assessments to weigh trade-offs and establish suitable cost and performance metrics.

Regardless of the pathway chosen, the researchers stress the need for active research and development and deployment of these technologies. They also emphasize the importance of workforce training and development running in parallel to technology development. As André Taylor, the director of DC-MUSE, explains, "There is a healthy skepticism in the industry regarding electrification and adoption of these technologies, as it involves processing chemicals in a new way." The workforce at different levels of the industry hasn't necessarily been exposed to ideas related to the grid, electrochemistry, or plasma. The researchers say that workforce training at all levels will help build greater confidence in these different solutions and support customer-driven industry adoption.

"There's no silver bullet, which is kind of the standard line with all climate change solutions," says Mallapragada. "Each option has pros and cons, as well as unique advantages. But being aware of the portfolio of options in which you can use electricity allows us to have a better chance of success and of reducing emissions—and doing so in a way that supports grid decarbonization."

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Kelley Travers, MITEI

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For more information, please see the following:

D.S. Mallapragada, Y. Dvorkin, M.A. Modestino, D.V. Esposito, W.A. Smith, B-M.Hodge, M.P. Harold, V.M. Donnelly, A. Nuz, C. Bloomquist, K. Baker, L.C. Grabow, Y. Yan, N.N. Rajput, R.L. Hartman, E.J. Biddinger, E.S. Aydil, and A.D. Taylor. "Decarbonization of the chemical industry through electrification: Barriers and opportunities." *Joule*, vol. 7, issue 1, pages 23-41, January 18, 2023. Online: doi.org/10.1016/j.joule.2022.12.008.

A healthy wind

Health benefits of using wind energy instead of fossil fuels could quadruple if the most polluting power plants are selected for dialing down, MIT study finds.

Nearly 10% of today's electricity in the United States comes from wind power. The renewable energy source benefits climate, air quality, and public health by displacing emissions of greenhouse gases and air pollutants that would otherwise be produced by fossil fuel–based power plants.

A new MIT study finds that the health benefits associated with wind power could more than quadruple if operators prioritized turning down output from the most polluting fossil fuel–based power plants when energy from wind is available.

In the study, published in *Science Advances*, researchers analyzed the hourly activity of wind turbines, as well as the reported emissions from every fossil fuel–based power plant in the country, between the years 2011 and 2017. They traced emissions across the country and mapped the pollutants to affected demographic populations. They then calculated the regional air quality and associated health costs to each community.

The researchers found that in 2014, wind power that was associated with state-level policies improved air quality overall, resulting in $2 billion in health benefits across the country. However, only roughly 30% of these health benefits reached disadvantaged communities.

The team further found that if the electricity industry were to reduce the output of the most polluting fossil fuel–based power plants, rather than the most cost-saving plants, in times of wind-generated power, the overall health benefits could quadruple to $8.4 billion nationwide. However, the results would have a similar demographic breakdown.

"We found that prioritizing health is a great way to maximize benefits in a widespread way across the U.S., which is a very positive thing. But it suggests it's not going to address disparities," says study co-author Noelle Selin, a professor in the Institute for Data, Systems, and Society and the Department of Earth, Atmospheric and Planetary Sciences at MIT. "In order to address air pollution disparities, you can't just focus on the electricity

A new MIT study finds that the health benefits associated with wind power could more than quadruple if operators prioritized turning down output from the most polluting fossil fuel–based power plants when energy from wind is available. Photo: MIT sector or renewables and count on the overall air pollution benefits addressing these real and persistent racial and ethnic disparities. You'll need to look at other air pollution sources, as well as the underlying systemic factors that determine where plants are sited and where people live."

Selin's co-authors are lead author and former MIT graduate student Minghao Qiu PhD '21, now at Stanford University, and Corwin Zigler at the University of Texas at Austin.

Turn-down service

In their new study, the team looked for patterns between periods of wind power generation and the activity of fossil fuel–based power plants, to see how regional electricity markets adjusted the output of power plants in response to influxes of renewable energy.

"One of the technical challenges, and the contribution of this work, is trying to identify which are the power plants that respond to this increasing wind power," Qiu notes.

To do so, the researchers compared two historical datasets from the period between 2011 and 2017: an hour-by-hour record of energy output of wind turbines across the country, and a detailed record of emissions measurements from every fossil fuel–based power plant in the United States. The datasets covered each of seven major regional electricity markets, each market providing energy to one or multiple states.

"California and New York are each their own market, whereas the New England market covers around seven states, and the Midwest covers more," Qiu explains. "We also cover about 95 percent of all the wind power in the U.S."

In general, they observed that, in times when wind power was available, markets adjusted by essentially scaling back the power output of natural gas and sub-bituminous coal-fired power plants. They noted that the plants that were turned down were likely chosen for cost-saving reasons, as certain plants were less costly to turn down than others.

The team then used a sophisticated atmospheric chemistry model to simulate the wind patterns and chemical transport of emissions across the country, and determined where and at what concentrations the emissions generated fine particulates and ozone—two pollutants that are known to damage air quality and human health. Finally, the researchers mapped the general demographic populations across the country, based on U.S. census data, and applied a standard epidemiological approach to calculate a population's health cost as a result of their pollution exposure.

This analysis revealed that, in the year 2014, a general cost-saving approach to displacing fossil fuel–based energy in times of wind energy resulted in $2 billion in health benefits, or savings, across the country. A smaller share of these benefits went to disadvantaged populations, such as communities of color and low-income communities, though this disparity varied by state.

"It's a more complex story than we initially thought," Qiu says. "Certain population groups are exposed to a higher level of air pollution, and those would be low-income people and racial minority groups. What we see is, developing wind power could reduce this gap in certain states but further increase it in other states, depending on which fossil fuel plants are displaced."

Tweaking power

The researchers then examined how the pattern of emissions and the associated health benefits would change if they prioritized turning down different fossil fuel–based plants in times of wind-generated power. They tweaked the emissions data to reflect several alternative scenarios: one in which the most health-damaging, polluting power plants are turned down first; and two other scenarios in which plants producing the most sulfur dioxide and carbon dioxide respectively, are first to reduce their output.

They found that while each scenario increased health benefits overall, and the first scenario in particular could quadruple health benefits, the original disparity persisted: Communities of color and low-income communities still experienced smaller health benefits than more well-off communities.

"We got to the end of the road and said, there's no way we can address this disparity by being smarter in deciding which plants to displace," Selin says.

Nevertheless, the study can help identify ways to improve the health of the general population, says Julian Marshall, a professor of environmental engineering at the University of Washington.

"The detailed information provided by the scenarios in this paper can offer a roadmap to electricity-grid operators and to state air-quality regulators regarding which power plants are highly damaging to human health and also are likely to noticeably reduce emissions if wind-generated electricity increases," says Marshall, who was not involved in the study.

"One of the things that makes me optimistic about this area is, there's a lot more attention to environmental justice and equity issues," Selin concludes. "Our role is to figure out the strategies that are most impactful in addressing those challenges."

This work was supported, in part, by the U.S. Environmental Protection Agency, and by the National Institutes of Health.

Jennifer Chu, MIT News Office

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For further information, please see the following:

M. Qiu, C.M. Zigler, and N.E. Selin. "Impacts of wind power on air quality, premature mortality, and exposure disparities in the United States." *Science Advances*, vol. 8, issue 48, Dec. 2, 2022. Online: doi.org/10.1126/sciadv.abn8762.

Minimizing electric vehicles' impact on the grid

Careful planning of charging station placement could lessen or eliminate the need for new power plants, a new study shows.

MIT researchers have found that, by encouraging the placing of charging stations for electric vehicles (EVs) in strategic ways, as well as setting up systems to initiate car charging at delayed times, EVs could have less impact on the power grid. Photo: Melanie Gonick, MIT

National and global plans to combat climate change include increasing the electrification of vehicles and the percentage of electricity generated from renewable sources. But some projections show that these trends might require costly new power plants to meet peak loads in the evening when cars are plugged in after the workday. What's more, overproduction of power from solar farms during the daytime can waste valuable electricity-generation capacity.

In a new study, MIT researchers have found that it's possible to mitigate or eliminate both these problems without the need for advanced technological systems of connected devices and real-time communications, which could add to costs and energy consumption. Instead, encouraging the placing of charging stations for electric vehicles (EVs) in strategic ways, rather than letting them spring up anywhere, and setting up systems to initiate car charging at delayed times could potentially make all the difference.

The study, published in the journal *Cell Reports Physical Science*, is by Zachary Needell PhD '22, postdoc Wei Wei, and Professor Jessika Trancik of MIT's Institute for Data, Systems, and Society.

In their analysis, the researchers used data collected in two sample cities: New York and Dallas. The data were gathered from, among other sources, anonymized records collected via onboard devices in vehicles and surveys that carefully sampled populations to cover variable travel behaviors. They showed the times of day cars are used and for how long, and how much time the vehicles spend at different kinds of locations—residential, workplace, shopping, entertainment, and so on.

The findings, Trancik says, "round out the picture on the question of where to strategically locate chargers to support EV adoption and also support the power grid."

Better availability of charging stations at workplaces, for example, could help to soak up peak power being produced at midday from solar power installations, which might otherwise go to waste because it is not economical to build enough battery or other storage capacity to save all of it for later in the day. Thus, workplace chargers can provide a double benefit, helping to reduce the evening peak load from EV charging and also making use of the solar electricity output.

These effects on the electric power system are considerable, especially if the system must meet charging demands for a fully electrified personal vehicle fleet alongside the peaks in other demand for electricity, for example, on the hottest days of the year. If unmitigated, the evening peaks in EV charging demand could require installing upwards of 20% more power-generation capacity, the researchers say.

"Slow workplace charging can be more preferable than faster charging technologies for enabling a higher utilization of midday solar resources," Wei says.

Meanwhile, with delayed home charging, each EV charger could be accompanied by a simple app to estimate the time to begin its charging cycle so that it charges just before it is needed the next day. Unlike other proposals that require a centralized control of the charging cycle, such a system needs no interdevice communication of information and can be preprogrammed—and can accomplish a major shift in the demand on the grid caused by increasing EV penetration. The reason it works so well, Trancik says, is because of the natural variability in driving behaviors across individuals in a population.

By "home charging," the researchers aren't only referring to charging equipment in individual garages or parking areas. They say it's essential to make charging stations available in on-street parking locations and in apartment building parking areas as well.

Trancik says the findings highlight the value of combining the two measures—workplace charging and delayed home charging—to reduce peak electricity demand, store solar energy, and conveniently meet drivers' charging needs on all days. As the team showed in earlier research, home charging can be a particularly effective component of a strategic package of charging locations; workplace charging, they have found, is not a good substitute for home charging for meeting drivers' needs on all days.

"Given that there's a lot of public money going into expanding charging infrastructure," Trancik says, "how do you incentivize the location such that this is going to be efficiently and effectively integrated into the power grid without requiring a lot of additional capacity expansion?" This research offers some guidance to policy makers on where to focus rules and incentives.

"I think one of the fascinating things about these findings is that by being strategic you can avoid a lot of physical infrastructure that you would otherwise need," she adds. "Your electric vehicles can displace some of the need for stationary energy storage, and you can also avoid the need to expand the capacity of power plants, by thinking about the location of chargers as a tool for managing demands—where they occur and when they occur."

Delayed home charging could make a surprising amount of difference, the team found. "It's basically incentivizing people to begin charging later. This can be something that is preprogrammed into your chargers. You incentivize people to delay the onset of charging by a bit, so that not everyone is charging at the same time, and that smooths out the peak."

Such a program would require some advance commitment on the part of participants. "You would need to have enough people committing to this program in advance to avoid the investment in physical infrastructure," Trancik says. "So, if you have enough people signing up, then you essentially don't have to build those extra power plants."

It's not a given that all of this would line up just right, and putting in place the right mix of incentives would be crucial. "If you want electric vehicles to act as an effective storage technology for solar energy, then the [EV] market needs to grow fast enough in order to be able to do that," Trancik says.

To best use public funds to help make that happen, she says, "you can incentivize charging installations, which would go through ideally a competitive process—in the private sector, you would have companies bidding for different projects, but you can incentivize installing charging at workplaces, for example, to tap into both of these benefits." Chargers people can access when they are parked near their residences are also important, Trancik adds, but for other reasons. Home charging is one of the ways to meet charging needs while avoiding inconvenient disruptions to people's travel activities.

The study was supported by the European Regional Development Fund Operational Program for Competitiveness and Internationalization, the Lisbon Portugal Regional Operation Program, and the Portuguese Foundation for Science and Technology.

David L. Chandler, MIT News Office

NOTES

For more information, please see the following:

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Paper-thin solar cell can turn any surface into a power source

Researchers develop a scalable fabrication technique to produce ultrathin, lightweight solar cells that can be seamlessly added to any surface.

MIT engineers have developed ultralight fabric solar cells that can quickly and easily turn any surface into a power source.

These durable, flexible solar cells, which are much thinner than a human hair, are glued to a strong, lightweight fabric, making them easy to install on a fixed surface. They can provide energy on the go as a wearable power fabric or be transported and rapidly deployed in remote locations for assistance in emergencies. They are one-hundredth the weight of conventional solar panels, generate 18 times more power-per-kilogram, and are made from semiconducting inks using printing processes that can be scaled in the future to large-area manufacturing.

Because they are so thin and lightweight, these solar cells can be laminated onto many different surfaces. For instance, they could be integrated onto the sails of a boat to provide power while at sea, adhered onto tents and tarps that are deployed in disaster recovery operations, or applied onto the wings of drones to extend their flying range. This lightweight solar technology can be easily integrated into built environments with minimal installation needs.

"The metrics used to evaluate a new solar cell technology are typically limited to their power conversion efficiency and their cost in dollars-per-watt. Just as important is integrability—the ease with which the new technology can be adapted. The lightweight solar fabrics enable integrability, providing impetus for the current work. We strive to accelerate solar adoption, given the present urgent need to deploy new carbon-free sources of energy," says Vladimir Bulović, the Fariborz Maseeh Chair in Emerging Technology, leader of the Organic and Nanostructured Electronics Laboratory (ONE Lab), director of MIT.nano, and senior author of a paper describing the work.

Joining Bulović on the paper are co-lead authors Mayuran Saravanapavanantham, an electrical engineering and computer science graduate student at MIT; and Jeremiah Mwaura, a research scientist in the MIT Research Laboratory of Electronics. The research was published in *Small Methods*.

Slimmed down solar

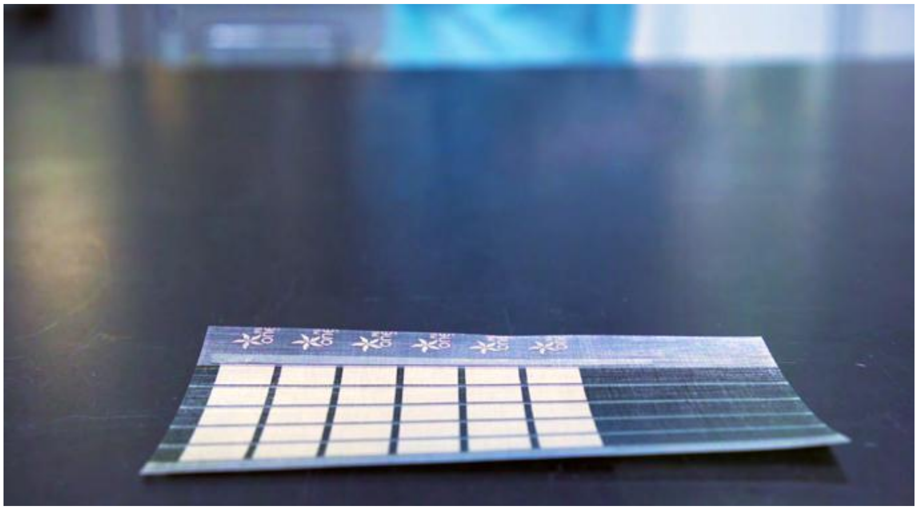
Traditional silicon solar cells are fragile, so they must be encased in glass and packaged in heavy, thick aluminum framing, which limits where and how they can be deployed.

Six years ago, the ONE Lab team produced solar cells using an emerging class of thin-film materials that were so lightweight they could sit on top of a soap bubble. But these ultrathin solar cells were fabricated using complex, vacuum-based processes, which can be expensive and challenging to scale up.

In this work, they set out to develop thin-film solar cells that are entirely printable, using ink-based materials and scalable fabrication techniques.

To produce the solar cells, they use nanomaterials that are in the form of a

MIT researchers have developed a scalable fabrication technique to produce ultrathin, lightweight solar cells that can be stuck onto any surface. Photo: Melanie Gonick, MIT



The thin-film solar cells weigh about 100 times less than conventional solar cells while generating about 18 times more power-per-kilogram. Photo: Melanie Gonick, MIT

printable electronic ink. Working in the MIT.nano clean room, they coat the solar cell structure using a slot-die coater, which deposits layers of the electronic materials onto a prepared, releasable substrate that is only 3 microns thick. Using screen printing (a technique similar to how designs are added to silkscreened T-shirts), an electrode is deposited on the structure to complete the solar module.

The researchers can then peel the printed module, which is about 15 microns in thickness, off the plastic substrate, forming an ultralight solar device.

But such thin, freestanding solar modules are challenging to handle and can easily tear, which would make them difficult to deploy. To solve this challenge, the MIT team searched for a lightweight, flexible, and high-strength substrate they could adhere the solar cells to. They identified fabrics as the optimal solution, as they provide mechanical resilience and flexibility with little added weight.

They found an ideal material—a composite fabric that weighs only 13 grams per square meter, commercially known as Dyneema. This fabric is made of fibers that are so strong they were used as ropes to lift the sunken cruise ship *Costa Concordia* from the bottom of the Mediterranean Sea. By adding a layer of UV-curable glue, which is only a few microns thick, they adhere the solar modules to sheets of this fabric. This forms an ultra-light and mechanically robust solar structure.

"While it might appear simpler to just print the solar cells directly on the fabric, this would limit the selection of possible fabrics or other receiving surfaces to the ones that are chemically and thermally compatible with all the processing steps needed to make the devices. Our approach decouples the solar cell manufacturing from its final integration," Saravanapavanantham explains.

Outshining conventional solar cells

When they tested the device, the MIT researchers found it could generate 730 watts of power per kilogram when freestanding and about 370 watts-per-kilogram if deployed on the high-strength Dyneema fabric, which is about 18 times more power-per-kilogram than conventional solar cells.

"A typical rooftop solar installation in Massachusetts is about 8,000 watts. To generate that same amount of power, our fabric photovoltaics would only add about 20 kilograms (44 pounds) to the roof of a house," he says.

They also tested the durability of their devices and found that, even after rolling and unrolling a fabric solar panel more than 500 times, the cells still retained more than 90% of their initial power generation capabilities.

While their solar cells are far lighter and much more flexible than traditional cells, they would need to be encased in another material to protect them from the environment. The carbon-based organic material used to make the cells could be modified by interacting with moisture and oxygen in the air, which could deteriorate their performance.

"Encasing these solar cells in heavy glass, as is standard with the traditional silicon solar cells, would minimize the value of the present advancement, so the team is currently developing ultrathin packaging solutions that would only fractionally increase the weight of the present ultralight devices," says Mwaura.

"We are working to remove as much of the non-solar-active material as possible while still retaining the form factor and performance of these ultralight and flexible solar structures. For example, we know the manufacturing process can be further streamlined by printing the releasable substrates, equivalent to the process we use to fabricate the other layers in our device. This would accelerate the translation of this technology to the market," he adds.

This research is funded, in part, by Eni S.p.A. through the MIT Energy Initiative, the U.S. National Science Foundation, and the Natural Sciences and Engineering Research Council of Canada.

Adam Zewe, MIT News Office

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For more information, please see the following:

M. Saravanapavanantham, J. Mwaura, and V. Bulović. "Printed organic photovoltaic modules on transferable ultra-thin substrates as additive power sources." *Small Methods*, December 2022. Online: doi.org/10.1002/smtd.202200940.

MIT engineers devise technology to prevent fouling in photobioreactors for carbon dioxide capture

Applying a small voltage to the walls of algae growing tanks can prevent cloudy buildup and allow more photosynthesis to happen.

Algae grown in transparent tanks or tubes supplied with carbon dioxide can convert the greenhouse gas into other compounds, such as food supplements or fuels. But the process leads to a buildup of algae on the surfaces that clouds them and reduces efficiency, requiring laborious cleanout procedures every couple of weeks.

MIT researchers have come up with a simple and inexpensive technology that could substantially limit this fouling, potentially allowing for a much more efficient and economical way of converting the unwanted greenhouse gas into useful products.

The key is to coat the transparent containers with a material that can hold an electrostatic charge, and then apply a very small voltage to that layer. The system has worked well in lab-scale tests, and with further development might be applied to commercial production within a few years.

A new, inexpensive technology can limit the buildup of algae on the walls of photobioreactors that can help convert carbon dioxide into useful products. Reducing this fouling avoids costly cleanouts and allows more photosynthesis to happen within tanks. Image: Jose-Luis Olivares, MIT

The findings are reported in the journal *Advanced Functional Materials*, in a paper by recent MIT graduate Victor Leon PhD '23, professor of mechanical engineering Kripa Varanasi, former postdoc Baptiste Blanc, and undergraduate student Sophia Sonnert.

No matter how successful efforts to reduce or eliminate carbon emissions may be, there will still be excess greenhouse gases that will remain in the atmosphere for centuries to come, continuing to affect global climate, Varanasi points out. "There's already a lot of carbon dioxide there, so we have to look at negative emissions technologies as well," he says, referring to ways of removing the greenhouse gas from the air or oceans, or from their sources before they get released into the air in the first place.

When people think of biological approaches to carbon dioxide reduction, the first thought is usually of planting or protecting trees, which are indeed a crucial "sink" for atmospheric carbon. But there are others. "Marine algae account for about 50 percent of global carbon dioxide absorbed today on Earth," Varanasi says. These algae grow anywhere from 10 to 50 times more quickly than land-based plants, and they can be grown in ponds or tanks that take up only a tenth of the land footprint of terrestrial plants.

What's more, the algae themselves can then be a useful product. "These algae are rich in proteins, vitamins, and other nutrients," Varanasi says, noting they could produce far more nutritional output per unit of land used than some traditional agricultural crops.

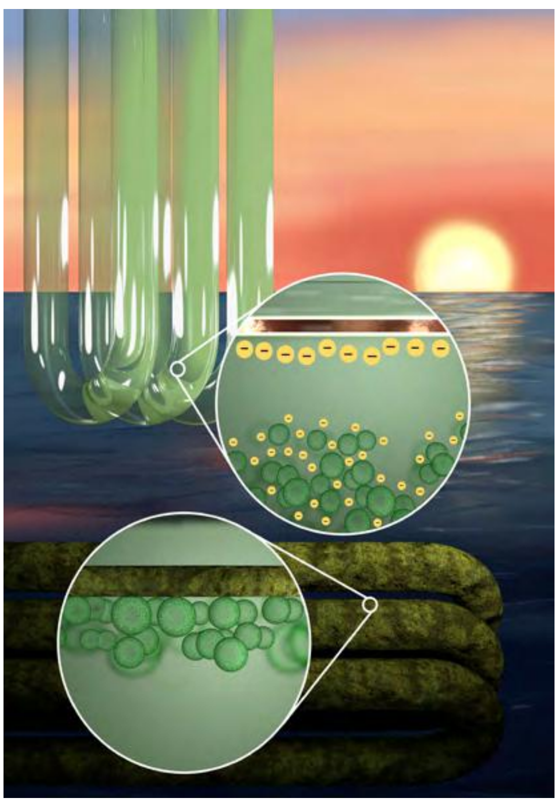
If attached to the flue gas output of a coal or gas power plant, algae could not only thrive on the carbon dioxide as a nutrient source, but some of the microalgae species could also consume the associated nitrogen and sulfur oxides present in these emissions. "For every two or three kilograms of CO_2, a kilogram of algae could be produced, and these could be used as biofuels, or for Omega-3, or food," Varanasi says.

Omega-3 fatty acids are a widely used food supplement, as they are an essential part of cell membranes and other tissues but cannot be made by the body and must be obtained from food. "Omega 3 is particularly attractive because it's also a much higher-value product," Varanasi says.

Most algae grown commercially are cultivated in shallow ponds, while others are grown in transparent tubes called photobioreactors. The tubes can produce seven to 10 times greater yields than ponds for a given amount of land, but they face a major problem: The algae tend to build up on the transparent surfaces, requiring frequent shutdowns of the whole production system for cleaning, which can take as long as the productive part of the cycle, thus cutting overall output in half and adding to operational costs.

The fouling also limits the design of the system. The tubes can't be too small because the fouling would begin to block the flow of water through the bioreactor and require higher pumping rates.

Varanasi and his team decided to try to use a natural characteristic of the algae cells to defend against fouling. Because the cells naturally carry a small negative electric charge on their membrane surface, the team figured that electrostatic repulsion could be used to push them away.



Because the algae cells naturally carry a small negative electric charge on their membrane surface, the team figured that electrostatic repulsion could be used to push them away. Image courtesy of the researchers

The idea was to create a negative charge on the vessel walls, such that the electric field forces the algae cells away from the walls. To create such an electric field requires a high-performance dielectric material, which is an electrical insulator with a high "permittivity" that can produce a large change in surface charge with a smaller voltage.

"What people have done before with applying voltage [to bioreactors] has been with conductive surfaces," Leon explains, "but what we're doing here is specifically with nonconductive surfaces."

He adds: "If it's conductive, then you pass current and you're kind of shocking the cells. What we're trying to do is pure electrostatic repulsion, so the surface would be negative and the cell is negative so you get repulsion. Another way to describe it is like a force field, whereas before the cells were touching the surface and getting shocked."

The team worked with two different dielectric materials, silicon dioxide—essentially glass—and hafnia (hafnium oxide), both of which turned out to be far more efficient at minimizing fouling than conventional plastics used to make photobioreactors. The material can be applied in a coating that is vanishingly thin, just 10 to 20 nanometers (billionths of a meter) thick, so very little would be needed to coat a full photobioreactor system.

"What we are excited about here is that we are able to show that purely from electrostatic interactions, we are able to control cell adhesion," Varanasi says. "It's almost like an on-off switch, to be able to do this."

Additionally, Leon says, "Since we're using this electrostatic force, we don't really expect it to be cell-specific, and we think there's potential for applying it with other cells than just algae. In future work, we'd like to try using it with mammalian cells, bacteria, yeast, and so on." It could also be used with other valuable types of algae, such as spirulina, that are widely used as food supplements.

The same system could be used to either repel or attract cells by just reversing the voltage, depending on the particular application. Instead of algae, a similar setup might be used with human cells to produce artificial organs by producing a scaffold that could be charged to attract the cells into the right configuration, Varanasi suggests.

"Our study basically solves this major problem of biofouling, which has been a bottleneck for photobioreactors," he says. "With this technology, we can now really achieve the full potential" of such systems, although further development will be needed to scale up to practical, commercial systems.

As for how soon this could be ready for widespread deployment, he says, "I don't see why not in three years' timeframe, if we get the right resources to be able to take this work forward."

The study was supported by energy company Eni S.p.A. through the MIT Energy Initiative.

David L. Chandler, MIT News Office

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Details of the work can be found in:

V.J. Leon, B. Blanc, S.D. Sonnert, and K.K. Varanasi. "Externally tunable, low power electrostatic control of cell adhesion with nanometric high-k dielectric films." *Advanced Functional Materials*, April 13, 2023. Online: doi.org/10.1002/adfm.202300732.

Straight from the cow's mouth

Desirée Plata aims to capture methane before it warms the climate.

Associate Professor Desirée Plata and her team are developing technologies and strategies for reducing emissions of methane, a short-lived gas with a disproportionate effect on near-term atmospheric warming. "By removing methane, we could potentially avoid critical climate tipping points," she says. Photo: Lillie Paquette

At one of the nation's largest dairy farms, environmental engineer Desirée Plata and her students wade through the muck of a thousand cattle. Inside the football field–sized barn, some animals sniff curiously at the devices Plata and her team are using to measure levels of methane in the air.

As part of their digestive process, cows and other livestock belch methane, releasing large quantities of the colorless, odorless gas to the atmosphere. Agriculture is the largest source of methane emissions in the United States, with oil and gas operations a close second.

According to the U.S. Environmental Protection Agency (EPA), methane is the second most impactful human-generated greenhouse gas after carbon dioxide (CO_2). Over the past two centuries, concentrations of methane—120 times stronger than CO_2 at trapping heat in the atmosphere—have more than doubled.

Plata, an associate professor of civil and environmental engineering at MIT, has developed tools aimed at reducing methane emissions. The good news, she says, is that because methane is short-lived compared to CO_2, cutting methane could have a fast, beneficial effect on atmospheric warming.

Plata is director of the MIT Methane Network—a group of more than two dozen researchers around the Institute and elsewhere dedicated to reducing methane emissions through innovative technologies, business strategies, and policies. The goal is to cut emissions by 45% by 2030, which would save up to 0.5 degree Celsius of warming by 2100. "By removing methane," Plata says, "we could potentially avoid critical climate tipping points."

Sustainable from the start

When she was seven or eight years old, Plata was driving with her mom through her rural hometown a short distance from the Atlantic coast. It struck her that many of the people they knew were sick—some with cancer, some with what turned out to be neurological diseases. "I said, 'It's gotta be something everybody shares, Mom.'"

Some residents didn't want to believe they were being sickened by the family-owned McKin Company, a seven-acre liquid waste disposal site that stored and buried toxic fuels, solvents, and chemicals such as trichloroethylene. In 1977, the EPA confirmed that the chemicals had leached into private wells, contaminating the groundwater.

"The thing that has really drawn me to environmental science and engineering is that this is a small town, and the people who owned that facility were family friends," Plata says. "It made me realize that we, as scientists, need to do a better job helping industries identify more environmentally sustainable routes to profitability."

At Union College, Plata studied chemistry. She earned her doctoral degree in chemical oceanography and environmental chemistry from the MIT/Woods Hole Oceanographic Institution's Joint Program in Oceanography.

"In grad school, I asked my professors if I could poke around the other engineering labs at MIT and ask people what they were making, how they were making it, and how [an environmental engineer] might help them make their design and innovation process sustainable from the start," she says. "That's the underlying theme of all that I do—help people build better technologies" in the hope of avoiding another McKin Company.

In 2021, she received MIT's Harold E. Edgerton Faculty Achievement Award for "excellence in service, mentorship, and research that impacts critical societal challenges in environmental sustainability and social justice." She mentors undergraduates pursuing energy research through the MIT Energy Initiative

(MITEI) Undergraduate Research Opportunities Program (UROP). She also serves on the faculty steering committee for MITEI's Future Energy Systems Center, which looks at how technology and policy, demographic trends, and economics are reshaping energy supply and demand.

Catalyzing a solution

Plata's primary teaching focus is aquatic sciences and water engineering. Her knowledge of oceanography got her thinking about how to neutralize methane the way certain ocean-dwelling microbes do—by processing it before it escapes into the oceans and the atmosphere.

When Plata and colleagues measured methane leaks from natural gas infrastructure, the overall levels coming from distribution pipelines were small, yet the problem was pervasive. "We were thinking, 'What engineered way could we take this low-level methane and turn it into something else?'"

Plata's lab found that passing methane through a heated zeolite—a clay-like material with a consistency between baby powder and cat litter—can help convert methane into CO_2 without a match or any other combustion process.

Converting methane to CO_2 may sound like a bad idea, but because methane is the more onerous contributor to global warming, it ends up being a net benefit. "And because methane is much more dilute than CO_2, the relative CO_2 contribution is minuscule," she says.

Initially, Plata's team envisioned incorporating zeolite into household air filters. But they decided to focus on the biggest methane offenders: dairy barns and coal mines.

The first time Plata toured a large indoor livestock facility, she was struck by the enormity of the air-moving systems that keep the cows' air fresh and germ-free. The sheer volume is "astronomical—it's like 10 tractor trailers moving past you in five seconds.

"That's our chief technical challenge—getting huge volumes of air" through the zeolite, she says.

At the moment, potential solutions are too energy-intensive for Plata's taste. "When you're proposing a climate technology, you don't want to eat up more fossil fuels than you're going to offset," she says. But it's early days, and plenty of strategies are left to explore.

At one of the nation's largest dairy farms, a curious cow inspects Desirée Plata and the devices she's holding, which she and her students use to measure levels of methane in the air. Agriculture is the largest source of methane emissions in the United States. Photo courtesy of Desirée Plata

The payoff could be significant. Deploying the technology in ventilation shafts at coal mines would have such a big effect, it could start to measurably reduce atmospheric levels of methane almost immediately. "And if you could deploy the filters at dairy barns, you'd solve the methane warming problem," she says. "It's equivalent to taking all the combustion engine vehicles in the entire world off the road—times three."

'We want to fix this'

As an engineer working on real-world solutions, Plata strives to design innovations that companies want to adopt because they're better for the environment, they perform better—and also because they cost less than existing technology.

However, even with her emphasis on cost co-optimization, Plata has noticed a shift in how corporations and individuals view potential costs associated with sustainability. "There's been a huge swing in the desire to spend a little extra money to prevent environmental damage. Today, people will come to us and say, 'We want to fix this problem because of the environment. And even if it costs us a little bit more, we're willing to do it.'"

When Plata thinks back on what happened in Maine, she doesn't believe the McKin Company was evil, or even hiding the truth. A lot of the time, she says, polluters don't know about the effect they're having on the environment. Or if they know, they don't know how to fix it.

"That's where our expertise can come in," Plata says. "We can say, 'Let's think about this problem a little differently. How do we get you the function you want without the damage?'

"One of the things my background and upbringing have taught me is: Industry and the people within industry, these are your neighbors. And they probably want the right outcome if you can innovate with them or help guide them to that."

Deborah Halber, MITEI correspondent

Responding to Ukraine's "ocean of suffering"

Former MIT Energy Initiative researcher Ian Miller funnels aid and expertise to the front line.

Within 72 hours of the first Russian missiles striking Kyiv, Ukraine, in February 2022, Ian Miller SM '19 boarded a flight for Poland.

Later, he'd say he felt motivated by Kyiv's "tragic ocean of suffering" and President Zelensky's pleas for help. But he arrived with little notion of what to do.

As he'd anticipated, his hotel in Rzeszów turned out to be a hub for aid workers and journalists. Miller was on his laptop, using the lobby Wi-Fi to work remotely as an MIT Energy Initiative (MITEI) project manager, when he overheard a reporter interviewing a Finnish man about his efforts to get bulletproof vests and helmets to the front lines.

Miller soon found himself loading supplies onto trains that had brought huge numbers of refugees—mostly women, children, and the elderly—to the station in Rzeszów. The trains ran back at night, their empty seats filled with medical supplies, generators, and baby food, their lights dimmed to reduce the chances of attack.

In April 2022, Miller and volunteers from a half dozen countries planned and drove a convoy of trucks packed with tourniquets, bandages, and bulletproof vests across the border, arriving at the site of the Bucha massacre soon after the Russians retreated.

Miller peered into a mass grave. "They were still excavating it, and those weren't soldiers, you know?" he says. "I try to avoid looking at things like that too often, because it doesn't help us save lives to be horrified all the time." He downplays any potential danger to himself, telling his family he's safer where he is than in parts of the United States.

Soon after his first trip across the border, Miller convinced his former MIT roommate, Evan Platt SM '20, to come help. "Just for a week," he told Platt.

Ian Miller SM '19 (left) with his colleague Evan Platt SM '20 in Kyiv's Mykhailivs'ka Square. Since almost the start of the Russian invasion of Ukraine, the two MIT alumni have been working with a large international team through Zero Line, a nonprofit they founded to deliver medical aid, vehicles, and equipment to Ukrainians on the front lines. The goal is to make front-line workers safer and more effective, thereby ending the war as soon as possible. Photo: Ta-Wei Lin

Inspired by energy

Miller and Platt met in 2008 in Washington, D.C., where Platt was interning at the White House and Miller was about to start his senior year at Georgetown University.

Miller majored in government, but his interest in energy policy and technology grew during the years after graduation he spent teaching science to primary and secondary school students in New York, where he'd grown up, in Boston, and in Kampala, Uganda. "Some of the most fun, inspiring, engaging lessons and modules I did with the kids were focused on energy," he recalls.

While pursuing an MIT master of science in chemical engineering from 2016 to 2018, he started researching photovoltaics and wind power. He held leadership positions with the MIT Energy Conference and the MIT Energy Club.

After joining MITEI, Miller worked on electric vehicles (EVs), EV charging patterns, and other applications. He became project manager and research specialist for the Sustainable Energy System Analysis Modeling Environment (SESAME), which models the levels of greenhouse gas emissions from multiple energy sectors in future scenarios.

Miller and Platt reconnected and shared an apartment for three years. Platt studied systems design and management through a joint MIT School of Engineering and Sloan School of Management program, then stayed on to work for the MIT Technology Licensing Office.

Platt left MIT to pursue other interests in 2020. The next time the two would see each other would be in Poland.

"It's not easy living and working in an active combat zone," Platt says. "There is

Ian Miller and Zero Line colleague Mark Lindquist deliver a lithium-ion battery to Ukrainian partners who are equipping front-line vehicles with electronics for missile defense. To date, Zero Line has delivered 300 large batteries and other electronics to these partners.
Photo: Alex Chernyavskiy

nobody on earth I would rather be navigating this environment with than Ian."

Navigating the last mile

In Rzeszów and Ukraine, Miller and U.S. Air Force veteran Mark Lindquist oversaw fulfillment for the new team. With the help of Google Translate, their phones exploded with encrypted texts to and from Polish customs agents and Ukrainian warehouse operators.

Platt and two Ukrainian team members took the lead on a needs analysis of what was most in demand at the front. Another team member led procurement. Their efforts crystallized in the creation of Zero Line (zeroline.org), a tax-exempt nonprofit that works closely with the Ukrainian government at the front line (a.k.a. "the zero line").

With Platt on board, "we got more rigorous and quantitative in terms of lives saved per dollar," Miller says. A hundred dollars buys four tourniquets. A thousand dollars adds crude steel armor to a Jeep. Two thousand dollars provides a small observation drone or a satellite phone, equipment that locates Russian artillery and detects Russian attacks.

"Russian artillery shells are the number one killer of Ukrainians, causing around 80 percent of casualties," he says. "Tourniquets save people injured by Russian shells, vehicles help evacuate them, and communications equipment prevents deadly injuries from occurring in the first place."

Miller's skills in transportation and power system modeling, developed at MITEI under Principal Research Scientist Emre Gençer, helped the team transport more than 150 used vehicles—Nissan Pathfinders and vans for moving civilians away from the front, Ford pickups for transporting anti-missile defense systems—and hundreds of batteries, generators, drones, bulletproof vests, and helmets to the front through nightmarish logistical bottlenecks.

Typically, supplies from the United States, Asia, and elsewhere in Europe move through Gdansk and Warsaw, then proceed via train or vehicle to warehouses in Lviv, around 70 kilometers east of the border. Next is the seven-hour trip to Kyiv or the 12-hour drive to Dnipro (the current southern edge of the safe "green zone") and the final 200 kilometers to the front. Here, says Miller, drivers with training and protective gear, often members of the Ukrainian military, take vehicles and supplies to front-line end users.

"From day one, we asked our Ukrainian members and partners for introductions, and we're constantly looking for more," Miller says. "When our vehicles reach the front lines, Evan's team always does interviews about needs, and what's working, what's not. What's saving the most lives."

"From my early days with Ian, it's clear he was always looking for ways to help people. Connections were really important to him," says MITEI Director Robert C. Armstrong. "When war broke out, he found the call to answer human need irresistible. I think many of us think of doing that, but we get bogged down in the mechanics of everyday life. He just picked up and went.

"Ian is just a terrific person and a great role model," Armstrong says.

Accelerating peace

From the time Miller arrived in late February through October 2022, he continued working remotely for MITEI. He now works full time as co-director of Zero Line. For the foreseeable future, Miller will remain in Ukraine and Poland.

He wants to see Ukrainians "follow in the happy, free, prospering footsteps of other ex-Soviet states, like the Baltics," he says. He'd like to see the supply-chain innovations he and Platt achieved applied to humanitarian crises elsewhere.

To date, Zero Line has raised more than $5 million in donations and delivered hundreds of tons of high-impact aid. "A key part of our approach has always been to support Ukrainians who excel in saving lives," Miller says. To that end, the group works with Ukrainian software programmers and military units to create digital maps and processes to replace paper maps and operations "reminiscent of World War II," Platt says. "Modernizing the intelligence infrastructure to facilitate better military operations is an important part of how a smaller military can beat a larger, more powerful military."

The fact that energy underlies so many aspects of the war is never far from Miller's mind. Russia cut off energy supplies to Europe, then targeted Ukraine's energy infrastructure. On one hand, he understands that billions of people in developing countries such as India need and deserve affordable energy. On the other hand, he says, oil and gas purchases by those countries are directly funding Russia's war machine.

"Everyone wants cheap renewables and we're getting there, but it's taking time. Lowering the costs of renewables and energy storage and supporting nascent commercial fusion—that's a very important focus of MITEI. In the long run, that'll help us reach a more peaceful world, without a doubt."

Work at MITEI and at Zero Line, Miller says, "truly could accelerate peace."

Deborah Halber, MITEI correspondent

3 Questions: Meet the Tata Fellows

The Tata Fellowship at MIT gives graduate students the opportunity to pursue interdisciplinary research and work with real-world applications in developing countries. Part of the MIT Tata Center for Technology and Design, this fellowship contributes to the center's goal of designing appropriate, practical solutions for resource-constrained communities. Three Tata Fellows—Serena Patel, Rameen Hayat Malik, and Ethan Harrison—discuss the impact of this program on their research, perspectives, and time at MIT.

Serena Patel. Photo: Kelley Travers, MITEI

Serena Patel

Serena Patel graduated from the University of California at Berkeley with a degree in energy engineering and a minor in energy and resources. She is currently pursuing her SM in technology and policy at MIT and is a Tata Fellow focusing on decarbonization in India using techno-economic modeling. Her interest in the intersection of technology, policy, economics, and social justice led her to attend COP27, where she experienced decision-maker and activist interactions firsthand.

Q How did you become interested in the Tata Fellowship, and how has it influenced your time at MIT?

A The Tata Center appealed to my interest in searching for creative, sustainable energy technologies that center collaboration with local-leading organizations. It has also shaped my understanding of the role of technology in sustainable development planning. Our current energy system disproportionately impacts marginalized communities, and new energy systems have the potential to perpetuate and/or create inequities. I am broadly interested in how we can put people at the core of our technological solutions and support equitable energy transitions. I specifically work on techno-economic modeling to analyze the potential for an early retirement of India's large coal fleet and conversion to long-duration thermal energy storage. This could mitigate job losses from rapid transitions, support India's energy system decarbonization plan, and provide a cost-effective way to retire stranded assets.

Q Why is interdisciplinary study important to real-world solutions for global communities, and how has working at the intersection of technology and policy influenced your research?

A Technology and policy work together in mediating and regulating the world around us. Technological solutions can be disruptive in all the good ways, but they can also do a lot of harm and perpetuate existing inequities. Interdisciplinary studies are important to mitigate these interrelated issues so innovative ideas in the ivory towers of Western academia do not negatively impact marginalized communities. For real-world solutions to positively impact individuals, marginalized communities need to be centered within the research design process. I think the research community's perspective on real-world, global solutions is shifting to achieve these goals, but much work remains for resources to reach the right communities.

The energy space is especially fascinating because it impacts everyone's quality of life in overt or nuanced ways. I've had the privilege of taking classes that sit at the intersection of energy technology and policy, involving land-use law, geographic representation, energy regulation, and technology policy. In general, working at the intersection of technology and policy has shaped my perspective on how regulation influences widespread technology adoption and the overall research directions and assumptions in our energy models.

Q How has your experience at COP27 influenced your approach to your research?

A Attending COP27 at Sharm El-Sheikh, Egypt, last November influenced my understanding of the role of science, research, and activism in climate negotiations and action. Science and research are often promoted as necessary for sharing knowledge at the higher levels, but they were also used as a delay tactic by negotiators. I heard how institutional bodies meant to support fair science and research often did not reach intended stakeholders. Lofty goals or financial commitments to ensure global climate stability and resilience still lacked implementation and coordination with deep technology transfer and support. On the face of it, these agreements have impact and influence, but I heard many frustrations over the lack of tangible, local support. This has driven my research to be as context specific as possible, to provide actionable insights and leverage different disciplines.

I also observed the role of activism in the negotiations. Decision makers are accountable to their country, and activists are spreading awareness and bringing transparency to the COP process. As a U.S. citizen, I suddenly became more aware of how political engagement and awareness in the country could push the boundaries of international climate agreements if the government were more aligned on climate action.

Rameen Hayat Malik. Photo: Kelley Travers, MITEI

Rameen Hayat Malik

Rameen Hayat Malik graduated from the University of Sydney with a bachelor's degree in chemical and biomolecular engineering and a Bachelor of Laws. She is currently pursuing her SM in technology and policy and is a Tata Fellow researching the impacts of electric vehicle (EV) battery production in Indonesia. Originally from Australia, she first became interested in the geopolitical landscape of resources trade and its implications for the clean energy transition while working in her native country's Department of Climate Change, Energy, the Environment and Water.

Q How did you become interested in the Tata Fellowship, and how has it influenced your time at MIT?

A I came across the Tata Fellowship while looking for research opportunities that aligned with my interest in understanding how a just energy transition will occur in a global context, with a particular focus on emerging economies. My research explores the techno-economic, social, and environmental impacts of nickel mining in Indonesia as it seeks to establish itself as a major producer of EV batteries. The fellowship's focus on community-driven research has given me the freedom to guide the scope of my research. It has allowed me to integrate a community voice into my work that seeks to understand the impact of this mining on forest-dependent communities, Indigenous communities, and workforce development.

Q Battery technology and production are highly discussed in the energy sector. How does your research on Indonesia's battery production contribute to the current discussion around batteries, and what drew you to this topic?

A Indonesia is one of the world's largest exporters of coal, while also having one of the largest nickel reserves in the world—a key mineral for EV battery production. This presents an exciting opportunity for Indonesia to be a leader in the energy transition, as it both seeks to phase out coal production and establish itself as a key supplier of critical minerals. It is also an opportunity to actually apply principles of a just transition to the region, which seeks to repurpose and reskill existing coal workforces, to bring Indigenous communities into the conversation around the future of their lands, and to explore whether it is actually possible to sustainably and ethically produce nickel for EV battery production.

I've always seen battery technologies and EVs as products that, at least today, are accessible to a small, privileged customer base that can afford such technologies. I'm interested in understanding how we can make such products more widely affordable and provide our lowest income communities with the opportunities to actively participate in the transition—especially since access to transportation is a key driver of social mobility. With nickel prices impacting EV prices in such a dramatic way, unlocking more nickel supply chains presents an opportunity to make EV batteries more accessible and affordable.

Q What advice would you give to new students who want to be a part of real-world solutions to the climate crisis?

A Bring your whole self with you when engaging these issues. Quite often we get caught up with the technology or modeling aspect of addressing the climate crisis and forget to bring people and their experiences into our work. Think about your positionality: Who is your community, what are the avenues you have to bring that community along, and what privileges do you hold to empower and amplify voices that need to be heard? Find a piece of this complex puzzle that excites you, and find opportunities to talk and listen to people who are directly impacted by the solutions you are looking to explore. It can get quite overwhelming working in this space, which carries a sense of urgency, politicization, and polarization with it. Stay optimistic, keep advocating, and remember to take care of yourself while doing this important work.

Ethan Harrison. Photo: Kelley Travers, MITEI

Ethan Harrison

After earning his degree in economics and applied science from the College of William and Mary, Ethan Harrison worked at the United Nations Development Programme in its Crisis Bureau as a research officer focused on conflict prevention and predictive analysis. He is currently pursuing his SM in technology and policy at MIT. In his Tata Fellowship, he focuses on the impacts of the Ukraine-Russia conflict on global vulnerability and the global energy market.

Q How did you become interested in the Tata Fellowship, and how has it influenced your time at MIT?

A Coming to MIT, one of my chief interests was figuring out how we can leverage gains from technology to improve outcomes and build pro-poor solutions in developing and crisis contexts. The Tata Fellowship aligned with many of the conclusions I drew while working in crisis contexts and some of the outstanding questions that I was hoping to answer during my time at MIT, specifically: How can we leverage technology to build sustainable, participatory, and ethically grounded interventions in these contexts?

My research currently examines the secondary impacts of the Ukraine-Russia conflict on low- and middle-income countries—especially fragile states—with a focus on shocks in the global energy market. This includes the development of a novel framework that systematically identifies factors of vulnerability—such as in energy, food systems, and trade dependence—and quantitatively ranks countries by their level of vulnerability. By identifying the specific mechanisms by which these countries are vulnerable, we can develop a map of global vulnerability and identify key policy solutions that can insulate countries from current and future shocks.

Q I understand that your research deals with the relationship between oil and gas price fluctuation and political stability. What has been the most surprising aspect of this relationship, and what are its implications for global decarbonization?

A One surprising aspect is the degree to which citizen grievances regarding price fluctuations can quickly expand to broader democratic demands and destabilization. In Sri Lanka last year and in Egypt during the Arab spring, initial protests around fuel prices and power outages eventually led to broader demands and the loss of power by heads of state. Another surprising aspect is the popularity of fuel subsidies despite the fact that they are economically regressive: They often comprise a large proportion of GDP in poor countries, disproportionately benefit higher-income populations, and leave countries vulnerable to fiscal stress during price spikes.

Regarding implications for global decarbonization, one project we are pursuing examines the implications of directing financing from fuel subsidies toward investments in renewable energy. Countries that rely on fossil fuels for electricity have been hit especially hard by price spikes from the Ukraine-Russia conflict, especially since many were carrying costly fuel subsidies to keep the price of fuel and energy artificially low. Much of the international community is advocating for low-income countries to invest in renewables and reduce their fossil fuel burden, but it's important to explore how global decarbonization can align with efforts to end energy poverty and other Sustainable Development Goals.

Q How does your research impact the Tata Center's goal of transforming policy research into real-world solutions, and why is this important?

A The crisis in Ukraine has shifted the international community's focus away from other countries in crisis, such as Yemen and Lebanon. By developing a global map of vulnerability, we're building a large evidence base on which countries have been most impacted by this crisis. Most importantly, by identifying individual channels of vulnerability for each country, we can also identify the most effective policy solutions to insulate vulnerable populations from shocks. Whether that's advocating for short-term social protection programs or identifying more medium-term policy solutions—like fuel banks or investment in renewables—we hope providing a detailed map of sources of vulnerability can help inform the global response to shocks imposed by the Russia-Ukraine conflict and post-Covid recovery.

Charlotte Whittle, MITEI

Energy Studies Minor graduates, June 2023

Katana Finlason
Engineering

Miller Geschke*
Mechanical Engineering

Jose Gomez
Chemical Engineering

Sylas Horowitz*
Mechanical Engineering

Arina Khotimsky
Materials Science and Engineering

Diane Li*
Materials Science and Engineering

Yuka Perera
Engineering

Peter Scott
Engineering

Brendan Vaughan
Nuclear Science and Engineering

Sandy Yang
Chemical Engineering

*February 2023 graduate.

MIT energy storage research highlighted in student slam competition

On March 21, 2023, ten graduate students and three undergraduates gathered at the MIT Welcome Center to compete in the MIT Energy Initiative's (MITEI) Energy Storage Student Slam. The students gave quick, dynamic presentations—each limited to three minutes—on energy storage research that they had recently completed or were currently working on at the Institute.

The slam followed the completion of MITEI's *The Future of Energy Storage* report and study, which explored the role energy storage can play in combatting climate change and the adoption of clean energy systems worldwide. Building on that theme, the event highlighted additional research taking place at MIT in the energy storage space. Topics ranged from the use of flame-assisted spray pyrolysis to create better battery materials to the role of pumped hydro storage in power sector decarbonization to a thermochemical approach to producing low-cost green hydrogen.

The competition was divided into two parts: The graduate students presented first, followed by the undergraduates, with separate judging for each group. The graduate student winners were Jim Owens (first), Aniket Patankar (second), and Mrigi Munjal (third). The undergraduate student winners were Pamela Duke (first), Melissa Stok (second), and Anakha Ganesh (third).

Kelley Travers, MITEI

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1. The Energy Storage Student Slam was emceed by MITEI's Director of Education Antje Danielson.

2. Pamela Duke, a senior majoring in finance and minoring in economics and environment and sustainability, won first place in the undergraduate student competition. In her presentation, she discussed using the En-ROADS climate solutions model to engage with utilities on decarbonization strategies.

3. Thirteen MIT graduate and undergraduate students competed in the slam with presentations on different topic areas in the energy storage space. Pictured (left to right): Joy Zeng, Thomas Lee, Melissa Stok, Jim Owens, Anakha Ganesh, Kyle Buznitsky, Pamela Duke, Chuwei Zhang, Carlos Díaz-Marín, Amanda Farnsworth, Ignacio Arzuaga Garcia, Mrigi Munjal, Aniket Patankar.

4. Carlos Díaz-Marín, a graduate student in the Department of Mechanical Engineering, presented his work developing ultra moisture-hungry hydrogels that have exceptional water capture capabilities and can be used for waste heat storage and reuse.

5. The third-place award went to Mrigi Munjal, a graduate student in the Department of Materials Science and Engineering, who described her project on unlocking industrial-scale sodium-ion batteries.

6. MITEI Director of Education Antje Danielson (left) presented the first-place award in the graduate student competition to Jim Owens, a PhD candidate in the Department of Chemical Engineering who conducts research at the intersection of electric vehicles and renewable energy systems.

Photos: Kelley Travers, MITEI

A welcome new pipeline for students invested in clean energy

FUSars program offers undergraduates in-depth research opportunities in fusion science and energy.

Akarsh Aurora aspired "to be around people who are actually making the global energy transition happen," he says. Sam Packman sought to "align his theoretical and computational interests to a clean energy project" with tangible impacts. Lauryn Kortman says she "really liked the idea of an in-depth research experience focused on an amazing energy source."

These three MIT students found what they wanted in FUSars (fusion undergraduate scholars), a new program launched by the MIT Plasma Science and Fusion Center (PSFC) to make meaningful fusion energy research accessible to undergraduates. Aurora, Kortman, and Packman are members of a cohort of 10 for the program's inaugural run, which began spring semester 2023.

FUSars operates like a high-wattage UROP (MIT's classic undergraduate research opportunity). The program requires a student commitment of 10 to 12 hours weekly on a research project during the course of an academic year, as well as participation in a for-credit seminar providing professional development, communication, and wellness support. Through this class and with the mentorship of graduate students, postdoctoral students, and research scientist advisors, students craft a publication-ready journal submission summarizing their research. Scholars who complete the entire year and submit a manuscript for review will receive double the ordinary UROP stipend—a payment that can reach $9,000.

"The opportunity just jumped out at me," says Packman. "It was an offer I couldn't refuse," adds Aurora.

Building a workforce

"I kept hearing from students wanting to get into fusion, but they were very frustrated because there just wasn't a pipeline for them to work at the PSFC," says Michael Short, Class of '42 Associate Professor of Nuclear Science and Engineering (NSE) and associate director of the PSFC. As MIT's largest lab, the PSFC bustles with research projects run by scientists and postdoctoral students. But since the PSFC isn't a university department with educational obligations, it does not have the regular machinery in place to integrate undergraduate researchers.

This poses a problem not just for students but for the field of fusion energy, which holds the prospect of unlimited, carbon-free electricity. There are promising advances afoot: MIT and one of its partners, Commonwealth Fusion Systems, are developing a prototype for a compact commercial fusion energy reactor. The start of a fusion energy industry will require a steady infusion of skilled talent.

MIT first-year Sam Packman (left) and his advisor Nicolo Riva, a postdoctoral researcher at the MIT Plasma Science and Fusion Center, examine a VIPER cable, a special type of high-temperature superconducting cable that holds promise for use in fusion reactors. Packman is optimizing the design of cables like this one to produce a strong, uniform magnetic field in a solenoid, an electromagnet composed of a coiled wire. Photo: Gretchen Ertl

Through the FUSar program, MIT junior Lauryn Kortman measures the material properties of REBCO (rare-earth barium copper oxide), a high-temperature superconductor, before and after being exposed to proton irradiation. Here she analyzes a sample next to a transient grating spectroscopy machine, which can be used to nondestructively measure the bulk modulus, thermal diffusivity, and other key properties of a material. Photo: Gretchen Ertl

"We have to think about the workforce needs of fusion in the future and how to train that workforce," says Rachel Shulman, who runs the FUSars program and co-instructs the FUSars class with Short. "Energy education needs to be thinking right now about what's coming after solar, and that's fusion."

Short, who earned his bachelor's, master's, and doctoral degrees at MIT, was himself the beneficiary of the Undergraduate Research Opportunity Program (UROP) at the PSFC. As a faculty member, he has become deeply engaged in building transformative research experiences for undergraduates. With FUSars, he hopes to give students a springboard into the field—with an eye to developing a diverse, highly trained, and zealous employee pool for a future fusion industry.

Taking a deep dive

Although these are early days for this initial group of FUSars, there is already a shared sense of purpose and enthusiasm. Chosen from 32 applicants in a whirlwind selection process—the program first convened in early February after crafting the experience over IAP—the students arrived with detailed research proposals and personal goals.

Aurora, a first-year majoring in mechanical engineering and artificial intelligence, became fixed on fusion while still in high school. Today he is investigating methods for increasing the availability, known as capacity factor, of fusion reactors. "This is key to the commercialization of fusion energy," he says.

Packman, a first-year planning on a math and physics double major, is developing approaches to help simplify the computations involved in designing the complex geometries of solenoid induction heaters in fusion reactors.

"This project is more immersive than my last UROP, and requires more time, but I know what I'm doing here and how this fits into the broader goals of fusion science," he says. "It's cool that our project is going to lead to a tool that will actually be used."

To accommodate the demands of their research projects, Shulman and Short discouraged students from taking on large academic loads.

Kortman, a junior majoring in materials science and engineering with a concentration in mechanical engineering, was eager to make room in her schedule for her project, which concerns the effects of radiation damage on superconducting magnets. A shorter research experience with the PSFC during the pandemic fired her determination to delve deeper and invest more time in fusion.

"It is very appealing and motivating to join people who have been working on this problem for decades, just as breakthroughs are coming through," she says. "What I'm doing feels like it might be directly applicable to the development of an actual fusion reactor."

Camaraderie and support

In the FUSar program, students aim to seize a sizeable stake in a multipronged research enterprise. "Here, if you have any hypotheses, you really get to pursue those because at the end of the day, the paper you write is yours," says Aurora. "You can take ownership of what sort of discovery you're making."

Enabling students to make the most of their research experiences requires abundant support—and not just for the students. "We have a whole separate set of programming on mentoring the mentors, where we go over topics with postdocs like how to teach someone to write a research paper rather than write it for them and how to help a student through difficulties," Shulman says.

The weekly student seminar, taught primarily by Short and Shulman, covers pragmatic matters essential to becoming a successful researcher—topics not always addressed directly or in the kind of detail that makes a difference. Topics include how to collaborate with lab mates, deal with a supervisor, find material in the MIT libraries, produce effective and persuasive research abstracts, and take time for self-care.

Kortman believes camaraderie will help the cohort through an intense year. "This is a tight-knit community that will be great for keeping us all motivated when we run into research issues," she says. "Meeting weekly to see what other students are able to accomplish will encourage me in my own project."

The seminar offerings have already attracted five additional participants outside the FUSars cohort. Adria Peterkin, a second-year graduate student in nuclear science and engineering, is sitting in to solidify her skills in scientific writing.

"I wanted a structured class to help me get good at abstracts and communicating with different audiences," says Peterkin, who is investigating radiation's impact on the molten salt used in fusion and advanced nuclear reactors. "There's a lot of assumed knowledge coming in as a PhD student, and a program like FUSars is really useful to help level out that playing field, regardless of your background."

Fusion research for all

Short would like FUSars to cast a wide net, capturing the interest of MIT undergraduates no matter their backgrounds or financial means. One way he hopes to achieve this end is with the support of private donors, who make possible premium stipends for fusion scholars.

"Many of our students are economically disadvantaged, on financial aid or supporting family back home, and need work that pays more than $15 an hour," he says. This generous stipend may be critical, he says, to "flipping students from something else to fusion."

Although this first FUSars class is composed of science and engineering students, Short envisions a cohort eventually drawn from the broad spectrum of MIT disciplines. "Fusion is not a nuclear-focused discipline anymore—it's no longer just plasma physics and radiation," he says. "We're trying to make a power plant now, and it's an all hands-on-deck kind of thing, involving policy and economics and other subjects."

Although many are just getting started on their academic journeys, FUSar students believe this year will give them a strong push toward potential energy careers. "Fusion is the future of the energy transition and how we're going to defeat climate change," says Aurora. "I joined the program for a deep dive into the field, to help me decide whether I should invest the rest of my life to it."

Leda Zimmerman, MITEI correspondent

MIT first-year Akarsh Aurora is investigating a special type of thin film tape made of rare-earth barium copper oxide, which is used in the superconductors that drive nuclear fusion, to understand how it behaves when exposed to neutron irradiation. Here he fixes the cryohead of a vacuum-sealed particle accelerator, which will be used to irradiate the tape and help his team glean insights about the material's thermomechanical properties. Photo: Gretchen Ertl

The answer may be blowing in the wind

MIT Energy Initiative's Spring Symposium highlights the vast potential of offshore turbines in decarbonizing the grid.

MITEI Director Robert C. Armstrong introduces MITEI's 2023 Spring Symposium on the role of offshore wind in decarbonizing the electric power system. Photo: Gretchen Ertl

Capturing energy from the winds gusting off the coasts of the United States could more than double the nation's electricity generation. It's no wonder the Biden administration views this immense, clean-energy resource as central to its ambitious climate goals of 100% carbon-emissions-free electricity by 2035 and a net-zero emissions economy by 2050. The White House is aiming for 30 gigawatts of offshore wind by 2030—enough to power 10 million homes.

At the MIT Energy Initiative's Spring Symposium on March 22, 2023, academic experts, energy analysts, wind developers, government officials, and utility representatives explored the immense opportunities and formidable challenges of tapping this titanic resource, both in the United States and elsewhere in the world.

"There's a lot of work to do to figure out how to use this resource economically—and sooner rather than later," said Robert C. Armstrong, MITEI director and the Chevron Professor of Chemical Engineering, in his introduction to the event.

In sessions devoted to technology, deployment and integration, policy, and regulation, participants framed the issues critical to the development of offshore wind, described threats to its rapid rollout, and offered potential paths for breaking through gridlock.

R&D advances

Moderating a panel on MIT research that is moving the industry forward, Robert Stoner, MITEI's deputy director for science and technology, provided context for the audience about the industry.

"We have a high degree of geographic coincidence between where that wind capacity is and where most of us are, and it's complementary to solar," he said. Turbines sited in deeper, offshore waters gain the advantage of higher velocity winds. "You can make these machines huge, creating substantial economies of scale," said Stoner. An onshore turbine generates approximately 3 megawatts; offshore structures can each produce 15 to 17 megawatts, with blades the length of a football field and heights greater than the Washington Monument.

To harness the power of wind farms spread over hundreds of nautical miles in deep water, Stoner said, researchers must first address some serious issues, including building and maintaining these massive rigs in harsh environments, laying out wind farms to optimize generation, and creating reliable and societally acceptable connections to the onshore grid. MIT scientists described how they are tackling a number of these problems.

"When you design a floating structure, you have to prepare for the worst possible conditions," said Paul Sclavounos, a professor of mechanical engineering and naval architecture who is developing turbines that can withstand severe storms that batter turbine blades and towers with thousands of tons of wind force. Sclavounos described systems used in the oil industry for tethering giant, buoyant rigs to the ocean floor that could be adapted for wind platforms. Relatively inexpensive components such as polyester mooring lines and composite materials "can mitigate the impact of high waves and big, big wind loads."

To extract the maximum power from individual turbines, developers must take into account the aerodynamics among turbines in a single wind farm and between adjacent wind farms, according to Michael Howland, the Esther and Harold E. Edgerton Assistant Professor of Civil and Environmental Engineering. Howland's work modeling turbulence in the atmosphere and wind speeds has demonstrated that angling turbines by just a small amount relative to each other can increase power production significantly for offshore installations, dramatically improving their efficiencies. Howland hopes his research will promote "changing the design of wind farms from the beginning of the process."

There's a staggering complexity to integrating electricity from offshore wind into regional grids such as the one operated by ISO New England, whether converting voltages or monitoring utility load. Steven B. Leeb, a professor of electrical engineering and computer science and mechanical engineering, is developing sensors that can indicate electronic failures in a micro grid connected to a wind farm. And Marija Ilić, a joint adjunct professor in the Department of Electrical Engineering and Computer Science and a senior research scientist at the MIT Laboratory for Information and Decision Systems, is developing software that would enable real-time scheduling of controllable equipment to compensate for the variable power generated by wind and other variable renewable resources. She is also working on adaptive distributed automation of this equipment to ensure a stable electric power grid.

"How do we get from here to there?"

Symposium speakers provided snapshots of the emerging offshore industry, sharing their sense of urgency as well as some frustrations.

Climate poses "an existential crisis" that calls for "a massive war-footing undertaking," said Melissa Hoffer, who occupies the newly created cabinet position of climate chief for the Commonwealth of Massachusetts. She views wind power "as the backbone of electric sector decarbonization." With the Vineyard Wind project, the state will be one of the first in the nation to add offshore wind to the grid. "We are actually going to see the first 400 megawatts … likely interconnected and coming online by the end of this year, which is a fantastic milestone for us," said Hoffer.

The journey to completing Vineyard Wind involved a plethora of painstaking environmental reviews, lawsuits over lease siting, negotiations over the price of the electricity it will produce, buy-in from towns where its underground cable comes ashore, and travels to an Eversource substation. It's a familiar story to Alla Weinstein, founder and CEO of Trident Winds Inc. On the West Coast, where deep waters (greater than 60 meters) begin closer to shore, Weinstein is trying to launch floating offshore wind projects. "I've been in marine renewables for 20 years, and when people ask why I do what I do, I tell them it's because it matters," she said. "Because if we don't do it, we may not have a planet that's suitable for humans."

Weinstein's "picture of reality" describes a multiyear process during which Trident Winds must address the concerns of such stakeholders as tribal communities and the fishing industry and ensure compliance with, among other regulations, the Marine Mammal Protection Act and the Migratory Bird Species Act. Construction of these massive floating platforms, when it finally happens, will require as-yet-unbuilt specialized port infrastructure and boats, and a large skilled labor force for assembly and transmission. "This is a once-in-a-lifetime opportunity to create a new industry," she said, but "how do we get from here to there?"

Melissa Hoffer, the climate chief in the Commonwealth of Massachusetts' Office of Climate Innovation and Resilience, calls wind power the "backbone of electric sector decarbonization" during her remarks at MITEI's Spring Symposium. Photo: Gretchen Ertl

(Left to Right) Panelists Tim Schittekatte (MIT), Christina Hoffman (Avangrid), Johannes Pfeifenberger (The Brattle Group), and Julia Bovey (Eversource) explore the policy and regulation issues associated with offshore wind. Photo: Gretchen Ertl

Danielle Jensen, technical manager for Shell's Offshore Wind Americas, is working on a project off of Rhode Island. The blueprint calls for high-voltage, direct-current cable snaking to landfall in Massachusetts, where DC lines switch to AC to connect to the grid. "None of this exists, so we have to find a space, the lands, and the right types of cables, tie into the interconnection point, and work with interconnection operators to do that safely and reliably," she said.

Utilities are partnering with developers to begin clearing some of those obstacles. Julia Bovey, director of offshore wind for Eversource, described her firm's redevelopment or improvement of five ports, and new transport vessels for offshore assembly of wind farm components in Atlantic waters. The utility is also digging under roads to lay cables for new power lines. Bovey notes that snags in supply chains and inflation have been driving up costs. This makes determining future electricity rates more complex, especially since utility contracts and markets work differently in each state.

Just seven up

Other nations hold a commanding lead in offshore wind: To date, the United States claims just seven operating turbines, while Denmark boasts 6,200 and the UK 2,600. Europe's combined offshore power capacity stands at 30 gigawatts—which, as MITEI Research Scientist Tim Schittekatte notes, is the U.S. goal for 2030.

The European Union wants 400 gigawatts of offshore wind by 2050, a target made all the more urgent by threats to Europe's energy security from the war in Ukraine. "The idea is to connect all those windmills, creating a mesh offshore grid," Schittekatte said, aided by EU regulations that establish "a harmonized process to build cross-border infrastructure."

Morten Pindstrup, the international chief engineer at Energinet, Denmark's state-owned energy enterprise, described one component of this pan-European plan: a hybrid Danish-German offshore wind network. Energinet is also constructing energy islands in the North Sea and the Baltic to pool power from offshore windfarms and feed power to different countries.

The European wind industry benefits from centralized planning, regulation, and markets, said Johannes P. Pfeifenberger, a principal of The Brattle Group. "The grid planning process in the U.S. is not suitable today to find cost-effective solutions to get us to a clean energy grid in time," he said. Pfeifenberger recommended that the United States immediately pursue a series of moves including a multistate agreement for cooperating on offshore wind and establishment by grid operators of compatible transmission technologies.

Symposium speakers expressed sharp concerns that complicated and prolonged approvals as well as partisan politics could hobble the nation's nascent offshore industry. "You can develop whatever you want and agree on what you're doing, and then the people in charge change, and everything falls apart," said Weinstein. "We can't slow down, and we actually need to accelerate."

Larry Susskind, the Ford Professor of Urban and Environmental Planning, had ideas for breaking through permitting and political gridlock. A negotiations expert, he suggested convening confidential meetings for stakeholders with competing interests for collaborative problem-solving sessions. He announced the creation of a Renewable Energy Facility Siting Clinic at MIT. "We get people to agree that there is a problem, and to accept that without a solution, the system won't work in the future, and we have to start fixing it now."

Other symposium participants were more sanguine about the success of offshore wind. "Trust me, floating wind is not a pie-in-the-sky, exotic technology that is difficult to implement," said Sclavounos. "There will be companies investing in this technology because it produces huge amounts of energy, and even though the process may not be streamlined, the economics will work itself out."

Leda Zimmerman, MITEI correspondent

Climate goals may take longer, but we'll get there

Mass. State Senator Mike Barrett describes state's progress on tackling global warming, remains optimistic despite short-term delays.

The Covid-19 pandemic, inflation, and the war in Ukraine have combined to cause unavoidable delays in implementation of Massachusetts' ambitious goals to tackle climate change, State Senator Mike Barrett said Wednesday, April 19, 2023, during his presentation at the MIT Energy Initiative (MITEI) Earth Day Colloquium. But, he added, he remains optimistic that the goals will be reached, with a lag of perhaps two years.

Barrett, who is Senate chair of the state's Joint Committee on Telecommunications, Utilities, and Energy, spoke on the topic of "Decarbonizing Massachusetts," at MIT's Wong Auditorium as part of the Institute's celebration of Earth Week. The event was accompanied by a poster session highlighting some of the work of MIT students and faculty aimed at tackling aspects of the climate issue.

Martha Broad, MITEI's executive director, introduced Barrett by pointing out that he was largely responsible for the passage of two major climate-related bills by the Massachusetts legislature, the Roadmap Act in 2021 and the Drive Act in 2022, which together helped to place the state as one of the nation's leaders in the implementation of measures to ratchet down greenhouse gas emissions.

The two key pieces of legislation, Barrett said, were complicated bills that included many components, but a major feature of the Roadmap Act was to reduce the time between reassessments of the state's climate plans from ten years to five, and to divide the targets for emissions reductions into six separate categories instead of just a single overall number.

The six sectors the bill delineated are transportation; commercial, industrial, and institutional buildings; residential buildings; industrial processes; natural gas infrastructure; and electricity generation. Each of these faces different challenges, and needs to be evaluated separately, he said.

The second bill, the Drive Act, set specific targets for implementation of carbon-free electricity generation. "We prioritize offshore wind," he pointed out, because that's one resource where Massachusetts has a real edge over other states and regions. Because of especially shallow offshore waters and strong, steady offshore winds that tend to be strongest during the peak demand hours of late afternoon and evening, the state's coastal waters are an especially promising site for offshore wind farms, he said.

At the MIT Energy Initiative's Earth Day Colloquium, Massachusetts State Senator Mike Barrett discussed Massachusetts' ambitious 2030 goals for cutting carbon dioxide emissions and the challenges the state has faced in meeting those goals. Photo: Caitlin Cunningham

Whereas the majority of offshore wind installations around the world are in deep water, which precludes fixed foundations and adds significantly to construction costs, Massachusetts' shallow waters can allow relatively inexpensive construction. "So you can see why offshore wind became a linchpin, not only to our cleaning up the grid, but to feeding it into the building system, and for that matter into transportation, through our electric vehicles," he said.

Massachusetts' needs in addressing climate change are quite different from global averages, or even U.S. averages, he pointed out. Worldwide, agriculture accounts for some 22% of greenhouse gas emissions, and 11% nationally. In Massachusetts the figure is less than a half of 1%. The industrial sector is also much smaller than the national average. Meanwhile, buildings account for only about 6% of U.S. emissions, but 13% in the state. That means that overall, "buildings, transportation, and power generation become the whole ballgame" for this state, "requiring a real focus in terms of our thinking," he said.

Because of that, in those climate bills "we really insisted on reducing emissions in the energy generation sector, and our primary way to get there… lies with wind, and most of that is offshore." The law calls for emissions from power generation to be cut by 53% by 2025, and 70% by 2030. Meeting that goal depends heavily on offshore wind. "Clean power is critical because the transmission and transportation and buildings depend on clean power, and offshore wind is critical to that clean power strategy," he said.

At the time the bills passed, plans for new offshore wind farm installations showed that the state was well on target to meet these goals, Barrett said. "There was plenty of reason for Massachusetts to feel very optimistic about offshore wind… Everyone was bullish." While Massachusetts is a small state—44th out of 50—because of its unusually favorable offshore conditions, "we are second in the United States in terms of plans to deploy offshore wind," after New York, he said.

But then the real world got in the way.

As Europe and the UK quickly tried to pivot away from natural gas and oil in the wake of Russia's invasion of Ukraine, the picture changed quickly. "Offshore wind suddenly had a lot of competition for the expertise, the equipment, and the materials," he said.

As just one example, he said, the ships needed for installation became unavailable. "Suddenly worldwide, there weren't enough installation vessels to hold these very heavy components that have to be brought out to sea," he said. About 20 to 40 such vessels are needed to install a single wind farm. "There are a limited number of these vessels capable of carrying these huge pieces of infrastructure in the world. And in the wake of stepped-up demand from Europe, and other places, including China, there was an enormous shortage of appropriate vessels."

That wasn't the only obstacle. Prices of some key commodities also shot up, partly due to supply chain issues associated with the pandemic, and the resulting worldwide inflation. "The ramifications of these kinds of disruptions obviously have been felt worldwide," he said. For example, the Hornsea Project off the coast of the UK is the largest proposed offshore wind farm in the world, and one the UK was strongly dependent on to meet climate targets. But the developer of the project, Ørsted, said it could no longer proceed without a major government bailout. At this point, the project remains in limbo.

In Massachusetts, the company Avangrid had a contract to build 60 offshore wind turbines to deliver 1,200 megawatts of power. But last month, in a highly unusual move for a major company, "they informed Massachusetts that they were terminating a contract they had signed." That contract was a big part of the state's overall clean energy strategy, he said. A second developer, that had also signed a contract for a 1,200-megawatt offshore farm, signaled that it too could not meet its contract.

"We technically haven't failed yet" in meeting the goals that were set for emissions reduction, Barrett said. "In theory, we have two years to recover from the setbacks that I'm describing." Realistically, though, he said "it is quite likely that we're not going to hit our 2025 and 2030 benchmarks."

But despite all this, Barrett ended his remarks on an essentially optimistic note. "I hate to see us fall off pace in any way," he said. But, he added, "the truth is that a short delay—and I think we're looking at just a couple of years delay—is a speed bump, it's not a roadblock. It is not the end of climate policy."

Worldwide demand for offshore wind power remains "extraordinary," said Barrett, mainly as a result of the need to get off of Russian fossil fuel. As a result, "eventually supply will come into balance with this demand… The balance will be restored."

To monitor the process, Barrett said he has submitted legislation to create a new independent Climate Policy Commission, to examine in detail the data on performance in meeting the state's climate goals and to make recommendations. The measure would provide open access to information for the public, allowing everyone to see the progress being made from an unbiased source.

"Setbacks are going to happen," he said. "This is a tough, tough job. While the real world is going to surprise us, persistence is critical."

He concluded that "I think we're going to wind up building every windmill that we need for our emissions-reduction policy. Just not on the timeline that we had hoped for."

The poster session was co-hosted by the MIT Abdul Latif Jameel Water & Food Systems Lab and the MIT Environmental Solutions Initiative. The full event was sponsored by the MIT Climate Nucleus.

MIT Energy Initiative

Power to the people

MITEI spinoff Waya Energy helps countries work toward universal access to electricity.

When MIT electrical engineer Reja Amatya PhD '12 arrived in Rwanda in 2015, she was whisked off to a village. She saw that diesel generators provided power to the local health center, bank, and shops, but like most of rural Rwanda, Karambi's 200 homes did not have electricity. Amatya knew the hilly terrain would make it challenging to connect the village to high-voltage lines from the capital, Kigali, 50 kilometers away.

While many consider electricity a basic human right, there are places where people have never flipped a light switch. Among the United Nations' Sustainable Development Goals is global access to affordable, reliable, and sustainable energy by 2030. Recently, the UN reported that progress in global electrification had slowed due to the challenge of reaching those hardest to reach.

Researchers from the MIT Energy Initiative (MITEI) and Comillas Pontifical University in Madrid created Waya Energy Inc., a Cambridge-based startup commercializing MIT-developed planning and analysis software to help governments determine the most cost-effective ways to provide electricity to all their citizens.

The researchers' 2015 trip to Rwanda marked the beginning of four years of phone calls, Zoom meetings, and international travel to help the east African country—still reeling from the 1994 genocide that killed more than a million people—develop a national electrification strategy and extend its power infrastructure.

Amatya, Waya president and one of five Waya co-founders, knew that electrifying Karambi and the rest of the country would provide new opportunities for work, education, and connections—and the ability to charge cell phones, often an expensive and inconvenient undertaking.

To date, Waya—with funding from the Asian Development Bank, the African Development Bank, the Inter-American Development Bank for Latin America, and the World Bank—has helped governments develop electrification plans in 22 countries on almost every continent, including in refugee camps in sub-Saharan Africa's Sahel and Chad regions, where violence has led to 3 million internally displaced people.

"With a modeling and visualization tool like ours, we are able to look at the entire spectrum of need and demand and say, 'Okay, what might be the most optimized solution?'" Amatya says.

More than 15 graduate students and researchers from MIT and Comillas contributed to the development of Waya's software under the supervision of Robert Stoner, the deputy director for science and technology at MITEI, and Ignacio Pérez-Arriaga, a visiting professor at the MIT Sloan School of Management from Comillas. Pérez-Arriaga looks at how changing electricity use patterns have forced utilities worldwide to rethink antiquated business models.

The team's Reference Electrification Model (REM) software pulls information from population density maps, satellite images, infrastructure data, and geospatial points of interest to determine where extending the grid will be most cost-effective and where other solutions would be more practical.

"I always say we are agnostic to the technology," Amatya says. "Traditionally, the only way to provide long-term reliable access was through the grid, but that's changing. In many developing countries, there are many more challenges for utilities to provide reliable service."

Off-grid solutions

Waya co-founder Stoner, who is also the founding director of the MIT Tata Center for Technology and Design, recognized early on that connecting homes to existing infrastructure was not always economically feasible. What's more, billions of people with grid connections had unreliable access due to uneven regulation and challenging terrain.

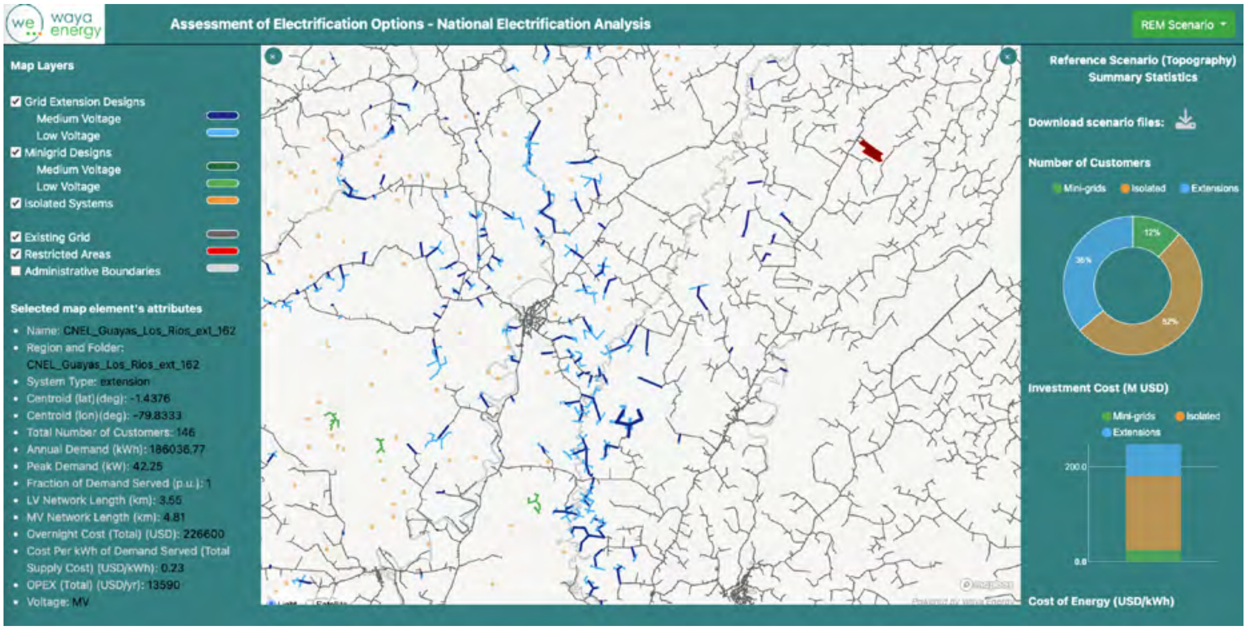
With Waya co-founders Andres Gonzalez-Garcia, a MITEI affiliate researcher, and Professor Fernando de Cuadra Garcia of Comillas, Pérez-Arriaga and Stoner led a team that developed a set of principles to guide universal regional electrification. Their approach—which they dubbed the Integrated Distribution Framework—incorporates elements of optimal planning as well as novel business models and regulation. Getting all three right is "necessary," Stoner says, "if you want a viable long-term outcome."

Amatya says, "Initially, we designed REM to understand what the level of demand is in these countries with very rural and poor populations, and what the system should look like to serve it. We took a lot of that input into developing the model." In 2019, Waya was created to commercialize the software and add consulting to the package of services the team provides.

Now, in addition to advising governments and regulators on how to expand existing grids, Waya proposes options such as a mini-grid, powered by renewables like wind, hydropower, or solar, to serve single villages or large-scale mini-grid solutions for larger areas. In some cases, an even more localized, scalable solution is a mesh grid, which might consist of a single solar panel for a few houses that, over time, can be expanded and ultimately connected to the main grid.

The REM software has been used to design off-grid systems for remote and

This image shows results of a Waya analysis to determine the least-cost electrification options for a region in sub-Saharan Africa. Noted on the map at the center are the existing electricity distribution network (gray lines), optimized grid extensions (medium voltage in dark blue, low voltage in light blue), mini-grid networks (green lines), and solar home systems (orange dots). One restricted area is marked in red.
Image courtesy of Waya Energy



mountainous regions in Uganda, Peru, Nigeria, Cambodia, Indonesia, India, and elsewhere. When Tata Power, India's largest integrated power company, saw how well mini-grids would serve parts of east India, the company created a mini-grid division called Tata Renewables.

Amatya notes that the REM software enables her to come up with an entire national electrification plan from her workspace in Cambridge, Massachusetts. But site visits and on-the-ground partners are critical in helping the Waya team understand existing systems, engage with clients to assess demand, and identify stakeholders. In Haiti, an energy consultant reported that the existing grid had typically been operational only six out of every 24 hours. In Karambi, University of Rwanda students surveyed the village's 200 families and helped lead a community-wide meeting.

Waya connects with on-the-ground experts and agencies "who can engage directly with the government and other stakeholders, because many times those are the doors that we knock on," Amatya says. "Local energy ministries, utilities, and regulators have to be open to regulatory change. They have to be open to working with financial institutions and new technology."

The goals of regulators, energy providers, funding agencies, and government officials must align in real time "to provide reliable access to energy for a billion people," she says.

Moving past challenges

Growing up in Kathmandu, Amatya used to travel to remote villages with her father, an electrical engineer who designed cable systems for landlines for Nepal Telecom. She remembers being fascinated by the high-voltage lines crisscrossing Nepal on these trips. Now, she points out utility poles to her children and explains how the distribution lines carry power from local substations to customers.

After majoring in engineering science and physics at Smith College, Amatya completed her PhD in electrical engineering at MIT in 2012. Within two years, she was traveling to off-grid communities in India as a research scientist exploring potential technologies for providing access. There were unexpected challenges: At the time, digitized geospatial data didn't exist for many regions. In India in 2013, the team used phones to take pictures of paper maps spread out on tables. Team members now scour digital data available through Facebook, Google, Microsoft, and other sources for useful geographical information.

It's one thing to create a plan, Amatya says, but how it gets utilized and implemented becomes a big question. With all the players involved—funding agencies, elected officials, utilities, private companies, and regulators within the countries themselves—it's sometimes hard to know who's responsible for next steps.

"Besides providing technical expertise, our team engages with governments to, let's say, develop a financial plan or an implementation plan," she says. Ideally, Waya hopes to stay involved with each project long enough to ensure that its proposal becomes the national electrification strategy of the country. That's no small feat, given the multiple players, the opaque nature of government, and the need to enact a regulatory framework where none may have existed.

For Rwanda, Waya identified areas without service, estimated future demand, and proposed the most cost-effective ways to meet that demand with a mix of grid and off-grid solutions. Based on the electrification plan developed by the Waya team, officials have said they hope to have the entire country electrified by 2024.

In 2017, by the time the team submitted its master plan, which included an off-grid solution for Karambi, Amatya was surprised to learn that electrification in the village had already occurred—an example, she says, of the challenging nature of local planning.

Perhaps because of Waya's focus and outreach efforts, Karambi had become a priority. However it happened, Amatya is happy that Karambi's 200 families finally have access to electricity.

Deborah Halber, MITEI correspondent

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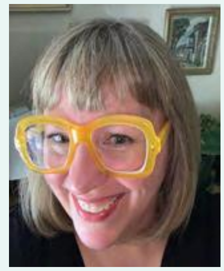
Announcing new hires at MITEI: Heather Leet and J.J. Laukaitis

The MIT Energy Initiative announced two key hires to its leadership team this spring: **Heather Leet** as development officer and **J.J. Laukaitis** as director of member relations.



Heather Leet

J.J. Laukaitis

Heather Leet joins MITEI from Tufts University, where she was director of development at the Friedman School of Nutrition Science and Policy. She spent the last 20 years in fundraising and leadership roles for educational, service, and humanitarian organizations, including the Bostonian Society and the Old State House in Boston, Rotary International, the United Way of Metro Chicago, and Housing Options for the Mentally Ill.

A native of Indiana and a graduate of Indiana University, Bloomington, she began her career as a high school history teacher. Leet served as a United States Peace Corps Volunteer in Silistra, Bulgaria, where she taught English as a second language and history. The Peace Corps gave her both fundraising and environmental experience: She obtained funding from the United States Agency for International Development (USAID) for a kayaking program with students to test chemical pollution levels in the Danube River.

"I look forward to elevating the work at MITEI by ensuring that faculty and researchers have the philanthropic funds they need for their efforts in transforming our energy systems," said Leet. "I also look forward to providing opportunities for donors to achieve their charitable dreams of a sustainable future."

J.J. Laukaitis joins MITEI from within MIT. He was most recently program director in the MIT Office of Corporate Relations. He joined MIT in 2012 as a senior industrial liaison officer. Throughout his MIT career he has focused on managing the growth of collaborations between Institute faculty, researchers and innovators, and leading corporations in the materials, water, and energy sectors. Laukaitis's MIT experience includes working with MITEI and other dynamic initiatives such as the Abdul Latif Jameel Water and Food Systems Lab and several manufacturing innovation institutes.

Laukaitis has more than 25 years of experience in engineering, product management, and large account sales management. He has worked in such industries as mechanical design, software, electronics, and semiconductor manufacturing. His industry experiences have included working in large, global, hard-tech organizations and a highly successful software startup. A native of Pennsylvania, he earned his bachelor's degree in mechanical engineering from Lehigh University and a master's in science from the MIT Sloan School of Management. He also graduated from MIT's Leader to Leader (L2L), the Institute's leadership development program.

"I am thrilled to be joining MITEI at this important phase of the energy transition," said Laukaitis. "To join this deeply experienced team is a great opportunity. I look forward to being a part of MITEI's efforts to work with industry to help transform the way energy is produced and used, to address the global crisis of climate change."

Tom Melville, MITEI

Photos: (left) courtesy of Heather Leet; (right) Gretchen Ertl

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MIT Energy Initiative (MITEI) student research slam highlights work on energy storage

On March 21, 2023, thirteen MIT students took part in MITEI's energy storage student research slam. The students were given just three minutes to describe their ongoing or recently completed research focusing on some aspect of energy storage—an area chosen to build on MITEI's major study and report, *The Future of Energy Storage*. Topics addressed at the slam included using moisture-hungry hydrogels for sorption-based thermal energy storage; assessing materials barriers to scaling of sodium-ion batteries; creating computationally lightweight, large-scale battery models; using flame-assisted spray pyrolysis to produce lithium-ion battery materials; and more. Winners were selected in two categories: graduate students and undergraduate students. To find out more, please turn to page 32. Photo: Kelley Travers, MITEI