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Energy Futures

MIT
ENERGY
INITIATIVE

AUTUMN 2021

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MIT Energy Initiative podcast

In our two most recent podcast episodes, we explore the energy transition with two prominent leaders, one from the business world and one right here at MIT. Our podcast is currently on pause, but you can explore all episodes at energy.mit.edu/podcast.

Episode #40: Carbon and the cloud

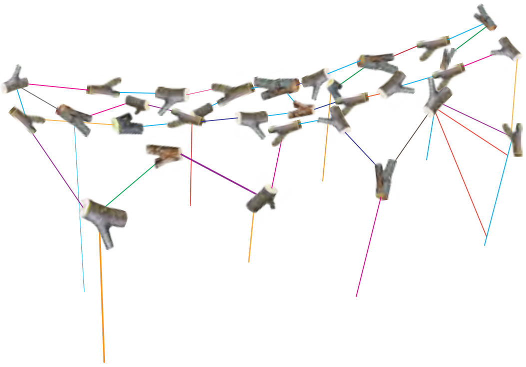
Guest: Maud Texier, head of energy development at Google
Producer and host: Jenn Schlick, digital project manager at MITEI

We don't often think about the energy we consume and the carbon we emit into the atmosphere when we are moving about the Internet. Maud Texier does think about these things. She has led the teams responsible for developing and scaling 24/7 carbon-free energy for Google's data centers around the world. We explore with her the carbon footprint of the Internet, the role of data centers, and how Google and other organizations are working to make the Internet carbon-free.

Episode #39: Starting from space

Guest: Maria Zuber, vice president for research and E.A. Griswold Professor of Geophysics at MIT
Producer and host: Jenn Schlick, digital project manager at MITEI

Maria Zuber grew up in Pennsylvania coal country, where both of her grandfathers worked in the mines and suffered from black lung disease. As a child she studied the stars and dreamed of outer space. Her career would take her to a prominent position at NASA and later to MIT, where, in her portfolio of duties as vice president for research, she leads the Institute's efforts to help the planet achieve net-zero carbon emissions. In this podcast episode we hear the story of her journey and of MIT's response to the climate crisis. You can read excerpts of this episode on page 38.



On the cover

The construction industry is moving to use sustainable timber in place of concrete and steel. But when timber is harvested, irregular sections such as knots and forks are rejected. MIT researchers have developed methods that enable architects to quickly allocate a pile of discarded forks among the Y-shaped nodes in an architectural design and then to cut and mark them to match up with straight timbers, making assembly of the final structure fast and easy. Read more on page 5.
Image: Wing Ngan, Ink Design, inc.

Energy Futures

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MIT Energy Initiative
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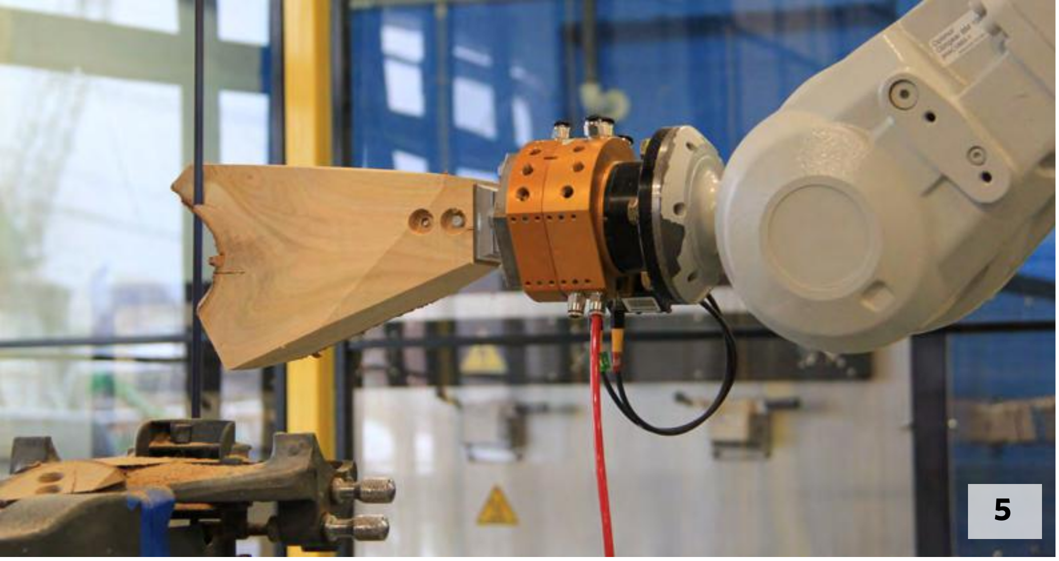

Autumn 2021

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PERSPECTIVES

MEMBERS

REPORT FROM COP26

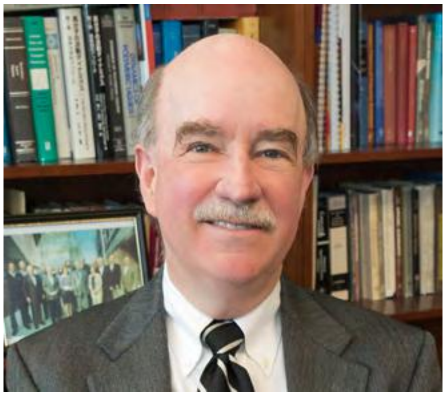
A letter from the director

Dear friends,

UN Secretary-General António Guterres struck us all when he called the Intergovernmental Panel on Climate Change report "a code red for humanity." Yet at the MIT Energy Initiative we *also* see reason for hope. On our campus, there is great progress being made toward the energy transition. In Washington, Congress passed an infrastructure bill addressing climate change. And in Scotland this fall, thousands of world leaders—with some 20 MIT representatives among them—gathered to address climate change at COP26.

Earlier this year, the Institute published "Fast Forward: MIT's Climate Action Plan for the Decade," addressing climate change on campus and around the globe. An element of the plan is MITEI's Future Energy Systems Center, a research consortium with industry launched this fall to explore how best to navigate the energy transition based on multi-sectorial analyses of emerging technologies, changing policies, and evolving economics. Read more on page 3.

We recently completed our three-day annual research conference with the theme "Getting to net-zero by 2050." We explored a number of opportunities and challenges in reaching net-zero—potential technology solutions; hydrogen in the energy transition; the power grid of the future; and thermal energy storage and conversion. Also this fall, with partners at Stanford, Texas A&M, and the U.S. Department of Energy, we sponsored our tenth annual U.S. C3E Women in Clean Energy Symposium, focusing on equity and justice in the clean energy transition (c3e.org/2021).



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

As always, *Energy Futures* offers a rich taste of research at MITEI and MIT. In September, MIT's Plasma Science and Fusion Center and MIT spinoff and MITEI member Commonwealth Fusion Systems demonstrated a high-temperature superconducting electromagnet, breaking magnetic field strength records for a fusion magnet (page 20). You'll read about the potential role and economic value of hydropower in Quebec in a future low-carbon power system in New England (page 10); how architects are using discarded tree forks as load-bearing joints in their structures (page 5); and how a new fundamental understanding developed by MIT chemists can help speed the conversion of biomass into useful fuels and chemicals (page 15). You can also read about two hydrogen projects. One shows that hydrogen-fired power generation can be a more economical option than lithium-ion batteries as a source of clean electricity (page 22); the other shows hydrogen as a pathway for decarbonization in hard-to-abate sectors such as transportation, buildings, and industry (page 26). And MITEI awarded seven Seed Fund grants to early-stage energy research by faculty and researchers (page 18). Since it began in 2008, the MITEI Seed Fund Program has supported 193 energy-focused seed projects through grants totaling more than $26 million.

As always, education is central to our mission. In this edition, we feature Marija Ilic, a senior research scientist in MIT's Laboratory for Information and Decisions Systems, who has designed a new edX course: Principles of Modeling, Simulation, and Control for Electric Energy Systems (page 35). It's one of an expanding set of online courses MITEI has funded to provide global learners with a view of the shifting energy landscape. On page 24, read about two undergraduates funded by MITEI through the Undergraduate Research Opportunities Program who contributed to a timely MIT study showing how classroom configurations may affect air quality and contribute to the spread of Covid-19.

We also share the stories of remarkable MIT graduates. Latifah Hamzah '12 has co-founded a nonprofit to find sustainable and empowering solutions to help disadvantaged populations in Malaysia (page 33). Former MIT visiting student and postdoc Francesco Benedetti led a team that won the 2021 MIT $100K Entrepreneurship Competition for the startup Osmoses, which has developed a novel way to separate molecules (page 31).

We welcome some new leadership to MITEI. Christopher Knittel, the George P. Shultz Professor of Energy Economics at the MIT Sloan School of Management, has become MITEI's deputy director for policy (page 28). Also at Sloan, in January, we'll welcome Andy Sun of Georgia Tech as the inaugural Iberdrola-Avangrid Professor of Electric Power Systems (page 29). At MITEI, Andy will serve as a faculty lead for the electric power system focus area at our new Future Energy Systems Center.

Hoping you enjoy *Energy Futures* and wishing you restful holidays,

Robert C Armstrong

Professor Robert C. Armstrong
MITEI Director
November 2021

MIT Energy Initiative launches the Future Energy Systems Center

The MIT Energy Initiative (MITEI) has launched a new research consortium—the Future Energy Systems Center—to address the climate crisis and the role energy systems can play in solving it. This integrated effort engages researchers from across all of MIT to help the global community reach its goal of net-zero carbon emissions. The Center examines the accelerating energy transition and collaborates with industrial leaders to reform the world's energy systems. The Center is part of "Fast Forward: MIT's Climate Action Plan for the Decade" (climate.mit.edu/climateaction/fastforward), MIT's multi-pronged effort announced earlier this year to address the climate crisis.

The Future Energy Systems Center investigates the emerging technology, policy, demographics, and economics reshaping the landscape of energy supply and demand. The Center conducts integrative analysis of the entire energy system—a holistic approach essential to understanding the cross-sectorial impact of the energy transition. The Center encompasses energy-consuming sectors—transportation, industry, and buildings—and key energy system areas essential to decarbonization, including electric power systems, energy storage and low-carbon fuels, and carbon management.

"The Future Energy Systems Center marries MIT's deep knowledge of energy science and technology with advanced tools for systems analysis to examine how advances in technology and system economics may respond to various policy scenarios," says MITEI Director Robert C. Armstrong, the Chevron Professor of Chemical Engineering. "We must act quickly to get to net-zero greenhouse gas emissions. At the same time, we have a billion people around the world with

Image courtesy of MITEI

inadequate access, or no access, to electricity—and we need to deliver it to them."

The overarching focus of the Center is integrative analysis of the entire energy system, providing insights into the complex multi-sectorial transformations needed to alter the three major energy-consuming sectors of the economy—transportation, industry, and buildings—in conjunction with three major decarbonization-enabling technologies—electricity, energy storage and low-carbon fuels, and carbon management. "These six areas overlap and interact with one another, making a systems approach essential," says Martha Broad, MITEI's executive director. "The Future Energy Systems Center seeks to eliminate silos in research, in technology, and in policy so that we can work quickly and collaboratively with one another to address the existential crisis of climate change."

Through techno-economic and systems-oriented research, the Center analyzes important interactions among these areas. For example:

- Greater electrification of transportation, industry, and buildings will require expansion of demand management and other solutions for balancing of electricity supply and demand across these areas.
- Likewise, balancing of supply and demand will also require deployment of grid-scale energy storage and conversion of the electricity to low-carbon fuels (hydrogen and liquid fuels), which can in turn play a vital role in the energy transition for hard-to-decarbonize segments of transportation, industry, and buildings.
- Carbon management will also play a critical role in decarbonizing industry, electricity, and fuels both as a carbon-mitigation solution and as a negative-carbon technology.

As a member-supported research consortium, the Center collaborates with industrial experts and leaders—from both energy's consumer and supplier sides—to gain insights to help researchers anticipate challenges and opportunities of deploying technology at the scale needed to achieve decarbonization. "The Future Energy Systems Center gives us a powerful way to engage with industry to accelerate the energy transition," says Armstrong. "Working together, we can better understand how our current technology toolbox can be more effectively put to use *now* to reduce emissions, and what new technologies and policies will ultimately be needed to reach net-zero."

A steering committee, made up of 11 MIT professors and led by Armstrong, selects projects to create a research program with high impact on decarbonization, while leveraging MIT strengths and addressing interests of Center members in pragmatic and scalable solutions. "MIT—through our recently released Climate Action Plan—is committed to moving with urgency and speed to transition away from economy-wide emissions of greenhouse gases to help resolve the growing climate crisis," says Armstrong. "We have no time to waste."

MITEI has historically engaged with industry, including through its group of Low-Carbon Energy Centers (LCECs). All existing LCEC projects and memberships continue, having been integrated into the Future Energy Systems Center. The Center members to date are: AECI, Chevron, ConocoPhillips, Copec, Dominion, Duke Energy, Enerjisa, Eneva, Eni, ENN, Equinor, Eversource, Exelon, ExxonMobil, Ferrovial, Golden Spread, Iberdrola, IHI, National Grid, Rio Tinto, Shell, Toyota Research Institute, and Washington Gas.

For more information about the Center, please visit energy.mit.edu/futureenergysystemscenter.

MIT Energy Initiative

Focus areas of the Future Energy Systems Center

Transportation. Within the transportation sector, the Center will examine how electrification, low-carbon fuels, charging/fueling infrastructure, urban mobility systems, shared mobility trends, new technology, policy, and other solutions can contribute to the decarbonization of ground, water, and air transportation.

Industry. The industrial sector includes production of all materials needed for infrastructure, buildings, vehicles, energy production, energy storage, agriculture, etc. Although this sector of the economy is large and diverse, a dozen materials constitute more than half of the greenhouse gas emissions from the industry sector.

Buildings. Buildings currently account for about 30% of greenhouse gas emissions based on the embodied carbon from building materials and construction as well as emissions due to operations including heating, cooling, humidity control, and lighting.

Electric power. The electric power system is a vital part of any decarbonization strategy. It is currently one of the leading sectors for decarbonization and yet electric power supply must grow multifold to meet demand from greater electrification of transportation, industry, and buildings.

Energy storage and low-carbon fuels. Balancing supply and demand also requires large-scale deployment of a range of energy storage solutions including electrochemical storage, mechanical storage, thermal storage, and chemical storage (low-carbon fuels).

Carbon management. Carbon management will also play a critical role in decarbonizing industry, electricity, and fuels. The scope within this focus area is extensive and includes power generation, biomass conversion, production of low-carbon fuels, carbon capture from industry, utilization of carbon, carbon storage, and carbon removal.

Using nature's structures in wooden buildings: Tools for designing with forked tree branches

Nancy W. Stauffer, MITEI

IN BRIEF

Forks in tree trunks and branches are exceptionally strong, yet they are rejected in timber construction because they are not straight. MIT researchers have developed an approach that enables architects to use discarded tree forks as load-bearing joints in their structures. Using digital and computational methods, the MIT process distributes a collection of discarded tree forks among the Y-shaped nodes in an architectural design, allocating them so as to maximize the use of the inherent strength in the wood fiber—and reallocating them instantly if the architect changes the design geometry. Computer-driven robotic machining adjusts and marks the forks for easy assembly with straight wooden elements. Using recovered material from felled city trees, the MIT team used this process to create part of a wooden pavilion destined for installation at the site of the felled trees.

Concern about climate change has focused significant attention on the buildings sector, in particular on the extraction and processing of construction materials. The concrete and steel industries together are responsible for as much as 15% of global carbon dioxide emissions. In contrast, wood provides a natural form of carbon sequestration, so there's a move to use timber instead. Indeed, some countries are calling for public buildings to be made at least partly from timber, and large-scale timber buildings have been appearing around the world.

Observing those trends, Caitlin Mueller '07, SM '14, PhD '14, an associate professor of architecture and civil and environmental engineering in the Building Technology Program at MIT, sees an opportunity for further sustainability gains. As the timber industry seeks to produce wooden replacements for traditional concrete and steel elements, the focus is on harvesting the straight sections of trees. Irregular sections such as knots and forks are turned into pellets and burned, or ground up to make garden mulch, which will decompose within a few years; both approaches release the carbon trapped in the wood to the atmosphere.

For the past four years, Mueller and her Digital Structures research group have been developing a strategy for "upcycling" those waste materials by using them in construction—not as cladding or finishes aimed at improving appearance but as structural components. "The greatest value you can give to a material is to give it a load-bearing role in a structure," she says. But when builders use virgin materials, those structural components are the most emissions-intensive parts of buildings due to their large volume of high-strength materials. Using upcycled materials in place of those high-carbon systems is therefore especially impactful in reducing emissions.

Mueller and her team focus on tree forks, that is, spots where the trunk or branch of a tree divides in two, forming a Y-shaped piece. In architectural drawings, there are many similar Y-shaped nodes where straight elements come together. In such cases, those units must be strong enough to support critical loads.

"Tree forks are naturally engineered structural connections that work as cantilevers in trees, which means that they have the potential to transfer force very efficiently thanks to their internal fiber structure," says Mueller. "If you take a tree fork and slice it down the middle, you see an unbelievable network of fibers that are intertwining to create these often three-dimensional load transfer points in a tree. We're starting to do the same thing using 3D printing, but we're nowhere near what nature does in terms of complex fiber orientation and geometry."

She and her team have developed a five-step "design-to-fabrication workflow" that combines natural structures such as tree forks with the digital and computational tools now used in architectural design. While there's long been a "craft" movement to use natural wood in railings and decorative features, the use of computational tools makes it possible to use wood in structural roles—without excessive cutting, which is costly and may compromise the natural geometry and internal grain structure of the wood.

Above This photo shows some of the processed tree forks in the researchers' inventory. Their goal is to support the so-called circular economy of materials, an approach to sustainability that calls for "upcycling" such waste materials, in this case, by using them as structural joints in timber buildings.
Photo: Felix Amtsberg

Given the wide use of digital tools by today's architects, Mueller believes that her approach is "at least potentially scalable and potentially achievable within our industrialized materials processing systems." In addition, by combining tree forks with digital design tools, the novel approach can also support the trend among architects to explore new forms. "Many iconic buildings built in the past two decades have unexpected shapes," says Mueller. "Tree branches have a very specific geometry that sometimes lends itself to an irregular or nonstandard architectural form—driven not by some arbitrary algorithm but by the material itself."

Step 0: Find a source, set goals

Before starting their design-to-fabrication process, the researchers needed to locate a source of tree forks. Mueller found help in the Urban Forestry Division of the City of Somerville, Massachusetts, which maintains a digital inventory of more than 2,000 street trees—including more than 20 species—and records information about the location, approximate trunk diameter, and condition of each tree.

With permission from the forestry division, the team was on hand in 2018 when a large group of trees was cut down near the site of the new Somerville High School. Among the heavy equipment on site was a chipper, poised to turn all the waste wood into mulch. Instead, the workers obligingly put the waste wood into the researchers' truck to be brought to MIT.

In their project, the MIT team sought not only to upcycle that waste material but also to use it to create a structure that would be valued by the public. "Where I live, the city has had to take down a lot of trees due to damage from an invasive species of beetle," Mueller explains. "People get really upset—understandably. Trees are an important part of the urban fabric, providing shade and beauty." She and her team hoped to reduce that animosity by "reinstalling the removed trees in the form of a new functional structure that would re-create the atmosphere and spatial experience previously provided by the felled trees."

With their source and goals identified, the researchers were ready to demonstrate the five steps in their design-to-fabrication workflow for making spatial structures using an inventory of tree forks.

Step 1: Create a digital material library

The first task was to turn their collection of tree forks into a digital library. They began by cutting off excess material to produce isolated tree forks, some of which are shown in the photo above. They then created a 3D scan of each fork. Mueller notes that as a result of recent progress in photogrammetry (measuring objects using photographs) and 3D scanning, they could create high-resolution digital representations of the individual tree forks with relatively inexpensive equipment, even using apps that run on a typical smartphone.

In the digital library, each fork is represented by a "skeletonized" version showing three straight bars coming together at a point. The relative geometry and orientation of the branches are of particular interest because they determine the internal fiber orientation that gives the component its strength.

Step 2: Find the best match between the initial design and the material library

Like a tree, a typical architectural design is filled with Y-shaped nodes where three straight elements meet up to support a critical load. The goal was therefore to match the tree forks in the material library with the nodes in a sample architectural design.

First, the researchers developed a "mismatch metric" for quantifying how well the geometries of a particular tree fork aligned with a given design node. "We're trying to line up the straight elements in the structure with where the branches originally were in the tree," explains Mueller. "That gives us the optimal orientation for load transfer and maximizes use of the inherent strength of the wood fiber." The poorer the alignment, the higher the mismatch metric.

The goal was to get the best overall distribution of all the tree forks among the nodes in the target design. Therefore, the researchers needed to try different fork-to-node distributions and, for each distribution, add up the individual fork-to-node mismatch errors to generate an overall, or global, matching score. The distribution with the best matching score would produce the most structurally efficient use of the total tree fork inventory.

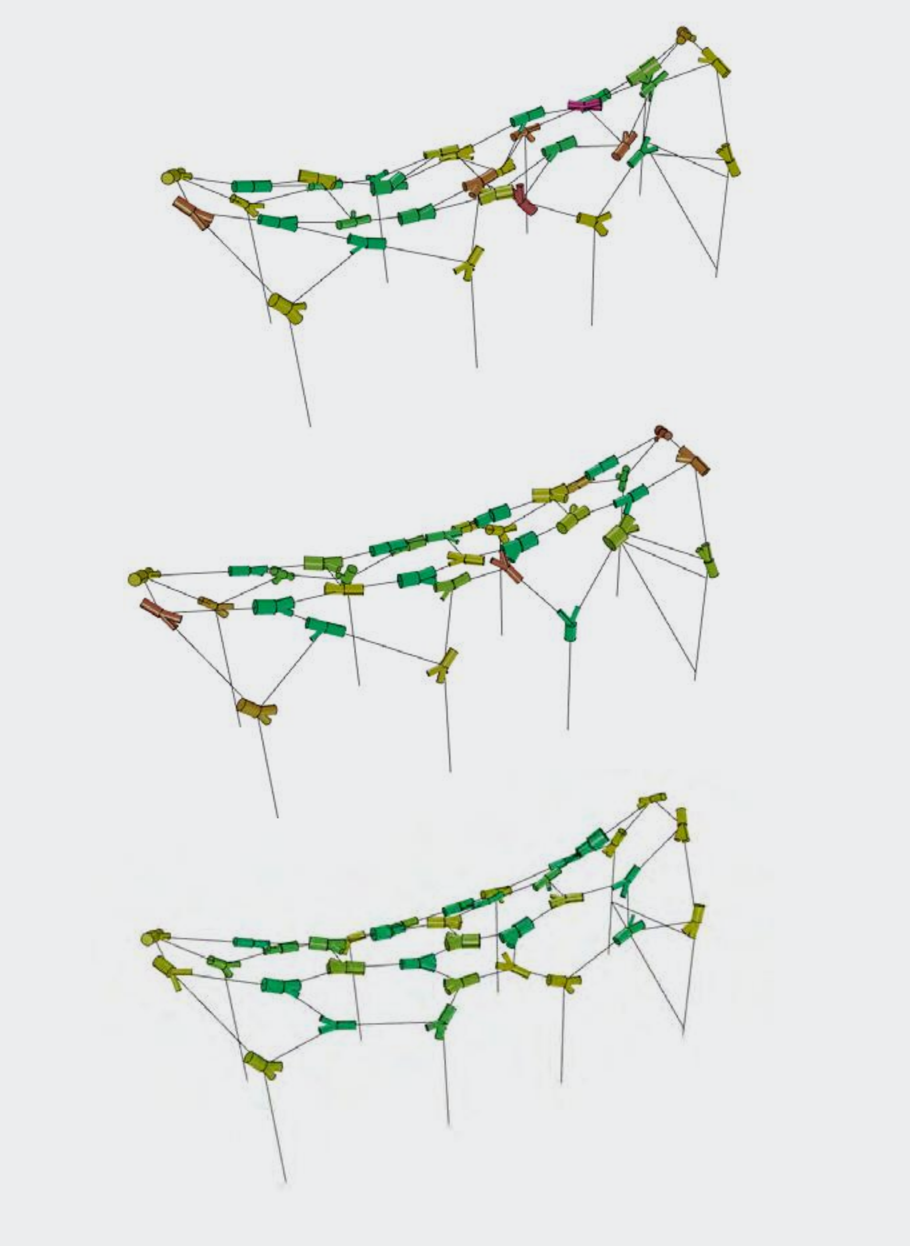
Since performing that process manually would take far too long to be practical, they turned to the "Hungarian algorithm," a technique developed in 1955 for solving such problems. "The brilliance of the algorithm is solving that [matching] problem very quickly," Mueller says. She notes that it's a very general-use algorithm. "It's used for things like marriage match-making. It can be used any time you have two collections of things that you're trying to find unique matches between. So, we definitely didn't invent the algorithm, but we were the first to identify that it could be used for this problem."

The figure at the right presents a sample structure design with three possible distributions of the tree forks in the researchers' inventory. The forks colored green are well matched with their nodes; the strings in the design pass through the centerline of the fork. The red forks are less well matched. The top option includes many red forks, so it has lots of mismatches and a high global mismatch score. The bottom option achieves the most green forks and thus the lowest mismatch score of the three options.

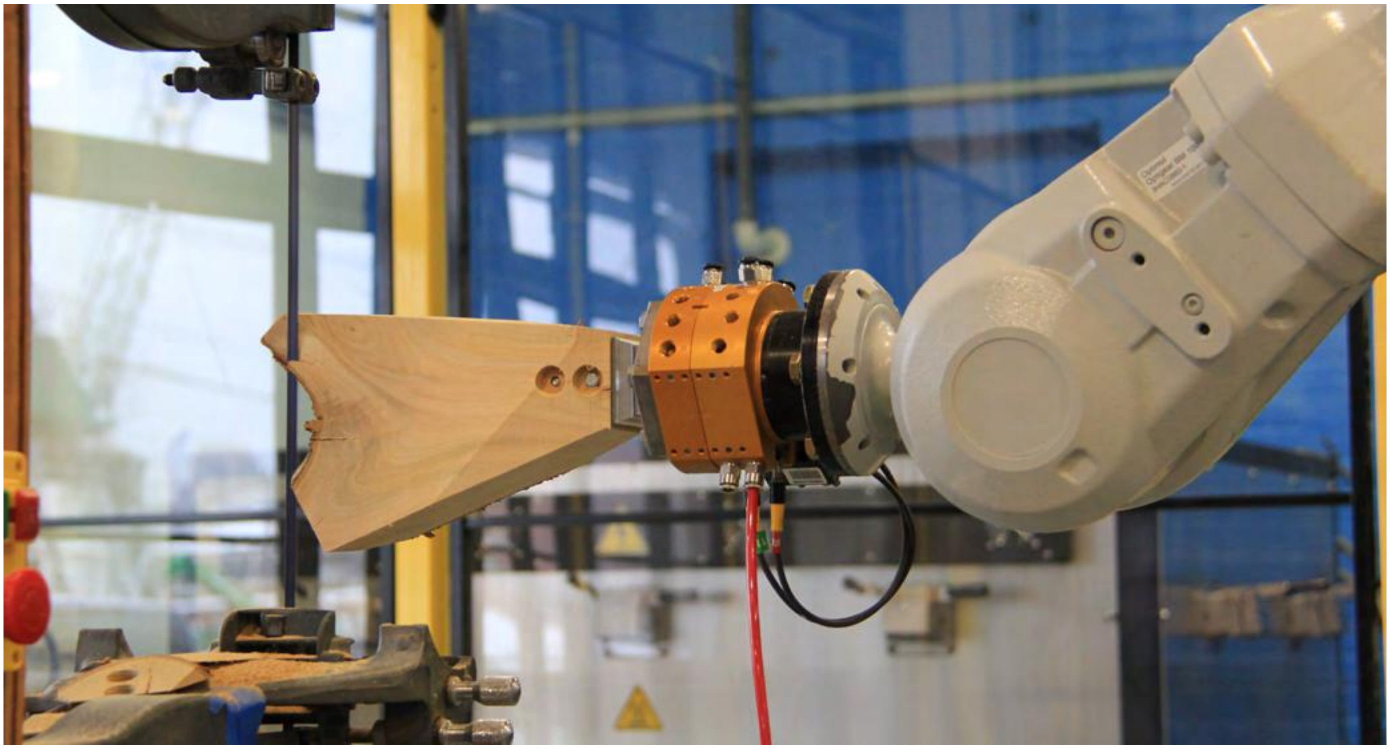
Repeated tests showed that the matching score improved as the number of forks available in the material library increased—up to a point. In general, the researchers concluded that the mismatch score was lowest, thus best, when there were about three times as many forks in the material library as there were nodes in the target design.

Step 3: Balance designer intention with structural performance

The next step in the process was to incorporate the intention or preference of the designer. To permit that flexibility, each design includes a limited number of critical parameters, such as bar length and bending strain. Using those parameters, the designer can manually change the overall shape, or geometry, of the design or can use an algorithm that automatically changes, or "morphs," the geometry. And every time the design geometry changes, the Hungarian algorithm recalculates the optimal fork-to-node matching.



This figure shows three possible distributions of the researchers' tree fork inventory within a target architectural structure. The green-colored forks are well matched with their design node; the red forks are poorly matched. The global matching score of the bottom option is lower than those of the top and middle options. The bottom option thus makes better use of the available forks as load-bearing joints.



At the Autodesk Boston Technology Center Build Space, a robotic arm automatically pushes a tree fork through a band saw in different orientations, guided by computer-generated instructions. Ultimately, each tree fork will interface well with its neighboring straight timbers, with marks and drill holes for the structural connections, making assembly straightforward. Photo: Felix Amtsberg

"Because the Hungarian algorithm is extremely fast, all the morphing and the design updating can be really fluid," notes Mueller. In addition, any change to a new geometry is followed by a structural analysis that checks the deflections, strain energy, and other performance measures of the structure. On occasion, the automatically generated design that yields the best matching score may deviate far from the designer's initial intention. In such cases, an alternative solution can be found that satisfactorily balances the design intention with a low matching score.

Step 4: Automatically generate the machine code for fast cutting

When the structural geometry and distribution of tree forks have been finalized, it's time to think about actually building the structure. To simplify assembly and maintenance, the researchers prepare the tree forks by recutting their end faces to better match adjoining straight timbers and cutting off any remaining bark to reduce susceptibility to rot and fire.

To guide that process, they developed a custom algorithm that automatically computes the cuts needed to make a given tree fork fit into its assigned node and to strip off the bark. The goal is to remove as little material as possible but also to avoid a complex, time-consuming machining process. "If we make too few cuts, we'll cut off too much of the critical structural material. But we don't want to make a million tiny cuts because it will take forever," Mueller explains.

The photo above shows the setup they use to prepare their tree forks. The team uses facilities at the Autodesk Boston Technology Center Build Space, where the robots are far larger than any at MIT and the processing is all automated. To prepare each tree fork, they mount it on a robotic arm that pushes the joint through a traditional band saw in different orientations, guided by computer-generated instructions. The robot also mills all the holes for the structural connections. "That's helpful because it ensures that everything is aligned the way you expect it to be," says Mueller.

Step 5: Assemble the available forks and linear elements to build the structure

The final step is to assemble the structure. The tree-fork-based joints are all irregular, and combining them with the precut straight wooden elements could be difficult. However, they're all labeled. "All the information for the geometry is embedded in the joint, so the assembly process is really low-tech," says Mueller. "It's like a child's toy set. You just follow the instructions on the joints to put all the pieces together."

The top photograph on page 9 shows their final structure, which they installed temporarily on the MIT campus. Mueller notes that it was only a portion of the structure they plan to build. "It had

12 nodes that we designed and fabricated using our process," she says, adding that the team's work was "a little interrupted by the pandemic." As activity on campus resumes, the researchers plan to finish designing and building the complete structure, which will include about 40 nodes and will be installed as an outdoor pavilion on the site of the felled trees in Somerville.

In addition, they will continue their research. Plans include working with larger material libraries, some with multi-branch forks, and replacing their 3D-scanning technique with computerized tomography scanning technologies that can automatically generate a detailed geometric representation of a tree fork, including its precise fiber orientation and density. And in a parallel project, they've been exploring using their process with other sources of materials, with one case study focusing on using material from a demolished wood-framed house to construct more than a dozen geodesic domes.

To Mueller, the work to date already provides new guidance for the architectural design process. With digital tools, it has become easy for architects to analyze the embodied carbon or future energy use of a design option. "Now we have a new metric of performance: How well am I using available resources?" she says. "With the Hungarian algorithm, we can compute that metric basically in real time, so we can work rapidly and creatively with that as another input to the design process."

The researchers produced and installed this structure on the MIT campus using waste tree forks as structural elements. In the future, they plan to use their process to design and build a complete outdoor pavilion, which will be located at the site of the felled trees from which the wood forks were recovered. Photo: Felix Amtsberg

In summer 2021, MIT Facilities took down a number of trees to make way for the new MIT Music Building. Associate Professor Caitlin Mueller and her team received the material shown above to further their research on the use of salvaged materials in architecture. Photo: Neil Patel of Lee Kennedy Co.

NOTES

This research was supported by MIT's School of Architecture and Planning via the HASS Award. In summer 2021, MIT Facilities removed some campus trees prior to construction and gave all the material to Mueller and her team to use in their research (see photo at left). Further information about the research can be found in:

F. Amtsberg, Y. Huang, D.J.M. Marshall, K.M. Gata, and C. Mueller. "Structural upcycling: Matching digital and natural geometry." *Advances in Architectural Geometry 2020*, April 2021. Online: bit.ly/structural-upcycling.

Y. Huang, L. Alkhayat, C. De Wolf, and C. Mueller. "Algorithmic circular design with reused structural elements: method and tool." *Conceptual Design of Structures 2021*, International *fib* Symposium, September 2021. Online: bit.ly/circular-design-mueller, page 457.

New England renewables + Canadian hydropower: A pathway to clean electricity in 2050

Nancy W. Stauffer, MITEI

IN BRIEF

In planning for a carbon-free electric power system in 2050, U.S. states in New England have looked to hydropower imported from Quebec as one source of clean electricity alongside wind and solar and others. But engaging Canadian hydropower strictly as an electricity supplier may not be the best way to go. An MIT analysis shows that two-way exchanges between the regions could yield significant benefits. Under such an arrangement, Quebec sends electricity south to New England to meet demand when wind and solar aren't producing enough power. When they produce an excess, New England sends electricity north to cover demand in Quebec, allowing the hydro systems to pause and reservoirs to refill with water. The hydro system thus provides energy storage—over hours or days or months—and both regions benefit: Two-way trading lowers the cost of decarbonization and accelerates the process. Based on their findings, the researchers suggest that such interregional cooperation could prove beneficial wherever hydropower resources are available.

The urgent need to cut carbon emissions has prompted a growing number of U.S. states to commit to achieving 100% clean electricity by 2040 or 2050. But figuring out how to meet those commitments and still have a reliable and affordable power system is a challenge. Wind and solar installations will form the backbone of a carbon-free power system, but what technologies can meet electricity demand when those intermittent renewable sources are not adequate?

In general, the options being discussed include nuclear power, natural gas with carbon capture and storage (CCS), and energy storage technologies such as new and improved batteries and chemical storage in the form of hydrogen. But in the northeastern United States, there is one more possibility being proposed: electricity imported from hydropower plants in the neighboring Canadian province of Quebec.

The proposition makes sense. Those plants can produce as much electricity as about 40 large nuclear power plants, and some power generated in Quebec already comes to the Northeast. So, there could be abundant additional supply to fill any shortfall when New England's intermittent renewables underproduce. However, U.S. wind and solar investors view Canadian hydropower as a competitor and argue that reliance on foreign supply discourages further U.S. investment.

Two years ago, three researchers affiliated with the MIT Center for Energy and Environmental Policy Research (CEEPR)—Emil Dimanchev SM '18, now a PhD candidate at the Norwegian University of Science and Technology; Joshua Hodge, CEEPR's executive director; and John Parsons, a senior lecturer in the MIT Sloan School of Management—began wondering whether viewing Canadian hydro as another source of electricity might be too narrow. "Hydropower is a more-than-hundred-year-old technology, and plants are already built up north," says Dimanchev. "We might not need to build something new. We might just need to use those plants differently or to a greater extent."

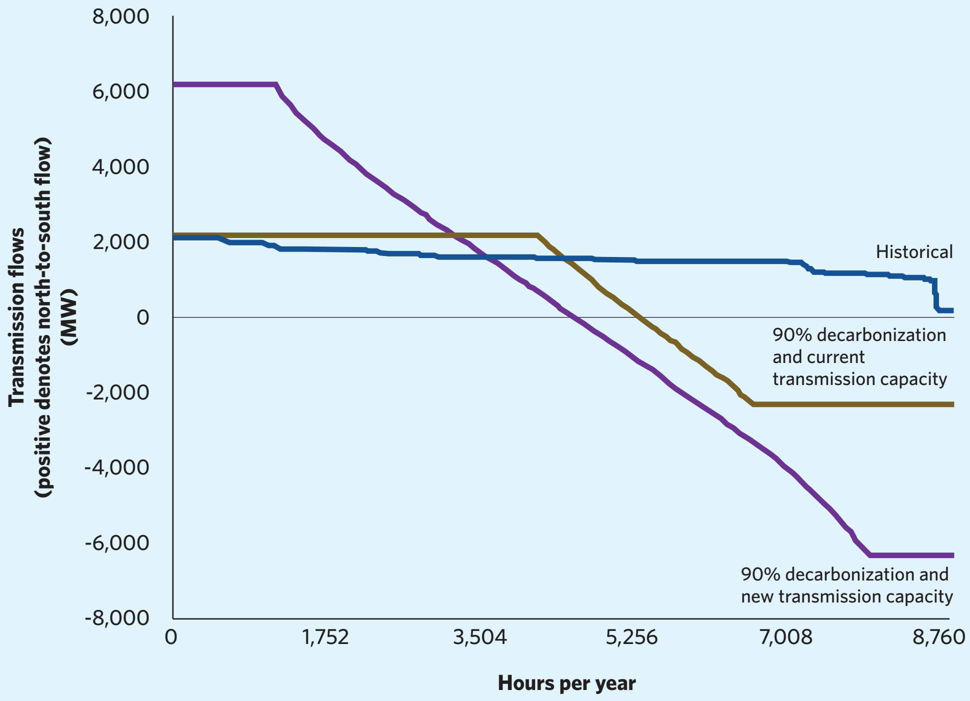
So the researchers decided to examine the potential role and economic value of Quebec's hydropower resource in a future low-carbon system in New England. Their goal was to help inform policy makers, utility decision makers, and others about how best to incorporate Canadian hydropower into their plans and to determine how much time and money New England should spend to integrate more hydropower into its system. What they found out was surprising, even to them.

The analytical methods

To explore possible roles for Canadian hydropower to play in New England's power system, the MIT researchers first needed to predict how the regional power system might look in 2050—both the resources in place and how they would be operated, given any policy constraints. To perform that analysis, they used GenX, a modeling tool originally developed by Jesse Jenkins SM '14, PhD '18 and Nestor Sepulveda SM '16, PhD '20 while they were researchers at the MIT Energy Initiative (MITEI).

The GenX model is designed to support decision-making related to power system investment and real-time operation and to examine the impacts of possible policy initiatives on those decisions. Given information on current and future technologies—different kinds of power plants, energy storage technologies, and so on—GenX calculates the combination of equipment and operating conditions that can meet a defined future demand at the lowest cost. The GenX modeling tool can also incorporate specified policy constraints, such as limits on carbon emissions.

For their study, Dimanchev, Hodge, and Parsons set parameters in the GenX model using data and assumptions derived from a variety of sources to build



Effects of transmission infrastructure change on flow of electricity between New England and Quebec
This figure shows the level of electricity flow from north to south (positive numbers) and from south to north (negative numbers) versus the number of hours per year. The flows in 2018, shown in blue, are always from Quebec to New England and are capped by the transmission capacity limit of 2,225 megawatts (MW). Model results for 2050 are shown in brown and purple and assume current and expanded transmission capacity, respectively. In both cases, flow is at the maximum in both directions for many hours of the year.

a representation of the interconnected power systems in New England, New York, and Quebec. (They included New York to account for that state's existing demand on the Canadian hydro resources.) For data on the available hydropower, they turned to Hydro-Québec, the public utility that owns and operates most of the hydropower plants in Quebec.

It's standard in such analyses to include real-world engineering constraints on equipment, such as how quickly certain power plants can be ramped up and down. With help from Hydro-Québec, the researchers also put hour-to-hour operating constraints on the hydropower resource.

Most of Hydro-Québec's plants are "reservoir hydropower" systems. In them, when power isn't needed, the flow on a river is restrained by a dam downstream of a reservoir, and the reservoir fills up. When power is needed, the dam is opened, and the water in the reservoir runs through downstream pipes, turning turbines and generating electricity. Proper management of such a system requires adhering to certain operating constraints. For example, to prevent flooding, reservoirs must not be allowed to overfill—especially prior to spring snowmelt. And generation can't be increased too quickly because a sudden flood of water could erode the river edges or disrupt fishing or water quality.

Based on projections from the National Renewable Energy Laboratory and elsewhere, the researchers specified electricity demand for every hour of the year 2050, and the model calculated the cost-optimal mix of technologies and system operating regime that would satisfy that hourly demand, including the dispatch of the Hydro-Québec hydropower system. In addition, the model determined how electricity would be traded among New England, New York, and Quebec.

Effects of decarbonization limits on technology mix and electricity trading

To examine the impact of the emissions-reduction mandates in the New England states, the researchers ran the model assuming reductions in carbon emissions between 80% and 100% relative to 1990 levels. The results of those runs show that, as emissions limits get more stringent, New England uses more wind and solar and extends the lifetime of its existing nuclear plants. To balance the intermittency of the renewables, the region uses natural gas plants, demand-side management, battery storage (modeled as lithium-ion batteries), and trading with Quebec's hydropower-based system. Meanwhile, the optimal mix in Quebec is mostly composed of existing hydro generation. Some solar is added, but new reservoirs are built only if renewable costs are assumed to be very high.

The most significant—and perhaps surprising—outcome is that in all the scenarios, the hydropower-based system of Quebec is not only an exporter but also an importer of electricity, with the direction of flow on the Quebec-New England transmission lines changing over time.

The figure on this page shows transmission flows north and south. Historically, energy has always flowed from Quebec to

New England, as shown by the blue curve, which represents 2018. That curve remains above the zero line, indicating that the flow is always north to south, and it's capped by the current transmission capacity limit of 2,225 megawatts (MW).

The brown curve shows the model results for 2050, assuming that New England decarbonizes 90% and the capacity of the transmission lines remains the same. Now the flows go both ways. Looking at the right-hand side of the figure, there are nearly 3,500 hours where the curve is below the zero line, so electricity is flowing from New England to Quebec. As the flat section shows, for more than 2,200 hours, the flow going north is at the maximum the transmission lines can carry.

The direction of flow is motivated by economics. When renewable generation is abundant in New England, prices are low, and it's cheaper for Quebec to import electricity from New England and conserve water in its reservoirs. Conversely, when New England's renewables are scarce and prices are high, New England imports hydro-generated electricity from Quebec.

So rather than delivering electricity, Canadian hydro provides a means of storing the electricity generated by the intermittent renewables in New England.

"We see this in our modeling because when we tell the model to meet electricity demand using these resources, the model decides that it is cost-optimal to use the reservoirs to store energy rather than anything else," says Dimanchev. "We should be sending the energy back and forth, so the reservoirs in Quebec are in essence a battery that we use to store some of the electricity produced by our intermittent renewables and discharge it when we need it."

Given that outcome, the researchers decided to explore the impact of expanding the transmission capacity between New England and Quebec. Building transmission lines is always contentious, but what would be the impact if it could be done?

The purple line in the figure on page 11 shows the impact of expanding transmission capacity from 2,225 MW to 6,225 MW: Flows in both directions are greater, and in both cases the flow is at the new maximum for more than 1,000 hours.

Results of the analysis thus confirm that the economic response to expanded transmission capacity is more two-way trading. To continue the battery analogy, more transmission capacity to and from Quebec effectively increases the rate at which the battery can be charged and discharged.

Effects of two-way trading on the energy mix

What impact would the advent of two-way trading have on the mix of energy-generating sources in New England and Quebec in 2050?

The figure on page 13 shows the energy mix in the two regions, with the panel on the left representing New England, and the panel on the right, Quebec. Here, the researchers have included a second kind of hydro plant—"run of river" (ROR), in which whatever water is available on a river simply flows through a turbine and generates electricity. In Quebec, ROR plants are considered part of the overall reservoir system because they are situated downstream of reservoirs, and their output is thus partly controlled by decisions at those reservoirs.

In each panel, moving from the left to the center bar shows the impact of moving from traditional one-way trading to two-way trading. In New England, that change increases both wind (dark blue) and solar (yellow) power generation and to a lesser extent nuclear (orange); it also decreases the use of natural gas with CCS (navy blue). The hydro reservoirs in Canada can provide long-duration storage—over weeks, months, and even seasons—so there is less need for natural gas with CCS to cover any gaps in supply. The level of imports (green) is slightly lower, but now there are also exports (purple). Meanwhile, in Quebec, two-way trading reduces solar power generation, and the use of wind disappears. Exports are roughly the same, but now there are imports as well. Thus, two-way trading reallocates renewables from Quebec to New England, where it's more economical to install and operate solar and wind systems.

The right-hand bars in the two panels show the energy mix in New England and Quebec assuming two-way trading with expanded transmission capacity. Comparing the middle and right-hand bars in the New England panel shows that expanded transmission allows wind, solar, and nuclear to expand further; natural gas with CCS all but disappears; and both imports and exports increase significantly. In the Quebec panel, solar decreases still further, and both exports and imports of electricity increase.

Those results assume that the New England power system decarbonizes by 99% in 2050 relative to 1990 levels. But at 90% and even 80% decarbonization levels, the model concludes that natural gas capacity decreases with the addition of new transmission relative to the current transmission scenario. Existing plants are retired, and new plants are not built as they are no longer economically justified. Since natural gas plants are the only source of carbon emissions in the 2050 energy system, the researchers conclude that the greater access to hydro reservoirs made possible by expanded transmission would accelerate the decarbonization of the electricity system.

Effects of transmission changes on costs

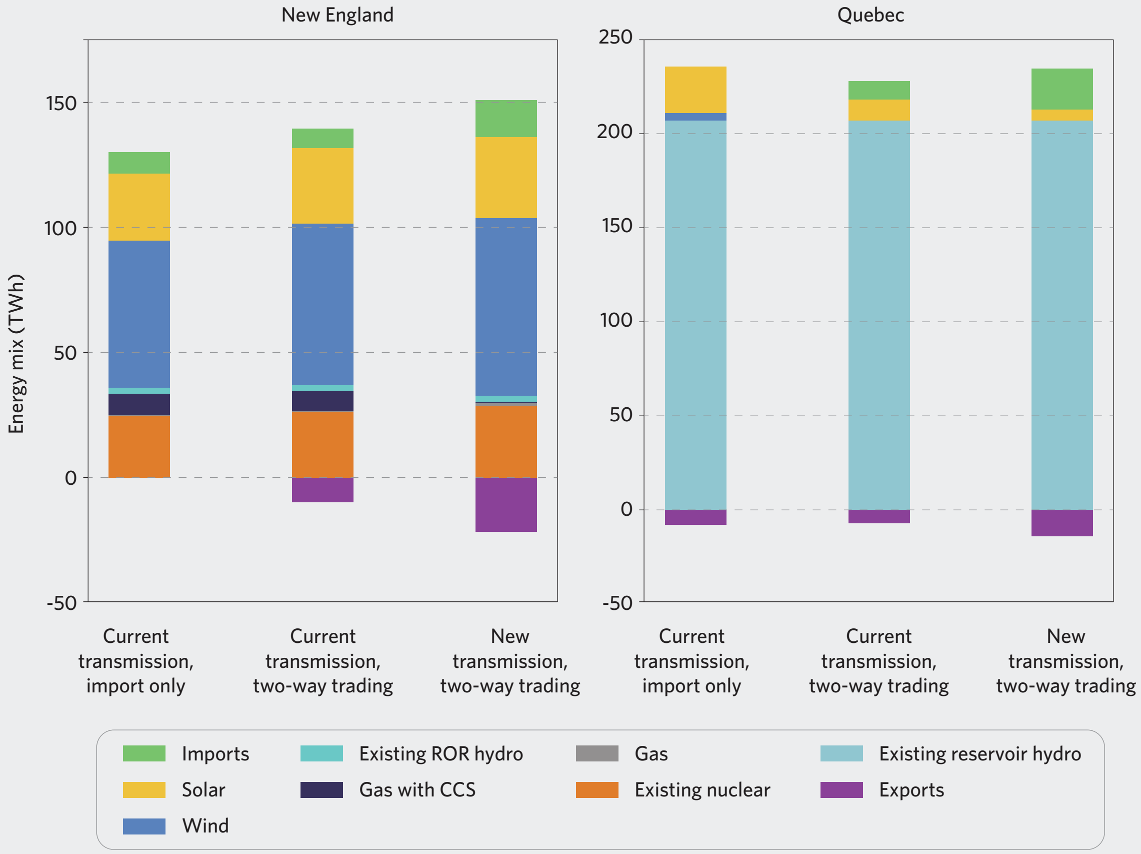
The researchers also explored how two-way trading with expanded transmission capacity would affect costs in New England and Quebec. The figure on page 14 summarizes their findings (assuming 99% decarbonization in New England). The blue bar shows cost savings in the two regions, divided into fixed costs (investments in new equipment) and variable costs (operating costs). New England's savings on fixed costs are largely due to a decreased need to invest in more natural gas with CCS, and its savings on variable costs are due to a reduced need to run those plants. Quebec's savings on fixed costs come from a reduced need to invest in solar generation. The increase in cost (orange bar)—borne by New England—reflects the construction and operation of the increased transmission capacity. The net benefit for the region (green bar) is substantial.

Thus, the analysis shows that everyone wins as transmission capacity increases—and the benefit grows as the decarbonization target tightens. At 99% decarbonization, the overall New England-Quebec region pays about $21 per megawatt-hour (MWh) of electricity with today's transmission capacity but only $18/MWh with expanded transmission. Assuming 100% reduction in carbon emissions, the region pays $29/MWh with current transmission capacity and only $22/MWh with expanded transmission.

Addressing misconceptions

These results shed light on several misconceptions that policy makers, supporters of renewable energy, and others tend to have.

The first misconception is that the New England renewables and Canadian hydropower are competitors. The modeling results instead show that they're complementary. When the power systems



Energy mix in New England (left) and Quebec (right) under varied assumptions about transmission capacity and operation
This figure shows the impact on the energy mix in 2050 of expanding transmission capacity and operating transmission in an economically optimal manner. In each panel, the left-hand bar shows results assuming current transmission capacity and one-way flow; the center bar assumes current capacity and two-way flows; and the right-hand bar assumes expanded capacity and two-way flows. In Quebec, run-of-river (ROR) plants typically occur downstream of reservoirs, so their output is not reported separately. All cases assume that New England's electricity is 99% decarbonized.

in New England and Quebec work together as an integrated system, the Canadian reservoirs are used part of the time to store the renewable electricity. And with more access to hydropower storage in Quebec, there's generally more renewable investment in New England.

The second misconception arises when policy makers refer to Canadian hydro as a "baseload resource," which implies a dependable source of electricity—particularly one that supplies power all the time. "Our study shows that by viewing Canadian hydropower as a baseload source of electricity—or indeed a source of electricity at all—you're not taking full advantage of what that resource can provide," says Dimanchev. "What we show is that Quebec's reservoir hydro can provide storage, specifically for wind and solar. It's a solution to the intermittency problem that we foresee in carbon-free power systems for 2050."

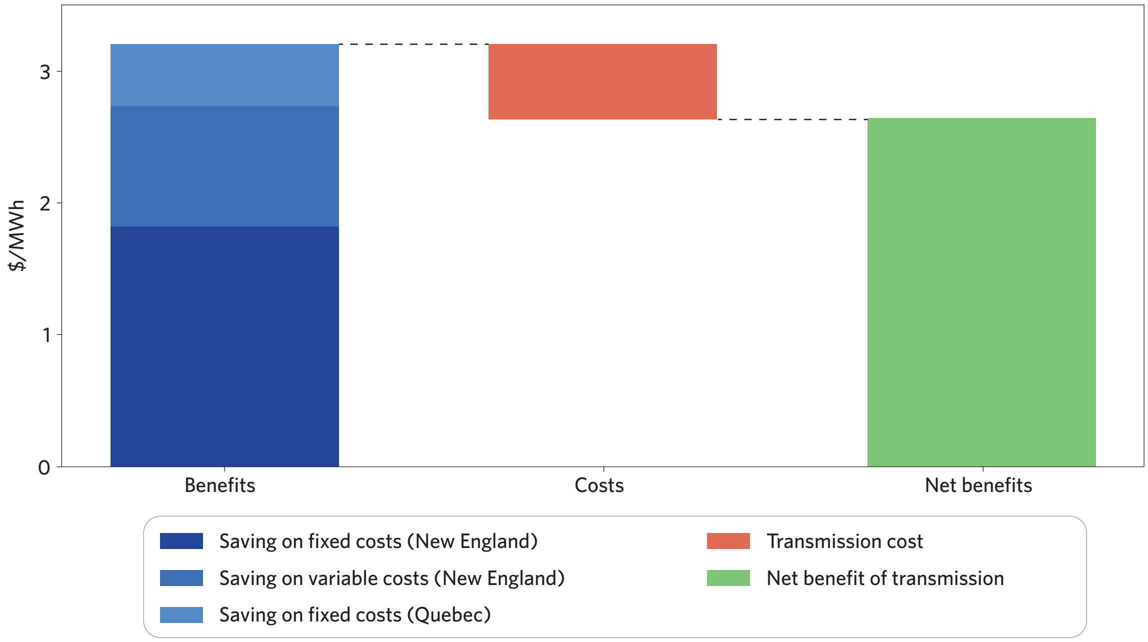
While the MIT analysis focuses on New England and Quebec, the researchers believe that their results may have wider implications. As power systems in many regions expand production of renewables, the value of storage grows. Some hydropower systems have storage capacity that has not yet been fully utilized and could be a good complement to renewable generation. Taking advantage of that capacity can lower the cost of deep decarbonization and help move some regions toward a decarbonized supply of electricity.

NOTES

This research was funded by the MIT Center for Energy and Environmental Policy Research (ceepr.mit.edu), which is supported in part by a consortium of industry and government associates. The GenX modeling tool is now being maintained jointly by teams of contributors at the MIT Energy Initiative, led by research scientist Dharik Mallapragada, and the Princeton University ZERO Lab, led by Assistant Professor Jesse Jenkins SM '14, PhD '18. More information about this research can be found in:

E.G. Dimanchev, J.L. Hodge, and J.E. Parsons. "The role of hydropower reservoirs in deep decarbonization policy." *Energy Policy*, May 2021. Online: doi.org/10.1016/j.enpol.2021.112369.

E.G. Dimanchev, J.L. Hodge, and J.E. Parsons. *Two-Way Trade in Green Electrons: Deep Decarbonization of the Northeastern U.S. and the Role of Canadian Hydropower*. CEEPR working paper WP-2020-003, February 2020. Online: ceepr.mit.edu/publications/working-papers.



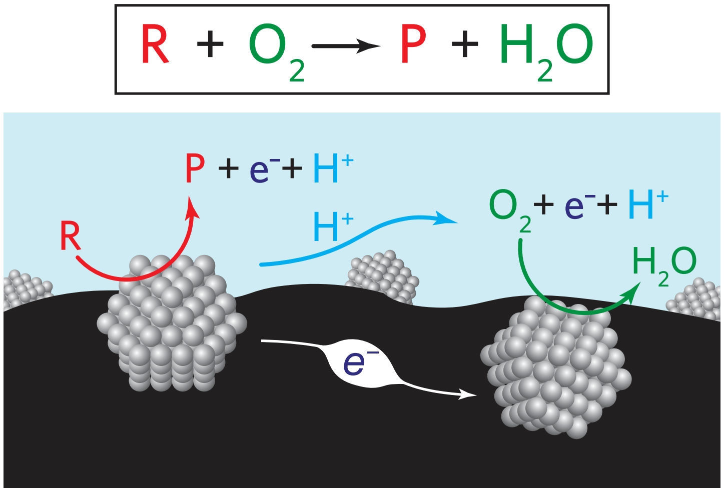
Effects of two-way trading and expanded transmission on the cost of electricity in New England and Quebec
The blue bar at the left shows savings in 2050 from implementing two-way trading and expanding transmission capacity. The orange bar in the center shows the additional cost to New England of building and operating the added transmission lines. The green bar at the right represents the net benefit of two-way trading and expanded transmission to the New England-Quebec region. This analysis assumes 99% decarbonization in New England.

Chemical reactions for the energy transition: New insights reveal pathways to improvement

Nancy W. Stauffer, MITEI

IN BRIEF

Chemists worldwide are working to design catalysts that will speed up critical chemical reactions needed to convert renewable resources such as biomass into useful fuels and chemicals. Now, chemists at MIT have demonstrated that such reactions can actually take place as two separate but coordinated "half-reactions," activated by the transfer of charged particles. As a result, researchers can design separate catalysts for each half-reaction—a far easier task than finding a single catalyst effective for the overall reaction. The approach increases the likelihood of finding low-cost materials that can do the job, and—because the transfer of charged particles is involved—the MIT team can now use its expertise in electrochemistry to design catalysts for this type of reaction, thereby aiding in the production of renewable fuels for a clean energy system.



Two views of the chemical reactions critical for producing renewable fuels and chemicals
The chemical equation at the top represents the conversion of the reactant (R) plus oxygen (O_2) to a product (P) plus water (H_2O). The diagram below illustrates the researchers' hypothesis that the overall reaction is the result of two coordinated half-reactions occurring on separate catalyst materials, here represented by the two gray structures. On the left-hand catalyst, the reactant turns into a product, sending electrons (e^-) into the carbon support material (black) and protons (H^+) into the water (blue). On the right-hand catalyst, electrons and protons are consumed as they drive the reaction of oxygen to water.

One challenge in decarbonizing the energy system is knowing how to deal with new types of fuels. Traditional fuels such as natural gas and oil can be combined with other materials and then heated to high temperatures so they chemically react to produce other useful fuels or substances, or even energy to do work. But new materials such as biofuels can't take as much heat without breaking down.

A key ingredient in such chemical reactions is a specially designed solid catalyst that is added to encourage the reaction to happen but isn't itself consumed in the process. With traditional materials, the solid catalyst typically interacts with a gas; but with fuels derived from biomass, for example, the catalyst must work with a liquid—a special challenge for those who design catalysts.

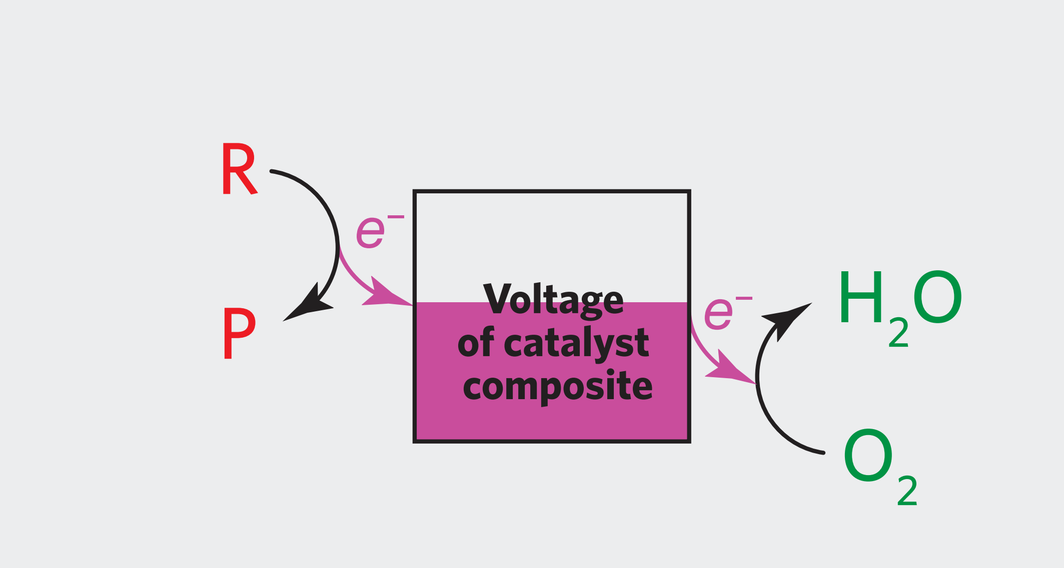
For nearly a decade, Yogesh Surendranath, an associate professor of chemistry, has been focusing on chemical reactions between solid catalysts and liquids but in a different situation: Rather than using heat to drive reactions, he and his team input electricity from a battery or a renewable source such as wind or solar to give chemically inactive molecules more energy so they react. And key to their research is designing and fabricating solid catalysts that work well for reactions involving liquids.

Recognizing the need to use biomass to develop sustainable liquid fuels, Surendranath wondered whether he and his team could take the principles they have learned about designing catalysts to drive liquid-solid reactions with electricity and apply them to reactions that occur at liquid-solid interfaces without any input of electricity.

To their surprise, they found that their knowledge is directly relevant. Why? "What we found—amazingly—is that even when you don't hook up wires to your catalyst, there are tiny internal 'wires' that do the reaction," says Surendranath. "So, reactions that people generally think operate without any flow of current actually do involve electrons shuttling from one place to another." And that means that Surendranath and his team can bring the powerful techniques of electrochemistry to bear on the problem of designing catalysts for sustainable fuels.

A novel hypothesis

Their work has focused on a class of chemical reactions important in the energy transition that involve adding oxygen to small organic (carbon-containing) molecules such as ethanol, methanol, and formic acid. The chemical equation summarizing such reactions appears in the box above. Here, the reactant, R (one of those small molecules), and oxygen, O_2, react together to form the product, P, plus water, H_2O.



Pairing up catalysts to maximize the rate of chemical conversion
In this diagram, the two “hidden” half-reactions responsible for the observed catalysis are depicted on opposite sides of a box in which the voltage level of the catalyst composite (the catalysts plus the carbon substrate) is indicated as pink. The conversion of reactant to product is on the left, and the conversion of oxygen to water is on the right. With a well-matched pair of catalysts, the reaction at the left will release electrons at the same rate as the reaction at the right picks them up, and the voltage will be constant. The goal is for that matching to occur when both reaction rates are high.

The conventional approach would consider the reaction in just that way—the reactant plus oxygen chemically react to form the product plus water. And a solid catalyst—often a combination of metals—would be present to provide sites on which the reactant and oxygen can interact.

But Surendranath proposed a different view, as shown in the schematic on page 15. Two catalysts are represented, each one composed of many nanoparticles. (The catalyst materials can be combined into a composite with separate reaction sites, but they are shown here as separate entities for clarity.) The catalysts are mounted on a conductive carbon substrate (shown in black) and submerged in water (blue). Negatively charged electrons (e^-) can flow easily through the carbon, while positively charged protons (H^+) can flow easily through water.

Surendranath’s hypothesis was that the conversion of reactant to product progresses by means of two separate “half-reactions” on the two catalysts. As shown in the schematic, on the left-hand catalyst, the reactant (R) turns into a product (P), in the process sending electrons into the carbon substrate and protons into the water. On the right-hand catalyst, electrons and protons are picked up and drive the oxygen-to-water conversion. So, instead of a single reaction, two separate but coordinated half-reactions together achieve the net conversion of reactant to product.

As a result, the overall reaction doesn’t actually involve any net electron production or consumption. It is a standard “thermal” reaction resulting from the energy in the molecules and maybe some added heat. The conventional approach to designing a catalyst for such a reaction would focus on increasing the rate of that reactant-to-product conversion. And the best catalyst for that kind of reaction could turn out to be, say, gold or palladium or some other expensive precious metal.

However, if that reaction actually involves two half-reactions, as Surendranath proposed, there is a flow of electrical charge (the electrons and protons) between them. So Surendranath and others in the field could instead use techniques of electrochemistry to design not a single catalyst for the overall reaction but rather two separate catalysts—one to speed up one half-reaction and one to speed up the other half-reaction. “That means we don’t have to design one catalyst to do all the heavy lifting of speeding up the entire reaction,” says Surendranath. “We might be able to pair up two low-cost, earth-abundant catalysts, each of which does half of the reaction well, and together they carry out the overall transformation quickly and efficiently.”

But there’s one more consideration: Electrons can flow through the entire catalyst composite, which encompasses the catalyst particle(s) and the carbon substrate. For the chemical conversion to happen as quickly as possible, the rate at which electrons are put into the catalyst composite must exactly match the rate at which they are taken out. The drawing on this page illustrates the concept. Focusing just on the electrons, if the reaction-to-product conversion at the left sends the same number of electrons per second into the “bath of electrons” in the catalyst composite as the oxygen-to-water conversion at the right takes out, the two half-reactions will be balanced, and the electron flow—and the rate of the combined reaction—will be fast. The trick is to find good catalysts for each of the half-reactions that are perfectly matched in terms of electrons in and electrons out.

“A good catalyst or pair of catalysts can maintain an electrical potential—essentially a voltage—at which both half-reactions are fast and are balanced,” says Jaeyune Ryu PhD ’21, a former member of the Surendranath lab and lead author of the study; Ryu is now a postdoc at Harvard University. “The rates of the reactions are equal, and the voltage in the catalyst composite won’t change during the overall thermal reaction.”

Drawing on electrochemistry

Based on their new understanding, Surendranath, Ryu, and their colleagues turned to electrochemistry techniques to identify a good catalyst for each half-reaction that would also pair up to work well together. Their analytical framework for guiding catalyst development for systems that combine two half-reactions is based on a theory that has been used to understand corrosion for almost 100 years, but has rarely been applied to understand or design catalysts for reactions involving small molecules important for the energy transition.

Key to their work is a potentiostat, a type of voltmeter that can either passively measure the voltage of a system or actively change the voltage to cause a reaction to occur. In their experiments, Surendranath and his team use the potentiostat to measure the voltage of the catalyst in real time, monitoring how it changes millisecond to millisecond. They then correlate those voltage measurements with simultaneous but separate measurements of the overall rate of catalysis to understand the reaction pathway.

For their study of the conversion of small, energy-related molecules, they first tested a series of catalysts to find good ones for each half-reaction—one to convert the reactant to product, producing electrons and protons, and another to convert the oxygen to water, consuming electrons and protons. In each case, a promising candidate would yield a rapid reaction, that is, a fast flow of electrons and protons out or in.

To help identify an effective catalyst for performing the first half-reaction, the researchers used their potentiostat to input carefully controlled voltages and measured the resulting current that flowed through the catalyst. A good catalyst will generate lots of current for little applied voltage; a poor catalyst will require high applied voltage to get the same amount of current. The team then followed the same procedure to identify a good catalyst for the second half-reaction.

To expedite the overall reaction, the researchers needed to find two catalysts that matched well—where the amount of current at a given applied voltage was high for each of them, ensuring that as one produced a rapid flow of electrons and protons, the other one consumed them at the same rate.

To test promising pairs, the researchers used the potentiostat to measure the voltage of the catalyst composite during net catalysis—not changing the voltage as before but now just measuring it from tiny samples. In each test, the voltage will naturally settle at a certain level, and the goal is for that to happen when the rate of both reactions is high.

Validating their hypothesis and looking ahead

By testing the two half-reactions, the researchers could measure how the reaction rate for each one varied with changes in the applied voltage. From those measurements, they could predict the voltage at which the full reaction would proceed fastest. Measurements of the full reaction matched their predictions, supporting their hypothesis.

The team's novel approach of using electrochemistry techniques to examine reactions thought to be strictly thermal in nature provides new insights into the detailed steps by which those reactions occur and therefore into how to design catalysts to speed them up. "We can now use a divide-and-conquer strategy," says Ryu. "We know that the net thermal reaction in our study happens through two 'hidden' but coupled half-reactions, so we can aim to optimize one half-reaction at a time"—possibly using low-cost catalyst materials for one or both.

Adds Surendranath, "One of the things that we're excited about in this study is that the result is not final in and of itself. It has really seeded a brand-new thrust area in our research program, including new ways to design catalysts for the production and transformation of renewable fuels and chemicals."

NOTES

This research was supported primarily by the Air Force Office of Scientific Research. Jaeyune Ryu PhD '21 was supported by a Samsung Scholarship. Additional support was provided by a National Science Foundation Graduate Research Fellowship. More information about this research can be found in:

J. Ryu, D.T. Bregante, W.C. Howland, R.P. Bisbey, C.J. Kaminsky, and Y. Surendranath. "Thermochemical aerobic oxidation catalysis in water can be analysed as two coupled electrochemical half-reactions." *Nature Catalysis*, September 6, 2021. Online: doi.org/10.1038/s41929-021-00666-2.

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

The MIT Energy Initiative (MITEI) has awarded seven Seed Fund grants to support novel, early-stage energy research by faculty and researchers at MIT. The awardees hail from a range of disciplines, but all strive to use their backgrounds and expertise to address the global climate crisis by improving the efficiency, scalability, and adoption of clean energy technologies.

"Solving climate change is truly an interdisciplinary challenge," says MITEI Director Robert C. Armstrong. "The Seed Fund grants foster collaboration and innovation from across all five of MIT's schools and one college, encouraging an 'all hands on deck' approach to developing the energy solutions that will prove critical in combatting this global crisis."

This year, MITEI's Seed Fund grant program received 70 proposals from 86 different principal investigators (PIs) across 25 departments, labs, and centers. Of these proposals, 31 involved collaborations between two or more PIs, including 24 that involved multiple departments.

The winning projects reflect this collaborative nature with topics addressing the optimization of low-energy thermal cooling in buildings; the design of safe, robust, and resilient distributed power systems; and the design and siting of wind farms with consideration of wind resource uncertainty due to climate change. The complete list of winning projects appears on page 19.

Increasing public support for low-carbon technologies

One winning team aims to leverage work done in the behavioral sciences to motivate sustainable behaviors and promote the adoption of clean energy technologies.

"Objections to scalable low-carbon technologies such as nuclear energy and

One of the seven novel energy research projects to win an MIT Energy Initiative Seed Fund award will develop a siting and design methodology that can enable a more accurate risk analysis of wind farm development and energy grid expansion under climate change-driven energy resource uncertainty. Image: Thomas Richter on Unsplash carbon sequestration have made it difficult to adopt these technologies and reduce greenhouse gas emissions," says Howard Herzog, a senior research engineer at MITEI and co-PI. "These objections tend to neglect the sheer scale of energy generation required and the inability to meet this demand solely with other renewable energy technologies."

This interdisciplinary team—which includes researchers from MITEI, the Department of Nuclear Science and Engineering, and the MIT Sloan School of Management—plans to convene industry professionals and academics, as well as behavioral scientists, to identify common objections, design messaging to overcome them, and prove that these messaging campaigns have long-lasting impacts on attitudes toward scalable low-carbon technologies.

"Our aim is to provide a foundation for shifting the public and policy makers' views about these low-carbon technologies from something they, at best, tolerate, to something they actually welcome," says co-PI David Rand, the Erwin H. Schell Professor and professor of management science and brain and cognitive sciences at MIT.

Siting and designing wind farms

Michael Howland, an assistant professor of civil and environmental engineering, will use his Seed Fund grant to develop a foundational methodology for wind farm siting and design that accounts for the uncertainty of wind resources resulting from climate change.

"The optimal wind farm design and its resulting cost of energy is inherently dependent on the wind resource at the location of the farm," says Howland. "But wind farms are currently sited and designed based on short-term climate records that do not account for the future effects of climate change on wind patterns."

Wind farms are capital-intensive infrastructure that cannot be relocated and often have lifespans exceeding 20 years—making it especially important that developers choose the right locations and designs based not only on wind patterns in the historical climate record, but also on future predictions. The new siting and design methodology has the potential to replace current industry standards to enable a more accurate risk analysis of wind farm development and energy grid expansion under climate change-driven energy resource uncertainty.

Membraneless electrolyzers for hydrogen production

Producing hydrogen from renewable energy-powered water electrolyzers is central to realizing a sustainable and low-carbon hydrogen economy, says Kripa Varanasi, a professor of mechanical engineering and a Seed Fund award recipient. The idea of using hydrogen as a fuel has existed for decades, but it has yet to be widely realized at a considerable scale. Varanasi hopes to change that with his Seed Fund grant.

"The critical economic hurdle for successful electrolyzers to overcome is the minimization of the capital costs associated with their deployment," says Varanasi. "So, an immediate task at hand to enable electrochemical hydrogen production at scale will be to maximize the effectiveness of the most mature, least complex, and least expensive water electrolyzer technologies."

To do this, he aims to combine the advantages of existing low-temperature alkaline electrolyzer designs with a novel membraneless electrolyzer technology that harnesses a gas management system architecture to minimize complexity and costs while also improving efficiency. Varanasi hopes his project will demonstrate scalable concepts for cost-effective electrolyzer technology design to help realize a decarbonized hydrogen economy.

Since its establishment in 2008, the MITEI Seed Fund Program has supported 193 energy-focused seed projects through grants totaling more than $26 million. This funding comes primarily from MITEI's Founding and Sustaining members, supplemented by gifts from generous donors.

Kelley Travers, MITEI

Recipients of the 2021 MITEI Seed Fund grants

Design automation of safe, robust, and resilient distributed power systems
Chuchu Fan
Department of Aeronautics and Astronautics

Advanced MHD topping cycles—for fission, fusion, and solar power plants
Jeffrey Freidberg
Department of Nuclear Science and Engineering
Dennis Whyte
Plasma Science and Fusion Center

Robust wind farm siting and design under climate change-driven wind resource uncertainty
Michael Howland
Department of Civil and Environmental Engineering

Low-energy thermal comfort for buildings in the Global South: Optimal design of integrated structural-thermal systems
Leslie Norford
Department of Architecture
Caitlin Mueller
Departments of Architecture and Civil and Environmental Engineering

New low-cost, high energy-density boron-based redox electrolytes for nonaqueous flow batteries
Alexander Radosevich
Department of Chemistry

Increasing public support for scalable low-carbon energy technologies using behavioral science insights
David Rand
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MIT-designed project achieves major advance toward fusion energy

It was a moment three years in the making, based on intensive research and design work: On September 5, 2021, for the first time, a large high-temperature superconducting electromagnet was ramped up to a field strength of 20 tesla, the most powerful magnetic field of its kind ever created on Earth. That successful demonstration helps resolve the greatest uncertainty in the quest to build the world's first fusion power plant that can produce more power than it consumes, according to the project's leaders at MIT and startup company Commonwealth Fusion Systems (CFS).

That advance paves the way, they say, for the long-sought creation of practical, inexpensive, carbon-free power plants that could make a major contribution to limiting the effects of global climate change.

"Fusion in a lot of ways is the ultimate clean energy source," says Maria Zuber, MIT's vice president for research and E.A. Griswold Professor of Geophysics. "The amount of power that is available is really game-changing." The fuel used to create fusion energy comes from water, and "the Earth is full of water—it's a nearly unlimited resource. We just have to figure out how to utilize it."

Developing the new magnet is seen as the greatest technological hurdle to making that happen; its successful operation now opens the door to demonstrating fusion in a lab on Earth, which has been pursued for decades with limited progress. With the magnet technology now successfully demonstrated, the MIT-CFS collaboration is on track to build the world's first fusion device that can create and confine a plasma that produces more energy than it consumes. That demonstration device, called SPARC, is targeted for completion in 2025.

"The challenges of making fusion happen are both technical and scientific," says Dennis Whyte, director of MIT's Plasma Science and Fusion Center (PSFC), which is working with CFS to develop SPARC. But once the technology is proven, he says, "it's an inexhaustible, carbon-free source of energy that you can deploy anywhere and at any time. It's really a fundamentally new energy source."

Whyte, who is the Hitachi America Professor of Engineering, says this demonstration represents a major milestone, addressing the biggest questions remaining about the feasibility of the SPARC design. "It's really a watershed moment, I believe, in fusion science and technology," he says.

The sun in a bottle

Fusion is the process that powers the sun: the merger of two small atoms to make a larger one, releasing prodigious amounts of energy. But the process requires temperatures far beyond what any solid material could withstand. To capture the sun's power source here on Earth, what's needed is a way of capturing and containing something that hot—100,000,000 degrees or more—by suspending it in a way that prevents it from coming into contact with anything solid.

That's done through intense magnetic fields, which form a kind of invisible

A collaborative team works on the magnet inside the test stand housed at MIT. Research, construction, and testing of this magnet has been the single largest activity for the SPARC team, which has grown to include 270 members. Photo: Gretchen Ertl, CFS/MIT-PSFC, 2021

MITEI's role facilitating important research collaborations

On September 5, 2021, project leaders from MIT's Plasma Science and Fusion Center (PSFC) and MIT spinoff Commonwealth Fusion Systems (CFS) experienced what PSFC Director Dennis Whyte called "a Kitty Hawk moment": the successful demonstration of a high-temperature superconducting electromagnet producing a record magnetic field strength. This milestone brings the world a major step closer to the commercialization of practical, inexpensive, carbon-free fusion power that could significantly advance the transition toward a clean energy future.

The MIT Energy Initiative (MITEI) is proud to have played a seminal role in bringing the players together to allow this remarkable advance toward fusion energy. In 2016, Whyte and Professor Anne E. White, head of the Department of Nuclear Science and Engineering, presented the ideas behind these advances to the MITEI External Advisory Board. The discussions at that meeting (and many more) ultimately led MITEI Founding Member Eni to sponsor significant fundamental fusion research at the PSFC and to become an early investor in CFS, spurring other investors to support the startup. CFS joined MITEI as its first Startup Member.

CFS is now racing to take this technology and the data from the test to produce carbon-free fusion power plants that can be deployed around the world. In the next three years, CFS plans to use the new magnet technology to demonstrate the first net-power-out fusion reactor. Then, over the next 10 years, it plans to construct the first full-scale fusion power plant to feed energy into the grid.

bottle to contain the hot swirling soup of protons and electrons, called a plasma. Because the particles have an electric charge, they are strongly controlled by the magnetic fields, and the most widely used configuration for containing them is a donut-shaped device called a tokamak. Most of these devices have produced their magnetic fields using conventional electromagnets made of copper, but the latest and largest version under construction in France, called ITER, uses what are known as low-temperature superconductors.

The major innovation in the MIT-CFS fusion design is the use of high-temperature superconductors, which enable a much stronger magnetic field in a smaller space. This design was made possible by a new kind of superconducting material that became commercially available a few years ago. The idea initially arose as a class project in a nuclear engineering class taught by Whyte. The idea seemed so promising that it continued to be developed over the next few iterations of that class, leading to the ARC power plant design concept in early 2015. SPARC, designed to be about half the size of ARC, is a testbed to prove the concept before construction of the full-size, power-producing plant.

Until now, the only way to achieve the colossally powerful magnetic fields needed to create a magnetic "bottle" capable of containing plasma heated up to hundreds of millions of degrees was to make them larger and larger. But the new high-temperature superconductor material, made in the form of a flat, ribbon-like tape, makes it possible to achieve a higher magnetic field in a smaller device, equaling the performance that would be achieved in an apparatus 40 times larger in volume using conventional low-temperature superconducting magnets. That leap in power versus size is the key element in ARC's revolutionary design.

The use of the new high-temperature superconducting magnets makes it possible to apply decades of experimental knowledge gained from the operation of tokamak experiments, including MIT's own Alcator series. The new approach, led by Zach Hartwig, the MIT principal investigator and the Robert N. Noyce Career Development Assistant Professor of Nuclear Science and Engineering, uses a well-known design but scales everything down to about half the linear size and still achieves the same operational conditions because of the higher magnetic field.

A series of scientific papers published last year outlined the physical basis and, by simulation, confirmed the viability of the new fusion device (news.mit.edu/2020/physics-fusion-studies-0929). The papers showed that, if the magnets worked as expected, the whole fusion system should indeed produce net power output, for the first time in decades of fusion research.

Martin Greenwald, deputy director and senior research scientist at the PSFC, says unlike some other designs for fusion experiments, "the niche that we were filling was to use conventional plasma physics, and conventional tokamak designs and engineering, but bring to it this new magnet technology. So, we weren't requiring innovation in a half-dozen different areas. We would just innovate on the magnet, and then apply the knowledge base of what's been learned over the last decades."

That combination of scientifically established design principles and game-changing magnetic field strength is what makes it possible to achieve a plant that could be economically viable and developed on a fast track. "It's a big moment," says Bob Mumgaard, CEO of CFS. "We now have a platform that is both scientifically very well-advanced, because of the decades of research on these machines, and also commercially very interesting. What it does is allow us to build devices faster, smaller, and at less cost," he says of the successful magnet demonstration.

Proof of the concept

Bringing that new magnet concept to reality required three years of intensive work on design, establishing supply chains, and working out manufacturing methods for magnets that may eventually need to be produced by the thousands.

"We built a first-of-a-kind, superconducting magnet. It required a lot of work to create unique manufacturing processes and equipment. As a result, we are now well-prepared to ramp up for SPARC production," says Joy Dunn, head of operations at CFS. "We started with a physics model and a CAD design, and worked through lots of development and prototypes to turn a design on paper into this actual physical magnet." That entailed building manufacturing capabilities and testing facilities, including an iterative process with multiple suppliers of the superconducting tape, to help them reach the ability to produce material that met the needed specifications—and for which CFS is now overwhelmingly the world's biggest user.

They worked with two possible magnet designs in parallel, both of which ended up meeting the design requirements, she says. "It really came down to which one would revolutionize the way that we make superconducting magnets, and which one was easier to build." The design they adopted clearly stood out in that regard, she says.

In this test, the new magnet was gradually powered up in a series of steps until reaching the goal of a 20-tesla magnetic field—the highest field strength ever for a high-temperature superconducting fusion magnet. The magnet is composed of 16 plates stacked together, each one of which by itself would be the most powerful high-temperature superconducting magnet in the world.

"Three years ago we announced a plan," says Mumgaard, "to build a 20-tesla magnet, which is what we will need for future fusion machines." That goal has now been achieved, right on schedule, even with the pandemic, he says.

Citing the series of physics papers published last year, Brandon Sorbom, the chief science officer at CFS, says "basically the papers conclude that if we build the magnet, all of the physics will work in SPARC. So, this demonstration answers the question: Can they build the magnet? It's a very exciting time! It's a huge milestone."

The next step will be building SPARC, a smaller-scale version of the planned ARC power plant. The successful operation of

SPARC will demonstrate that a full-scale commercial fusion power plant is practical, clearing the way for the rapid design and construction of that pioneering device to proceed at full speed.

Zuber says that "I now am genuinely optimistic that SPARC can achieve net positive energy, based on the demonstrated performance of the magnets. The next step is to scale up, to build an actual power plant. There are still many challenges ahead, not the least of which is developing a design that allows for reliable, sustained operation. And realizing that the goal here is commercialization, another major challenge will be economic. How do you design these power plants so it will be cost-effective to build and deploy them?"

Someday in a hoped-for future, when there may be thousands of fusion plants powering clean electric grids around the world, Zuber says, "I think we're going to look back and think about how we got there, and I think the demonstration of the magnet technology, for me, is the time when I believed that, wow, we can really do this."

The successful creation of a power-producing fusion device would be a tremendous scientific achievement, Zuber notes. But that's not the main point. "None of us are trying to win trophies at this point. We're trying to keep the planet livable."

David L. Chandler, MIT News Office

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A team of engineers and scientists from CFS and MIT's PSFC lower the superconducting magnet into the test stand in which the magnet was cooled and powered to produce a magnetic field of 20 tesla. Photo: Gretchen Ertl, CFS/MIT-PSFC, 2021

Making the case for hydrogen in a zero-carbon economy: Hydrogen-generated electricity for backing up wind and solar

As the United States races to achieve its goal of zero-carbon electricity generation by 2035, energy providers are swiftly ramping up renewable resources such as solar and wind. But because these technologies churn out electrons only when the sun shines or the wind blows, they need backup from other energy sources, especially during seasons of high electric demand. Currently, plants burning fossil fuels, primarily natural gas, fill in the gaps.

"As we move to more and more renewable penetration, this intermittency will make a greater impact on the electric power system," says Emre Gençer, a research scientist at the MIT Energy Initiative (MITEI). That's because grid operators will increasingly resort to fossil-fuel-based "peaker" plants that compensate for the intermittency of the variable renewable energy (VRE) sources, sun and wind. "If we're to achieve zero-carbon electricity, we must replace all greenhouse gas-emitting sources," Gençer says.

Low- and zero-carbon alternatives to greenhouse gas-emitting peaker plants are in development, such as arrays of lithium-ion batteries and hydrogen power generation. But each of these evolving technologies comes with its own set of advantages and constraints, and it has proven difficult to frame the debate about these options in a way that's useful for policy makers, investors, and utilities engaged in the clean energy transition.

Now, Gençer and Drake D. Hernandez SM '21 have come up with a model that makes it possible to pin down the pros and cons of these peaker-plant alternatives with greater precision. Their hybrid technological and economic analysis, based on a detailed inventory of California's power system, was published in the July 6, 2021, online edition of *Applied Energy* (with an October 2021 print publication date). While their work focuses on the most cost-effective solutions for replacing peaker power plants, it also contains insights intended to contribute to the larger conversation about transforming energy systems.

"Our study's essential takeaway is that hydrogen-fired power generation can be the more economical option when compared to lithium-ion batteries—even today, when the costs of hydrogen production, transmission, and storage are very high," says Hernandez, who worked on the study while a graduate research assistant for MITEI. Adds Gençer, "If there is a place for hydrogen in the cases we analyzed, that suggests there is a promising role for hydrogen to play in the energy transition."

Adding up the costs

California serves as a stellar paradigm for a swiftly shifting power system. The state draws more than 20% of its electricity from solar and approximately 7% from wind, with more VRE coming online rapidly. This means its peaker plants already play a pivotal role, coming online each evening when the sun goes down or when events such as heat waves drive up electricity use for days at a time.

"We looked at all the peaker plants in California," recounts Gençer. "We wanted to know the cost of electricity if we replaced them with hydrogen-fired turbines or with lithium-ion batteries." The researchers used a core metric called the levelized cost of electricity (LCOE) as a way of comparing the costs of different technologies to each other. The LCOE measures the average total cost of building and operating a particular energy-generating asset per unit of total electricity generated over the hypothetical lifetime of that asset.

Selecting 2019 as their base study year, the researchers looked at the costs of running natural gas-fired peaker plants, which they defined as plants operating 15% of the year in response to gaps in intermittent renewable electricity. In addition, they determined the amount of carbon dioxide released by these plants and the expense of abating these emissions. Much of this information was publicly available.

Coming up with prices for replacing peaker plants with massive arrays of lithium-ion batteries was also relatively straightforward: "There are no technical limitations to lithium-ion, so you can build as many as you want; but they are super expensive in terms of their footprint for energy storage and the mining required to manufacture them," says Gençer.

But then came the hard part: nailing down the costs of hydrogen-fired electricity generation. "The most difficult thing is finding cost assumptions for new technologies," says Hernandez. "You can't do this through a literature review, so we had many conversations with equipment manufacturers and plant operators."

The team considered two forms of hydrogen fuel to replace natural gas, one produced through electrolyzer facilities that convert water and electricity into hydrogen, and another that reforms natural gas, yielding hydrogen and carbon waste that can be captured to reduce emissions. They also ran the numbers on retrofitting natural gas plants to burn hydrogen as opposed to building entirely new facilities. Their model includes both the identification of likely locations throughout the state and the expenses involved in construction of these facilities.

The researchers spent months compiling a giant data set before setting out on the task of analysis. The results from their modeling were clear: "Hydrogen can be a more cost-effective alternative to lithium-ion batteries for peaking operations on a power grid," says Hernandez. In addition, notes Gençer, "While certain technologies worked better in particular locations, we found that on average, reforming hydrogen rather than electrolytic hydrogen turned out to be the cheapest option for replacing peaker plants."

A tool for energy investors

When he began this project, Gençer admits he "wasn't hopeful" about hydrogen replacing natural gas in peaker plants. "It was kind of shocking to see in our different scenarios that there was a place for hydrogen." That's because the overall price tag for converting a fossil fuel-based plant to one based on hydrogen is very high, and such conversions likely won't take place until more sectors of the economy embrace hydrogen, whether as a fuel for transportation or for varied manufacturing and industrial purposes.

A nascent hydrogen production infrastructure does exist, mainly in the production of ammonia for fertilizer. But enormous investments will be necessary to expand this framework to meet grid-scale needs, driven by purposeful incentives. "With any of the climate solutions proposed today, we will need a carbon tax or carbon pricing; otherwise nobody will switch to new technologies," says Gençer.

The researchers believe studies like theirs could help key energy stakeholders make better-informed decisions. To that end, they have integrated their analysis into SESAME, a lifecycle and techno-economic assessment tool for a range of energy systems that was developed by MIT researchers. Users can leverage this sophisticated modeling environment to compare costs of energy storage and emissions from different technologies, for instance, or to determine whether it is cost-efficient to replace a natural gas-powered plant with one powered by hydrogen.

"As utilities, industry, and investors look to decarbonize and achieve zero-emissions targets, they have to weigh the costs of investing in low-carbon technologies today against the potential impacts of climate change moving forward," says Hernandez, who is currently a senior associate in the energy practice at Charles River Associates. Hydrogen, he believes, will become increasingly cost-competitive as its production costs decline and markets expand.

A study group member of MITEI's soon-to-be published Future of Energy Storage study, Gençer knows that hydrogen alone will not usher in a zero-carbon future. But, he says, "Our research shows we need to seriously consider hydrogen in the energy transition, start thinking about key areas where hydrogen should be used, and start making the massive investments necessary."

Funding for this research was provided by MITEI's Low-Carbon Energy Centers and Future of Energy Storage study.

Leda Zimmerman, MITEI correspondent

MIT study provides suggestions for keeping classroom air fresh during Covid-19 pandemic

Open windows and a good heating, ventilation, and air conditioning (HVAC) system are starting points for keeping classrooms safe during the Covid-19 pandemic. But they are not the last word, according to a new study from researchers at MIT.

The study shows how specific classroom configurations may affect air quality and necessitate additional measures, beyond HVAC use or open windows, to reduce the spread of aerosols—those tiny, potentially Covid-carrying particles that can stay suspended in the air for hours.

"There are sets of conditions where we found clearly there's a problem, and when you look at the predicted concentration of aerosols around other people in the room, in some cases it was much higher than what the [standard] models would say," says Leon Glicksman, an MIT architecture and engineering professor who is co-author of a new paper detailing the research.

Indeed, the study shows that some circumstances can create a concentration of potentially problematic aerosols ranging from 50% to 150% higher than the standard baseline concentration that experts regard as "well-mixed" indoor air.

"It gets complicated, and it depends on the particular conditions of the room," Glicksman adds.

The paper, "Patterns of SARS-CoV-2 aerosol spread in typical classrooms," appeared on July 21, 2021, in advance online form in the journal *Building and Environment* and on October 15, 2021, in the same journal. The authors are Gerhard K. Rencken and Emma K. Rutherford, MIT undergraduates who participated in the research through the Undergraduate Research Opportunities Program with support from the MIT Energy Initiative; Nikhilesh Ghanta, a graduate student at MIT's Center for Computational Science and Engineering; John Kongoletos, a graduate student in the Building Technology Program at MIT and a fellow at MIT's Tata Center; and Glicksman, the senior author and a professor of building technology and mechanical engineering at MIT who has been studying air circulation issues for decades.

Regular ventilation may not be enough to prevent the spread of Covid-19; MIT research examines classroom configurations and suggests modifications to enhance safety. Image: MIT News

The battle between vertical and horizontal

SARS-CoV-2, the virus that causes Covid-19, is transmitted in airborne fashion via aerosols, which people exhale, and which can remain in the air for long periods of time if a room is not well-ventilated. Many indoor settings with limited air flow, including classrooms, could thus contain a relatively higher concentration of aerosols, including those exhaled by infected individuals. HVAC systems and open windows can help create "well-mixed" conditions, but in certain scenarios, additional ventilation methods may be needed to minimize SARS-CoV-2 aerosols.

To conduct the study, the researchers used computational fluid dynamics—sophisticated simulations of air flow—to examine 14 different classroom ventilation scenarios, nine involving HVAC systems and five involving open windows. The research team also compared their modeling to past experimental results.

One ideal scenario involves fresh air entering a classroom near ground level and moving steadily higher, until it exits the room through ceiling vents—termed displacement ventilation. This process is aided by the fact that hot air rises, and people's body warmth naturally generates rising "heat plumes," which carry air toward ceiling vents, at the rate of about 0.15 meters per second.

Given ceiling ventilation, then, the aim is to create upward vertical air movement to cycle air out of the room, while limiting horizontal air movement, which spreads aerosols among seated students.

This is why wearing masks indoors makes sense: Masks limit the horizontal speed of exhaled aerosols, keeping those particles near heat plumes so the aerosols rise vertically, as the researchers observed in their simulations. Normal exhaling creates aerosol speeds of 1 meter per second, and coughing creates still higher speeds—but masks keep that speed low.

"If you wear well-fitting masks, you suppress the velocity of the [breath] exhaust to the point where the air that comes out is carried by the plumes above the individuals," Glicksman says. "If it's a loose-fitting mask or no mask at all, the air comes out at a high enough horizontal velocity that it does not get captured by these rising plumes, and rises at much lower rates, remaining in the breathing zone."

Two problematic scenarios

But even so, the researchers found, complications can emerge. In their set of simulations focused on closed windows and HVAC use, airflow problems emerged in a simulated classroom in winter, with cold windows on the side. In this case, because the cold air near the windows naturally sinks, it disrupts the overall upward flow of classroom air, despite people's heat plumes.

"Because of the cold air from the window, some air moves down," Glicksman says. "What we found in the simulations is, yes, a masked person's heat plume would rise toward the ceiling, but if a person is close to the window, the aerosols get up to the ceiling and in some cases get captured by that downward flow and brought down to the breathing level in the room. And we found the colder the window is, the larger this problem is."

In this scenario, someone infected with Covid-19 sitting near a window would be particularly likely to spread their aerosols around. But there are fixes for this problem: Among other things, placing heaters near cold windows limits their impact on classroom airflow.

In the other set of simulations, involving open windows, additional issues became evident. While open windows are good for fresh air flow overall, the researchers did identify one problematic scenario: Horizontal air movement from open windows aligned with seating rows creates significant aerosol spread.

The researchers suggest a simple fix for this problem: installing window baffles, fittings that can be set to deflect the air downward. By doing this, the cooler fresh air from outside will enter the classroom near the feet of its occupants and help generate a better overall circulation pattern.

"The advantage is, you bring the clean air in from outside to the floor, and then [by using baffles] you have something that starts to look like displacement ventilation, where again the warm air from individuals will draw the air upward, and it will move toward the ceiling," Glicksman says. "And again that's what we found when we did the simulations; the concentration of aerosol was much lower in those cases than if you just allow the air to come in directly horizontally."

Alejandra Menchaca PhD '12, a vice president and expert in building science and ventilation at the engineering consulting firm Thornton Thomasetti, calls the research a useful step forward. The paper "provides critical new insight into an aspect of indoor airflow exhaled aerosol dispersal," says Menchaca, who was not involved in the research. "I hope the [building] industry is able to use these results to enhance its understanding of aerosol dispersal and key variables—many ignored until now—that influence it."

The energy penalty

In addition to the safety implications during the pandemic, Glicksman notes that better air flow in all classrooms has energy and environmental consequences.

If an HVAC system alone is not creating optimal conditions inside a classroom, the temptation might be to crank up the system full blast in hopes of creating greater flow. But that is both expensive and environmentally taxing. An alternate approach is to look for classroom-specific solutions—like baffles or the use of high-efficiency filters in the recirculating HVAC air supply.

"The more outside air you bring in, the lower the average concentration of these aerosols will be," Glicksman says. "But there's an energy penalty associated with it."

Glicksman also emphasizes that the current study examines air quality under specific circumstances. The research also took place before the more transmissible Delta variant of the Covid-19 virus became prevalent. This development, Glicksman observes, reinforces the importance of "reducing the aerosol concentration level through masking and higher ventilation rates" throughout a given classroom, and especially underscores that "the local concentration in the breathing zone [near the heads of room occupants] should be minimized."

And Glicksman emphasizes that it would be useful to have more studies exploring the issues in depth.

"What we've done is a limited study for particular forms of geometry in the classroom," Glicksman says. "It depends to some extent on what the particular conditions are. There is no one simple recipe for better airflow. What this really says is that we would like to see more research done."

Peter Dizikes, MIT News Office

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Coupling power and hydrogen sector pathways to benefit decarbonization goals

Governments and companies worldwide are increasing their investments in hydrogen research and development, indicating a growing recognition that hydrogen could play a significant role in meeting global energy system decarbonization goals. Since hydrogen is light, energy-dense, storable, and produces no direct carbon dioxide emissions at the point of use, this versatile energy carrier has the potential to be harnessed in a variety of ways in a future clean energy system.

Often considered in the context of grid-scale energy storage, hydrogen has garnered renewed interest in part due to expectations that our future electric grid will be dominated by variable renewable energy (VRE) sources such as wind and solar, as well as decreasing costs for water electrolyzers—both of which could make clean, "green" hydrogen more cost-competitive with fossil-fuel-based production. But hydrogen's versatility as a clean energy fuel also makes it an attractive option to meet energy demand and to open pathways for decarbonization in hard-to-abate sectors where direct electrification is difficult, such as transportation, buildings, and industry.

"We've seen a lot of progress and analysis around pathways to decarbonize electricity, but we may not be able to electrify all end uses. This means that just decarbonizing electricity supply is not sufficient, and we must develop other decarbonization strategies as well," says Dharik Mallapragada, a research scientist at the MIT Energy Initiative (MITEI). "Hydrogen is an interesting energy carrier to explore, but understanding the role for hydrogen requires us to study the interactions between the electricity system and a future hydrogen supply chain."

In a paper published in *Energy & Environmental Science* in August 2021, researchers from MIT and Shell present a framework to systematically study the role and impact of hydrogen-based technology pathways in a future low-carbon, integrated energy system, taking into account interactions with the electric grid and the spatio-temporal variations in energy demand and supply. The developed framework co-optimizes infrastructure investment and operation across the electricity and hydrogen supply chain under various emissions price scenarios. When applied to a Northeast U.S. case study, the researchers find this approach results in substantial benefits—in terms of costs and emissions reduction—as it takes advantage of hydrogen's potential to provide the electricity system with a large flexible load when produced through electrolysis, while also enabling decarbonization of difficult-to-electrify, end-use sectors.

The research team includes Mallapragada; Guannan He, a postdoctoral associate at MITEI; Abhishek Bose, a graduate research assistant at MITEI at the time of publication; Clara Heuberger-Austin, a researcher at Shell; and Emre Gençer, a research scientist at MITEI.

Cross-sector modeling

"We need a cross-sector framework to analyze each energy carrier's economics and role across multiple systems if we are to really understand the cost-benefits of direct electrification or other decarbonization strategies," says He.

To do that analysis, the team developed the Decision Optimization of Low-carbon Power-HYdrogen Network (DOLPHYN) model, which allows the user to study the role of hydrogen in low-carbon energy systems, the effects of coupling the power and hydrogen sectors, and the trade-offs between various technology options across both supply chains—spanning production, transport, storage, and end use, and their impact on decarbonization goals.

"We are seeing great interest from industry and government because they are all asking questions about where to invest their money and how to prioritize their decarbonization strategies," says Gençer. Heuberger-Austin adds, "Being able to assess the system-level interactions between electricity and the emerging hydrogen economy is of paramount importance to drive technology development and support strategic value chain decisions. The DOLPHYN model can be instrumental in tackling those kinds of questions."

For a predefined set of electricity and hydrogen demand scenarios, the model determines the least-cost technology mix across the power and hydrogen sectors while adhering to a variety of operation and policy constraints. The model can incorporate a range of technology options—from VRE generation, to carbon capture and storage (CCS) used with both power and hydrogen generation, to trucks and pipelines used for hydrogen transport. With its flexible structure, the model can be readily adapted to represent emerging technology options and evaluate their long-term value to the energy system.

As an important addition, the model takes into account process-level carbon emissions by allowing the user to add a cost penalty on emissions in both sectors. "If you have a limited emissions budget, we are able to explore the question of where to prioritize the limited emissions to get the best bang for your buck in terms of decarbonization," says Mallapragada.

Insights from a case study

To test their model, the researchers investigated the Northeast U.S. energy system under a variety of demand, technology, and carbon price scenarios. While their major conclusions can be generalized for other regions, the Northeast U.S. proved to be a particularly interesting case study. This region has current legislation and regulatory support

An MIT-led research team studies the role and impact of hydrogen-based technology pathways in a future low-carbon, integrated energy system and finds benefits from co-optimizing hydrogen and power supply chains. Photo: iStock.com/Scharfsinn86

for renewable generation, as well as increasing emission-reduction targets, a number of which are quite stringent. It also has a high demand for energy for heating—a sector that is difficult to electrify and could particularly benefit from hydrogen and from coupling the power and hydrogen systems.

The researchers find that when combining the power and hydrogen sectors through electrolysis or hydrogen-based power generation, there is more operational flexibility to support VRE integration in the power sector and a reduced need for alternative grid-balancing supply-side resources such as battery storage or dispatchable gas generation, which in turn reduces the overall system cost. This increased VRE penetration also leads to a reduction in emissions compared to scenarios without sector-coupling. "The flexibility that electricity-based hydrogen production provides in terms of balancing the grid is as important as the hydrogen it is going to produce for decarbonizing other end uses," says Mallapragada. The researchers found this type of grid interaction to be more favorable than conventional hydrogen-based electricity storage, which can incur additional capital costs and efficiency losses when converting hydrogen back to power. This suggests that the role of hydrogen in the grid could be more beneficial as a source of flexible demand than as storage.

The researchers' multi-sector modeling approach also highlighted that CCS is more cost-effective when utilized in the hydrogen supply chain versus the power sector. They note that counter to this observation, by the end of the decade, six times more CCS projects will be deployed in the power sector than for use in hydrogen production—a fact that emphasizes the need for more cross-sectoral modeling when planning future energy systems.

In this study, the researchers tested the robustness of their conclusions against a number of factors, such as how the inclusion of non-combustion greenhouse gas emissions (including methane emissions) from natural gas used in power and hydrogen production impacts the model outcomes. They find that including the upstream emissions footprint of natural gas within the model boundary does not impact the value of sector coupling in regards to VRE integration and cost savings for decarbonization; in fact, the value actually grows because of the increased emphasis on electricity-based hydrogen production over natural gas-based pathways.

"You cannot achieve climate targets unless you take a holistic approach," says Gençer. "This is a systems problem. There are sectors that you cannot decarbonize with electrification, and there are other sectors that you cannot decarbonize without carbon capture, and if you think about everything together, there is a synergistic solution that significantly minimizes the infrastructure costs."

This research was supported in part by Shell Global Solutions International B.V. in Amsterdam, the Netherlands, and by MITEI's Low-Carbon Energy Centers for Electric Power Systems and Carbon Capture, Utilization, and Storage. The paper, "Sector coupling *via* hydrogen to lower the cost of energy system decarbonization," appeared in *Energy & Environmental Science* and is available online at doi.org/10.1039/D1EE00627D.

Kelley Travers, MITEI

MITEI appoints Professor Christopher Knittel as deputy director for policy

Christopher Knittel has held a number of titles at MIT. Among them: Professor of Applied Economics at the Sloan School of Management … George P. Shultz Professor of Energy Economics … Director of the Center for Energy and Environmental Policy Research (CEEPR) … Co-Director of the Low-Carbon Energy Center for Electric Power Systems at the MIT Energy Initiative (MITEI). Now he adds another: Deputy Director for Policy at MITEI.

This is a new position at MITEI, MIT's hub for energy research, education, and outreach. "This is a big step for a place like MIT, which has the word 'technology' in its title," says Knittel. "The focus of solutions in a technology school like MIT is often on technology. But policy *has* to play a big role, if not a bigger role, in the solution to climate change."

In summer 2021, Christopher Knittel became the MIT Energy Initiative's deputy director for policy—a newly created role at MITEI. Knittel is the George P. Shultz Professor of Energy Economics at the MIT Sloan School of Management. Photo courtesy of Professor Knittel

Knittel assumed the policy role at MITEI in summer 2021, and he has embraced it. "What has me excited about working on policy at MITEI is to think about how all the great technologies being researched and developed at MIT might play a role in solving climate change—if the right incentive structure through policy is in place."

"As the urgency of the climate crisis grows, we need every tool at our disposal to help make the energy transition and ease the warming of our planet," says MITEI Director and Chevron Professor of Chemical Engineering Robert C. Armstrong. "Chris Knittel is such an important policy voice—who can help us craft the new and innovative climate and energy policies we need to pursue rapidly to protect our planet."

Knittel arrived at MIT in 2011 from the University of California (UC), Davis, where he was associate professor of economics. He is a product of the California state university system. He earned his BA in economics and political science from the California State University, Stanislaus; his MA in economics from UC Davis; and his PhD in economics from UC Berkeley. He maintains a strong California connection: He co-directs the E2e Project, a research initiative founded by UC Berkeley and MIT to undertake rigorous evaluation of energy efficiency investments.

A central focus of Knittel's research is carbon pricing. "Fundamentally," he says, "solving climate change and all other environmental issues is a policy problem—in that it is often free to put pollution in the air. While economists focus on pricing pollution directly, we also admit that pricing might not be the outcome of the political process. So, a lot of economics research and policy research wants to understand what those trade-offs are. How much more expensive will it be to do it through some other means, such as a clean energy standard? And, how can we design these alternatives in such a way to limit their unintended consequences? It's not my job necessarily to advocate for any policy. It's my job to tell policy makers if you do a pollution tax, this will happen. If you do policy X instead, that will happen."

Knittel sees his role as policy researcher and analyst. That doesn't mean he can't see the value in one solution over another. "Sometimes I have to catch myself," he says. "I try not to advocate for a carbon tax. I try to educate policy makers that that's necessary if we want to reduce greenhouse gases in the cheapest way possible. But I'm also happy if a policy maker comes to me and says, 'I'm thinking about this policy, but I want to understand all the trade-offs and all the advantages and disadvantages and who the winners and losers will be. Can you help me analyze that policy?' And I'm game to do that."

Knittel is not a dispassionate economist. He exudes purposeful devotion to MITEI and its mission to help the planet achieve net-zero carbon emissions. He is an advocate for diversity, equity, and inclusion in his work; for environmental justice; and for solving the world's energy poverty issues. "I worry constantly about how we're going to decarbonize and not leave people behind based on social or economic status or racial identity," he says. "How do places like India, China, and the countries of Africa decarbonize and still grow their economies? So many people don't have the luxury we do to worry about decarbonization. So many are worried about the next meal on their plate. The right solution in the U.S. might be very different from the right solution in countries with developing economies."

Knittel's concerns about equity are borne out in the body of his research. A major study in 2020, *Distributed Effects of Climate Policy: A Machine Learning Approach*, written with Tomas W. Green of the nonprofit Energy Futures Initiative, highlighted the regressivity of climate standards and articulated a pathway to allow a carbon-tax-and-dividend program to have a positive policy and climate impact without punishing the lower income groups. Knittel and Green wrote that "allowing household dividends to depend on certain readily observable features of the household allows policy makers to protect certain vulnerable populations." Knittel's policy work seeks to reduce carbon emissions, address climate change, *and* protect the incomes of families.

"Policy has always played an important role in our work at MITEI," says MITEI Executive Director Martha Broad. "Never more so than now. As local, national, and international efforts grow in urgency and scope to address climate change, the importance of well-crafted policies—to harness new energy technologies—grows as well. MITEI's new deputy director for policy—Chris Knittel—is helping us advance policies to strategically address the climate crisis."

Tom Melville, MITEI

Andy Sun announced as new Iberdrola-Avangrid Professor of Electric Power Systems at MIT Sloan

Professor Andy Sun will serve as faculty lead for the electric power system focus area and as a member of the steering committee of the MIT Energy Initiative's new Future Energy Systems Center.
Photo courtesy of the Georgia Institute of Technology

On September 15, 2021, MIT Sloan School of Management announced that Andy Sun will be joining the faculty as associate professor (tenured) of operations research and statistics and the inaugural Iberdrola-Avangrid Professor of Electric Power Systems on January 1, 2022.

Sun will also serve as a faculty lead for the electric power system focus area and a member of the steering committee of the MIT Energy Initiative's (MITEI's) new Future Energy Systems Center (energy.mit.edu/futureenergysystemscenter), which launched on October 1, 2021. The Future Energy Systems Center is an industry research consortium providing insights on how best to navigate the energy transition based on multi-sectoral analyses of emerging technologies, changing policies, and evolving economics.

Sun's research focuses on developing optimization algorithms for large-scale power systems, in particular, to help with the integration of renewable energy resources into large electric power systems. He also studies the planning and operations of power grids and other infrastructure, such as electrified transportation systems, alternative fuel systems, and battery supply chains.

Sun holds an MS in media arts and sciences and a PhD in operations research from MIT. He currently serves as an associate professor at the H. Milton Stewart School of Industrial and Systems Engineering at the Georgia Institute of Technology.

"I'm excited to be returning to MIT," said Sun. "I look forward to working with students in the areas of optimization and energy systems, as well as leading the collaborative, interdisciplinary efforts of MITEI's new Future Energy Systems Center."

Sun will develop and teach a new course at MIT Sloan on energy systems modeling and optimization.

"We are delighted that Professor Andy Sun will be joining the faculty of the MIT Sloan School. It is always rewarding to see our graduates excel and come back to MIT," said Michael Cusumano, the SMR Distinguished Professor of Management and Deputy Dean at MIT Sloan. "Andy has established himself as a global expert on modeling the electric power grid. His skills are essential both to make sure communities have adequate power on a day-to-day basis and to ensure that we are generating and distributing energy in a sustainable way."

"We at the MIT Energy Initiative are thrilled that Professor Sun is returning to his alma mater, and we are deeply grateful to Iberdrola and Avangrid for creating the Iberdrola-Avangrid Professorship that is enabling this," said Robert C. Armstrong, Chevron Professor of Chemical Engineering and director of MITEI. "Andy's work on core optimization problems for electric power system operations, infrastructure, and regulation, and his collaboration with major utilities and system operators, make him a natural leader in the energy transition. His research, teaching, and leadership are just what the world needs to help address the climate crisis."

Multinational electric utility company Iberdrola and its U.S. affiliate Avangrid are funding this newly endowed chair. Iberdrola, headquartered in Bilbao, Spain, is one of the world's largest producers of wind power and supplies energy to nearly 100 million people around the world. Avangrid, headquartered in Orange, Connecticut, with approximately $39 billion in assets and operations in 24 U.S. states, serves more than 3.3 million utility customers in New York and New England and is one of the largest producers of wind power in the country.

"MIT and Iberdrola share the same commitment to tackle one of the world's great challenges: the transition towards a sustainable energy model," said Iberdrola Chief Innovation and Sustainability Officer Agustin Delgado. "We are pleased to continue this collaboration with Professor Sun. Research and education are critical to the advancement of technologies and policies that will contribute to the electrification of the economy and the fight against climate change."

"This professorship deepens Avangrid and Iberdrola's support of the visionary minds at the MIT Energy Initiative at a critical moment of the clean energy transition," said Avangrid Chief Executive Officer Dennis V. Arriola. "We are proud to support the work of Professor Sun and his team at MIT, whose research into large-scale systems optimization is well-aligned with the critical goal of decarbonizing the energy infrastructure in the U.S."

Sun added, "Integrating renewable energy sources into the power grid is very difficult. Renewable energy resources are very different from traditional energy sources—and at the same time, the power grid is highly complicated and interconnected. I look forward to tackling these timely and important challenges in my new roles at MIT."

Stefanie Koperniak, MIT Sloan correspondent

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Francesco Benedetti: Building communities, founding a startup with people in mind

MIT postdoctoral researcher Francesco Benedetti admits he wasn't always a star student. But the people he met along his educational journey inspired him to strive, which led him to conduct research at MIT, launch a startup, and even lead the team that won the 2021 MIT $100K Entrepreneurship Competition. Now he is determined to make sure his company, Osmoses, succeeds in boosting the energy efficiency of traditional and renewable natural gas processing, hydrogen production, and carbon capture—thus helping to address climate change.

"I can't be grateful enough to MIT for bringing together a community of people who want to change the world," Benedetti says. "Now we have a technology that can solve one of the big problems of our society."

Benedetti and his team have developed an innovative way to separate molecules using a membrane fine enough to extract impurities such as carbon dioxide (CO_2) or hydrogen sulfide (H_2S) from raw natural gas to obtain higher quality fuel, fulfilling a crucial need in the energy industry. "Natural gas now provides about 40% of the energy used to power homes and industry in the United States," Benedetti says. Using his team's technology to upgrade natural gas more efficiently could reduce emissions of greenhouse gases while saving enough energy to power the equivalent of 7 million additional U.S. homes for a year, he adds.

The MIT community

Benedetti first came to MIT in 2017 as a visiting student from the University of Bologna in Italy, where he was working on membranes for gas separation for his PhD in chemical engineering. Having completed a master's thesis on water desalination at the University of Texas (UT) at Austin, he connected with UT alum Zachary P. Smith, the Robert N. Noyce Career Development Professor of Chemical Engineering at MIT, and the two discovered they shared a vision. "We found ourselves very much aligned on the need for new technology in industry to lower the energy consumption of separating components," Benedetti says.

Although Benedetti had always been interested in making a positive impact on the world, particularly the environment, he says it was his university studies that first sparked his interest in more efficient separation technologies. "When you study chemical engineering, you understand hundreds of ways the field can have a positive impact in the world. But we learn very early that 15% of the world's energy is wasted because of inefficient chemical separation—because we still rely on centuries-old technology," he says. Most

Inspired by the MIT community and assisted by his collaborators, postdoc Francesco Benedetti launched a startup to provide innovative technology for energy-efficient, high-performance chemical separations—and won the MIT $100K Entrepreneurship Competition. Photo: Maisie O'Brien

separation processes still use heat or toxic solvents to separate components, he explains.

Still, Benedetti says, his main drive comes from the joy of working with terrific mentors and colleagues. "It's the people I've met that really inspired me to tackle the biggest challenges and find that intrinsic motivation," he says.

To help build his community at MIT and provide support for international students, Benedetti co-founded the MIT Visiting Student Association (VISTA) in September 2017. By February 2018, the organization had hundreds of members and official Institute recognition. In May 2018, the group won two Institute awards, including the Golden Beaver Award for enhancing the campus environment. "VISTA gave me a sense of belonging; I loved it," Benedetti says.

Membrane technology

Benedetti also published two papers on membrane research during his stint as a visiting student at MIT, so he was delighted to return in 2019 for postdoctoral work through the MIT Energy Initiative, where he was a 2019-2020 ExxonMobil-MIT Energy Fellow. "I came back because the research was extremely exciting, but also because I got extremely passionate about the energy I found on campus and with the people," he says.

Returning to MIT enabled Benedetti to continue his work with Smith and Holden Lai, both of whom helped co-found Osmoses. Lai, a recent Stanford PhD in chemistry who was also a visiting student at MIT in 2018, is now the chief technology officer at Osmoses. Co-founder Katherine Mizrahi Rodriguez '17, an MIT PhD candidate, joined the team more recently.

Together, the Osmoses team has developed polymer membranes with microporosities capable of filtering gases by separating out molecules that differ by as little as a fraction of an angstrom—a unit of length equal to one hundred-millionth of a centimeter. "We can get up to five times higher selectivity than commercially available technology for methane upgrading, and this has been observed operating the membranes in industrially relevant environments," Benedetti says.

Today, methane upgrading—removing CO_2 from raw natural gas to obtain a higher grade fuel—is often accomplished using amine absorption, a process that uses toxic solvents to capture CO_2 and burns methane to fuel the regeneration of those solvents for reuse. Using Osmoses' filters would eliminate the need for such solvents while reducing CO_2 emissions by up to 16 million metric tons per year in the United States alone, Benedetti says.

The technology has a wide range of applications—in oxygen and nitrogen generation, hydrogen purification, and carbon capture, for example—but Osmoses plans to start with the $5 billion market for natural gas upgrading because the need to bring innovation and sustainability to that space is urgent, says Benedetti, who received guidance in bringing technology to market from MIT's Deshpande Center for Technological Innovation. The Osmoses team has also received support from the MIT Sandbox Innovation Fund Program.

The next step for the startup is to build an industrial-scale prototype, and Benedetti says the company got a huge boost toward that goal in May when it won the MIT $100K Entrepreneurship Competition, a student-run contest that has launched more than 160 companies since it began in 1990. Ninety teams began the competition by pitching their startup ideas; 20 received mentorship and development funding; then eight finalists presented business plans to compete for the $100,000 prize. "Because of this, we're getting a lot of interest from venture capital firms, investors, companies, corporate funds, et cetera, that want to partner with us or to use our product," he says. In June, the Osmoses team received a two-year Activate Fellowship, which will support moving its research to market; in October, it won the Northeast Regional and Carbon Sequestration Prizes at the Cleantech Open Accelerator; and in November, the team closed a $3 million Pre-Seed round of financing.

FAIL!

Naturally, Benedetti hopes Osmoses is on the path to success; but he wants everyone to know that there is no shame in failures that come from best efforts. He admits it took him three years longer than usual to finish his undergraduate and master's degrees; and he says, "I have experienced the pressure you feel when society judges you like a book by its cover and how much a lack of inspired leaders and a supportive environment can kill creativity and the will to try."

That's why in 2018 he, along with other MIT students and VISTA members, started FAIL!–Inspiring Resilience, an organization that provides a platform for sharing unfiltered stories and the lessons leaders have gleaned from failure. "We wanted to help destigmatize failure, appreciate vulnerabilities, and inspire humble leadership, eventually creating better communities," Benedetti says. "If we can make failures, big and small, less intimidating and all-consuming, individuals with great potential will be more willing to take risks, think outside the box, and try things that may push new boundaries. In this way, more breakthrough discoveries are likely to follow, without compromising anyone's mental health."

Benedetti says he will strive to create a supportive culture at Osmoses, because people are central to success. "What drives me every day is the people. I would have no story without the people around me," he says. "The moment you lose touch with people, you lose the opportunity to create something special."

Kathryn M. O'Neill, MITEI correspondent

Latifah Hamzah '12: Creating sustainable solutions in Malaysia and beyond

Latifah Hamzah graduated from MIT in 2012 with an SB in mechanical engineering and minors in energy studies and music. During their time at MIT, Latifah participated in various student organizations, including the MIT Symphony Orchestra, Alpha Phi Omega, and the MIT Design/Build/Fly team. They also participated in MITEI's Undergraduate Research Opportunities Program (UROP) in the lab of former Professor of Mechanical Engineering Alexander Mitsos examining solar-powered thermal and electrical cogeneration systems. After graduating from MIT, Latifah worked as a subsea engineer at Shell Global Solutions and co-founded Engineers Without Borders–Malaysia (bit.ly/EWBMalaysia), a nonprofit organization dedicated to finding sustainable and empowering solutions that impact disadvantaged populations in Malaysia. More recently, Latifah received a master of science in mechanical engineering from Stanford University, where they are currently pursuing a PhD in environmental engineering with a focus on water and sanitation in developing contexts.

Latifah Hamzah '12 is working to find sustainable water and sanitation solutions for the developing world. Photo: Casey Valentine

Q What inspired you to pursue energy studies as an undergraduate student at MIT?

A I grew up in Malaysia, where I was at once aware of both the extent to which the oil and gas industry is a cornerstone of the economy and the need to transition to a lower carbon future. The Energy Studies Minor was therefore enticing because it gave me a broader view of the energy space, including technical, policy, economic, and other viewpoints. This was my first exposure to how things worked in the real world—in that many different fields and perspectives had to be considered cohesively in order to have a successful, positive, and sustained impact. Although the minor was predominantly grounded in classroom learning, what I learned drove me to want to discover for myself how the forces of technology, society, and policy interacted in the field in my subsequent endeavors.

In addition to the breadth that the minor added to my education, it also provided a structure and focus for me to build on my technical fundamentals. This included taking graduate-level classes and participating in UROPs that had specific energy foci. These were my first forays into questions that, while still predominantly technical, were more open-ended and with as-yet-unknown answers that would be substantially shaped by the framing of the question. This shift in mindset required from typical undergraduate classes and problem sets took a bit of adjusting to but ultimately gave me the confidence and belief that I could succeed in a more challenging environment.

Q How did these experiences with energy help shape your path forward, particularly in regard to your work with Engineers Without Borders–Malaysia and now at Stanford?

A When I returned home after graduation, I was keen to harness my engineering education and explore in practice what the Energy Studies Minor curriculum had taught by theory and case studies: to consider context, nuance, and interdisciplinary and myriad perspectives to craft successful, sustainable solutions. Recognizing that there were many underserved communities in Malaysia, I co-founded Engineers Without Borders–Malaysia with some friends with the aim of working with these communities to bring simple and sustainable engineering solutions. Many of these projects did have an energy focus. For example, we designed, sized, and installed micro-hydro or solar-power systems for various indigenous communities, allowing them to continue living on their ancestral lands while reducing energy poverty. Many other projects incorporated other aspects of engineering, such as hydrotherapy pools for folks with special needs, and water and sanitation systems for stateless maritime communities.

Through my work with Engineers Without Borders–Malaysia, I found a passion for the broader aspects of sustainability, development, and equity. By spending time with communities in the field and sharing in their experiences, I recognized gaps in my skill set that I could work on to be more effective in advocating for social and environmental justice. In particular, I wanted to better understand communities and their perspectives while being mindful of my positionality. In addition, I wanted to address the more systemic aspects of the problems they faced, which I felt in many cases would only be possible through a combination of research, evidence, and policy. To this end, I embarked on a PhD in environmental engineering with a minor in anthropology and pursued a Community-Based Research Fellowship with Stanford's Haas Center for Public Service. I have also participated in the Rising Environmental Leaders Program (RELP), which helps graduate students "hone their leadership and communications skills to maximize the impact of their research." RELP afforded me the opportunity to interact with representatives from government, NGOs, think tanks, and industry from which I gained a better understanding of the policy and adjacent ecosystems at both the federal and state levels.

Q What are you currently studying, and how does it relate to your past work and educational experiences?

A My dissertation investigates waste management and monitoring for improved planetary health in three distinct projects. Suboptimal waste management can lead to poor outcomes, including environmental contamination, overuse of resources, and lost economic and environmental opportunities in resource recovery. My first project showed that three combinations of factors resulted in ruminant feces contaminating the stored drinking water supplies of households in rural Kenya, and the results were published in the *International Journal of Environmental Research and Public Health*. Consequently, water and sanitation interventions must also consider animal waste for communities to have safe drinking water.

My second project seeks to establish a circular economy in the chocolate industry with indigenous Malaysian farmers and the Chocolate Concierge (bit.ly/ChocolateConcierge), a tree-to-bar social enterprise. Having designed and optimized apparatuses and processes to create biochar from cacao husk waste, we are now examining its impact on the growth of cacao saplings and their root systems. The hope is that biochar will increase the resilience of saplings for when they are transplanted from the nursery to the farm. As biochar can improve soil health and yield while reducing fertilizer inputs and sequestering carbon, farmers can accrue substantial economic and environmental benefits, especially if they produce, use, and sell it themselves.

My third project investigates the gap in sanitation coverage worldwide and potential ways of reducing it. Globally, 46% of the population lacks access to safely managed sanitation, while the majority of the 54% who do have access use on-site sanitation facilities such as septic tanks and latrines. Given that on-site, decentralized systems typically have a lower space and resource footprint, are cheaper to build and maintain, and can be designed to suit various contexts, they could represent the best chance of reaching the sanitation Sustainable Development Goal. To this end, I am part of a team of researchers at the Criddle Group at Stanford working to develop a household-scale system as part of the Gates Reinvent the Toilet Challenge, an initiative aimed at developing new sanitation and toilet technologies for developing contexts.

The thread connecting these projects is a commitment to investigating both the technical and socio-anthropological dimensions of an issue to develop sustainable, reliable, and environmentally sensitive solutions, especially in low- and middle-income countries (LMICs). I believe that an interdisciplinary approach can provide a better understanding of the problem space, which will hopefully lead to effective potential solutions that can have a greater community impact.

Q What do you plan to do once you obtain your PhD?

A I hope to continue working in the spheres of water and sanitation and/or sustainability post-PhD. It is a fascinating moment to be in this space as a person of color from an LMIC, especially as ideas such as community-based research and decolonizing fields and institutions are becoming more widespread and acknowledged. Even during my time at Stanford, I have noticed some shifts in the discourse, although we still have a long way to go to achieve substantive and lasting change. Folks like me are under-represented in forums where the priorities, policies, and financing of aid and development are discussed at the international or global scale. I hope I'll be able to use my qualifications, experience, and background to advocate for more just outcomes.

Turner Jackson, MITEI

Preparing global online learners for the clean energy transition

After a career devoted to making the electric power system more efficient and resilient, Marija Ilic came to MIT in 2018 eager not just to extend her research in new directions but to prepare a new generation for the challenges of the clean energy transition.

To that end, Ilic, a senior research scientist in MIT's Laboratory for Information and Decisions Systems (LIDS) and a senior staff member at Lincoln Laboratory in the Energy Systems Group, has designed a new edX course that captures her methods and vision: Principles of Modeling, Simulation, and Control for Electric Energy Systems. edX is a provider of massive, open, online courses produced in partnership with MIT, Harvard, and other leading universities. Ilic's class made its online debut in June 2021, running for 12 weeks; and it is one of an expanding set of online courses funded by the MIT Energy Initiative (MITEI) to provide global learners with a view of the shifting energy landscape.

Ilic first taught a version of the class while a professor at Carnegie Mellon University, rolled out a second iteration at MIT just as the pandemic struck, and then revamped the class for its current online presentation. But no matter the course location, Ilic focuses on a central theme: "With the need for decarbonization, which will mean accommodating new energy sources such as solar and wind, we must rethink how we operate power systems," she says. "This class is about how to pose and solve the kinds of problems we will face during this transformation."

Hot global topic

The edX class has been designed to welcome a broad mix of students. In summer 2021, more than two thousand signed up from 109 countries, ranging from high schoolers to retirees. In surveys, some said they were drawn to the class by the opportunity to advance their knowledge of modeling. Many others hoped to learn about the move to decarbonize energy systems.

"The energy transition is a hot topic everywhere in the world, not just in the U.S.," says teaching assistant Miroslav Kosanic. "In the class, there were veterans of the oil industry and others working in investment and finance jobs related to energy who wanted to understand the potential impacts of changes in energy systems, as well as students from different fields and professors seeking to update their curricula—all gathered into a community."

Kosanic, who is currently a PhD student at MIT in electrical engineering and computer science, had taken this class remotely in the spring semester of 2021, while he was still in college in Serbia. "I knew I was interested in power systems, but this course was eye-opening for me, showing how to apply control theory and to model different components of these systems," he says. "I finished the course and thought, this is just the beginning, and I'd like to learn a lot more." Kosanic performed so well online that Ilic recruited him to MIT, as a LIDS researcher and edX course teaching assistant, where he grades homework assignments and moderates a lively learner community forum.

A platform for problem-solving

The course starts with fundamental concepts in electric power systems operations and management, and it steadily adds layers of complexity, posing real-world problems along the way. Ilic explains how voltage travels from point to point across transmission lines and how grid managers modulate systems to ensure that enough, but not too much, electricity flows. "To deliver power from one location to the next one, operators must constantly make adjustments to ensure that the receiving end can handle the voltage transmitted, optimizing voltage to avoid overheating the wires," she says.

In her early lectures, Ilic notes the fundamental constraints of current grid operations, organized around a hierarchy of regional managers dealing with a handful of very large oil, gas, coal, and nuclear power plants, and occupied primarily with the steady delivery of megawatt-hours to far-flung customers. But historically, this top-down structure doesn't do a good job of preventing loss of

The electric power system is changing rapidly as carbon-free sources such as solar and wind play an increasing role. In an online MIT course, participants from around the world learn new tools and techniques for operating and managing the evolving power grid. Image: NAR studio/Shutterstock

energy due to suboptimal transmission conditions or due to outages related to extreme weather events.

These issues promise to grow for grid operators as distributed resources such as solar and wind enter the picture, Ilic tells students. In the United States, under new rules dictated by the Federal Energy Regulatory Commission, utilities must begin to integrate the distributed, intermittent electricity produced by wind farms, solar complexes, and even by homes and cars, which flows at voltages much lower than electricity produced by large power plants.

Finding ways to optimize existing energy systems and to accommodate low- and zero-carbon energy sources requires powerful new modes of analysis and problem-solving. This is where Ilic's toolbox comes in: a mathematical modeling strategy and companion software that simplifies the input and output of electrical systems, no matter how large or how small. "In the last part of the course, we take up modeling different solutions to electric service in a way that is technology-agnostic, where it only matters how much a black-box energy source produces, and the rates of production and consumption," says Ilic.

This black-box modeling approach, which Ilic pioneered in her research, enables students to see, for instance, "what is happening with their own household consumption, and how it affects the larger system," says Rupamathi Jaddivada PhD '20, a co-instructor of the edX class and a postdoctoral associate in electrical engineering and computer science. "Without getting lost in details of current or voltage, or how different components work, we think about electric energy systems as dynamical components interacting with each other, at different spatial scales." This means that with just a basic knowledge of physical laws, high school and undergraduate students can take advantage of the course "and get excited about cleaner and more reliable energy," adds Ilic.

What Jaddivada and Ilic describe as "zoom in, zoom out" systems thinking leverages the ubiquity of digital communications and the so-called "internet of things." Energy devices of all scales can link directly to other devices in a network instead of just to a central operations hub, allowing for real-time adjustments in voltage, for instance, vastly improving the potential for optimizing energy flows.

"In the course we discuss how information exchange will be key to integrating new end-to-end energy resources and, because of this interactivity, how we can model better ways of controlling entire energy networks," says Ilic. "It's a big lesson of the course to show the value of information and software in enabling us to decarbonize the system and build resilience, rather than just building hardware."

By the end of the course, students are invited to pursue independent research projects. Some might model the impact of a new energy source on a local grid or investigate different options for reducing energy loss in transmission lines.

"It would be nice if they see that we don't have to rely on hardware or large-scale solutions to bring about improved electric service and a clean and resilient grid, but instead on information technologies such as smart components exchanging data in real time, or microgrids in neighborhoods that sustain themselves even when they lose power," says Ilic. "I hope students walk away convinced that it does make sense to rethink how we operate our basic power systems and that with systematic, physics-based modeling and IT methods we can enable better, more flexible operation in the future."

Leda Zimmerman, MITEI correspondent

NOTES

Principles of Modeling, Simulation, and Control for Electric Energy Systems (bit.ly/edX-modeling) is currently archived on the edX site for learners who wish to view lectures and assignments; it will be offered again in 2022. Other MITEI courses on edX include Sustainable Building Design (bit.ly/edX-sustainablebuilding) and Sustainable Energy (bit.ly/edX-sustainableenergy).

Energy Studies Minor graduates, June 2021

Issa Rais Aoudou Bassirou
Chemical Engineering

Caroline Boone*
Engineering

Madeline Bundy
Chemical Engineering

Alex Encinas Maqueda
Mechanical Engineering

Christopher Eschler
Materials Science and Engineering

Johaun Hatchett
Physics

Vanshika Jain
Mathematics

Natalie Montoya
Nuclear Science and Engineering

Abdalla Osman
Mechanical Engineering

Arnav Patel
Mechanical Engineering

Awele Uwagwu
Chemical Engineering

Shannon Cassady
Aerospace Engineering

*December 2021 graduate

Energy Fellows, 2021–2022

The Society of Energy Fellows at MIT welcomed 29 new members in fall 2021. Their fellowships were made possible through the generous support of four MITEI Member companies and MITEI internal funds.

Photo: Mira Whiting Photography

Chevron

Anthony Atto
System Design and Management

Matthew Brian Barnes
System Design and Management

Doo Hyun Mark Chung
System Design and Management

Sarah Bryson Coyle
System Design and Management

Seiji Engelkemier
Mechanical Engineering

Andre Hicks
System Design and Management

Seoyeon Hong
System Design and Management

Thitisak Kittipeerapat
System Design and Management

Jason John Lehman
System Design and Management

Katherine Patricia Papageorge
System Design and Management

Benjamin Sterling Radelet
System Design and Management

Amir Ali Ravassipour
System Design and Management

William Kolbe Schwab
System Design and Management

Arman Tanzharikov
System Design and Management

Mark Joseph Tozzi
System Design and Management

Joy Zeng
Chemical Engineering

Zhao Zhang
System Design and Management

Commonwealth Fusion Systems

Richard Ibekwe
Nuclear Science and Engineering
Assignment in Plasma Science and Fusion Center

Theodore Mouratidis
Nuclear Science and Engineering
Assignment in Plasma Science and Fusion Center

ExxonMobil

Rui Guo
Mechanical Engineering

Jesse Hinricher
Materials Science and Engineering

Aliza Khurram, PhD
Institute for Data, Systems, and Society

Kate Reidy
Materials Science and Engineering

Kara Rodby
Chemical Engineering

Daniele Vivona
Mechanical Engineering

Ella Wassweiler
Electrical Engineering and Computer Science

MIT Energy Initiative

Caroline White-Nockleby
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"Starting from space": MITEI podcast interviews MIT Vice President for Research Maria Zuber

In spring 2021, MIT announced its new climate action plan, "Fast Forward: MIT's Climate Action Plan for the Decade." As MIT's vice president for research, Maria Zuber oversaw its development and will help lead the Institute's efforts to address the world's urgent climate crisis. Photo courtesy of Maria Zuber

Maria Zuber, MIT's vice president for research and E. A. Griswold Professor of Geophysics, is responsible for research administration and policy at the Institute. She oversees MIT Lincoln Laboratory and more than a dozen interdisciplinary research laboratories and centers, as well as MIT's Climate Action Plan for the Decade. Zuber has held leadership roles associated with a dozen scientific experiments or instrumentation on ten NASA missions, most notably serving as principal investigator of the Gravity Recovery and Interior Laboratory (GRAIL) mission. She is the first woman to lead a science department at MIT. She is a member of the National Academy of Sciences and a fellow of the American Academy of Arts and Sciences. In 2021, President-elect Biden named her as co-chair of the President's Council of Advisors on Science and Technology. In 2013, President Obama appointed Zuber to the National Science Board; she was reappointed by President Trump in 2018. The following excerpts are from the MIT Energy Initiative (MITEI) podcast episode "Starting from space," during which Zuber spoke about her lifelong interest in space, her upbringing in coal country, and MIT as a testbed for climate solutions. The excerpts have been edited and arranged for a print format.

On growing up in coal country and looking to the stars...

[Carbon County, Pennsylvania] was a mining area—anthracite coal—and many of the people there worked in the mines. The mines were already starting to lay people off when I was small. One of my grandfathers died of black lung before I was born. My other grandfather lived with it. He would, many nights, sleep in his recliner because he couldn't breathe if he laid down in bed. This really drove home, I think, the human side of people who work incredibly hard to provide the world with energy.

The skies were very dark at night, and I loved space as long as I can remember. I got interested in building telescopes and spent a lot of time with my grandfather, who quit school when he was in eighth grade to go work in the mines. I didn't find out until after he died that he was able to keep a little bit of the money that he made in the mines and he bought himself a telescope. The story in my family is that there's this recessive gene that causes some members of the family periodically to want to explore outer space. I spent lots and lots of nights in my back yard learning all about things that were in the sky. Really, there was never anything else that I ever wanted to do but study space. I never thought about working. I never thought about getting a job. All I thought about was exploring space. So, it all turned out all right.

On pursuing your dreams...

I have counseled a lot of students who have said, "I really would love to go to college and major in physics or astrophysics or something, but my parents think that I should go to medical school or study business." The fact of the matter is that if you study what you like, there's a much higher chance that you're going to do really well in it. If you do well at whatever you decide to study, it really doesn't close off options, it opens up options. There are just many pathways to doing what you want to do.

It could be you'll never use anything specific that you studied in college; but the ability to learn how to think analytically, to solve problems, to write coherently, to communicate are all skills that you develop, that if you have them, really provide a pathway for you to develop yourself professionally and lead to really interesting opportunities.

On MIT's climate action plans...

The first [2015 climate action] plan was motivated by a group of students who had made an appointment to go see [MIT President Reif] and told him that MIT should divest of fossil fuels. His point of view was, "I don't know how many people think this. We should certainly think about what MIT should do and how MIT could make the biggest impact with respect to mitigating climate change. But we should find out what our entire community thinks, and everything can be on the table there."

So, I convened a committee. It was a committee of students, faculty, staff, and postdocs, and they spent a year meeting. They wrote a report which we then released to the community. We got comments, but we also held events over the course of the year and took all of that input together and made a plan. The plan had five pillars to it—the science, the technology, our own campuses as a testbed, reaching out to the community, and climate education.

Then, after five years, we decided that it really made a lot of sense to revisit it. We convened another committee, led by Professor Paul Joskow, and they set up a half dozen Institute-wide symposia on different aspects of climate and clean energy. We had people from within the MIT community and external people coming in to discuss topics of interest and what we've learned and where things were headed in the future.

Then, over the course of the pandemic year, we did over two dozen convening exercises to get further input from the community. We had student convenings, we did topical convenings, we had convenings about our decisions to, rather than divest, engage with companies and work with them. We had two engagement forums—one was convened by MITEI, the other was convened by [the Environmental Solutions Initiative].

The outcome of that was no one thought that we should abandon any of the things that we were doing in the first climate action plan. Nobody says, "We know enough about climate science. We can just put that one to bed." Quite the contrary. When we, five years later, looked at it, virtually everyone we talked to said that it is imperative that MIT step up its game. That, yes, we're doing things, but CO_2 continues to accumulate in the atmosphere, and we really need a full-out, all-of-Institute effort on this.

We looked at who was doing climate and clean energy research. For example, we found out that there was a lot more climate and energy research going on outside of MITEI than in MITEI. People who were taking the kind of research that they were doing and thinking, "How could I contribute to climate or sustainability?" We found that the interest had just grown. That really provided an opportunity for us to think bigger, and that's what we hope that we've done in terms of a cohesive plan to get a lot of people involved.

A good example, I think, is the SESAME [Sustainable Energy System Analysis Modeling Environment] program within MITEI, which is really looking at how do we decarbonize the energy sector. Really going in and looking at serious decarbonization scenarios. Let's put the technology in there; let's look at the efficiencies; let's look at how much sunlight a place gets; let's look at the level of maturity of battery technology. Then add in the economics to it: When do things become economically feasible? It turns out to be a very useful tool for planning how we're going to really make that transition.

On new climate initiatives...

With regard to the Climate Action Plan, I think the two big new things that we started were a Grand Challenges program [and the Climate and Sustainability Consortium]. President Reif articulated the vision: "We need to take what we know, and we need to go as fast and as far as we can with what we know. But we don't know enough. We need to, in parallel, be learning new science and feeding that new knowledge into technological discoveries, and then having that feed into policies that are necessary to decarbonize."

For the Grand Challenges competition, we asked our community to give us their ideas. We had nearly 100 initial letters that were submitted. It was just extraordinary. Four hundred faculty were involved in some way, shape, or form. We've now down-selected to 28 finalists. Each of those finalists has been given $100K in order to develop their ideas. Each one of those finalists is being asked to, wherever appropriate, consider policy implications.

The Climate and Sustainability Consortium is looking at [non-energy] companies who are out at the cutting edge—they may have made commitments that they are going to decarbonize, or they've made these commitments and they don't know how to do it, or they know how to start but they want to be first-movers. They are choosing companies in a range of sectors so that they are motivated to be collaborative as opposed to competitive. But really [it is about] hearing from industry about what they need and what it's going to take to get there. Then the discoveries that are happening within MIT, getting them out to those companies so that they can deploy. Then these companies acting essentially as role models for other companies in their sector. That is our goal.

We've also made it quite clear that these companies within the Climate and Sustainability Consortium have access to researchers in MITEI, and we are hoping for additional collaboration. This is all about collaboration and getting the best ideas together so we can push things forward as fast as we can.

On MIT's achieving net-zero carbon emissions by 2026...

We dearly would love to [achieve this] without offsets. We don't have the technology to do it; we don't know how to do it; and no one else does either. But we're going to get there as quickly as we can using offsets and not stop there. We're on track from the first plan. We did things with our own campus. We went from steam to hot water, which reduced emissions. We also started a solar farm down in North Carolina, 650 acres, which actually caused a coal-fired power plant to be retired.

Then, of course, in parallel, we want to decarbonize the campus. We're doing this at the same time that our researchers have ambitions for more energy-intensive machines. We opened the Nano building, which has big fans blowing, and still we reduced our emissions at least slightly. How do we keep the ambitions of Institute researchers moving forward as we're trying to decarbonize? Part of what we're doing is renovating our buildings. We're now trying to electrify our vehicle fleet. We're putting more charging stations on campus. We'll be installing more solar cells. Also, the College of Computing has expressed an interest in working with us to—using AI—optimize energy usage in buildings.

On climate and the humanities...

The reception that we've gotten from the new Climate Action Plan has been just exceedingly positive from our community. I think the reason that we are where we are is because people look at the plan and everybody sees that there's something in it for them.

In the humanities and social sciences, human behavior plays such an important role. We're on this path to zero. All of us are going to have to live our lives a little bit differently than we did. We have certain routines, and we have certain comfort levels, and we're not going to be able to do everything exactly the way we used to do it. The humanities and the social sciences can play a remarkably important role there.

The other thing that we heard a great deal from many parts of our community, [in terms of] where the humanities and social sciences can really play a role [in climate action], is lots of desire to help the developing world. We cannot solve this problem just for wealthy nations that can afford to use the newest gadgets. We have to find energy solutions that work, and they have to be the least expensive.

We also have to be concerned about equity, and we have to be concerned about justice. Individuals who are being displaced by rising seas and changes in agricultural conditions really dictate that poverty is a real risk there. It's so important for us to look at the challenges that everybody is going to face and to make sure that we are developing solutions that are going to work for everybody. In the case of adaptation, since we're already seeing the effects of climate change, we [need to] take into account the people who aren't in a position to be at the table making the decisions. There needs to be representation at the table making sure that we understand the needs of everybody.

Kelley Travers, MITEI

To listen to the full podcast episode, go to bit.ly/Zuber-podcast.

3 Questions: Daniel Cohn on the benefits of high-efficiency, flexible fuel engines for heavy-duty trucking

The California Air Resources Board has adopted a regulation that requires truck and engine manufacturers to reduce the nitrogen oxide (NO_x) emissions from new heavy-duty trucks by 90% starting in 2027. NO_x from heavy-duty trucks is one of the main sources of air pollution, creating smog and threatening respiratory health. This regulation requires the largest air pollution cuts in California in more than a decade. How can manufacturers achieve this aggressive goal efficiently and affordably? Daniel Cohn, a MITEI research scientist, and Leslie Bromberg, a principal research scientist at the MIT Plasma Science and Fusion Center, have been working on a high-efficiency, gasoline-ethanol engine that is cleaner and more cost-effective than existing diesel engine technologies. Here, Cohn explains the flexible fuel engine approach and why it may be the most realistic solution—in the near term—to help California meet its stringent vehicle emission reduction goals. This research was sponsored by the Arthur Samberg MIT Energy Innovation fund.

Q How does your high-efficiency, flexible fuel gasoline engine technology work?

A Our goal is to provide an affordable solution for heavy-duty vehicle (HDV) engines to emit low levels of NO_x emissions that would meet California's NO_x regulations, while also quick-starting reductions in greenhouse gas (GHG) emissions in a substantial fraction of the HDV fleet.

Presently, large trucks and other HDVs generally use diesel engines. The main reason for this is because of their high efficiency, which reduces fuel cost—a key factor for commercial trucks (especially long-haul trucks) because of the large number of miles that are driven. However, the NO_x emissions from these diesel-powered vehicles are around 10 times greater than those from spark-ignition engines powered by gasoline or ethanol.

Spark-ignition gasoline engines are primarily used in cars and light trucks (light-duty vehicles), which employ a 3-way catalyst exhaust treatment system (generally referred to as a catalytic converter) that reduces vehicle NO_x emissions by at least 98% and at a modest cost. The use of this highly effective exhaust treatment system is enabled by the capability of spark-ignition engines to be operated at a stoichiometric air/fuel ratio (where the amount of air matches what is needed for complete combustion of the fuel).

Diesel engines do not operate with stoichiometric air/fuel ratios, making it much more difficult to reduce NO_x emissions. Their state-of-the art exhaust treatment system is much more complex and expensive than catalytic converters; and even with it, vehicles produce NO_x emissions around 10 times higher than spark-ignition engine vehicles. Consequently, it is very challenging for diesel engines to further reduce their NO_x emissions to meet the new California regulations.

Our approach uses spark-ignition engines that can be powered by gasoline, ethanol, or mixtures of gasoline and ethanol as a substitute for diesel engines in HDVs. Gasoline has the attractive feature of being widely available and having a comparable or lower cost than diesel fuel. In addition, presently available ethanol in the U.S. produces 20% to 40% lower GHG emissions than diesel fuel or gasoline and has a widely available distribution system.

To make gasoline- and/or ethanol-powered spark-ignition engine HDVs attractive for widespread HDV applications, we developed ways to make spark-ignition engines more efficient, so their fuel costs are more palatable to owners of heavy-duty trucks. Our approach provides diesel-like high efficiency and high power in gasoline-powered engines by using various methods to prevent engine knock (unwanted self-ignition that can damage the engine) in spark-ignition gasoline engines. This enables greater levels of turbocharging and use of a higher engine compression ratio. These features provide high efficiency, comparable to that provided by diesel engines. Plus, when the engine is powered by ethanol, the required knock resistance is provided by the intrinsic high knock resistance of the fuel itself.


Daniel Cohn (left) and Leslie Bromberg have been developing a highly efficient, gasoline-ethanol engine that could help to reduce greenhouse gas emissions quickly and effectively in the heavy-duty trucking sector. Photo: Stuart Darsch

Q What are the major challenges to implementing your technology in California?

A California has always been the pioneer in air pollutant control, with states such as Washington, Oregon, and New York often following suit. As the most populous state, California has a lot of sway—it's a trendsetter. What happens in California has an impact on the rest of the United States.

The main challenge to implementation of our technology is the argument that a better internal combustion engine technology is not needed because battery-powered HDVs—particularly long-haul trucks—can play the required role in reducing NO_x and GHG emissions by 2035. We think that substantial market penetration of battery electric vehicles (BEVs) in this vehicle sector will take a considerably longer time. In contrast to light-duty vehicles, there has been very little penetration of battery power into the HDV fleet, especially in long-haul trucks, which are the largest users of diesel fuel. One reason for this is that long-haul trucks using battery power face the challenge of reduced cargo capability due to substantial battery weight. Another challenge is the substantially longer charging time for BEVs compared to that of most present HDVs.

Hydrogen-powered trucks using fuel cells have also been proposed as an alternative to BEV trucks, which might limit interest in adopting improved internal combustion engines. However, hydrogen-powered trucks face the formidable challenges of producing zero-GHG hydrogen at affordable cost, as well as the cost of storage and transportation of hydrogen. At present, the high-purity hydrogen needed for fuel cells is generally very expensive.

Q How does your idea compare overall to battery-powered and hydrogen-powered HDVs? And how will you persuade people that it is an attractive pathway to follow?

A Our design uses existing propulsion systems and can operate on existing liquid fuels, and for these reasons, in the near term, it will be economically attractive to the operators of long-haul trucks. In fact, it can even be a lower-cost option than diesel power because of the significantly less expensive exhaust treatment and smaller size engines for the same power and torque. This economic attractiveness could enable the large-scale market penetration that is needed to have a substantial impact on reducing air pollution. Alternatively, we think it could take at least 20 years longer for BEVs or hydrogen-powered vehicles to obtain the same level of market penetration.

Our approach also uses existing corn-based ethanol, which can provide a greater near-term GHG reduction benefit than battery- or hydrogen-powered long-haul trucks. While the GHG reduction from using existing ethanol would initially be in the 20% to 40% range, the scale at which the market is penetrated in the near term could be much greater than for BEV or hydrogen-powered vehicle technology. The overall impact in reducing GHGs could be considerably greater.

Moreover, we see a migration path beyond 2030 where further reductions in GHG emissions from corn ethanol can be possible through carbon capture and sequestration of the carbon dioxide (CO_2) that is produced during ethanol production. In this case, overall CO_2 reductions could potentially be 80% or more. Technologies for producing ethanol (and methanol, another alcohol fuel) from waste at attractive costs are emerging and can provide fuel with zero or negative GHG emissions. One pathway for providing a negative GHG impact is through finding alternatives to landfilling for waste disposal, as landfilling leads to potent methane GHG emissions. A negative GHG impact could also be obtained by converting biomass waste into clean fuel since the biomass waste can be carbon neutral, and CO_2 from the production of the clean fuel can be captured and sequestered.

In addition, our flex fuel engine technology may be synergistically used as range extenders in plug-in hybrid HDVs, which use limited battery capacity, thereby lessening the cargo capability reduction and fueling disadvantages of long-haul trucks powered by battery alone.

With the growing threats from air pollution and global warming, our HDV solution is an increasingly important option for near-term reduction of air pollution and offers a faster start in reducing heavy-duty fleet GHG emissions. It also provides an attractive migration path for longer-term, larger GHG reductions from the HDV sector.

MIT Energy Initiative

3 Questions: Massachusetts Secretary of Energy and Environmental Affairs Kathleen Theoharides on climate and energy

Massachusetts is poised to be a national and global leader in the fight against climate change. This spring, Kathleen Theoharides, the secretary of the Executive Office of Energy and Environmental Affairs of Massachusetts, spoke with MITEI Director Robert C. Armstrong at a seminar focused on Massachusetts' emissions reductions plans. Here, Theoharides discusses the state's initiatives to address the decarbonization of key sectors to help the state achieve these goals. (Note: Most of the initiatives, programs, and legislation mentioned in this article can be found by searching on the Massachusetts government website, bit.ly/MAGovernment.)

Q In March 2021, Massachusetts Governor Charlie Baker signed new legislation addressing climate change. What is the scope and mission of this bill? And how does it work with preexisting programs to address key climate concerns for the state?

A Governor Baker has offered long-term support to make Massachusetts a model of climate action. He further strengthened this commitment to achieving net-zero by 2050 when he signed that [March] climate change legislation, which now gives Massachusetts the most ambitious emissions reduction goals in the country. So, what does this legislation do? There are a number of really critical pieces in it, some of which we have been working very hard on at the executive branch level already. First and foremost, it codifies into law the state's net-zero target. This will help to accomplish things such as provisions to make our appliances more energy-efficient and allow municipalities to opt into highly efficient codes for new construction; it includes important nation-leading provisions that will help us protect our environmental justice communities, significantly push development in offshore wind, and much, much more.

We recently released a 2050 Decarbonization Roadmap which has set the table for much of the work that we will be doing in the next 10 years to get us on track to hit our 30-year target. This report is a combination of two years of science-based analysis using models and analytical tools to explore in great detail what steps the commonwealth and the region need to take to achieve this goal while maintaining a healthy, thriving, and equitable economy.

The long-range analysis of the 2050 Decarbonization Roadmap has helped inform our Clean Energy and Climate Plan for 2030, which aims to achieve a 50% emissions limit by the end of the decade. Based off the report, we determined a number of really ambitious goals that we need to meet by 2030. For the heating sector, this includes retrofitting about one million homes, making sure that all new construction is highly efficient, and helping people adopt clean heating solutions. In the transportation sector, we need around 750,000 electric vehicles on the road, and also to achieve a reduction in vehicle miles traveled by 15%. We also need to build and interconnect 6000 megawatts (MW) of clean energy and modernize our electric grid to support the development of these clean energy resources. This plan is really our map of how to make these changes over the next decade, and a lot hinges on the work we do with our federal partners and with other states.

Here are some specific programs we're working on to help us achieve our 2030 plan.

- First, we're working on wholescale market reform by modernizing our electric grid to support the development of clean energy in the commonwealth and across New England.
- Second, we're convening a first-in-the-nation Commission on Clean Heat, which will bring together many different stakeholders to provide the governor recommendations on the heating sector.
- Further, we are updating our Energy Efficiency Plan (bit.ly/MAEfficiencyPlan). Massachusetts is a national leader in energy efficiency, and we hope to further align energy

Kathleen Theoharides (center), the secretary of the Executive Office of Energy and Environmental Affairs of Massachusetts, oversees the commonwealth's six environmental, natural resource, and energy regulatory agencies. In this role, Theoharides joined MassWildlife for a prescribed burn on April 8, 2021, at the Birch Hill Wildlife Management Area. This habitat management practice benefits wildlife, can enhance firefighter and public safety, and improves outdoor recreational opportunities for commonwealth citizens and visitors. Photo: Josh Qualls

efficiency with the state's climate goals and to improve program equity by increasing participation from groups that have traditionally been excluded from this process.

- Energy storage has been a large component of our work in this space, especially since the governor took office and we launched the Energy Storage Initiative in 2015. One notable success is that by including energy storage incentives directly into our solar program, we have approved nearly 1600 MW hours of energy storage, exceeding our initial 2025 target of 1000 MW hours.

- Finally, we have been working hard on our Transportation and Climate Initiative program, which is a cap-and-invest program that's been in the works for the past five years. We anticipate that this will drive pollution in the sector down 26% by 2030. We've been working with nine other states and expect many more to come into the program—this has been a critical opportunity to reduce emissions in the sector, deliver cleaner energy, and reinvest the proceeds in paving the way for a new future of transportation.

Q What are some of the most exciting and recent developments for the state in terms of climate and energy?

A On May 10th, the federal-level Bureau of Ocean Energy Management approved the development of Vineyard Wind—an 800 MW offshore wind project located off the southern Massachusetts coast—making it the largest approved offshore wind project in the United States to date. This key, long-awaited milestone was supposed to happen in my first couple of months on the job as secretary in June of 2019. It was close to being final, and then it got pulled back in the federal permitting process as more projects came on. This recent approval has given us a lot of momentum and a lot of hope for the future as these projects move forward and start delivering the clean energy, jobs, and environmental benefits that are so needed.

On March 11th, we extended that momentum. Our Department of Energy Resources filed a request for proposals (RFP) for the third round of our 83C Offshore Wind Energy Solicitation (bit.ly/MAOffshoreWind). That RFP is now open for bids, and there are several key changes we've made in the solicitation that are worth highlighting. First, we've baked in a little bit more time for the federal permitting and review process. Second, we're proposing to allow bids from 200 MW all the way up to 1600 MW, which would be a doubling of any of the approved projects we've had to date. The allowance for larger-sized bids is intended to capture potential efficiencies related to transmission cabling, as well as the use of onshore transmission interconnection points. Additionally, this RFP is really a result of extensive stakeholder engagement, which has led to some important changes that will allow us to build on the commonwealth's commitment to environmental justice and to diversity, equity, and inclusion (DEI) in the workforce. For the first time, the RFP will require bidders to submit DEI plans that include a workforce diversity plan, a supplier diversity program plan, and more. Finally, the RFP includes both an environmental and socioeconomic impact evaluation. This will ask bidders to detail any potential impacts—both positive and negative—including assessments of cumulative environmental impacts on environmental justice populations and host communities. Overall, we are really excited about these developments in the offshore wind space and think it helps to move the entire industry in the right direction.

Q In what way do you see Massachusetts being able to work with federal, private, and public partners moving forward? Are there any areas where you see room for growth and collaboration?

A Our administration and the legislature have had a long-standing, bipartisan record of partnership, particularly around energy and climate issues, which has helped us to make Massachusetts a leader in the field. I think the state's bipartisanship really could serve as a model for how those at the federal level could go about passing important climate change and environmental laws. One of the things I've spent a lot of time on in this role and in my prior role as the state's undersecretary of climate change was trying to highlight bipartisanship and consensus around the need for climate change solutions. We as a nation have the opportunity to build strong economies, to create a clean energy workforce, and to really be leaders among other nations on these issues. Thanks to the new legislation and other activities being undertaken within the commonwealth, we once again added to our record of national leadership on climate change and have taken a significant step to reduce emissions and to really turn up the action on climate change in this next critical decade, while also protecting vulnerable communities in the pursuit of achieving this goal.

It is critical that we continue to work with other states and regions in addition to fostering federal partnerships. Working to upgrade transmission capacity with our neighbors in both New England and Canada in order to ensure the connection and distribution of new renewable sources, from hydropower in Québec to onshore wind in places like Maine, is one critical component. Additionally, our six-state regional transmission organization, ISO New England, doesn't currently reflect the policy goals around climate change that most of the states have. Moving forward, there needs to be more input from participating state leadership toward ISO's governance, and we all need to engage in scenario-based, forward-looking, long-term transition planning to understand how to meet the energy needs of the future. Finally, we all need to accommodate greater proactive participation from environmental justice communities so that we're building this new, regional energy system in a way that is inclusive and avoids conflict.

We are looking forward to finding new ways to partner with educational institutions and initiatives such as the MIT Energy Initiative and others at MIT. We have a great richness of resources here in the commonwealth, especially in terms of our educational opportunities. There are tremendous areas of overlap, and I am excited to see how we can all work together toward this major decarbonization goal we have as a state and now as a nation.

Turner Jackson, MITEI

MIT Energy Initiative Members

MITEI Founding and Sustaining Members

MITEI's Founding and Sustaining Members support "flagship" energy research programs and projects at MIT to advance energy technologies to benefit their businesses and society. They also provide seed funding for early-stage innovative research projects and support named Energy Fellows at MIT. To date, members have made possible 193 seed grant projects across the campus as well as fellowships for more than 500 graduate students and postdoctoral fellows in 29 MIT departments and divisions.

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MITEI's Startup Member category is designed to help energy startups clear technology hurdles and advance toward commercialization by accessing the talent and facilities at MIT.

COMMONWEALTH FUSION SYSTEMS

MITEI Associate Members

MITEI's Associate Members support a range of MIT research consortia, education programs, and outreach activities together with multiple stakeholders from industry, government, and academia. In general, these efforts focus on near-term policy issues, market design questions, and the impact of emerging technologies on the broader energy system.

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

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Robert Stoner: Home from COP26—and optimistic

MITEI Deputy Director for Science and Technology Robert Stoner attended COP26 in his role as secretary of the Global Commission to End Energy Poverty. The commission helped inform the Global Energy Alliance for People and Planet. Launched at COP, the new alliance is a multibillion-dollar commitment by the Rockefeller and IKEA foundations and Bezos Earth Fund to support access to renewable energy around the world. Upon his return to MIT from Scotland, Stoner shared his COP26 takeaways with Energy Futures. *Here is an excerpt:*

There was an overall feeling of doom and gloom at COP26. And it was one that I *didn't* share, partly because of what we were doing—which is very positive—talking about how we're mobilizing billions of dollars of new money to get people access to renewable energy quickly. But, also, partly because I'm an engineer, and I live amongst engineers, and I see the things that are developing here.

Okay—we can't agree on a global carbon price and what we are all going to do together.

But the options are coming. To misquote Hemingway, who talked about his personal finances ('Bankruptcy comes slowly and then suddenly'), it's important to recognize with the current climate situation vis-à-vis technology, innovation comes slowly and then suddenly. You cross thresholds, where things that used to be preposterously expensive—suddenly become affordable.

We've seen it with electric cars—suddenly we've got electric cars. The electric Ford F-150 is going to cost less than the gas-powered Ford F-150—before subsidies. Nine percent of the cars sold in the world last month were electric. Can you believe that? These things are happening.

Solar is getting cheaper. Batteries are getting cheaper. We're going to have long-term storage.

We're going to see hydrogen emerge rapidly throughout our economies as a carbon-free energy carrier and fuel feedstock, and for energy storage.

So how could you feel bad about the world knowing that's all coming down the pike? The engineers have the ball. That was my takeaway.

Tom Melville, MITEI

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Work to improve wind farm design and siting is among seven MITEI Seed Fund projects awarded in 2021

Companies typically design and site new wind farms based on current wind conditions. But climate change will alter wind patterns over the lifetime of a wind farm, and relocating an installation isn't an option. In a project launched with MIT Energy Initiative (MITEI) seed funding, MIT experts are now developing a methodology that will account for climate change-driven resource uncertainty, permitting more accurate risk analysis during wind farm planning. Other winners of 2021 MITEI Seed Fund grants are focusing on low-energy thermal comfort for buildings; low-cost, high energy-density electrolytes for nonaqueous flow batteries; membraneless electrolyzers for efficient hydrogen production; and more. Since 2008, the MITEI Seed Fund Program has supported 193 seed projects through grants totaling more than $26 million. Read more about the 2021 winners on page 18. Image: Thomas Richter on Unsplash