MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Energy Futures

WINTER 2023

MIT ENERGY INITIATIVE

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What are we currently reading?

"Unpacking U.S. climate and infrastructure laws," by Tom Melville
MIT Energy Initiative Deputy Director Robert Stoner takes stock of climate and infrastructure laws enacted in the last year in the United States and the impact these laws can have in the global energy transition.

"Turning carbon dioxide into valuable products," by Nancy W. Stauffer
MIT chemical engineers are speeding up a chemical reaction key to converting carbon dioxide emissions into useful, valuable products. The secret to their success? DNA.

"3 Questions: Emre Gençer on the role of blue hydrogen in decarbonizing the world's energy systems," by Turner Jackson
MIT Energy Initiative Research Scientist Emre Gençer discusses findings from research analyzing the climate impacts of blue hydrogen.

…and more

On the cover
The demand for lithium-ion batteries is expected to skyrocket in coming decades as our clean energy systems evolve. Research led by Assistant Professor Sili Deng of mechanical engineering aims to reduce the cost of making those batteries. Her team has developed a combustion-based process for synthesizing cathode powders key to their production. Compared to current techniques, the process is simpler, lower cost, and less energy-intensive; and the fabricated batteries will perform as well as those in use today. Here, postdoc Jianan Zhang heats and compresses powder samples in preparation for performance tests in the lab. To read more, turn to page 8. Photo: Gretchen Ertl

Energy Futures

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Winter 2023

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MIT Energy Initiative

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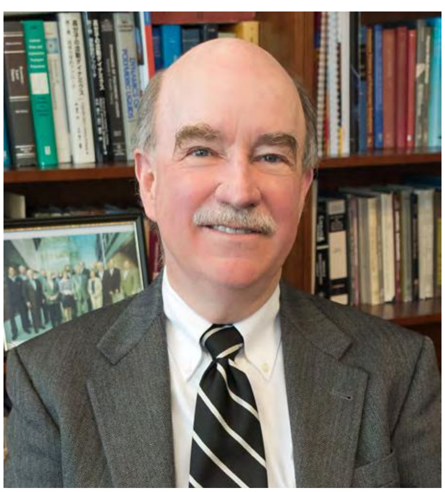
A letter from the director

Dear friends,

As I write, COP27 has just concluded in Sharm el-Sheikh, Egypt. Climate-fueled disasters brought urgency to the negotiations and to our mission to rid our energy systems of greenhouse gas emissions. MITEI Deputy Director for Science and Technology Robert Stoner attended the climate conference, along with several of our students, as part of MIT's delegation. While there, he met with leaders from emerging economy nations, such as Indonesia, Colombia, and South Africa, in connection with an MIT Climate Grand Challenges proposal that aims to help these countries adopt low-carbon economic growth trajectories. On page 44, you can read about some of his expectations and thoughts leading into the conference.

Here in the United States, Congress recently passed the most sweeping legislation in our history to address climate change. At our Fall Colloquium, MITEI External Advisory Board member Philip R. Sharp, the former president of Resources for the Future and former member of the U.S. House of Representatives, spoke optimistically about this new federal surge in action and spending, which he predicted will have vast spillover effects around the globe (see page 40).



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

On campus, research efforts continue to make strides toward a decarbonized energy future. On page 8 read about exciting developments to produce cathodes for lithium-ion batteries more quickly and simply, and with less energy use and expense; the goal now is to speed commercialization and technology scale-up to further hasten the energy transition. You can also read about a promising MITEI study of the potential for vehicle-to-grid technology to leverage electric vehicles as "energy storage on wheels" (see page 23). We highlight more battery-related research on page 3: As the world seeks economically viable, abundant materials for long-duration, grid-scale batteries, a new modeling framework can help by calculating the total cost of various options, taking into account not only capital costs but also operating expenses over the lifetime of the battery. And on page 20, we look at a new low-cost battery architecture that uses three inexpensive, readily-available components: aluminum, sulfur, and salts.

Other articles focus on our education activities. In an interview on page 29, MITEI Director of Education Antje Danielson shares her vision for education as an energy transition accelerator—giving the learner the knowledge, skills, practical experience, and courage to jump into action. MITEI Deputy Director for Policy Christopher Knittel, a professor in the MIT Sloan School, is leading a promising new initiative called Climate Action Through Education; on page 31, learn how Chris and his team are designing an interdisciplinary climate change curriculum in several core disciplines for U.S. high schools. On page 33, read about another MIT professor who brought eight students from Malden Catholic High School in Massachusetts to her lab last summer to develop electrodes for energy-generating bioreactors. And on page 27 you'll find a profile of MIT undergraduate mechanical engineering major Sylas Horowitz, who has minors in energy studies and environment and sustainability. Sylas assembled and retrofitted a high-performance underwater drone to measure greenhouse gas emitted by thawing permafrost; the drone was deployed in the summer of 2022 on a field run in the Canadian high Arctic.

Our Focus on Faculty highlights Assistant Professor Michael Howland of civil and environmental engineering. He and his team have developed a model that predicts the power produced by individual wind turbines in a wind farm. The quantitative understanding of the wakes generated by front-row turbines—like the wakes that boats create in water—allows the team to intentionally misalign upwind turbines so downwind turbines face less wake turbulence, increasing the overall energy output of the wind farm. Read more about Mike's research and teaching on page 25.

And please don't put this edition down before reading stories on six novel energy research projects receiving MITEI Seed Fund grants (page 14), as well as nine new projects from MITEI's Future Energy Systems Center (page 16). They all share a common goal: to advance decarbonization.

I thank you as always for reading *Energy Futures* and for your support. Please stay in touch.

Yours in the energy transition,

Robert C Armstrong

Professor Robert C. Armstrong
MITEI Director
December 2022

Flow batteries for grid-scale energy storage: Guiding future research pathways

Above: Associate Professor Fikile Brushett (left) and Kara Rodby PhD '22 have demonstrated a modeling framework that can help guide the development of flow batteries for large-scale, long-duration electricity storage on a future grid dominated by intermittent solar and wind power generators. Sample analyses show that some options with low initial capital costs may actually be prohibitively expensive when lifetime servicing costs are taken into account.
Brushett photo: Lillie Paquette. Rodby photo: Mira Whiting Photography.

IN BRIEF

One challenge in decarbonizing the power grid is developing a device that can store energy from intermittent clean energy sources such as solar and wind generators. Now, MIT researchers have demonstrated a modeling framework that can help. Their work focuses on the flow battery, an electrochemical cell that looks promising for the job—except for one problem: Current flow batteries rely on vanadium, an energy-storage material that's expensive and not always readily available. So, investigators worldwide are exploring a variety of other less-expensive, more-abundant options. Using their modeling framework, the MIT researchers calculated the total cost of some of those options, considering operating expenses as well as initial capital costs. The results show that in many cases the low capital costs may be more than offset by high operating costs over the lifetime of the battery. Such results can help focus today's disparate efforts on designs with the most promise, speeding development of this grid-scale battery for the energy transition.

In the coming decades, renewable energy sources such as solar and wind will increasingly dominate the conventional power grid. Because those sources only generate electricity when it's sunny or windy, ensuring a reliable grid—one that can deliver power 24/7—requires some means of storing electricity when supplies are abundant and delivering it later when they're not. And because there can be hours and even days with no wind, for example, some energy storage devices must be able to store a large amount of electricity for a long time.

A promising technology for performing that task is the flow battery, an electrochemical device that can store hundreds of megawatt-hours of energy—enough to keep thousands of homes running for many hours on a single charge. Flow batteries have the potential for long lifetimes and low costs in part due to their unusual design. In the everyday batteries used in phones and electric vehicles, the materials that store the electric charge are solid coatings on the electrodes. "A flow battery takes those solid-state charge-storage materials, dissolves them in electrolyte solutions, and then pumps the solutions through the electrodes," says Fikile Brushett, an associate professor of chemical engineering.

That design offers many benefits and poses a few challenges.

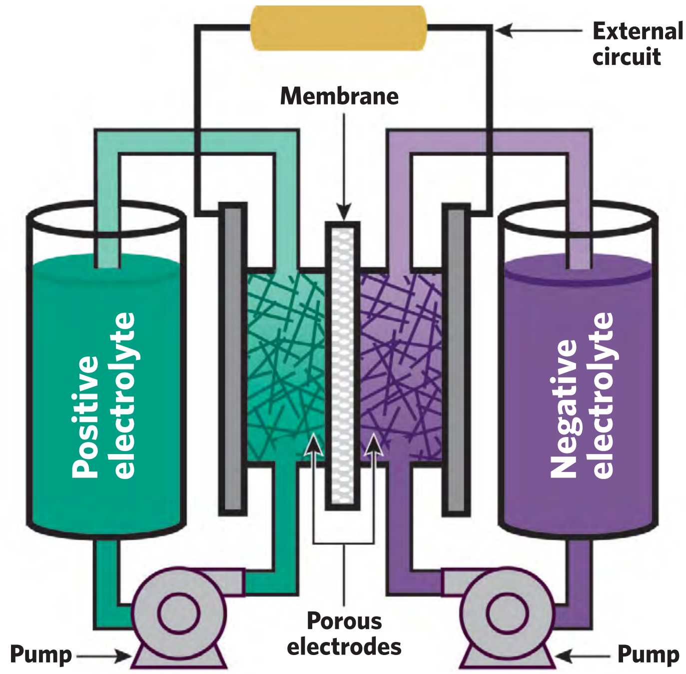
Flow batteries: Design and operation

A flow battery contains two substances that undergo electrochemical reactions in which electrons are transferred from one to the other. When the battery is being charged, the transfer of electrons forces the two substances into a state that's "less energetically favorable" as it stores extra energy. (Think of a ball being pushed up to the top of a hill.) When the battery is being discharged, the transfer of electrons shifts the substances into a more energetically favorable state as the stored energy is released. (The ball is set free and allowed to roll down the hill.)

The schematic to the right shows the key components of a flow battery. Two large tanks hold liquid electrolytes that contain the dissolved "active species"—atoms or molecules that will electrochemically react to release or store electrons. During charging, one species is "oxidized" (releases electrons), and the other is "reduced" (gains electrons); during discharging, they swap roles. Pumps are used to circulate the two electrolytes through separate electrodes, each made of a porous material that provides abundant surfaces on which the active species can react. A thin membrane between the adjacent electrodes keeps the two electrolytes from coming into direct contact and possibly reacting, which would release heat and waste energy that could otherwise be used on the grid.

When the battery is being discharged, active species on the negative side oxidize, releasing electrons that flow through an external circuit to the positive side, causing the species there to be reduced. The flow of those electrons through the external circuit can power the grid. In addition to the movement of the electrons, "supporting" ions—other charged species in the electrolyte—pass through the membrane to help complete the reaction and keep the system electrically neutral.

Once all the species have reacted and the battery is fully discharged, the system can be recharged. In that process, electricity from wind turbines, solar farms, and other generating sources drives the reverse reactions. The active species on the positive side oxidize to release electrons back through the wires to the negative side, where they rejoin their original active species. The battery is now reset and ready to send out more electricity when it's needed. Brushett adds, "The battery can be cycled in this way over and over again for years on end."



Design and operation of a flow battery. Negative and positive electrolytes in large tanks contain atoms or molecules that can electrochemically react to release or store electrons. Pumps send the electrolytes through separate loops to porous electrodes that are separated by a membrane. When the battery is delivering power, electrons liberated by reactions on one side travel to the other side, passing along an external circuit and powering devices on the grid. That movement forces other charged species called ions to pass through the membrane from one electrolyte to the other to keep the system electrically neutral. During charging, the opposite set of flows and reactions occurs as the battery stores power. Diagram: Dorothy Loudermilk, SCS Graphic Services, University of Illinois Urbana-Champaign

Benefits and challenges

A major advantage of this system design is that where the energy is stored (the tanks) is separated from where the electrochemical reactions occur (the so-called reactor, which includes the porous electrodes and membrane). As a result, the capacity of the battery—how much energy it can store—and its power—the rate at which it can be charged and discharged—can be adjusted separately. "If I want to have more capacity, I can just make the tanks bigger," explains Kara Rodby PhD '22, a former member of Brushett's lab and now a technical analyst at Volta Energy Technologies. "And if I want to increase its power, I can increase the size of the reactor." That flexibility makes it possible to design a flow battery to suit a particular application and to modify it if needs change in the future.

However, the electrolyte in a flow battery can degrade with time and use. While all batteries experience electrolyte degradation, flow batteries in particular suffer from a relatively faster form of degradation called "crossover." The membrane is designed to allow small supporting ions to pass through and block the larger active species, but in reality, it isn't perfectly selective. Some of the active species in one tank can sneak through (or "cross over") and mix with the electrolyte in the other tank. The two active species may then chemically react, effectively discharging the battery. Even if they don't, some of the active species is no longer in the first tank where it belongs, so the overall capacity of the battery is lower.

Recovering capacity lost to crossover requires some sort of remediation, for example, replacing the electrolyte in one or both tanks or finding a way to reestablish the "oxidation states" of the active species in the two tanks. (Oxidation state is a number assigned to an atom or compound to tell if it has more or fewer electrons than it has when it's in its neutral state.) Such remediation is more easily—and therefore more cost-effectively—executed in a flow battery because all the components are more easily accessed than they are in a conventional battery.

The state of the art: Vanadium

A critical factor in designing flow batteries is the selected chemistry. The two electrolytes can contain different chemicals, but today the most widely used setup has vanadium in different oxidation states on the two sides. That arrangement addresses the two major challenges with flow batteries.

First, vanadium doesn't degrade. "If you put 100 grams of vanadium into your battery and you come back in 100 years, you should be able to recover 100 grams of that vanadium—as long as the battery doesn't have some sort of a physical leak," says Brushett.

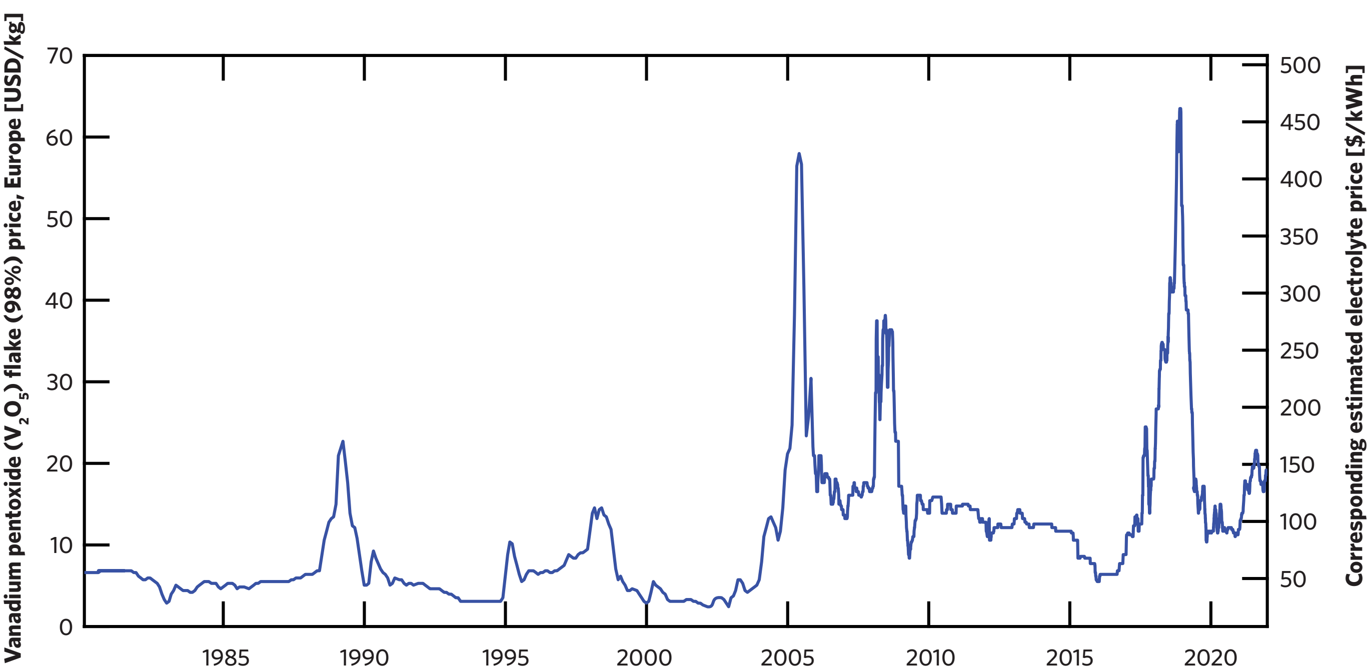
And second, if some of the vanadium in one tank flows through the membrane to the other side, there is no permanent cross-contamination of the electrolytes, only a shift in the oxidation states, which is easily remediated by rebalancing the electrolyte volumes and restoring the oxidation state via a minor charge step. Most of today's commercial systems include a pipe connecting the two vanadium tanks that automatically transfers a certain amount of electrolyte from one tank to the other when the two get out of balance.

However, as the grid becomes increasingly dominated by renewables, more and more flow batteries will be needed to provide long-duration storage. Demand for vanadium will grow, and that will be a problem. "Vanadium is found around the world but in dilute amounts, and extracting it is difficult," says Rodby. "So there are limited places—mostly in Russia, China, and South Africa—where it's produced, and the supply chain isn't reliable." As a result, vanadium prices are both high and extremely volatile—an impediment to the broad deployment of the vanadium flow battery (see the figure on this page).

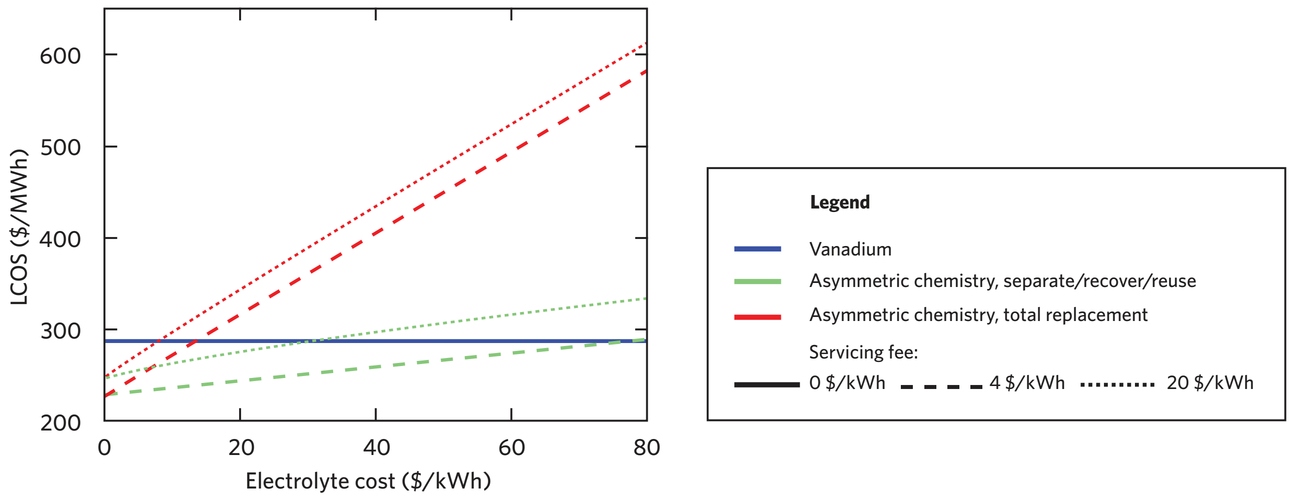
Beyond vanadium

The question then becomes: If not vanadium, then what? Researchers worldwide are trying to answer that question, and many are focusing on promising chemistries using materials that are more abundant and less expensive than vanadium. But it's not that easy, notes Rodby. While other chemistries may offer lower initial capital costs, they may be more expensive to operate over time. They may require periodic servicing to rejuvenate one or both of their electrolytes. "You may even need to replace them, so you're essentially incurring that initial (low) capital cost again and again," says Rodby.

Indeed, comparing the economics of different options is difficult because "there are so many dependent variables," says Brushett. "A flow battery is an electrochemical system, which means that there are multiple components working together in order for the device to function. Because of that, if you are trying to improve a system—performance,



Vanadium prices and corresponding electrolyte prices from 1980 through 2021. The left-hand Y axis measures the market price of vanadium pentoxide, a common source of vanadium sold on the global market. The right-hand Y axis translates those prices into prices for vanadium-based electrolytes for flow batteries. The magnitude and volatility of vanadium prices is considered a key impediment to broad deployment of vanadium flow batteries. Note the 10-fold increase between the price at the start of 2016 and the peak price in late 2018.



Levelized cost of storage as a function of electrolyte cost. These curves show how the electrolyte cost in an asymmetric system with finite-lifetime materials affects the levelized cost of storage (LCOS), assuming a constant decay rate and two methods of remediation: separating out, recovering, and reusing the decayed species (in green) and totally replacing the electrolyte (in red). The dashed lines assume a remediation servicing fee of $4/kilowatt-hour, the dotted lines a servicing fee of $20/kilowatt-hour. The horizontal blue line is the cost of a vanadium electrolyte, presented as a baseline for comparison. Clearly, levelized cost in finite-lifetime systems is highly dependent on both the electrolyte cost and the method used to remediate the decayed species.

cost, whatever—it's very difficult because when you touch one thing, five other things change."

So how can we compare these new and emerging chemistries—in a meaningful way—with today's vanadium systems? And how do we compare them with one another, so we know which ones are more promising and what the potential pitfalls are with each one? "Addressing those questions can help us decide where to focus our research and where to invest our research and development dollars now," says Brushett.

Techno-economic modeling as a guide

A good way to understand and assess the economic viability of new and emerging energy technologies is using techno-economic modeling. With certain models, one can account for the capital cost of a defined system and—based on the system's projected performance—the operating costs over time, generating a total cost discounted over the system's lifetime. That result allows a potential purchaser to compare options on a "levelized cost of storage" basis.

Using that approach, Rodby developed a framework for estimating the levelized cost for flow batteries. The framework includes a dynamic physical model of the battery that tracks its performance over time, including any changes in storage capacity. The calculated operating costs therefore cover all services required over decades of operation, including the remediation steps taken in response to species degradation and crossover.

Analyzing all possible chemistries would be impossible, so the researchers focused on certain classes. First, they narrowed the options down to those in which the active species are dissolved in water. "Aqueous systems are furthest along and are most likely to be successful commercially," says Rodby. Next, they limited their analyses to "asymmetric" chemistries, that is, setups that use different materials in the two tanks. (As Brushett explains, vanadium is unusual in that using the same "parent" material in both tanks is rarely feasible.) Finally, they divided the possibilities into two classes: species that have a finite lifetime and species that have an infinite lifetime, that is, ones that degrade over time and ones that don't.

Results from their analyses aren't clear-cut; there isn't a particular chemistry that leads the pack. But they do provide general guidelines for choosing and pursuing the different options.

Finite-lifetime materials

While vanadium is a single element, the finite-lifetime materials are typically organic molecules made up of multiple elements, among them carbon. One advantage of organic molecules is that they can be synthesized in a lab and at an industrial scale, and the structure can be altered to suit a specific function. For example, the molecule can be made more soluble, so more will be present in the electrolyte and the energy density of the system will be greater; or it can be made bigger so it won't fit through the membrane and cross to the other side. Finally, organic molecules can be made from simple, abundant, low-cost elements, potentially even waste streams from other industries.

Despite those attractive features, there are two concerns. First, organic molecules would probably need to be made in a chemical plant, and upgrading the low-cost precursors as needed may prove to be more expensive than desired. Second, these molecules are large chemical structures that aren't always very stable, so they're prone to degradation. "So along with crossover, you now have a new degradation mechanism that occurs over time," says Rodby. "Moreover, you may figure out the degradation process and how to reverse it in one type of organic molecule, but the process may be totally different in the next molecule you work on, making the discovery and development of each new chemistry require significant effort."

Research is ongoing, but at present, Rodby and Brushett find it challenging to make the case for the finite-lifetime chemistries, mostly based on their capital costs. Citing studies that have estimated the manufacturing costs of these materials, Rodby believes that current options cannot be made at low enough costs to be economically viable (see the figure on page 6). "They're cheaper than vanadium, but not cheap enough," says Rodby.

The results send an important message to researchers designing new chemistries using organic molecules: Be sure to consider operating challenges early on. Rodby and Brushett note that it's often not until way down the "innovation pipeline" that researchers start to address practical questions concerning the long-term operation of a promising-looking system. The MIT team recommends that understanding the potential decay mechanisms and how they might be cost-effectively reversed or remediated should be an upfront design criterion.

Infinite-lifetime species

The infinite-lifetime species include materials that—like vanadium—are not going to decay. The most likely candidates are other metals, for example, iron or manganese. "These are commodity-scale chemicals that will certainly be low cost," says Rodby.

Here, the researchers found that there's a wider "design space" of feasible options that could compete with vanadium. But there are still challenges to be addressed. While these species don't degrade, they may trigger side reactions when used in a battery. For example, many metals catalyze the formation of hydrogen, which reduces efficiency and adds another form of capacity loss. While there are ways to deal with the hydrogen-evolution problem, a sufficiently low-cost and effective solution for high rates of this side reaction is still needed.

In addition, crossover is a still a problem requiring remediation steps. The researchers evaluated two methods of dealing with crossover in systems combining two types of infinite-lifetime species.

The first is the "spectator strategy." Here, both of the tanks contain both active species. Explains Brushett, "You have the same electrolyte mixture on both sides of the battery, but only one of the species is ever working and the other is a spectator." As a result, crossover can be remediated in similar ways to those used in the vanadium flow battery. The drawback is that half of the active material in each tank is unavailable for storing charge, so it's wasted. "You've essentially doubled your electrolyte cost on a per-unit energy basis," says Rodby.

The second method calls for making a membrane that is perfectly selective: It must let through only the supporting ion needed to maintain the electrical balance between the two sides. However, that approach increases cell resistance, hurting system efficiency. In addition, the membrane would need to be made of a special material—say, a ceramic composite—that would be extremely expensive based on current production methods and scales. Rodby notes that work on such membranes is under way, but the cost and performance metrics are "far off from where they'd need to be to make sense."

Time is of the essence

The researchers stress the urgency of the climate change threat and the need to have grid-scale, long-duration storage systems at the ready. "There are many chemistries now being looked at," says Rodby, "but we need to hone in on some solutions that will actually be able to compete with vanadium and can be deployed soon and operated over the long term."

The techno-economic framework is intended to help guide that process. It can calculate the levelized cost of storage for specific designs for comparison with vanadium systems and with one another. It can identify critical gaps in knowledge related to long-term operation or remediation, thereby identifying technology development or experimental investigations that should be prioritized. And it can help determine whether the trade-off between lower upfront costs and greater operating costs makes sense in these next-generation chemistries.

The good news, notes Rodby, is that advances achieved in research on one type of flow battery chemistry can often be applied to others. "A lot of the principles learned with vanadium can be translated to other systems," she says. She believes that the field has advanced not only in understanding but also in the ability to design experiments that address problems common to all flow batteries, thereby helping to prepare the technology for its important role of grid-scale storage in the future.

Nancy W. Stauffer, MITEI

NOTES

This research was supported by the MIT Energy Initiative. Kara Rodby PhD '22 was supported by an ExxonMobil-MIT Energy Fellowship in 2021–2022. More information about this research can be found in the first article listed below. The other three articles report on related research.

K.E. Rodby, M.L. Perry, and F.R. Brushett. "Assessing capacity loss remediation methods for asymmetric redox flow battery chemistries using levelized cost of storage." *Journal of Power Sources*, September 2021. Online: doi.org/10.1016/j.jpowsour.2021.230085.

F.R. Brushett, M.J. Aziz, and K.E. Rodby. "On lifetime and cost of redox-active organics for aqueous flow batteries." *ACS Energy Letters*, February 2020. Online: dx.doi.org/10.1021/acsenergylett.0c00140.

M.L. Perry, K.E. Rodby, and F.R. Brushett. "Untapped potential: The need and opportunity for high-voltage aqueous redox flow batteries." *ACS Energy Letters*, January 2022. Online: doi.org/10.1021/acsenergylett.1c02225.

K.E. Rodby, T.J. Carney, Y.A. Gandomi, J.L. Barton, R.M. Darling, and F.R. Brushett. "Assessing the levelized cost of vanadium redox flow batteries with capacity fade and rebalancing." *Journal of Power Sources*, April 2020. Online: doi.org/10.1016/j.jpowsour.2020.227958.

Using combustion to make lithium-ion batteries: Electricity storage for the energy transition

IN BRIEF

MIT combustion experts have designed a system that uses flames to produce materials for cathodes of lithium-ion batteries—materials that now contribute to both the high cost and the high performance of those batteries. Based on extensive lab-scale experiments, the researchers' system promises to be simpler, much quicker, and far less energy-intensive than the conventional method now used to manufacture cathode materials. Electrochemical tests show that their materials should produce lithium-ion batteries that perform as well as those used in electric vehicles today, providing a comparable driving range, charge and discharge rate, and lifetime. The components in the system are already used in industry, so the researchers believe that rapid commercialization and scale-up should be possible.

For more than a century, much of the world has run on the combustion of fossil fuels. Now, to avert the threat of climate change, the energy system is changing. Notably, solar and wind systems are replacing fossil fuel combustion for generating electricity and heat, and batteries are replacing the internal combustion engine for powering vehicles. As the energy transition progresses, researchers worldwide are tackling the many challenges that arise.

Sili Deng has spent her career thinking about combustion. Now an assistant professor in the Department of Mechanical Engineering and the Class of 1954 Career Development Professor, Deng leads an MIT group that, among other things, develops theoretical models to help understand and control combustion systems to make them more efficient and to control the formation of emissions, including particles of soot.

"So we thought, given our background in combustion, what's the best way we can contribute to the energy transition?" says Deng. In considering the possibilities, she notes that combustion refers only to the process—not to what's burning. "While we generally think of fossil fuels when we think of combustion, the term 'combustion' encompasses many high-temperature chemical reactions that involve oxygen and typically emit light and large amounts of heat," she says.

Given that definition, she saw another role for the expertise she and her team have developed: They could explore the use of combustion to make materials for the energy transition. Under carefully controlled conditions, combusting flames can be used to produce not polluting soot but rather valuable materials, including some that are critical in the manufacture of lithium-ion batteries.

Improving the lithium-ion battery by lowering costs

The demand for lithium-ion batteries is projected to skyrocket in the coming decades. Batteries will be needed to power the growing fleet of electric cars and to store the electricity produced by solar and wind systems so it can be delivered later when those sources aren't generating. Some experts project that the global demand for lithium-ion batteries may increase tenfold or more in the next decade.

Given such projections, many researchers are looking for ways to improve the lithium-ion battery technology. Deng and her group aren't materials scientists, so they don't focus on making new and better battery chemistries. Instead, their goal is to find a way to lower the high cost of making all of those batteries. And much of the cost of making a lithium-ion battery can be traced to the manufacture of materials used to make one of its two electrodes—the cathode.

The MIT researchers began their search for cost savings by considering the methods now used to produce cathode materials. The raw materials are typically salts of several metals, including lithium, which provides ions—the electrically charged particles that move when the battery is charged and discharged. The processing technology aims to produce tiny particles, each one made up of a mixture of those ingredients with the atoms arranged in the specific crystalline structure that will deliver the best performance in the finished battery.

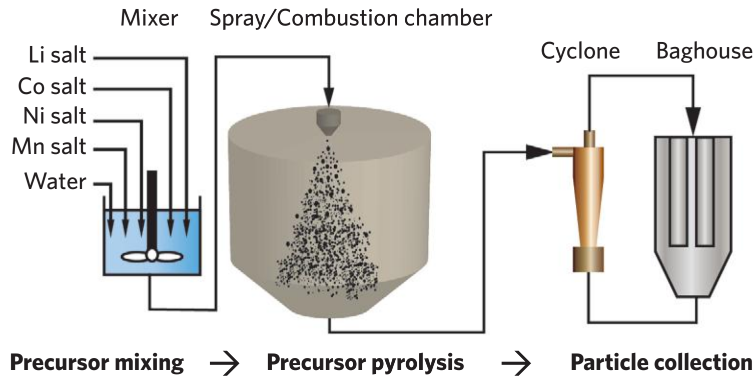
For the past several decades, companies have manufactured those cathode materials using a two-stage process called coprecipitation. In the first stage, the metal salts—excluding the lithium—are dissolved in water and thoroughly mixed inside a chemical reactor. Chemicals are added to change the acidity (the pH) of the mixture, and particles made up of the combined salts precipitate out of the solution. The particles are then removed, dried, ground up, and put through a sieve.

A change in pH won't cause lithium to precipitate, so it is added in the second stage. Solid lithium is ground together with the particles from the first stage until lithium atoms permeate the particles. The resulting material is then heated, or "annealed," to ensure complete mixing and to achieve the targeted crystalline structure. Finally, the particles go through

Facing page: Left to right: Graduate student Chuwei Zhang, Assistant Professor Sili Deng, graduate student Maanasa Bhat, and postdoc Jianan Zhang stand behind the lab-scale apparatus they use to investigate a combustion-based method of synthesizing materials critical to the manufacture of lithium-ion batteries. Experiments show that their method could significantly lower the cost of making those materials with no sacrifice in performance. Photo: Gretchen Ertl a "deagglomerator" that separates any particles that have joined together, and the cathode material emerges.

Coprecipitation produces the needed materials, but the process is time-consuming. The first stage takes about 10 hours, and the second stage requires about 13 hours of annealing at a relatively low temperature (750°C). In addition, to prevent cracking during annealing, the temperature is gradually "ramped" up and down, which takes another 11 hours. The process is thus not only time-consuming but also energy-intensive and costly.

For the past two years, Deng and her group have been exploring better ways to make the cathode material. "Combustion is very effective at oxidizing things, and the materials for lithium-ion batteries are generally mixtures of metal oxides," says Deng. That being the case, they thought this could be an opportunity to use a combustion-based process called flame synthesis.



Synthesizing cathode materials using flame-assisted spray pyrolysis (FASP). From the left: In the researchers' system, lithium, cobalt, nickel, and manganese salts are mixed with water and sprayed as fine droplets into a combustion chamber. Inside that chamber, a flame of burning methane heats the salts, causing them to decompose and chemically react—a process called pyrolysis. The water evaporates, and the solid particles left behind are sorted and filtered by size in the cyclone and the baghouse to produce the cathode powder. The powders could then undergo the standard annealing process, but the researchers have found a faster, more energy-efficient way to accomplish that final step.

"Our first thought was, what if we can mix together all of the substances—including the lithium—at the beginning?" says Deng. "Then we would not need to have the two stages"—a clear simplification over coprecipitation.

A new way of making a high-performance cathode material

The first task for Deng and her team—mechanical engineering postdoc Jianan Zhang, Valerie L. Muldoon SB '20, SM '22, and current graduate students Maanasa Bhat and Chuwei Zhang—was to choose a target material for their study. They decided to focus on a mixture of metal oxides consisting of nickel, cobalt, and manganese plus lithium. Known as "NCM811," this material is widely used and has been shown to produce cathodes for batteries that deliver high performance; in an electric vehicle, that means a long driving range, rapid discharge and recharge, and a long lifetime. To better define their target, the researchers examined the literature to determine the composition and crystalline structure of NCM811 that has been shown to deliver the best performance as a cathode material.

They then considered three possible approaches to improving on the coprecipitation process for synthesizing NCM811: They could simplify the system (to cut capital costs), speed up the process, or cut the energy required.

Introducing FASP

One process widely used in the chemical and other industries to fabricate nanoparticles is a type of flame synthesis called flame-assisted spray pyrolysis, or FASP. Deng's concept for using FASP to make their targeted cathode powders appears in the schematic above.

Postdoc Jianan Zhang heats and compresses powders produced in the lab-scale FASP setup prior to fabricating a cell for performance tests. Photo: Gretchen Ertl

At the left, the precursor materials—the metal salts (including the lithium)—are mixed with water, and the resulting solution is sprayed as fine droplets by an atomizer into a combustion chamber. There, a flame of burning methane heats up the mixture. The water evaporates, leaving the precursor materials to decompose, oxidize, and solidify to form the powder product. The cyclone separates particles of different sizes, and the baghouse filters out those that aren't useful. The collected particles would then be annealed and deagglomerated.

To investigate and optimize this concept, the researchers developed a lab-scale FASP setup consisting of a homemade ultrasonic nebulizer, a preheating section, a burner, a filter, and a vacuum pump that withdraws the powders that form. Using that system, they could control the details of the heating process: The preheating section replicates conditions as the material first enters the combustion chamber, and the burner replicates conditions as it passes the flame. That setup allowed the team to explore operating conditions that would give the best results.

Their experiments showed marked benefits over coprecipitation. The nebulizer breaks up the liquid solution into fine droplets, ensuring atomic-level mixing. The water simply evaporates, so there's no need to change the pH or to separate the solids from a liquid. As Deng notes, "You just let the gas go, and you're left with the particles, which is what you want." With lithium included at the outset, there's no need for mixing solids with solids, which is neither efficient nor effective.

They could even control the structure, or "morphology," of the particles that formed. In one series of experiments, they tried exposing the incoming spray to different rates of temperature change over time. They found that the temperature "history" has a direct impact on morphology. With no preheating, the particles burst apart; and with rapid preheating, the particles were hollow. The best outcomes came when they used temperatures ranging from 175°C to 225°C. Experiments with coin-cell batteries (laboratory devices used for testing battery materials) confirmed that by adjusting the preheating temperature, they could achieve a particle morphology that would optimize the performance of their materials.

Best of all, the particles formed in seconds. Assuming the time needed for conventional annealing and deagglomerating, the new setup could synthesize the finished cathode material in half the total time needed for coprecipitation. Moreover, the first stage of the coprecipitation system is replaced by a far simpler setup—a savings in capital costs.

"We were very happy," says Deng. "But then we thought, if we've changed the precursor side so the lithium is mixed well with the salts, do we need to have the same process for the second stage? Maybe not!"

Using a sample of their powders, graduate student Chuwei Zhang (left) assembles a coin-cell battery for performance testing, while Assistant Professor Sili Deng looks on. Working inside a "glove box" is critical because the electrolyte is flammable and the electrodes can degrade in air. Photo: Gretchen Ertl

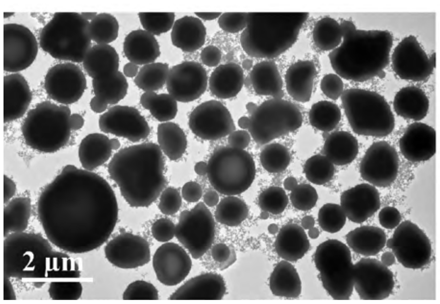
Improving the second stage

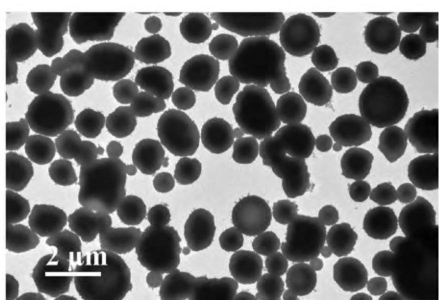
The key time- and energy-consuming step in the second stage is the annealing. In today's coprecipitation process, the strategy is to anneal at a low temperature for a long time, giving the operator time to manipulate and control the process. But running a furnace for some 20 hours—even at a low temperature—consumes a lot of energy.

Based on their studies thus far, Deng thought, "What if we slightly increase the temperature but reduce the annealing time by orders of magnitude? Then we could cut energy consumption, and we might still achieve the desired crystal structure."

However, experiments at slightly elevated temperatures and short treatment times didn't bring the results they hoped for. As the left-hand transmission electron microscope (TEM) image below shows, the particles that formed had clouds of light-looking nanoscale particles attached to their surfaces. When they performed the same experiments without adding the lithium, those nanoparticles didn't appear. Based on that and other tests, they concluded that the nanoparticles were pure lithium. So, it seemed like long-duration annealing would be needed to ensure that the lithium made its way inside the particles.

But they then came up with a different solution to the lithium-distribution problem. They added a small amount—just 1% by weight—of an inexpensive compound called urea to their mixture. As the right-hand TEM image shows, the "undesirable nanoparticles were then largely gone," says Deng.

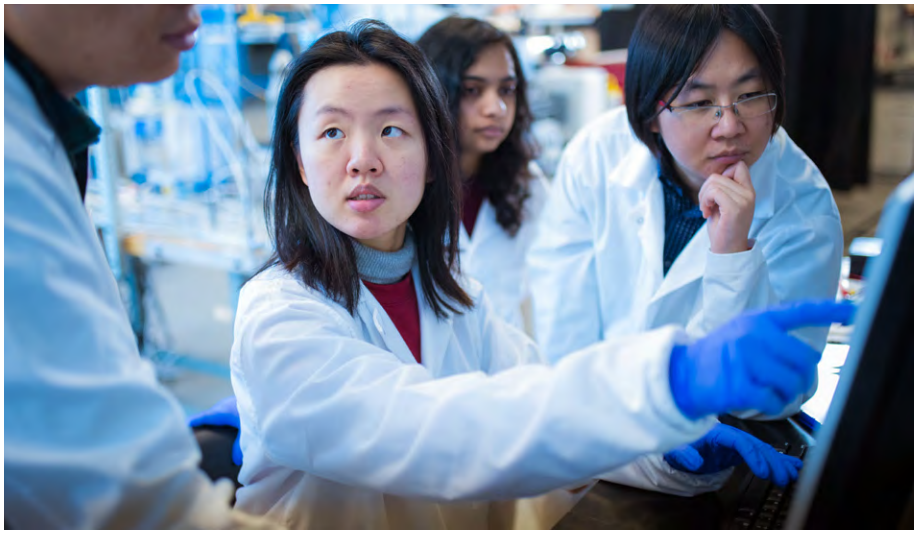




Elevating the temperature and shortening the duration of annealing. Initial experiments treating the as-synthesized powders at slightly elevated temperatures and short treatment times produced the particles shown in the transmission electron microscope (TEM) image on the left. The light nanoscale particles that appear in clouds on their surfaces are lithium, suggesting that far more time is needed to get the lithium to mix in. Performing the same experiments after adding a small amount of an inexpensive compound called urea produced the particles in the TEM image on the right, which show few attached lithium nanoparticles.

Experiments in the laboratory coin cells showed that the addition of urea significantly altered the response to changes in the annealing temperature. When the urea was absent, raising the annealing temperature led to a dramatic decline in performance of the cathode material that formed. But with the urea present, the performance of the material that formed was unaffected by any temperature change.

That result meant that—as long as the urea was added with the other precursors—they could push up the temperature, shrink the annealing time, and omit the gradual ramp-up and cool-down process. Further imaging



Above left: The team discusses results of performance tests of coin-cell batteries made using powders synthesized in the lab-scale FASP apparatus under carefully controlled conditions. During testing, the batteries are placed into a series of clamps, and measurements of flowing current and remaining capacity over time are displayed for each one on the computer monitor at the lower right. **Above right:** A container of coin-cell batteries ready for testing.
Photos: Gretchen Ertl

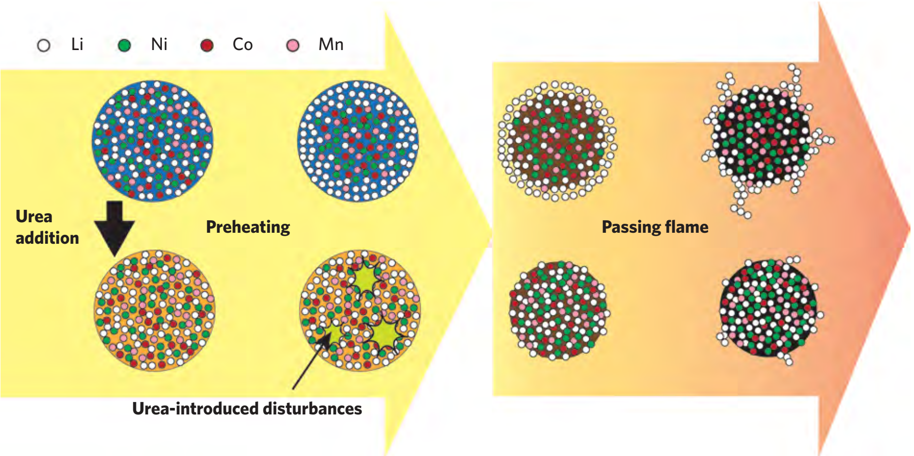
studies confirmed that their approach yields the desired crystal structure and the homogeneous elemental distribution of the cobalt, nickel, manganese, and lithium within the particles. Moreover, in tests of various performance measures, their materials did as well as materials produced by coprecipitation or by other methods using long-time heat treatment. Indeed, the performance was comparable to that of commercial batteries with cathodes made of NCM811.

So now the long and expensive second stage required in standard coprecipitation could be replaced by just 20 minutes of annealing at about 870°C plus 20 minutes of cooling down at room temperature.

Theory, continuing work, and planning for scale-up

While experimental evidence supports their approach, Deng and her group are now working to understand why it works. "Getting the underlying physics right will help us design the process to control the morphology and to scale up the process," says Deng.

The figure below presents their hypothesis for why the lithium nanoparticles in their flame synthesis process end up on the surfaces of the larger particles—and why the presence of urea solves that problem.

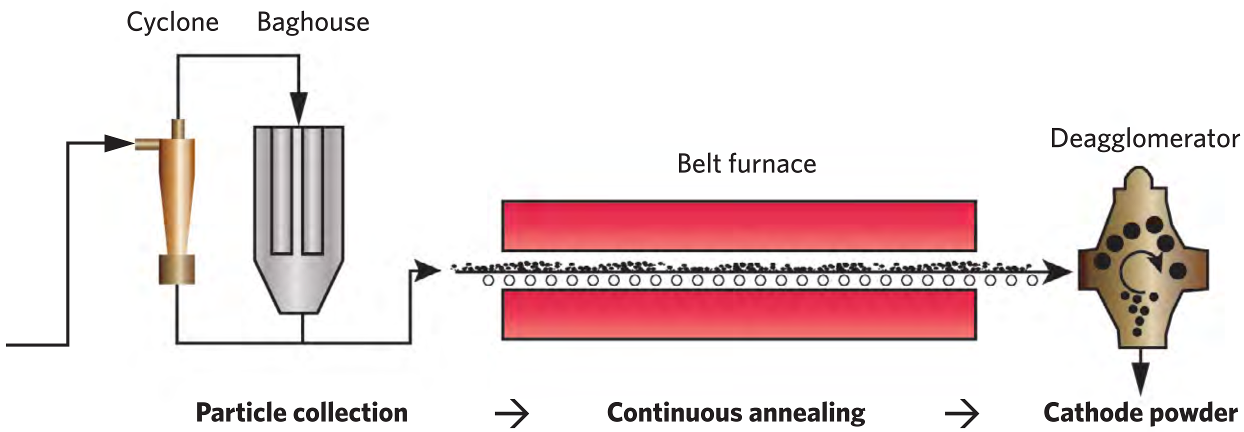


The fate of the lithium, without and with the urea additive: A proposed mechanism. The researchers theorize that without the urea present—the top row of drawings—all the metal salts start out well-mixed within the droplet; but over time, the lithium diffuses to the surface. The lithium ends up in nanoparticles attached to the solidified particle, and a long heat treatment is needed for the lithium to mix in. When the urea is present—the bottom row of drawings—the rising temperature causes the urea to form bubbles. The bubbles burst, increasing circulation, which keeps the lithium from diffusing to the surface. The lithium is distributed uniformly, so the final heat treatment can be very short.

The top series of drawings shows a droplet made of lithium and the other metal salts, without any urea present. In the sketch at the left, the metal and lithium atoms are well-mixed. Moving to the right, the lithium nanoparticles rise toward the surface; then they appear in a surface coating; and—after the droplet is heated by the flame and becomes a solid—they end up as nanoparticles loosely attached to the particle surface. The researchers' theory? As the droplets evolve, atoms of the different metals remain mixed, but the lithium diffuses rapidly to the surface and remains there as the particle solidifies. Therefore, a long annealing process is needed to move the lithium in among the other atoms.

With the urea present, the lithium mixes in. Why? The bottom row of sketches shows their theory. As the first sketch shows, the urea and the lithium both mix with the other atoms. When the urea is heated, it decomposes, forming bubbles that pop. That popping enhances mixing inside the droplet, so the lithium doesn't rise to the surface but instead remains mixed up with the rest of the atoms. Because the lithium is already mostly mixed throughout, the annealing time that follows can be very short.

The researchers are now designing a system to suspend a droplet of their mixture so they can observe the



Design of an integrated system for manufacturing cathode materials. The FASP system illustrated on page 10 will produce particles in 20 minutes or less. At that rate, they can be continuously deposited from the baghouse onto a belt that carries them through a furnace for just 10 to 20 minutes, as shown above. A deagglomerator is still needed to break apart any particles that have become attached. The cathode powders for high-performance lithium-ion batteries could thus be manufactured at unprecedented speed, low cost, and low energy use. The components in the complete FASP-based system are already used in industry, so the researchers believe that rapid commercialization and scale-up should be possible.

circulation inside it, with and without the urea present. They're also developing experiments to examine how droplets vaporize, employing tools and methods they have used in the past to study how hydrocarbons vaporize inside internal combustion engines.

They also have ideas about how to streamline and scale up their process. One concept is illustrated above. Their novel FASP process generates particles in 20 minutes or less—a rate that's consistent with continuous processing. In coprecipitation, the first stage takes 10 to 20 hours, so one batch at a time moves on to the second stage to be annealed. With FASP, the particles coming out of the baghouse are deposited on a belt that carries them for 10 or 20 minutes through a furnace, as shown in the illustration. A deagglomerator then breaks any attached particles apart, and the cathode powder comes out, ready to be fabricated into a high-performance cathode for a lithium-ion battery.

Deng notes that every component in their "integrated synthesis system" is already used in industry, generally at a large scale and high flow-through rate. "That's why we see great potential for our technology to be commercialized and scaled up," she says. "Where our expertise comes into play is in designing the combustion chamber to control the temperature and heating rate so as to produce particles with the desired morphology." And while a detailed economic analysis has yet to be performed, it seems clear that their technique will be faster, the equipment simpler, and the energy use lower than other methods of manufacturing cathode materials for lithium-ion batteries—potentially a major contribution to the ongoing energy transition.

Nancy W. Stauffer, MITEI

NOTES

This research was supported by the MIT Department of Mechanical Engineering. Further information can be found in:

J. Zhang, V.L. Muldoon, and S. Deng. "Accelerated synthesis of $Li(Ni_{0.8}Co_{0.1}Mn_{0.1})O_2$ cathode materials using flame-assisted spray pyrolysis and additives." *Journal of Power Sources*, March 2, 2022. Online: doi.org/10.1016/j.jpowsour.2022.231244.

Graduate student Maanasa Bhat has developed a device in which she can observe the circulation within an individual droplet as it evaporates. Developing a fundamental understanding of the physics controlling the synthesis process is critical to the successful design and operation of a full-scale commercial system. Photo: Gretchen Ertl

Six novel energy research projects win MIT Energy Initiative Seed Fund grants

In spring 2022, the MIT Energy Initiative (MITEI) awarded funding to six novel energy research projects at $150,000 each for a total of $900,000. As recipients of MITEI's 2021-2022 Seed Fund grants, these projects represent new lines of research and analysis with potential for high impact across longer time horizons.

"Our energy systems are rapidly changing," says Robert C. Armstrong, the director of MITEI. "The Seed Fund Program supports the sort of high-risk, high-reward innovation and research that is necessary to meet our growing energy needs while accelerating the reduction of greenhouse gas emissions harming our planet."

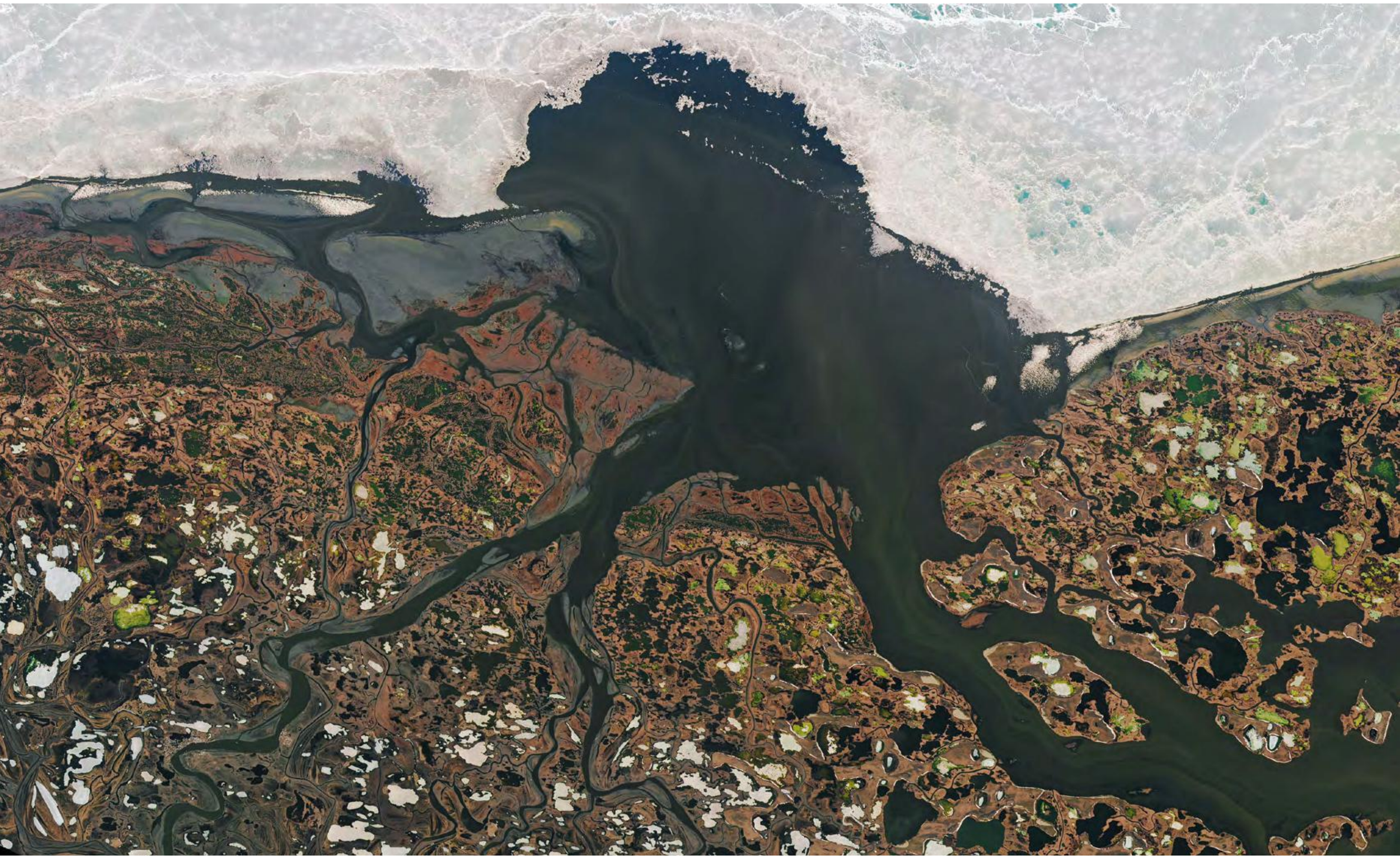
Highly competitive, the program received 41 proposals from 57 different principal investigators (PIs) across MIT's various departments, labs, and centers.

The winning projects span a wide breadth of topics and lines of inquiry in the energy space. They include satellite-based remote sensing for emissions and energy infrastructure monitoring, tools designed to support electrifying urban transportation fleets, a process that will capture and mineralize carbon dioxide (CO_2) from flue gas emissions, and more. Brief descriptions of the six projects follow.

Electrochemical carbon capture

The International Energy Agency's Sustainable Development Scenario predicts that carbon capture technologies must scale globally from 40 million tonnes in 2020 to 10 gigatonnes/year in 2070 to keep global temperature rise to below 2°C. This project aims to develop a less energy- and capital-intensive carbon capture technology, leveraging a novel electrochemical process that exploits

One of the six novel energy research projects to win an MIT Energy Initiative Seed Fund award will explore the use of space-based remote sensing to monitor energy infrastructure and emissions. Image: USGS/NASA Landsat



nitrate-carbonate conversion to separate CO_2 from a process stream and output a concentrated CO_2 stream.

PIs: Betar Gallant, the Class of 1922 Career Development Professor in Mechanical Engineering, and T. Alan Hatton, the Ralph Landau Professor of Chemical Engineering Practice

CO_2 mineralization and lithium extraction

Demand for lithium—which is used in electric vehicles, large-scale energy storage, and more—is rapidly increasing. But the current process to produce lithium from brines requires large areas of land and can have significant impacts on the environment. This project proposes a new approach that will utilize a hybrid electrochemical-thermal process in a compact system to purify lithium brine, which will then be mineralized by CO_2 captured from flue gas emissions. This will allow not only for the efficient recovery of lithium as a pure carbonate product, but also for the capture and mineralization of CO_2.

PIs: T. Alan Hatton, the Ralph Landau Professor of Chemical Engineering Practice, and Kripa Varanasi, a professor of mechanical engineering

Optimizing energy investment decisions

This project aims to provide better guidance for investments at the project level and at local scales by filling an important gap in decision analytics and optimization. The researchers will develop a novel optimization framework that will allow for multi-sector (energy, water, environment) project portfolio investment decisions, allowing a user to strategically select different project combinations that together provide greater benefits at lower costs, while also incorporating variability in the individual project performances.

PIs: Olivier de Weck, the Apollo Professor of Astronautics and Engineering Systems, and Afreen Siddiqi, a research scientist in the Department of Aeronautics and Astronautics

Recycling CO_2

This project focuses on copper as an electrocatalyst for the conversion of CO_2 into valuable chemical products such as hydrocarbons and alcohols. The research team intends to perform systematic studies decoupling and leveraging the impacts of nanoscale (surface structure) and mesoscale (particle spacing, loading, and support) phenomena to overcome the stability limitations of copper, enabling efficient CO_2 reduction.

PI: Ariel Furst, the Paul M. Cook Career Development Professor of Chemical Engineering

Electrifying urban transportation fleets

As battery storage costs decline, interest has increased in decarbonizing the transportation sector, which relies heavily on fossil fuels. In the United States, many transit agencies have committed to 100% bus electrification. To aid efforts like these, this project will develop advanced decision-support tools and tailored-solution algorithms for planning electrification strategies for urban transportation fleets. It will consider detailed fleet operations and corresponding power grid impacts, while also analyzing the environmental justice and social equity dimensions of the energy transition.

PIs: Audun Botterud, a principal research scientist at the Laboratory for Information and Decision Systems, and Dharik Mallapragada, a principal research scientist at MITEI

Monitoring emissions and energy infrastructure

Energy companies currently rely mostly on ground-based networks to analyze emissions rates, potential leaks, and other hazards to the power supply. This project proposes to improve the way these companies monitor their infrastructure and investments by exploring the use of space-based remote sensing, ranging from the detection of methane emission leaks to the prevention of wildfires by monitoring vegetation overgrowth, dryness, and power line equipment health.

PI: Kerri Cahoy, an associate professor of aeronautics and astronautics

To date, the MITEI Seed Fund Program has supported 199 energy-focused projects through grants totaling $27.3 million. This funding comes primarily from MITEI's Founding and Sustaining Members, supplemented by gifts from generous donors.

Kelley Travers, MITEI

The MIT Energy Initiative's Future Energy Systems Center funds nine new projects to propel research advancing decarbonization

The Future Energy Systems Center, part of the MIT Energy Initiative (MITEI), has unveiled the nine winners of its latest round of projects devoted to decarbonization. These research awards are intended to navigate the energy transition based on multisectoral analyses of emerging technologies, changing policies, and evolving economics, according to Randall Field, the executive director of the Future Energy Systems Center.

"We're not funding research to develop the next battery, catalyst, or breakthrough science, but rather to identify how emerging technologies will impact energy systems in the long term and how policies can influence the deployment of various decarbonizing technologies," says Field.

As a pillar of MIT's Climate Action Plan for the Decade, the Center aims to unleash talent from all of MIT's schools and its college of computing to advance the energy transition. "We seek exceptional decarbonization ideas with a large impact," says Field, "with projects that connect researchers across the Institute and utilize MITEI's systems analysis experts and tools."

The Center takes a holistic approach to decarbonizing the economy, with a portfolio that encompasses the electric power system, transportation, industry, energy storage, low-carbon fuels, buildings, and carbon management, as well as linkages among these areas.

In its first funding round, the Center invited proposals on a target set of topics that took into account research interests expressed by members of the Center's consortium. The six awards, announced in January 2022, set in motion a range of projects, including:

- A study benchmarking the techno-economic outlook for existing low-carbon hydrogen production methods, and defining game-changing research opportunities for enabling gigaton-scale hydrogen production by mid-century
- A multi-scale analysis to identify alternate low-carbon routes for production of ethylene, a chemical vital to making many products and one that bears a relatively large carbon footprint
- Research assessing how much biomass can be produced in a sustainable way from dedicated land use and from waste and residues to generate bio-based low-carbon fuels suitable for transportation, with a focus on aviation and shipping

In its second call for decarbonization ideas, issued in February 2022, the Center sought ideas from 1,400 professors and research scientists across the Institute. This round resulted in 64 proposals and the selection of nine projects.

"The winning proposals demonstrated the potential of being highly relevant in addressing key decarbonization problems and also answered questions of interest to our member companies as they pursue the energy transition," says Field.

The following projects were selected for funding.

Accelerating building electrification through a science-based decision-making toolkit

In order to reach aggressive net-zero carbon targets, cities worldwide must rapidly electrify buildings. Cost-effective technologies for electrification of these buildings exist, such as high-efficiency air-source heat pumps; but uncertainty, awareness, and market barriers in the real estate sector threaten to slow their adoption.

To demonstrate that decarbonization makes good business sense, Siqi Zheng, the Samuel Tak Lee Professor of Urban and Real Estate Sustainability, and her colleagues are building a model that provides streamlined decision-making tools and behavioral intervention strategies for business stakeholders and policy makers.

"Real estate owners/developers need accurate information on the required monetary and nonmonetary costs and benefits involved in acquiring and deploying the technology in their buildings," she says. "We want to provide a toolkit for policy makers attempting to accelerate building electrification that will support the design of incentive programs, and serve as a decision-making model applicable and scalable in the real world," says Zheng.

Analyzing the large-scale supply of low-carbon hydrogen in Germany

Hydrogen will play an essential role in decarbonizing the economy, whether in industrial processes, long-haul transport, or renewable energy storage. Recently, Germany has unveiled an ambitious strategy for accelerating the move to hydrogen, which will require cost-efficient and ideally zero-carbon methods for generating and distributing hydrogen.

"We intend to develop a detailed low-carbon hydrogen supply chain model that will accurately represent Germany's targets and that will optimize for the

Photo: petrmalinak/Shutterstock

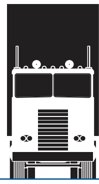
capacities of power and hydrogen production, storage, and transmission," says Emre Gençer, a principal research scientist at MITEI and the principal investigator. In the future, the model will be optimized for zero-carbon target scenarios.

The research will employ MITEI's Sustainable Energy System Analysis Modeling Environment (SESAME) to estimate the minimum-cost hydrogen supply chain design for different scenarios and timeframes, and to investigate the connection of Germany to other regions for importing hydrogen and low-carbon electricity for hydrogen production. This research, says Gençer, "will be modular in design to enable future case studies of other regions around the globe."

Comparative analysis of decarbonization strategies for transportation via direct air capture of carbon dioxide

Aircraft, ships, and heavy-duty trucks currently emit between two and four billion metric tons of carbon dioxide (CO_2) per year. Decarbonizing this transportation sector proves challenging: Batteries can't power such long-distance transportation, and current synthetic fuels cannot be produced in sufficient quantities and many synthetic fuels are not adequately low-carbon. Principal investigator Steven Barrett, a professor of aeronautics and astronautics, is studying how direct air capture (DAC) of CO_2 could be harnessed to address the need for long-distance transportation fuels. CO_2 taken directly from air can be used either as a feedstock for the production of synthetic fuels, or if permanently stored away, as a carbon offset to enable the continued use of petroleum-derived fuels.

"Our project will compare the economy-wide net emissions impacts, system costs, and abatement costs associated with these two DAC-enabled decarbonization pathways for tough-to-decarbonize transportation," says Barrett. "The goal will be to identify the conditions under which one solution is superior to the other and to analyze the role these pathways could have in decarbonizing tough-to-decarbonize transportation."



Comparative assessment of low-carbon liquid energy carriers for long-haul trucking

Long-haul trucking contributes a large and growing share of greenhouse gases. Since these vehicles must travel much longer distances each day than a typical car, switching to battery power trucks is not currently economical or practical because of the required size and weight of the battery and the required recharging times. Liquid fuels contain much more energy per volume than current batteries. Therefore, this project is looking at various liquid fuels, including fuels that are very similar to conventional fuels but are not made from fossil fuels, as well as fuels that do not emit any CO_2 when they are used to power a truck.

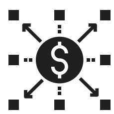
Co-investigators Gençer and William H. Green, the Hoyt Hottel Professor in Chemical Engineering, are developing an assessment platform to compare the cost and emission impacts of these liquid fuel options. "Since long-haul trucking costs directly affect most people in the world, including billions of poor people, it is important to develop a decarbonized long-haul trucking system based on a new energy carrier that is as inexpensive as possible and that poses the least number of barriers to transition for truck drivers and refueling station operators in all nations of the world," says Green.

Electricity retail rate design to support decarbonized power systems and economy-wide electrification

Increased electrification of the heating and transportation sectors and expansion of intermittent renewable energy generation make it more challenging to ensure that the supply of electricity will meet the demand at every moment in time. One strategy to help match supply and demand is to incentivize consumers to use more electricity when it is abundant and less when it is scarce. Such a solution could involve setting retail prices to provide that incentive and thereby make the entire system more efficient and economical.

But "most end users are unlikely to accept exposure to inherently volatile wholesale power prices, especially after such recent events as the Texas freeze and the ongoing EU energy crisis," says Dharik Mallapragada, a principal research scientist at MITEI and a project investigator.

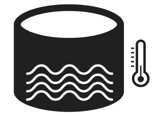
The researchers propose to investigate alternative rate structures that allow variability in the value of electricity across time to be passed through to retail customers, rewarding end users for efficient electricity consumption while limiting the risk associated with excessively high wholesale prices.



Ensuring a financially sustainable, just, and inclusive energy transition

Geopolitics, energy insecurity, and extreme climate events can lead to increased energy prices over prolonged periods of time, as has been demonstrated over the past two years. Soaring electricity prices in response to these events will lead to "affordability issues for a significant share of consumers, competition issues for industry, and will likely induce politicians to introduce often detrimental market interventions that can actually exacerbate the issues," says Christopher R. Knittel, the George P. Shultz Professor of Energy Economics and deputy director for policy at MITEI.

Knittel's group hopes to mitigate such issues with the help of "regulatory-driven long-term hedges to protect end users of electricity," according to Tim Schittekatte, a MITEI postdoctoral associate. The team will also review best international practices to address energy poverty, and identify innovative policies to "efficiently protect vulnerable customers and enable them to actively participate in the energy transition," says Schittekatte.



Liquid air energy storage techno-economic analysis

As renewable energy sources increase their contribution to electric power supply, there will be heightened demand for large-scale, long-duration energy storage (LDES). These systems provide more than 10 hours of energy storage for times when intermittent power sources such as sun and wind prove insufficient to meet demand. A project directed by Paul I. Barton, the Lammot du Pont Professor of Chemical Engineering, is investigating a new LDES technology called liquid air energy storage (LAES), which can store multiple gigawatt-hours of energy and offers advantages over other LDES systems.

"LAES is a clean technology that, in addition to electricity, only intakes and outputs ambient air," says Barton. "These systems offer flexibility over other approaches since they have the ability to generate electrical, mechanical, and thermal energy simultaneously and can operate either as stand-alone systems or be integrated with other industrial processes to further boost both processes' efficiencies."

Barton's team will model a stand-alone LAES system based on state-of-the-art design to determine if LAES is both technically and economically viable under expected grid conditions.

Maximizing security and resilience to cyber-attacks in a power grid

The energy grid has become an increasingly frequent target of cyber-attacks, exemplified most recently by such attacks against Ukrainian power plants and the Colonial oil pipeline in the United States.

"The integration of decarbonized, variable energy resources will only expand these threats, so we must have secure coordination structures to monitor, alert, and mitigate the effect of these attacks and to enhance the resilience of the power grid," says project co-principal investigator Anuradha M. Annaswamy, a senior research scientist in the Department of Mechanical Engineering.

Project researchers will provide grid system operators with situational awareness about grid operating conditions in real time, using Internet-of-Things technology. "We will identify methods for maximizing security and develop scores for resilience against risk in all subsystems of the energy grid, with particular emphasis on the grid edge," says Annaswamy. The proposed framework will be validated on a realistic power system model.

Cost-performance analysis and benchmarking of CO_2 capture systems for hard-to-abate industries

For hard-to-decarbonize industries such as iron, steel, cement, and chemical production, carbon capture and storage (CCS) appears to be a promising decarbonization strategy. There is a wide range of carbon capture technologies, each with different capabilities and levels of maturity. Likewise, the hard-to-abate industries have diverse needs with CO_2 generation at different concentrations and at high temperatures (300 to >1,400°C). The investigators behind this project want to assess how more established technologies and a new high-temperature CCS technology would match up with the needs of these different industries.

"This project will quantify the potential of molten salts as exemplar versatile-temperature capture media for CO_2 capture from various industrial flue gas streams and compare it against more mature carbon capture technologies," says Betar Gallant, a professor of mechanical engineering and one of three principal investigators on the project. "Specifically, we will determine the energy cost, process efficiency gains, capital and operating cost, and material scalability of various CCS systems to industry processes."

The Future Energy Systems Center is a research consortium established by MITEI that 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—an approach essential to understanding the cross-sectorial impact of the energy transition. The Future Energy Systems Center combines 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.

Leda Zimmerman, MITEI correspondent

A new concept for batteries made from inexpensive, abundant materials: Low-cost backup storage for renewable energy sources

As the world builds out ever larger installations of wind and solar power systems, the need is growing fast for economical, large-scale backup systems to provide power when the sun is down and the air is calm. Today's lithium-ion batteries are still too expensive for most such applications, and other options such as pumped hydro require specific topography that's not always available.

Now, researchers at MIT and elsewhere have developed a new kind of battery, made entirely from abundant and inexpensive materials, that could help to fill that gap.

The new battery architecture, which uses aluminum and sulfur as its two electrode materials, with a molten salt electrolyte in between, is described in the journal *Nature* in a paper by MIT Professor Donald Sadoway, along with 15 others at MIT and in China, Canada, Kentucky, and Tennessee.

"I wanted to invent something that was better, much better, than lithium-ion batteries for small-scale stationary storage, and ultimately for automotive [uses]," explains Sadoway, who is the John F. Elliott Professor Emeritus of Materials Chemistry.

In addition to being expensive, lithium-ion batteries contain a flammable electrolyte, making them less than ideal for transportation. So, Sadoway started studying the periodic table, looking for cheap, Earth-abundant metals that might be able to substitute for lithium. The commercially dominant metal, iron, doesn't have the right electrochemical properties for an efficient battery, he says. But the second-most-abundant metal in the marketplace—and actually the most abundant metal on Earth—is aluminum. "So, I said, well, let's just make that a bookend. It's gonna be aluminum," he says.

Then came deciding what to pair the aluminum with for the other electrode, and what kind of electrolyte to put in between to carry ions back and forth during charging and discharging. The cheapest of all the non-metals is sulfur, so that became the second electrode material. As for the electrolyte, "we were not going to use the volatile, flammable organic liquids" that have sometimes led to dangerous fires in cars and other applications of lithium-ion batteries, Sadoway says. They tried some polymers but ended

The three primary constituents of the battery are aluminum (left), sulfur (center), and rock salt crystals (right). All are domestically available Earth-abundant materials not requiring a global supply chain. Photo: Rebecca Miller up looking at a variety of molten salts that have relatively low melting points—close to the boiling point of water, as opposed to nearly 1,000 degrees Fahrenheit for many salts. "Once you get down to near body temperature, it becomes practical" to make batteries that don't require special insulation and anticorrosion measures, he says.

The three ingredients they ended up with are cheap and readily available—aluminum, no different from the foil at the supermarket; sulfur, which is often a waste product from processes such as petroleum refining; and widely available salts. "The ingredients are cheap, and the thing is safe—it cannot burn," Sadoway says.

In their experiments, the team showed that the battery cells could endure hundreds of cycles at exceptionally high charging rates, with a projected cost per cell of about one-sixth that of comparable lithium-ion cells. They showed that the charging rate was highly dependent on the working temperature, with 110 degrees Celsius (230 degrees Fahrenheit) showing 25 times faster rates than 25°C (77°F).

Surprisingly, the molten salt the team chose as an electrolyte simply because of its low melting point turned out to have a fortuitous advantage. One of the biggest problems in battery reliability is the formation of dendrites, which are narrow spikes of metal that build up on one electrode and eventually grow across to contact the other electrode, causing a short-circuit and hampering efficiency. But this particular salt, it happens, is very good at preventing that malfunction.

The chloro-aluminate salt they chose "essentially retired these runaway dendrites, while also allowing for very rapid charging," Sadoway says. "We did experiments at very high charging rates, charging in less than a minute, and we never lost cells due to dendrite shorting."

"It's funny," he says, because the whole focus was on finding a salt with the lowest melting point, but the catenated chloro-aluminates they ended up with turned out to be resistant to the shorting problem. "If we had started off with trying to prevent dendritic shorting, I'm not sure I would've known how to pursue that," Sadoway says. "I guess it was serendipity for us."

What's more, the battery requires no external heat source to maintain its operating temperature. The heat is naturally produced electrochemically by the charging and discharging of the battery. "As you charge, you generate heat, and that keeps the salt from freezing. And then, when you discharge, it also generates heat," Sadoway says. In a typical installation used for load-leveling at a solar generation facility, for example, "you'd store electricity when the sun is shining, and then you'd draw electricity after dark, and you'd do this every day. And that charge-idle-discharge-idle is enough to generate enough heat to keep the thing at temperature."

This new battery formulation, he says, would be ideal for installations of about the size needed to power a single home or small to medium business, producing on the order of a few tens of kilowatt-hours of storage capacity.

For larger installations, up to utility scale of tens to hundreds of megawatt-hours, other technologies might be more effective, including the liquid-metal batteries Sadoway and his students developed several years ago and which formed the basis for a spinoff company called Ambri, which hopes to deliver its first products within the next year. For that invention, Sadoway was recently awarded this year's European Inventor Award.

The smaller scale of the aluminum-sulfur batteries would also make them practical for uses such as electric vehicle charging stations, Sadoway says. He points out that when electric vehicles become common enough on the roads that several cars want to charge up at once, as happens today with gasoline fuel pumps, "if you try to do that with batteries and you want rapid charging, the amperages are just so high that we don't have that amount of amperage in the line that feeds the facility." So having a battery system such as this to store power and then release it quickly when needed could eliminate the need for installing expensive new power lines to serve these chargers.

The new technology is already the basis for a new spinoff company called Avanti, which has licensed the patents to the system, co-founded by Sadoway and Luis Ortiz '96, ScD '00, who was also a co-founder of Ambri. "The first order of business for the company is to demonstrate that it works at scale," Sadoway says, and then subject it to a series of stress tests, including running through hundreds of charging cycles.

Would a battery based on sulfur run the risk of producing the foul odors associated with some forms of sulfur? Not a chance, Sadoway says. "The rotten-egg smell is in the gas, hydrogen sulfide. This is elemental sulfur, and it's going to be enclosed inside the cells." If you were to try to open up a lithium-ion cell in your kitchen, he says (and please don't try this at home!), "the moisture in the air would react and you'd start generating all sorts of foul gases as well. These are legitimate questions, but the battery is sealed, it's not an open vessel. So I wouldn't be concerned about that."

The research team included members from Peking University, Yunnan University, and the Wuhan University of Technology, in China; the University of Louisville, in Kentucky; the University of Waterloo, in Canada; Argonne National Laboratory, in Illinois; and MIT. The work was supported by the MIT Energy Initiative, the MIT Deshpande Center for Technological Innovation, and ENN Group.

David L. Chandler, MIT News Office

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Details of the work can be found in:

Q. Pang, J. Meng, S. Gupta, X. Hong, C.Y. Kwok, J. Zhao, Y. Jin, L. Xu, O. Karahan, Z. Wang, S. Toll, L. Mai, L.F. Nazar, M. Balasubramanian, B. Narayanan, and D.R. Sadoway. "Fast-charging aluminium–chalcogen batteries resistant to dendritic shorting." *Nature*, vol. 608, pages 704-711, 2022. Online: doi.org/10.1038/s41586-022-04983-9.

Energy transition could leave fossil energy producers and investors with costly stranded assets

An oil rig in the Santa Barbara Channel. Photo: dirtsailor2003/Flickr

A 2021 study in the journal *Nature* found that in order to avert the worst impacts of climate change, most of the world's known fossil fuel reserves must remain untapped. According to the study, 90% of coal and nearly 60% of oil and natural gas must be kept in the ground in order to maintain a 50% chance that global warming will not exceed 1.5 degrees Celsius above preindustrial levels.

As the world transitions away from greenhouse-gas-emitting activities to keep global warming well below 2°C (and ideally 1.5°C) in alignment with the Paris Agreement on climate change, fossil fuel companies and their investors face growing financial risks (known as transition risks), including the prospect of ending up with massive stranded assets. This ongoing transition is likely to significantly scale back fossil fuel extraction and coal-fired power plant operations, exacting steep costs—most notably asset value losses—on fossil-energy producers and shareholders.

Now, a new study in the journal *Climate Change Economics* led by researchers at the MIT Joint Program on the Science and Policy of Global Change estimates the current global asset value of untapped fossil fuels through 2050 under four increasingly ambitious climate-policy scenarios. The least-ambitious scenario ("Paris Forever") assumes that initial Paris Agreement greenhouse gas emissions-reduction pledges are upheld in perpetuity; the most stringent scenario ("Net Zero 2050") adds coordinated international policy instruments aimed at achieving global net-zero emissions by 2050.

Powered by the MIT Joint Program's model of the world economy with detailed representation of the energy sector and energy industry assets over time, the study finds that the global net present value of untapped fossil fuel output through 2050 relative to a reference "No Policy" scenario ranges from $21.5 trillion (Paris Forever) to $30.6 trillion (Net Zero 2050). The estimated global net present value of stranded assets in coal power generation through 2050 ranges from $1.3 to $2.3 trillion.

"The more stringent the climate policy, the greater the volume of untapped fossil fuels, and hence the higher the potential asset value loss for fossil-fuel owners and investors," says Henry Chen, a research scientist at the MIT Joint Program and the study's lead author.

The global economy-wide analysis presented in the study provides a more fine-grained assessment of stranded assets than those performed in previous studies. Firms and financial institutions may combine the MIT analysis with details on their own investment portfolios to assess their exposure to climate-related transition risk.

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

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To read the 2021 article in *Nature*, go to nature.com/articles/s41586-021-03821-8. For information on the MIT Joint Program's model of the world economy, see globalchange.mit.edu/research/research-tools/human-system-model.

To read the 2022 article by the Joint Program team, see the following:

Y.-H. H. Chen, E. Landry, and J.M. Reilly. "An economy-wide framework for assessing the stranded assets of energy production sector under climate policies." *Climate Change Economics*, July 2022. Online: doi.org/10.1142/S2010007823500033.

Reversing the charge: Battery power from electric vehicles to the grid could open a fast lane to a net-zero future

Owners of electric vehicles (EVs) are accustomed to plugging into charging stations at home and at work and filling up their batteries with electricity from the power grid. But someday soon, when these drivers plug in, their cars will also have the capacity to reverse the flow and send electrons back to the grid. As the number of EVs climbs, the fleet's batteries could serve as a cost-effective, large-scale energy source, with potentially dramatic impacts on the energy transition, according to a new paper published by an MIT team in the journal *Energy Advances*.

"At scale, vehicle-to-grid (V2G) can boost renewable energy growth, displacing the need for stationary energy storage and decreasing reliance on firm [always-on] generators such as natural gas that are traditionally used to balance wind and solar intermittency," says Jim Owens, lead author and a doctoral student in the MIT Department of Chemical Engineering. Additional authors include Emre Gençer, a principal research scientist at the MIT Energy Initiative (MITEI), and Ian Miller, a research specialist for MITEI at the time of the study.

The group's work is the first comprehensive, systems-based analysis of future power systems, drawing on a novel mix of computational models integrating such factors as carbon emission goals, variable renewable energy (VRE) generation, and costs of building energy storage, production, and transmission infrastructure.

"We explored not just how EVs could provide service back to the grid—thinking of these vehicles almost like energy storage on wheels—but also the value of V2G applications to the entire energy system and if EVs could reduce the cost of decarbonizing the power system," says Gençer. "The results were surprising; I personally didn't believe we'd have so much potential here."

Displacing new infrastructure

As the United States and other nations pursue stringent goals to limit carbon emissions, electrification of transportation has taken off, with the rate of EV adoption rapidly accelerating. (Some projections show EVs supplanting internal combustion vehicles over the next 30 years.) With the rise of emission-free driving, though, there will be increased demand for energy. "The challenge is ensuring both that there's enough electricity to charge the vehicles and that this electricity is coming from renewable sources," says Gençer.

But solar and wind energy is intermittent. Without adequate backup for these sources, such as stationary energy storage facilities using lithium-ion batteries, for instance, or large-scale, natural gas- or hydrogen-fueled power plants, achieving clean energy goals will prove elusive.

More vexing, costs for building the necessary new energy infrastructure runs to the hundreds of billions.

This is precisely where V2G can play a critical, and welcome, role, the researchers reported. In their case study of a theoretical New England power system meeting strict carbon constraints, for instance, the team found that participation from just 13.9% of the region's eight million light-duty (passenger) EVs displaced 14.7 gigawatts of stationary energy storage. This added up to $700 million in savings—the anticipated costs of building new storage capacity.

Their paper also described the role EV batteries could play at times of peak demand, such as hot summer days. "V2G technology has the ability to inject electricity back into the system to cover these episodes, so we don't need to install or invest in additional natural gas

In the future, electric vehicles could boost renewable energy growth by serving as "energy storage on wheels"—charging their batteries from the power grid as they do now, as well as reversing the flow to send power back and provide support services to the grid. Image: Ehsan Faridi and Ehsan Keshavarzi, Inmywork Studio turbines," says Owens. "The way that EVs and V2G can influence the future of our power systems is one of the most exciting and novel aspects of our study."

Modeling power

To investigate the impacts of V2G on their hypothetical New England power system, the researchers integrated their EV travel and V2G service models with two of MITEI's existing modeling tools: the Sustainable Energy System Analysis Modeling Environment (SESAME) to project vehicle fleet and electricity demand growth and GenX, which models the investment and operation costs of electricity generation, storage, and transmission systems. They incorporated such inputs as different EV participation rates, costs of generation for conventional and renewable power suppliers, charging infrastructure upgrades, travel demand for vehicles, changes in electricity demand, and EV battery costs.

Their analysis found benefits from V2G applications in power systems (in terms of displacing energy storage and firm generation) at all levels of carbon emission restrictions, including one with no emissions caps at all. However, their models suggest that V2G delivers the greatest value to the power system when carbon constraints are most aggressive—at 10 grams of carbon dioxide per kilowatt-hour load. Total system savings from V2G ranged from \$183 million to \$1,326 million, reflecting EV participation rates between 5% and 80%.

"Our study has begun to uncover the inherent value V2G has for a future power system, demonstrating that there is a lot of money we can save that would otherwise be spent on storage and firm generation," says Owens.

Harnessing V2G

For scientists seeking ways to decarbonize the economy, the vision of millions of EVs parked in garages or in office spaces and plugged into the grid for 90% of their operating lives proves an irresistible provocation. "There is all this storage sitting right there, a huge available capacity that will only grow, and it is wasted unless we take full advantage of it," says Gençer.

This is not a distant prospect. Startup companies are currently testing software that would allow two-way communication between EVs and grid operators or other entities. With the right algorithms, EVs would charge from and dispatch energy to the grid according to profiles tailored to each car owner's needs, never depleting the battery and endangering a commute.

"We don't assume all vehicles will be available to send energy back to the grid at the same time, at 6 p.m. for instance, when most commuters return home in the early evening," says Gençer. He believes that the vastly varied schedules of EV drivers will make enough battery power available to cover spikes in electricity use over an average 24-hour period. And there are other potential sources of battery power down the road, such as electric school buses that are employed only for short stints during the day and then sit idle.

The MIT team acknowledges the challenges of V2G consumer buy-in. While EV owners relish a clean, green drive, they may not be as enthusiastic handing over access to their car's battery to a utility or an aggregator working with power system operators. Policies and incentives would help.

"Since you're providing a service to the grid, much as solar panel users do, you could be paid for your participation, and paid at a premium when electricity prices are very high," says Gençer.

"People may not be willing to participate 'round the clock, but if we have blackout scenarios like in Texas last year, or hot-day congestion on transmission lines, maybe we can turn on these vehicles for 24 to 48 hours, sending energy back to the system," adds Owens. "If there's a power outage and people wave a bunch of money at you, you might be willing to talk."

"Basically, I think this comes back to all of us being in this together, right?" says Gençer. "As you contribute to society by giving this service to the grid, you will get the full benefit of reducing system costs, and also help to decarbonize the system faster and to a greater extent."

Actionable insights

Owens, who is building his dissertation on V2G research, is now investigating the potential impact of heavy-duty electric vehicles in decarbonizing the power system. "The last-mile delivery trucks of companies like Amazon and FedEx are likely to be the earliest adopters of EVs," Owen says. "They are appealing because they have regularly scheduled routes during the day and go back to the depot at night, which makes them very useful for providing electricity and balancing services in the power system."

Owens is committed to "providing insights that are actionable by system planners, operators, and to a certain extent, investors," he says. His work might come into play in determining what kind of charging infrastructure should be built, and where.

"Our analysis is really timely because the EV market has not yet been developed," says Gençer. "This means we can share our insights with vehicle manufacturers and system operators—potentially influencing them to invest in V2G technologies, avoiding the costs of building utility scale storage, and enabling the transition to a cleaner future. It's a huge win, within our grasp."

The research for this study was funded by MITEI's Future Energy Systems Center.

Leda Zimmerman, MITEI Correspondent

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For more information, please see the following:

J. Owens, I. Miller, and E. Gençer. "Can vehicle-to-grid facilitate the transition to low carbon energy systems?" *Energy Advances*, October 2022. Online: doi.org/10.1039/d2ya00204c.

Michael Howland gives wind energy a lift

Michael Howland was in his office at MIT, watching real-time data from a wind farm seven thousand miles away in northwest India, when he noticed something odd: Some of the turbines weren't producing the expected amount of electricity.

Howland, the Esther and Harold E. Edgerton Assistant Professor of Civil and Environmental Engineering, studies the physics of the Earth's atmosphere and how that information can optimize renewable energy systems. To accomplish this, he and his team develop and use predictive models, supercomputer simulations, and real-life data from wind farms, such as the one in India.

The global wind power market is one of the most cost-competitive and resilient power sources across the world, the Global Wind Energy Council reported last year. The year 2020 saw record growth in wind power capacity, thanks to a surge of installations in China and the United States. Yet wind power needs to grow three times faster in the coming decade to address the worst impacts of climate change and achieve federal and state climate goals, the report says.

"Optimal wind farm design and the resulting cost of energy are dependent on the wind," Howland says. "But wind farms are often sited and designed based on short-term historical climate records."

In October 2021, Howland received a Seed Fund grant from the MIT Energy Initiative (MITEI) to account for how climate change might affect the wind of the future. "Our initial results suggest that considering the uncertainty in the winds in the design and operation of wind farms can lead to more reliable energy production," he says.

Most recently, Howland and his team came up with a model that predicts the power produced by each individual turbine based on the physics of the wind farm as a whole. The model can inform decisions that may boost a farm's overall output.

Assistant Professor Michael Howland of civil and environmental engineering aims to get more electricity out of renewable energy systems—and to prepare young scientists and engineers with the training and tools they need to tackle climate change mitigation. Photo: Gretchen Ertl

The state of the planet

Growing up in a suburb of Philadelphia, the son of neuroscientists, Howland's childhood wasn't especially outdoorsy. Later, he'd become an avid hiker with a deep appreciation for nature, but a ninth-grade class assignment made him think about the state of the planet, perhaps for the first time.

A history teacher had asked the class to write a report on climate change. "I remember arguing with my high school classmates about whether humans were the leading cause of climate change, but the teacher didn't want to get into that debate," Howland recalls. "He said climate change was happening, whether or not you accept that it's anthropogenic, and he wanted us to think about the impacts of global warming, and solutions. I was one of his vigorous defenders."

As part of a research internship after his freshman year of college, Howland visited a wind farm in Iowa, where wind produces more than half of the state's electricity. "The turbines look tall from the highway, but when you're underneath them, you're really struck by their scale," he says. "That's where you get a sense of how colossal they really are." (Not a fan of heights, Howland opted not to climb the turbine's internal ladder to snap a photo from the top.)

After receiving an undergraduate degree from Johns Hopkins University and master's and PhD degrees in mechanical engineering from Stanford University, he joined MIT's Department of Civil and Environmental Engineering to focus on the intersection of fluid mechanics, weather, climate, and energy modeling. His goal is to enhance renewable energy systems.

An added bonus to being at MIT is the opportunity to inspire the next generation, much like his ninth-grade history teacher did for him. Howland's graduate-level introduction to the atmospheric boundary layer is geared primarily to engineers and physicists, but as he sees it, climate change is such a multidisciplinary and complex challenge that "every skillset that exists in human society can be relevant to mitigating it."

"There are the physics and engineering questions that our lab primarily works on, but there are also questions related to social sciences, public acceptance, policy making, and implementation," he says. "Careers in renewable energy are rapidly growing. There are far more job openings than we can hire for right now. In many areas, we don't yet have enough people to address the challenges in renewable energy and climate change mitigation that need to be solved.

"I encourage my students—really, everyone I interact with—to find a way to impact the climate change problem," he says.

Unusual conditions

In fall 2021, Howland was trying to explain the odd data coming in from India.

Based on sensor feedback, wind turbines' software-driven control systems constantly tweak the speed and the angle of the blades, and what's known as yaw—the orientation of the giant blades in relation to the wind direction.

Existing utility-scale turbines are controlled "greedily," which means that every turbine in the farm automatically turns into the wind to maximize its own power production.

Though the turbines in the front row of the Indian wind farm were reacting appropriately to the wind direction, their power output was all over the place. "Not what we would expect based on the existing models," Howland says.

These massive turbine towers stood at 100 meters, about the length of a football field, with blades the length of an Olympic swimming pool. At their highest point, the blade tips lunged almost 200 meters into the sky.

Then there's the speed of the blades themselves: The tips move many times faster than the wind, around 80 to 100 meters per second—up to a quarter or a third of the speed of sound.

Using a state-of-the-art sensor that measures the speed of incoming wind before it interacts with the massive rotors, Howland's team saw an unexpectedly complex air-flow effect. He covers the phenomenon in his class. The data coming in from India, he says, displayed "quite remarkable wind conditions stemming from the effects of Earth's rotation and the physics of buoyancy that you don't always see."

Traditionally, wind turbines operate in the lowest 10% of the atmospheric boundary layer—the so-called surface layer—affected primarily by ground conditions. The Indian turbines, Howland realized, were operating in regions of the atmosphere that turbines haven't historically accessed.

Trending taller

Howland knew that air flow interactions can persist for kilometers. The interaction of high winds with the front-row turbines was generating wakes in the air similar to the way boats generate wakes in the water.

To address this, Howland's model trades off the efficiency of upwind turbines to benefit downwind ones. By misaligning some of the upwind turbines in certain conditions, the downwind units experience less wake turbulence, increasing the overall energy output of the wind farm by as much as 1% to 3%, without requiring additional costs. If a 1.2% energy increase was applied to the world's existing wind farms, it would be the equivalent of adding more than 3,600 new wind turbines—enough to power about 3 million homes.

Even a modest boost could mean fewer turbines generating the same output, or the ability to place more units into a smaller space, because negative interactions between the turbines can be diminished.

Howland says the model can predict potential benefits in a variety of scenarios at different types of wind farms. "The part that's important and exciting is that it's not just particular to this wind farm. We can apply the collective control method across the wind farm fleet," he says, which is growing taller and wider.

By 2035, the average hub height for offshore turbines in the United States is projected to grow from 100 meters to around 150 meters—the height of the Washington Monument.

"As we continue to build larger wind turbines and larger wind farms, we need to revisit the existing practice for their design and control," Howland says. "We can use our predictive models to ensure that we build and operate the most efficient renewable generators possible."

Looking to the future

Howland and other climate watchers have reason for optimism with the passage in August 2022 of the Inflation Reduction Act, which calls for a significant investment in domestic energy production and for reducing carbon emissions by roughly 40% by 2030.

But Howland says the act itself isn't sufficient. "We need to continue pushing the envelope in research and development as well as deployment," he says. The model he created with his team can help, especially for offshore wind farms experiencing low wind turbulence and larger wake interactions.

Offshore wind can face challenges of public acceptance. Howland believes that researchers, policy makers, and the energy industry need to do more to get the public on board by addressing concerns through open public dialogue, outreach, and education.

Howland once wrote and illustrated a children's book, inspired by Dr. Seuss's *The Lorax*, that focused on renewable energy. Howland recalls his "really terrible illustrations," but he believes he was onto something. "I was having some fun helping people interact with alternative energy in a more natural way at an earlier age," he says, "and recognize that these are not nefarious technologies but remarkable feats of human ingenuity."

Deborah Halber, MITEI correspondent

Sylas Horowitz: Responsive design meets responsibility for the planet's future

MIT senior Sylas Horowitz kneeled at the edge of a marsh, tinkering with a blue and black robot about the size and shape of a shoe box and studded with lights and mini propellers.

The robot was a remotely operated vehicle (ROV)—an underwater drone slated to collect water samples from beneath a sheet of Arctic ice. But its pump wasn't working, and its intake line was clogged with sand and seaweed.

"Of course, something must always go wrong," Horowitz, a mechanical engineering major with minors in energy studies and environment and sustainability, later blogged about the Falmouth, Massachusetts, field test. By making some adjustments, Horowitz was able to get the drone functioning on site.

Through a 2020 collaboration between MIT's Department of Mechanical Engineering and the Woods Hole Oceanographic Institute (WHOI), Horowitz had been assembling and retrofitting the high-performance ROV to measure the greenhouse gas emitted by thawing permafrost.

The Arctic's permafrost holds an estimated 1,700 billion metric tons of methane and carbon dioxide: roughly 50 times the amount of carbon tied to fossil fuel emissions in 2019, according to climate research from NASA's Jet Propulsion Laboratory. WHOI scientists wanted to understand the role the Arctic plays as a greenhouse gas source or sink.

Horowitz's ROV would be deployed from a small boat in sub-freezing temperatures to measure carbon dioxide and methane in the water. Meanwhile, a flying drone would sample the air.

An MIT Student Sustainability Coalition leader and one of the first members of the MIT Environmental Solutions Initiative's Rapid Response Group, Horowitz has focused on challenges related to clean energy, climate justice, and sustainable development.

To determine the greenhouse gas emissions from thawing permafrost, MIT senior Sylas Horowitz has been developing a high-performance, remotely operated vehicle (ROV) that can collect water samples from beneath a sheet of Artic ice. Here, Horowitz field tests the Arctic ROV at Lake Whitehall, Massachusetts. Photo: Victoria Preston

In addition to the ROV, Horowitz has tackled engineering projects through D-Lab, where community partners from around the world work with MIT students on practical approaches to alleviating global poverty. Horowitz worked on fashioning waste bins out of heat-fused recycled plastic for underserved communities in Liberia. Their thesis project, also initiated through D-Lab, is designing and building user-friendly, space- and fuel-efficient firewood cook stoves to improve the lives of women in Santa Catarina Palopó in northern Guatemala.

Through the Tata-MIT GridEdge Solar Research program, they helped develop flexible, lightweight solar panels to mount on the roofs of street vendors' e-rickshaws in Bihar, India.

The thread that runs through Horowitz's projects is user-centered design that creates a more equitable society. "In the transition to sustainable energy, we want our technology to adapt to the society that we live in," they said. "Something I've learned from the D-Lab projects and also from the ROV project is that when you're an engineer, you need to understand the societal and political implications of your work, because all of that should get factored into the design."

Horowitz describes their personal mission as creating systems and technology that "serve the well-being and longevity of communities and the ecosystems we exist within.

"I want to relate mechanical engineering to sustainability and environmental justice," they said. "Engineers need to think about how technology fits into the greater societal context of people in the environment. We want our technology to adapt to the society we live in and for people to be able, based on their needs, to interface with the technology."

Imagination and inspiration

In Dix Hills, New York, a Long Island suburb, Horowitz's dad is in banking and their mom is a speech therapist. The family hiked together, but Horowitz doesn't tie their love for the natural world to any one experience. "I like to play in the dirt," they said. "I've always had a connection to nature. It was a kind of childlike wonder."

Seeing footage of the massive 2010 oil spill in the Gulf of Mexico caused by an explosion on the Deepwater Horizon oil rig—which occurred when Horowitz was around 10—was a jarring introduction to how human activity can impact the health of the planet.

Their first interest was art—painting and drawing portraits, album covers, and more recently, digital images such as a figure watering a houseplant at a window while lightning flashes outside; a neon pink jellyfish in a deep blue sea; and, for an MIT-wide Covid quarantine project, two figures watching the sun set over a Green Line subway platform.

Art dovetailed into a fascination with architecture, then shifted to engineering. In high school, Horowitz and a friend were co-captains of an all-girls robotics team. "It was just really wonderful, having this community and being able to build stuff," they said. Horowitz and another friend on the team learned they were accepted to MIT on Pi Day 2018.

Art, architecture, engineering—"it's all kind of the same," Horowitz said. "I like the creative aspect of design, being able to create things out of imagination."

Sustaining political awareness

At MIT, Horowitz connected with a like-minded community of makers. They also launched themself into taking action against environmental injustice.

In 2022, through the Student Sustainability Coalition (SSC), they encouraged MIT students to get involved in advocating for the Cambridge Green New Deal, legislation aimed at reducing emissions from new large commercial buildings such as those owned by MIT and creating a green jobs training program.

In February 2022, Horowitz took part in a sit-in in Building 3 as part of MIT Divest, a student-led initiative urging the MIT administration to divest its endowment of fossil fuel companies.

"I want to see MIT students more locally involved in politics around sustainability, not just the technology side," Horowitz said. "I think there's a lot of power from students coming together. They could be really influential."

User-oriented design

The Arctic underwater ROV had to be waterproof and withstand water temperatures as low as 5°F. It was tethered to a computer by a 150-meter-long cable that had to spool and unspool without tangling. The pump and tubing that collected water samples had to work without kinking.

"It was cool, throughout the project, to think, 'Okay, what kind of needs will these scientists have when they're out in these really harsh conditions in the Arctic? How can I make a machine that will make their field work easier?'

"I really like being able to design things directly with the users, working within their design constraints," they said.

Inevitably, snafus occurred, but in photos and videos taken the day of the Falmouth field tests, Horowitz is smiling. "Here's a fun unexpected (or maybe quite expected) occurrence!" they reported later. "The plastic mount for the shaft collar [used in the motor's power transmission] ripped itself apart!" Undaunted, Horowitz jerry-rigged a replacement out of sheet metal.

Horowitz replaced broken wires in the winch-like device that spooled the cable. They added a filter at the intake to prevent sand and plants from clogging the pump.

With a few more tweaks, the ROV was ready to descend into frigid waters. In summer 2022, it was successfully deployed on a field run in the Canadian high Arctic. A few months later, Horowitz was slated to attend OCEANS 2022 Hampton Roads, their first professional conference, to present a poster on their contribution to the WHOI permafrost research.

Ultimately, Horowitz hopes to pursue a career in renewable energy, sustainable design, or sustainable agriculture, or perhaps graduate studies in data science or econometrics to quantify environmental justice issues such as the disproportionate exposure to pollution among certain populations and the effect of systemic changes designed to tackle these issues.

After graduating in February 2023, Horowitz will spend six months with MIT International Science and Technology Initiatives (MISTI), which fosters partnerships with industry leaders and host organizations around the world.

Horowitz is thinking of working with a renewable energy company in Denmark, one of the countries they toured during a summer 2019 field trip led by the MIT Energy Initiative's Director of Education Antje Danielson. They were particularly struck by Samsø, the world's first carbon-neutral island, run entirely on renewable energy. "It inspired me to see what's out there when I was a sophomore," Horowitz said. They're ready to see where inspiration takes them next.

Deborah Halber, MITEI correspondent

3 Questions: Antje Danielson on energy education and its role in climate action

The MIT Energy Initiative (MITEI) leads energy education at MIT, developing and implementing a robust educational toolkit for MIT graduate and undergraduate students, online learners around the world, and high school students who want to contribute to the energy transition. As MITEI's director of education, Antje Danielson manages a team devoted to training the next generation of energy innovators, entrepreneurs, and policy makers. Here, she discusses new initiatives in MITEI's education program and how they are preparing students to take an active role in climate action.

Q What role are MITEI's education efforts playing in climate action initiatives at MIT, and what more could we be doing?

A This is a big question. The carbon emissions from energy are such an important factor in climate mitigation; therefore, what we do in energy education is practically synonymous with climate education. This is well illustrated in a 2018 *Nature Energy* paper by Fuso Nerini, which outlines that affordable, clean energy is related to many of the United Nations Sustainable Development Goals (SDGs)—not just SDG 7, which specifically calls for "affordable, reliable, sustainable, and modern energy for all" by 2030. There are 17 SDGs containing 169 targets, of which 113 (65%) require actions to be taken concerning energy systems.

Now, can we equate education with action? The answer is yes, but only if it is done correctly. From the behavioral change literature, we know that knowledge alone is not enough to change behavior. So, one important part of our education program is practice and experience through research, internships, stakeholder engagement, and other avenues. At a minimum, education must give the learner the knowledge, skills, and courage to be ready to jump into action, but ideally, practice is a part of the offering. We also want our learners to go out into the world and share what they know and do. If done right, education is an energy transition accelerator.

At MITEI, our learners are not just MIT students. We are creating online offerings based on residential MIT courses to train global professionals, policy makers, and students in research methods and tools to support and accelerate the energy transition. These are free and open to learners worldwide. We have five courses available now, with more to come.

Our latest program is a collaboration with MIT's Center for Energy and Environmental Policy Research (CEEPR): Climate Action through Education, or CATE. This is a teach-the-teacher program for high school curriculum and is a part of the MIT Climate Action Plan. The aim is to develop interdisciplinary, solutions-focused climate change curricula for U.S. high school teachers with components in history/social science, English/language arts, math, science, and computer science.

We are rapidly expanding our programming. In the online space, for our global learners, we are bundling courses for professional development certificates; for our undergraduates, we are redesigning the Energy Studies Minor to reflect what we have learned over the past 12 years; and for our graduate students, we are adding a new program that allows them to garner industry experience related to the energy transition. Meanwhile, CATE is creating a support network for the teachers who adopt the curriculum. We are also working on creating an energy and climate alliance with other universities around the world.

On the Institute level, I am a member of the Climate Education Working Group, a subgroup of the Climate Nucleus, where we discuss and will soon recommend further climate action the Institute can take. Stay tuned for that.

Q You mentioned that you are leading an effort to create a consortium of energy and climate education programs at universities around the world. How does this effort fit into MITEI's educational mission?

A Yes, we are currently calling it the "Energy and Climate Education Alliance." The background to this is that the problem we are facing—transitioning the entire global energy system from high carbon emissions to low, no, and negative carbon emissions—is global, huge, and urgent. Following the proverbial "many hands make light work," we believe that the success of this very complex task is accomplished quicker with more participants. There is, of course, more to this as well. The complexity of the problem is such that (1) MIT doesn't have all the expertise needed to accomplish the educational needs of the climate and energy crisis, (2) there is a definite local and regional component to capacity

Antje Danielson is director of education at the MIT Energy Initiative. Photo: Gretchen Ertl building, and (3) collaborations with universities around the world will make our mission-driven work more efficient. Finally, these collaborations will be advantageous for our students as they will be able to learn from real-world case studies that are not U.S.-based and maybe even visit other universities abroad, do internships, and engage in collaborative research projects. Also, students from those universities will be able to come here and experience MIT's unique intellectual environment.

Right now, we are very much in the beginning stages of creating the Alliance. We have signed a collaboration agreement with the Technical University of Berlin, Germany, and are engaged in talks with other European and Southeast Asian universities. Some of the collaborations we are envisioning relate to course development, student exchange, collaborative research, and course promotion. We are very excited about this collaboration. It fits well into MIT's ambition to take climate action outside of the university, while still staying within our educational mission.

Q It is clear to me from this conversation that MITEI's education program is undertaking a number of initiatives to prepare MIT students and interested learners outside of the Institute to take an active role in climate action. But, the reality is that despite our rapidly changing climate and the immediate need to decarbonize our global economy, climate denialism and a lack of climate and energy understanding persist in the greater global population. What do you think must be done, and what can MITEI do, to increase climate and energy literacy broadly?

A I think the basic problem is not necessarily a lack of understanding but an abundance of competing issues that people are dealing with every day. Poverty, personal health, unemployment, inflation, pandemics, housing, wars—all are very immediate problems people have. And climate change is perceived to be in the future.

The United States is a very bottom-up country, where corporations offer what people buy, and politicians advocate for what voters want and what money buys. Of course, this is overly simplified, but as long as we don't come up with mechanisms to achieve a monumental shift in consumer and voter behavior, we are up against these immediate pressures. However, we are seeing some movement in this area due to rising gas and heating oil prices and the many natural disasters we are encountering now. People are starting to understand that climate change will hit their pocketbook, whether or not we have a carbon tax. The recent Florida hurricane damage, wildfires in the west, extreme summer temperatures, frequent droughts, increasing numbers of poisonous and disease-carrying insects—they all illustrate the relationship between climate change, health, and financial damage. Fewer and fewer people will be able to deny the existence of climate change because they will either be directly affected or know someone who is.

The question is one of speed and scale. The more we can help to make the connections even more visible and understood, the faster we get to the general acceptance that this is real. Research projects like CEEPR's Roosevelt Project, which develops action plans to help communities deal with industrial upheaval in the context of the energy transition, are contributing to this effect, as are studies related to climate change and national security. This is a fast-moving world, and our research findings need to be translated as we speak. A real problem in education is that we have the tendency to teach the tried and true. Our education programs have to become much nimbler, which means curricula have to be updated frequently, and that is expensive. And of course, the speed and magnitude of our efforts are dependent on the funding we can attract, and fundraising for education is more difficult than fundraising for research.

However, let me pivot: You alluded to the fact that this is a global problem. The immediate pressures of poverty and hunger are a matter of survival in many parts of the world, and when it comes to surviving another day, who cares if climate change will render your fields unproductive in twenty years? Or if the weather turns your homeland into a lake, will you think about lobbying your government to reduce carbon emissions, or will you ask for help to rebuild your existence? On the flip side, politicians and government authorities in those areas have to deal with extremely complex situations, balancing local needs with global demands. We should learn from them. What we need is to listen. What do these areas of the world need most and how can climate action be included in the calculations? The Global Commission to End Energy Poverty, a collaboration between MITEI and the Rockefeller Foundation to bring electricity to the billion people across the globe who currently live without it, is a good example of what we are already doing. Both our online education program and the Energy and Climate Education Alliance aim to go in this direction.

The struggle and challenge to solve climate change can be pretty depressing, and there are many days when I feel despondent about the speed and progress we are making in saving the future of humanity. But, the prospect of contributing to such a large mission, even if the education team can only nudge us a tiny bit away from the business-as-usual scenario, is exciting. In particular, working on an issue like this at MIT is amazing. So much is happening here, and there don't seem to be intellectual limits; in fact, thinking big is encouraged. It is very refreshing when one has encountered the old "you can't do this" too often in the past. I want our students to take this attitude with them and go out there and think big.

Kelley Travers, MITEI

NOTES

You can read more about the CATE program on page 31, and you can download the *Nature* article by Francesco Fuso Nerini and collaborators at doi.org/10.1038/s41560-017-0036-5.

New multidisciplinary climate change curriculum for high schools aims to engage and mobilize teachers and students

Photos, clockwise from left: Eyoel Kahssay, Kenny Eliason, Abbie Trayler-Smith, and Mark König

Several years ago, Christopher Knittel's father, then a math teacher, shared a mailing he had received at his high school. When he opened the packet, alarm bells went off for Knittel, who is the George P. Shultz Professor of Energy Economics at the MIT Sloan School of Management and the deputy director for policy at the MIT Energy Initiative (MITEI). "It was a slickly produced package of materials purporting to show how to teach climate change," he says. "In reality, it was a thinly veiled attempt to kindle climate change denial."

Knittel was especially concerned to learn that this package had been distributed to schools nationwide. "Many teachers in search of information on climate change might use this material because they are not in a position to judge its scientific validity," says Knittel, who is also the faculty director of the MIT Center for Energy and Environmental Policy Research (CEEPR). "I decided that MIT, which is committed to true science, was in the perfect position to develop its own climate change curriculum."

Today, Knittel is spearheading the Climate Action Through Education (CATE) program, a curriculum rolling out in pilot form this year in more than a dozen Massachusetts high schools, and eventually in high schools across the United States. To spur its broad adoption, says Knittel, the CATE curriculum features a unique suite of attributes: the creation of climate-based lessons for a range of disciplines beyond science, adherence to state-based education standards to facilitate integration into established curricula, material connecting climate change impacts to specific regions, and opportunities for students to explore climate solutions.

CATE aims to engage both students and teachers in a subject that can be overwhelming. "We will be honest about the threats posed by climate change but also give students a sense of agency that they can do something about this," says Knittel. "And for the many teachers—especially non-science teachers—starved for knowledge and background material, CATE offers resources to give them confidence to implement our curriculum."

Partnering with teachers

From the outset, CATE sought guidance and hands-on development help from educators. Project manager Aisling O'Grady surveyed teachers to learn about their experiences teaching about climate and to identify the kinds of resources they lacked. She networked with MIT's K-12 education experts and with Antje Danielson, MITEI director of education, "bouncing ideas off of them to shape the direction of our effort," she says.

She gained two critical insights from this process: "I realized that we needed practicing high school teachers as curriculum developers and that they had to represent different subject areas, because climate change is inherently interdisciplinary," she says. This echoes the philosophy behind MITEI's Energy Studies Minor, she remarks, which includes classes from MIT's different schools. "While science helps us understand and find solutions for climate change, it touches so many other areas, from economics, policy, environmental justice and politics, to history and literature."

In line with this thinking, CATE recruited Massachusetts teachers representing key subject areas in the high school curriculum: Amy Block, a full-time math teacher, and Lisa Borgatti, a full-time science teacher, both at the Governor's Academy in Byfield; and Kathryn Teissier du Cros, a full-time language arts teacher at Newton North High School.

The fourth member of this cohort, Michael Kozuch, is a full-time history teacher at Newton South High School, where he has worked for 24 years. Kozuch became engaged with environmental issues 15 years ago, introducing an elective in sustainability at Newton South. He serves on the coordinating committee for the Climate Action Network at the Massachusetts Teachers Association. He also is president of Earth Day Boston and organized Boston's 50th anniversary celebration of Earth Day. When he learned that MIT was seeking teachers to help develop a climate education curriculum, he immediately applied.

"I've heard time and again from teachers across the state that they want to incorporate climate change into the curriculum but don't know how to make it work, given lesson plans and schedules geared toward preparing students for specific tests," says Kozuch. "I knew that for a climate curriculum to succeed, it had to be part of an integrated approach."

Using climate as a lens

Over the course of a year, Kozuch and fellow educators created units that fit into their pre-existing syllabi but were woven through with relevant climate change themes. Kozuch already had some experience in this vein, describing the role of the Industrial Revolution in triggering the use of fossil fuels and the greenhouse gas emissions that resulted. For CATE, Kozuch explored additional ways of shifting focus in covering U.S. history. There are, for instance, lessons looking at westward expansion in terms of land use, expulsion of Indigenous people, and environmental justice, and at the Baby Boom period and the emergence of the environmental movement.

In English/language arts, there are units dedicated to explaining terms used by scientists and policy makers, such as "anthropogenic," as well as lessons devoted to climate change fiction and to student-originated sustainability projects.

The science and math classes work independently but also dovetail. For instance, there are science lessons that demystify the greenhouse effect, utilizing experiments to track fossil fuel emissions, which link to math lessons that calculate and graph the average rate of change of global carbon emissions. To make these classes even more relevant, there are labs where students compare carbon emissions in Massachusetts to those of a neighboring state, and where they determine the environmental and economic costs of plugging in electric devices in their own homes.

Throughout this curriculum-shaping process, O'Grady and the teachers sought feedback from MIT faculty from a range of disciplines, including David McGee, associate professor in the Department of Earth, Atmospheric and Planetary Sciences. With the help of CATE undergraduate researcher Heidi Li '22, the team held a focus group with the Sustainable Energy Alliance, an undergraduate student club. In spring 2022, CATE convened a professional development workshop in collaboration with the Massachusetts Teachers Association Climate Action Network, Earth Day Boston, and MIT's Office of Government and Community Relations, sponsored by the Beker Foundation, to evaluate 15 discrete CATE lessons. One of the workshop participants, Gary Smith, a teacher from St. John's Preparatory School in Danvers, Massachusetts, signed on as a volunteer science curriculum developer.

"We had a diverse pool of teachers who thought the lessons were fantastic but among their suggestions noted that their student cohorts included new English speakers, who needed simpler language and more pictures," says O'Grady. "This was extremely useful to us, and we revised the curriculum because we want to reach students at every level of learning."

Reaching all the schools

Now, the CATE curriculum is in the hands of a cohort of Massachusetts teachers. Each of these educators will test one or more of the lessons and lab activities over the next year, checking in regularly with MIT partners to report on their classroom experiences. The CATE team is building a Climate Education Resource Network of MIT graduate students, postdocs, and research staff who can answer teachers' specific climate questions and help them find additional resources or data sets. Additionally, teachers will have the opportunity to attend two in-person cohort meetings and be paired with graduate student "climate advisors."

In spring 2023, in honor of Earth Day, O'Grady and Knittel want to bring CATE first adopters—high school teachers, students, and their families—to campus. "We envision professors giving mini lectures, youth climate groups discussing how to get involved in local actions, and our team members handing out climate change packets to students to spark conversations with their families at home," says O'Grady.

By creating a positive experience around their curriculum in these pilot schools, the CATE team hopes to promote its dissemination to many more Massachusetts schools in 2023. The team plans on enhancing lessons, offering more paths to integration in high school studies, and creating a companion resource website for teachers. Knittel wants to establish footholds in school after school, in Massachusetts and beyond.

"I plan to spend a lot of my time convincing districts and states to adopt," he says. "If one teacher tells another that the curriculum is useful, with touchpoints in different disciplines, that's how we get a foot in the door."

Knittel is not shying away from places where "climate change is a politicized topic." He hopes to team up with universities in states where there might be resistance to including such lessons in schools to develop the curriculum. Although his day job involves computing household-level carbon footprints, determining the relationship between driving behavior and the price of gasoline, and promoting wise climate policy, Knittel plans to push CATE as far as he can. "I want this curriculum to be adopted by everybody—that's my goal," he says.

"In one sense, I'm not the natural person for this job," he admits. "But I share the mission and passion of MITEI and CEEPR for decarbonizing our economy in ways that are socially equitable and efficient, and part of doing that is educating Americans about the actual costs and consequences of climate change."

The CATE program is sponsored by MITEI, CEEPR, and the MIT Vice President for Research. For more information, please go to ceepr.mit.edu/cate.

Leda Zimmerman, MITEI correspondent

Shrinky Dinks, nail polish, and smelly bacteria: High school students spend their summer building a low-cost fuel cell

In a lab on the fourth floor of MIT's Building 56, a group of Massachusetts high school students gathered around a device that measures conductivity.

Vincent Nguyen, 15, from Saugus, thought of the times the material on their sample electrode flaked off the moment they took it out of the oven. Or how the electrode would fold weirdly onto itself. The big fails were kind of funny but discouraging. The students had worked for a month, experimenting with different materials, and 17-year-old Brianna Tong of Malden wondered if they'd finally gotten it right: Would their electrode work well enough to power a microbial fuel cell?

The students secured their electrode with alligator clips, someone hit start, and the teens watched anxiously as the device searched for even the faintest electrical current.

Capturing electrons from bacteria

In July 2022, Tong, Nguyen, and six other students from Malden Catholic High School commuted between the lab of MIT chemical engineer Ariel L. Furst and their school's chemistry lab. Their goal was to fashion electrodes for low-cost microbial fuel cells—miniature bioreactors that generate small amounts of electricity by capturing electrons transferred from living microbes. These devices can double as electrochemical sensors.

Furst, the Paul M. Cook Career Development Professor of Chemical Engineering, uses a mix of electrochemistry, microbial engineering, and materials science to address challenges in human health and clean energy. "The goal of all of our projects is to increase sustainability, clean energy, and health equity globally," she says.

Electrochemical sensors are powerful, sensitive detection and measurement tools. Typically, their electrodes need to be built in precisely engineered environments. "Thinking about ways of making devices without needing a clean room is important for coming up with inexpensive devices that can be deployed in low-resource settings under non-ideal conditions," Furst says.

For 17-year-old Angelina Ang of Everett, the project illuminated the significance of "coming together to problem-solve for a healthier and more sustainable Earth," she says. "It made me realize that we hold the answers to fix our dying planet."

With the help of a children's toy called Shrinky Dinks®, carbon-based materials, nail polish, and a certain smelly bacterium, the students got—literally—a trial-by-fire introduction to the scientific method. At one point, one of their experimental electrodes burst into flames. Other results were more promising.

The students took advantage of the electrical properties of a bacterium—*Shewanella oneidensis*—that's been called nature's microscopic power plant. As part of their metabolism, *Shewanella oneidensis* generate electricity by oxidizing organic matter. In essence, they spit out electrons. Put enough together, and you get a few milliamps.

To build bacteria-friendly electrodes, one of the first things the students did was culture *Shewanella*. They learned how to

Last summer, students from Malden Catholic High School worked with MIT chemical engineer Ariel Furst to create electrodes for low-cost microbial fuel cells. Pictured from left to right: Chengxiang (Eric) Lou, Christian Ogata, Angelina Ang, Phuc (Vincent) Nguyen, Ariel Furst, MaryKatherine Zablocki, Kenneth Ramirez, Brianna Tong, Isaac Toscano, and Seamus McGuire. Photo: Gretchen Ertl

Brianna Tong (left) and Angelina Ang add an electroactive solution to their electrode so that they can measure its conductivity. Next, they will use sophisticated testing equipment in Ariel Furst's lab to see if the electrode successfully conducts electricity. Photo: Gretchen Ertl

pour a growth medium into petri dishes where the reddish, normally lake-living bacteria could multiply. The microbes, Furst notes, are a little stinky, like cabbage. "But we think they're really cool," she says.

With the right engineering, *Shewanella* can produce electric current when they detect toxins in water or soil. They could be used for bioremediation of wastewater. Low-cost versions could be useful for areas with limited or no access to reliable electricity and clean water.

Next-generation chemists

The Malden Catholic-MIT program resulted from a fluke encounter between Furst and a Malden Catholic parent.

Mary-Margaret O'Donnell-Zablocki, then a medicinal chemist at a Kendall Square biotech startup, met Furst through a mutual friend. She asked Furst if she'd consider hosting high school chemistry students in her lab for the summer.

Furst was intrigued. She traces her own passion for science to a program she'd happened upon between her junior and senior years in high school in St. Louis. The daughter of a software engineer and a businesswoman, Furst was casting around for potential career interests when she came across a summer program that enlisted scientists in academia and private research to introduce high school students and teachers to aspects of the scientific enterprise.

"That's when I realized that research is not like a lab class where there's an expected outcome," Furst recalls. "It's so much cooler than that."

Using startup funding from an MIT Energy Initiative seed grant, Furst developed a curriculum with Malden Catholic chemistry teacher Seamus McGuire, and students were invited to apply. In addition to Tong, Ang, and Nguyen, participants included Chengxiang Lou, 18, from China; Christian Ogata, 14, of Wakefield; Kenneth Ramirez, 17, of Everett; Isaac Toscano, 17, of Medford; and MaryKatherine Zablocki, 15, of Revere and Wakefield. O'Donnell-Zablocki was surprised—and pleased—when her daughter applied to the program and was accepted.

Furst notes that women are still underrepresented in chemical engineering. She was particularly excited to mentor young women through the program.

A conductive ink

The students were charged with identifying materials that had high conductivity, low resistance, were a bit soluble, and—with the help of a compatible "glue"—were able to stick to a substrate.

Furst showed the Malden Catholic crew Shrinky Dinks–a common polymer popularized in the 1970s as a craft material that, when heated in a toaster oven, shrinks to a third of its size and becomes thicker and more rigid. Electrodes based on Shrinky Dinks would cost pennies, making it an ideal, inexpensive material for microbial fuel cells that could monitor, for instance, soil health in low- and middle-income countries.

"Right now, monitoring soil health is problematic," Furst says. "You have to collect a sample and bring it back to the lab to analyze in expensive equipment. But if we have these little devices that cost a couple of bucks each, we can monitor soil health remotely."

After a crash course in conductive carbon-based inks and solvent glues, the students went off to Malden Catholic to figure out what materials they wanted to try.

Tong rattled them off: carbon nanotubes, carbon nanofibers, graphite powder, activated carbon. Potential solvents to help glue the carbon to the Shrinky Dinks included nail polish, corn syrup, and embossing ink, to name a few. They tested and retested. When they hit a dead end, they revised their hypotheses.

They tried using a 3D printed stencil to daub the ink-glue mixture onto the

Shrinky Dinks. They hand-painted them. They tried printing stickers. They worked with little squeegees. They tried scooping and dragging the material. Some of their electro-materials either flaked off or wouldn't stick in the heating process.

"Embossing ink never dried after baking the Shrinky Dink," Ogata recalls. "In fact, it's probably still liquid! And corn syrup had a tendency to boil. Seeing activated carbon ignite or corn syrup boiling in the convection oven was quite the spectacle."

"After the electrode was out of the oven and cooled down, we would check the conductivity," says Tong, who plans to pursue a career in science. "If we saw there was a high conductivity, we got excited and thought those materials worked."

The moment of truth came in Furst's MIT lab, where the students had access to more sophisticated testing equipment. Would their electrodes conduct electricity?

Many of them didn't. Tong says, "At first, we were sad, but then Dr. Furst told us that this is what science is, testing repeatedly and sometimes not getting the results we wanted." Lou agrees. "If we just copy the data left by other scholars and don't collect and figure it out by ourselves, then it is difficult to be a qualified researcher," he says.

Some of the students plan to continue the project one afternoon a week at MIT and as an independent study at Malden Catholic. The long-term goal is to create a field-based soil sensor that employs a bacterium like *Shewanella*.

By chance, the students' very first electrode—made of graphite powder ink and nail polish glue—generated the most current. One of the team's biggest surprises was how much better black nail polish worked than clear nail polish. It turns out black nail polish contains iron-based pigment—a conductor. The unexpected win took some of the sting out of the failures.

"They learned a very hard lesson: Your results might be awesome, and things are exciting, but then nothing else might work. And that's totally fine," Furst says.

Deborah Halber, MITEI correspondent

Ariel Furst (right), Phuc (Vincent) Nguye (center), and his classmates from Malden Catholic High School watch the results of the testing equipment's electrochemical measurements, excited to discover that this set of carbon electrodes exhibits conductivity. Photo: Gretchen Ertl

Energy Studies Minor graduates, June 2022

Patricia Chan
Mechanical Engineering

Ana Fiallo
Electrical Engineering and Computer Science, Materials Science and Engineering

Jovier (Jovi) Jimenez
Nuclear Science and Engineering

Lucy Kitch-Peck
Materials Science and Engineering

Heidi Li
Materials Science and Engineering

Sarah Lohmar
Urban Studies and Planning, Electrical Engineering and Computer Science

Naomi Lutz
Mechanical Engineering

Manuel Morales
Electrical Science and Engineering, Physics

Alec Nguyen
Chemical Engineering

Natalia Perez-Lodieiro
Chemical Engineering

Adam Potter
Mechanical Engineering, Electrical Engineering and Computer Science

Devin Seyler
Physics

Julie Tung
Chemical Engineering

Logan Vawter
Mechanical Engineering

Paige Vincent
Materials Science and Engineering

Energy Fellows, 2022–2023

The Society of Energy Fellows at MIT welcomed 27 new members in fall 2022. Their fellowships were made possible through the generous support of four MITEI Member companies.

Photo: Gretchen Ertl

Chevron

Sam Abel
System Design and Management

Warren Anderson
System Design and Management

Cory Cochran
System Design and Management

Clay Coffey
System Design and Management

Justin Dargis
System Design and Management

Brooke DiMartino
System Design and Management

Nicholas Gonzalez
System Design and Management

Rabab Haider
Mechanical Engineering

Ethan Lindstrom
System Design and Management

Kenny Lum
System Design and Management

Jonathan Monning
System Design and Management

Holly Nihipali
System Design and Management

Edgar Paca
System Design and Management

Tanner Papenfuss
System Design and Management

Rashmi Ravishankar
Aeronautics and Astronautics

Stephen Tainter
System Design and Management

Russell Zhao
System Design and Management

Eni S.p.A.

Wande Cairang
Nuclear Science and Engineering

Alexis Devitre
Nuclear Science and Engineering

Mike Wigram, PhD
Plasma Science and Fusion Center

ExxonMobil

Subhash Chandra
Materials Science and Engineering

Thomas Defferriere, PhD
Materials Science and Engineering

Akshay Deshmukh, PhD
Mechanical Engineering

Serin Lee
Materials Science and Engineering

Daniele Vivona
Mechanical Engineering

Duhan Zhang, PhD
Materials Science and Engineering

Shell

Sydney Johnson
Chemical Engineering

MIT Energy Initiative's Annual Research Conference highlights both opportunities and obstacles in the race to a net-zero future

"The past six years have been the warmest on the planet, and our track record on climate change mitigation is drastically short of what it needs to be," said Robert C. Armstrong, MIT Energy Initiative (MITEI) director and the Chevron Professor of Chemical Engineering, introducing MITEI's 15th Annual Research Conference.

At the September 13-14, 2022, symposium, participants from academia, industry, and finance acknowledged the deepening difficulties of decarbonizing a world rocked by geopolitical conflicts and suffering from supply chain disruptions, energy insecurity, inflation, and a persistent pandemic. In spite of this grim backdrop, the conference offered evidence of significant progress in the energy transition. Researchers provided glimpses of a low-carbon future, presenting advances in such areas as long-duration energy storage, carbon capture, and renewable technologies.

In his keynote remarks, Ernest J. Moniz, the Cecil and Ida Green Professor of Physics and Engineering Systems Emeritus and former United States Secretary of Energy, highlighted "four areas that have materially changed in the last year" that could shake up, and possibly accelerate, efforts to address climate change.

Extreme weather seems to be propelling the public and policy makers of both U.S. parties toward "convergence… at least in recognition of the challenge," Moniz said. He perceives a growing consensus that climate goals will require—in diminishing order of certainty—firm (always on) power to complement renewable energy sources, a fuel (such as hydrogen) flowing alongside electricity, and removal of atmospheric carbon dioxide (CO_2).

Ernest Moniz, former U.S. secretary of energy and founding director of the MIT Energy Initiative, gives the keynote address on how the variety of crises currently facing the world may impact the energy transition. Photo: Gretchen Ertl

At the MIT Energy Initiative's 2022 Annual Research Conference, panelists discuss the challenges of scaling new energy startups and taking their technologies from the lab to the market. Photo: Kelley Travers, MITEI

Russia's invasion of Ukraine, with its "weaponization of natural gas" and global energy impacts, underscores the idea that climate, energy security, and geopolitics "are now more or less recognized widely as one conversation." Moniz pointed as well to new U.S. laws on climate change and infrastructure that will amplify the role of science and technology and "address the drive to technological dominance by China."

The rapid transformation of energy systems will require a comprehensive industrial policy, Moniz said. Government and industry must select and rapidly develop low-carbon fuels, firm power sources (possibly including nuclear power), CO_2 removal systems, and long-duration energy storage technologies. "We will need to make progress on all fronts literally in this decade to come close to our goals for climate change mitigation," he concluded.

Global cooperation?

Over the two days, conference participants delved into many of the issues Moniz raised. In one of the first panels, scholars pondered whether the international community could forge a coordinated climate change response. The United States' rift with China, especially over technology trade policies, loomed large.

"Hatred of China is a bipartisan hobby and passion, but a blanket approach isn't right, even for the sake of national security," said Yasheng Huang, the Epoch Foundation Professor of Global Economics and Management at the MIT Sloan School of Management. "Although the United States and China working together would have huge effects for both countries, it is politically unpalatable in the short term," said F. Taylor Fravel, the Arthur and Ruth Sloan Professor of Political Science and director of the MIT Security Studies Program. John E. Parsons, deputy director for research at the MIT Center for Energy and Environmental Policy Research, suggested that the United States should use this moment "to get our own act together…and start doing things," such as building nuclear power plants in a cost-effective way.

Debating carbon removal

Several panels took up the matter of carbon emissions and the most promising technologies for contending with them. Charles Harvey, MIT professor of civil and environmental engineering, and Howard Herzog, a senior research engineer at MITEI, set the stage early, debating whether capturing carbon was essential to reaching net-zero targets.

"I have no trouble getting to net zero without carbon capture and storage," said David Keith, the Gordon McKay Professor of Applied Physics at Harvard University, in a subsequent roundtable. Carbon capture seems more risky to Keith than solar geoengineering, which involves injecting sulfur into the stratosphere to offset CO_2 and its heat-trapping impacts.

There are new ways of moving carbon from where it's a problem to where it's safer. Kripa K. Varanasi SM '02, PhD '04, MIT professor of mechanical engineering, described a process for modulating the pH of ocean water to remove CO_2. Timothy Krysiek, managing director for Equinor Ventures, talked about construction of a 900-kilometer pipeline transporting CO_2 from northern Germany to a large-scale storage site located in Norwegian waters 3,000 meters below the seabed. "We can use these offshore Norwegian assets as a giant carbon sink for Europe," he said.

A startup showcase featured additional approaches to the carbon challenge. Mantel, which received MITEI Seed Fund money, is developing molten salt material to capture carbon for long-term storage or for use in generating electricity. Verdox has come up with an electrochemical process for capturing dilute CO_2 from the atmosphere.

But while much of the global warming discussion focuses on CO_2, other greenhouse gases are menacing. Another panel discussed measuring and mitigating these pollutants. "Methane has 82 times more warming power than CO_2 from the point of emission," said Desirée L. Plata, MIT associate professor of civil and environmental engineering. "Cutting methane is the strongest lever we have to slow climate change in the next 25 years—really the only lever."

Steven Hamburg, chief scientist and senior vice president of the Environmental Defense Fund, cautioned that emission of hydrogen molecules into the atmosphere can cause increases in other greenhouse gases such as methane, ozone, and water vapor. As researchers and industry turn to hydrogen as a fuel or as a feedstock for commercial processes, "we will need to minimize leakage…or risk increasing warming," he said.

Supply chains, markets, and new energy ventures

In panels on energy storage and the clean energy supply chain, there were interesting discussions about the challenges ahead. High-density energy materials such as lithium, cobalt, nickel, copper, and vanadium for grid-scale energy storage, electric vehicles (EVs), and other clean energy technologies, can be difficult to source. "These often come from water-stressed regions, and we need to be super thoughtful about environmental stresses," said Elsa Olivetti PhD '07, the Esther and Harold E. Edgerton Associate Professor in Materials Science and Engineering. She also noted that in light of the explosive growth in demand for metals such as lithium, recycling EVs won't be of much help. "The amount of material coming back from end-of-life batteries is minor," she said, until EVs are much further along in their adoption cycle.

Arvind Sanger, founder and managing partner of Geosphere Capital, said that the United States should be developing its own rare earths and minerals, although

Left to right: Anuradha Annaswamy (MIT), Louis Vézina (Hydro-Québec), Tim Schittekatte (MIT), and Paul Joskow (MIT) participate on a panel about the future of power markets in a low marginal cost world. Photo: Gretchen Ertl

Coordinating Minister for Maritime Affairs and Investment of the Republic of Indonesia Luhut Binsar Pandjaitan (right) discusses the opportunities and challenges of the energy transition in the developing world with MITEI Director Robert Armstrong. Photo: Kelley Travers, MITEI

gaining the know-how will take time, and overcoming "nimbyism" (Not In My Back Yard-ism) is a challenge. Sanger emphasized that we must continue to use "denser sources of energy" to catalyze the energy transition over the next decade. In particular, Sanger noted that "for every transition technology, steel is needed," and steel is made in furnaces that use coal and natural gas. "It's completely woolly headed to think we can just go to a zero-fossil-fuel future in a hurry," he said.

The topic of power markets occupied another panel, which focused on ways to ensure the distribution of reliable and affordable zero-carbon energy. Integrating intermittent resources such as wind and solar into the grid requires a suite of retail markets and new digital tools, said Anuradha Annaswamy, director of MIT's Active-Adaptive Control Laboratory. Tim Schittekatte, a postdoctoral associate at the MIT Sloan School of Management, proposed auctions as a way of insuring consumers against periods of high market costs.

Another panel described the very different investment needs of new energy startups, such as longer research and development phases. Hooisweng Ow, technology principal at Eni Next LLC Ventures, which is developing drilling technology for geothermal energy, recommends joint development and partnerships to reduce risk. Michael Kearney SM '11, PhD '19, SM '19 is a partner at The Engine, a venture firm built by MIT investing in pathbreaking technology to solve the toughest challenges in climate and other problems. Kearney believes the emergence of new technologies and markets will bring on "a labor transition on an order of magnitude never seen before in this country," he said. "Workforce development is not a natural zone for startups…and this will have to change."

Supporting the global South

The opportunities and challenges of the energy transition look quite different in the developing world. In conversation with Robert Armstrong, Luhut Binsar Pandjaitan, the coordinating minister for maritime affairs and investment of the Republic of Indonesia, reported that his "nation is rich with solar, wind, and energy transition minerals like nickel and copper," but cannot on its own tackle developing renewable energy or reducing carbon emissions and improving grid infrastructure. "Education is a top priority, and we are very far behind in high technologies," he said. "We need help and support from MIT to achieve our target."

Technologies that could springboard Indonesia and other nations of the global South toward their climate goals are emerging in MITEI-supported projects and at young companies MITEI helped spawn. Among the promising innovations unveiled at the conference are new materials and designs for cooling buildings in hot climates and reducing the environmental costs of construction, and a sponge-like substance that passively sucks moisture out of the air to lower the energy required for running air conditioners in humid climates.

Other ideas on the move from lab to market have great potential for industrialized nations as well, such as a computational framework for maximizing the energy output of ocean-based windfarms; a process for using ammonia as a renewable fuel with no CO_2 emissions; long-duration energy storage derived from the oxidation of iron; and a laser-based method for unlocking geothermal steam to drive power plants.

Leda Zimmerman, MITEI correspondent

At MITEI's Fall Colloquium, Philip R. Sharp highlighted steps the U.S. government has recently taken to combat climate change amid global crises

A global pandemic. Russia's invasion of Ukraine. Inflation. The first-ever serious challenge to the peaceful transfer of power in the United States.

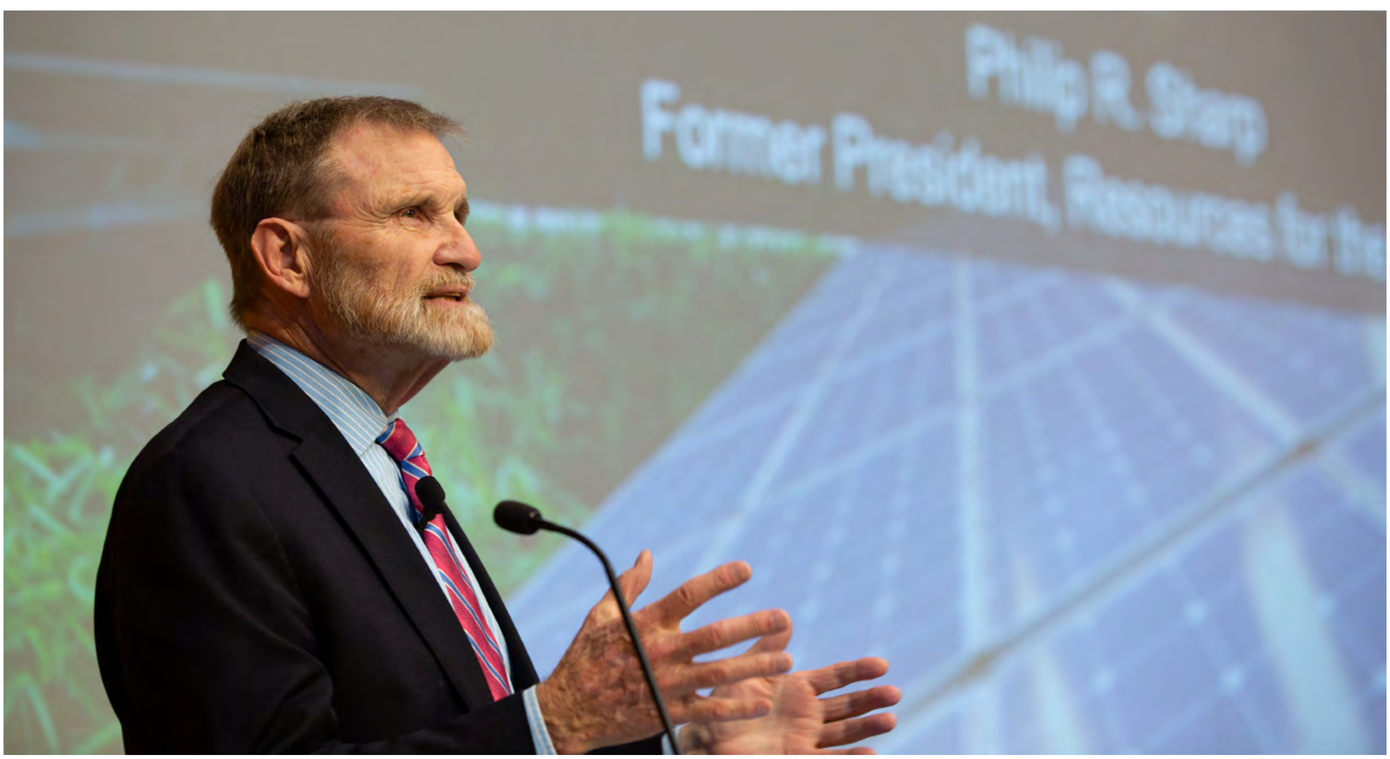
Forced to face a seemingly unending series of once-in-a-generation crises, how can the world continue to focus attention on goals around carbon emissions and climate change? That was the question posed by Philip R. Sharp, the former president of Resources for the Future and a former ten-term member of the U.S. House of Representatives from Indiana, during his MIT Energy Initiative Fall Colloquium address, titled "The prospects for decarbonization in America: Will global and domestic crises disrupt our plans?"

Perhaps surprisingly, Sharp sounded an optimistic note in his answer. Despite deep political divisions in the United States, he noted, Congress has passed five major pieces of legislation—under both President Donald Trump and President Joseph Biden—aimed at accelerating decarbonization efforts. Rather than hampering movement to combat climate change, Sharp said, domestic and global crises have seemed to galvanize support, create new incentives for action, and even unify political rivals around the cause.

"Almost everybody is dealing with, to some degree, the absolutely profound, churning events that we are amidst now. Most of them are unexpected, and therefore [we're] not prepared for [them], and they have had a profound shaking of our thinking," Sharp said. "The conventional wisdom has not held up in almost all of these areas, and therefore it makes it much more difficult for us to think we know how to predict an uncertain future, and [it causes us to] question our own ability as a nation—or anywhere—to actually take on these challenges. And obviously, climate change is one of the most important."

However, Sharp continued, these challenges have, in some instances, spurred action. The war in Ukraine, he noted, has upset European energy markets, but it has also highlighted the importance of countries achieving a more energy-independent posture through renewables. "In America," he added, "we've actually seen absolutely stunning… behavior by the United States Congress, of all places."

"What we've witnessed is, [Congress] put out incredible…sums of money under the previous administration, and then under this administration, to deal with the Covid crisis," Sharp added later in his talk. "And then the United States government



At the MIT Energy Initiative's Fall Colloquium, Philip R. Sharp highlights dramatic steps the U.S. government has recently taken to combat climate change. Sharp is the former president of Resources for the Future, an independent, nonprofit research institution in Washington, D.C. Photo: Kelley Travers, MITEI came together—red and blue—to support the Ukrainians against Russia. It saddens me to say, it seems to take a Russian invasion or the Chinese probing us economically to get us moving. But we are moving, and these things are happening."

Congressional action

Sharp cautioned against getting "caught up" in the familiar viewpoint that Congress, in its current incarnation, is fundamentally incapable of passing meaningful legislation. He pointed, in particular, to the passage of five laws over the previous two years:

- The 2020 Energy Act, which has been characterized as a "down payment on fighting climate change."
- The Infrastructure Investment and Jobs Act (sometimes called the "Bipartisan Infrastructure Bill"), which calls for investments in passenger rail, electric vehicle infrastructure, electric school buses, and other clean-energy measures.
- The CHIPS and Science Act, a $280 billion effort to revitalize the American semiconductor industry, which some analysts say could direct roughly one quarter of its funding toward accelerating zero-carbon industries and conducting climate research.
- The Inflation Reduction Act (called by some "the largest climate legislation in U.S. history"), which includes tax credits, incentives, and other provisions to help private companies tackle climate change, increase investments in renewable energy, and enhance energy efficiency.
- The Kigali Amendment to the Montreal Protocol, ratified by the Senate to little fanfare in September, under which the United States agreed to reduce the consumption and production of hydrofluorocarbons.

"It is a big deal," Sharp said of the dramatic increase in federal climate action. "It is very significant actions that are being taken—more than what we would expect, or I would expect, out of the Congress at any one time."

Along with the many billions of dollars of climate-related investments included in the legislation, Sharp said, these new laws will have a number of positive "spillover" effects.

"This enables state governments, in their policies, to be more aggressive," Sharp said. "Why? Because it makes it cheaper for some of the investments that they will try to force within their state." Another "pretty obvious" spillover effect, Sharp said, is that the new laws will enhance U.S. credibility in international negotiations. Finally, he said, these public investments will make the U.S. economy more competitive in international markets for clean-energy technology—particularly as the United States seeks to compete against China in the space.

"[Competition with China] has become a motivator in American politics, like it or not," Sharp said. "There is no question that it is causing and bringing together [politicians] across blue [states] and red [states]."

Holding onto progress

Even in an uncertain political climate in which Democrats and Republicans seem unable to agree on basic facts, recent funding commitments are likely to survive, no matter which party controls Congress and the presidency, Sharp said. That's because most of the legislation relies on broadly popular "carrots" that reward investments in decarbonization, rather than less popular "sticks" that create new restrictions or punishments for companies that fail to decarbonize.

"Politically, the impact of this is very significant," Sharp said. "It is so much easier in politics to give away tax [credits] than it is to penalize or put requirements onto people. The fact is that these tax credits are more likely to be politically sustained than other forms of government intervention. That, at least, has been the history."

Sharp stressed the importance of what he called "civil society"—institutions such as universities, nonprofits, churches, and other organizations that are apart from government and business—in promoting decarbonization efforts. "[Those groups] can act highly independently, and therefore, they can drive for things that others are not willing to do. Now this does not always work to good purposes. Partly, this diversity and this decentralization in civil society…led to deniers and others being able to stop some climate action. But now my view is, this is starting to all move in the right direction, in a very dynamic and a very important way. What we have seen over the last few years is a big uptick in philanthropy related to climate."

Looking ahead

Sharp's optimism even extended to the role of social media. He suggested that the "Wild West" era of social platforms may be ending, pointing to the celebrities who have recently lost valuable business partnerships for spreading hate speech and disinformation. "We're now a lot more alert to the dangers," he said.

Some in the audience questioned Sharp about specific paths toward decarbonization, but Sharp said that progress will require a number of disparate approaches—some of which will inevitably have a greater impact than others. "The current policy, and the policy embedded in this [new] legislation…is all about doing both," he said. "It's all about advancing [current] technologies into the marketplace, and at the same time driving for breakthroughs."

Above all, Sharp stressed the need for continued collective action around climate change. "The fact is, we're all contributors to some degree," he said. "But we also all can do something. In my view, this is clearly not a time for hand wringing. This is a time for action. People have to roll up their sleeves, and go to work, and not roll them down anytime soon."

Calvin Hennick, MITEI correspondent

MIT spinout Quaise Energy: Working to create geothermal wells made from the deepest holes in the world

Adapted and reprinted with permission of MIT News (news.mit.edu). First published on June 28, 2022.

There's an abandoned coal power plant in upstate New York that most people regard as a useless relic. But MIT's Paul Woskov sees things differently.

Woskov, a research engineer in MIT's Plasma Science and Fusion Center (PSFC), notes that the plant's power turbine is still intact and the transmission lines still run to the grid. Using an approach he's been working on for the last 14 years, he's hoping it will be back online, completely carbon-free, within the decade.

In fact, Quaise Energy, the company commercializing Woskov's work, believes if it can retrofit one power plant, the same process will work on virtually every coal power plant in the world.

Quaise is hoping to accomplish those lofty goals by tapping into the energy source below our feet. The company plans to vaporize enough rock to create the world's deepest holes and harvest geothermal energy at a scale that could satisfy human energy consumption for millions of years. They haven't yet solved all the related engineering challenges, but Quaise's founders have set an ambitious timeline to begin harvesting energy from a pilot well by 2026.

The plan would be easier to dismiss as unrealistic if it were based on a new and unproven technology. But Quaise's drilling systems center around a microwave-emitting device called a gyrotron that has been used in research and manufacturing for decades.

"This will happen quickly once we solve the immediate engineering problems of transmitting a clean beam and having it operate at a high energy density without breakdown," explains Woskov, who is not formally affiliated with Quaise but serves as an advisor. "It'll go fast because the underlying technology, gyrotrons, are commercially available. You could place an order with a company and have a system delivered right now—granted, these beam sources have never been used 24/7, but they are engineered to be operational for long time periods. In five or six years, I think we'll have a plant running if we solve these engineering problems. I'm very optimistic."

Woskov and many other researchers have been using gyrotrons to heat material in nuclear fusion experiments for decades. It wasn't until 2008, however, after the MIT Energy Initiative (MITEI) published a request for proposals on new geothermal drilling technologies, that Woskov thought of using gyrotrons for a new application.

Quaise Energy wants to repurpose coal power plants into deep geothermal wells by using high-frequency microwaves to melt rock. Image: Collage by MIT News with images courtesy of Quaise Energy

"[Gyrotrons] haven't been well-publicized in the general science community, but those of us in fusion research understood they were very powerful beam sources—like lasers, but in a different frequency range," Woskov says. "I thought, why not direct these high-power beams, instead of into fusion plasma, down into rock and vaporize the hole?"

As power from other renewable energy sources has exploded in recent decades, geothermal energy has plateaued, mainly because drilling at today's geothermal plants is generally limited to depths of less than 2 miles. That limitation significantly restricts where plants can be located, as there are few places where the Earth is hot that close to the surface. However, at a certain point, conventional drilling becomes impractical because deeper crust is both hotter and harder, which wears down mechanical drill bits.

Woskov's idea to use gyrotron beams to vaporize rock sent him on a research journey that has never really stopped. With some funding from MITEI, he began running tests, quickly filling his office with small rock formations he'd blasted with millimeter waves from a small gyrotron in MIT's Plasma Science and Fusion Center.

Around 2018, Woskov's rocks got the attention of Carlos Araque '01, SM '02, who had spent his career in the oil and gas industry and was the technical director of MIT's investment fund The Engine at the time.

That year, Araque and Matt Houde, who'd been working with geothermal company AltaRock Energy, founded Quaise. Quaise was soon given a grant by the U.S. Department of Energy (DOE) to scale up Woskov's experiments using a larger gyrotron.

With the larger machine, the team hopes to vaporize a hole 10 times the depth of Woskov's lab experiments. That is expected to be accomplished by the end of this year. After that, the team will vaporize a hole 10 times the depth of the previous one—what Houde calls a 100-to-1 hole.

"That's something [the DOE] is particularly interested in, because they want to address the challenges posed by material removal over those greater lengths—in other words, can we show we're fully flushing out the rock vapors?" Houde explains. "We believe the 100-to-1 test also gives us the confidence to go out and mobilize a prototype gyrotron drilling rig in the field for the first field demonstrations."

Tests on the 100-to-1 hole are expected to be completed sometime next year. Quaise is also hoping to begin vaporizing rock in field tests late next year. The short timeline reflects the progress Woskov has already made in his lab.

Although more engineering research is needed, ultimately, the team expects to be able to drill and operate these geothermal wells safely. "We believe, because of Paul's work at MIT over the past decade, that most if not all of the core physics questions have been answered and addressed," Houde says. "It's really engineering challenges we have to answer, which doesn't mean they're easy to solve, but we're not working against the laws of physics, to which there is no answer. It's more a matter of overcoming some of the more technical and cost considerations to making this work at a large scale."

The company plans to begin harvesting energy from pilot geothermal wells that reach rock temperatures at up to 500°C by 2026. From there, the team hopes to begin repurposing coal power plants using its system.

"We believe, if we can drill down to 20 kilometers, we can access these super-hot temperatures in greater than 90 percent of locations across the globe," Houde says.

Quaise's work with the DOE is addressing what it sees as the biggest remaining questions about drilling holes of unprecedented depth and pressure, such as material removal and determining the best casing to keep the hole stable and open. For the latter problem of well stability, Houde believes additional computer modeling is needed and expects to complete that modeling by the end of 2024.

By drilling the holes at existing coal power plants, Quaise will be able to move faster than if it had to get permits to build new plants and transmission lines. And by making their millimeter-wave drilling equipment compatible with the existing global fleet of drilling rigs, it will also allow the company to tap into the oil and gas industry's global workforce.

"At these high temperatures [we're accessing], we're producing steam very close to, if not exceeding, the temperature that today's coal-fired power plants operate at," Houde says. "So, we can go to existing power plants and say, 'We can replace 95 to 100 percent of your coal use by developing a geothermal field and producing steam from the Earth, at the same temperature you're burning coal to run your turbine, directly replacing carbon emissions."

Transforming the world's energy systems in such a short timeframe is something the founders see as critical to help avoid the most catastrophic global warming scenarios.

Woskov displaying samples in his lab in 2016.
Photo: Paul Rivenberg

"There have been tremendous gains in renewables over the last decade, but the big picture today is we're not going nearly fast enough to hit the milestones we need for limiting the worst impacts of climate change," Houde says. "[Deep geothermal] is a power resource that can scale anywhere and has the ability to tap into a large workforce in the energy industry to readily repackage their skills for a totally carbon-free energy source."

Zach Winn, MIT News Office

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In 2012, an article in *Energy Futures* described the "millimeter-wave drilling" concept and its early development by Woskov and his colleague Daniel Cohn, then of the PSFC and now a research scientist at MITEI. The article, "Reaching underground resources: Vaporize the rock—no drilling required," is available online at energy.mit.edu/news/reaching-underground-resources.

3 Questions: Robert Stoner on U.S. climate and infrastructure laws and their impact on the energy transition

This November, the 2022 United Nations Climate Change Conference (COP27) took place in Sharm El Sheikh, Egypt, bringing together governments, experts, journalists, industry, and civil society to discuss climate action to enable countries to collectively sharply limit anthropogenic climate change. As MIT Energy Initiative Deputy Director for Science and Technology Robert Stoner prepared to attend the conference, he took a moment to speak with us about the climate and infrastructure laws enacted in the last year in the United States and at the impact these laws can have in the global energy transition.

Q As we speak, you're getting ready to go to COP27. Can you set the scene?

A There's a lot of interest among vulnerable countries about compensation for the impacts climate change has had on them, or "loss and damage," a topic that the United States refused to address last year at COP26, for fear of opening up a floodgate and leaving U.S. taxpayers exposed to unlimited liability for our past (and future) emissions. This is a crucial issue of fairness for developed countries—and, well, of acknowledging our common humanity. But in a sense, it's also a sideshow, and addressing it won't prevent a climate catastrophe—we really need to focus on mitigation.

Robert Stoner is the deputy director of science and technology at the MIT Energy Initiative and the founding director of the MIT Tata Center for Technology and Design. He is also a member of the Global Commission to End Energy Poverty, serving as its secretary. Photo: Allison Bailey

With the passage of the Bipartisan Infrastructure Investment and Jobs Act and the Inflation Reduction Act (IRA), the United States is now in a strong position to twist some arms. These laws are largely about subsidizing the deployment of low-carbon technologies—pretty much all of them. We're going to do a lot in the United States in the next decade that will lead to dramatic cost reductions for these technologies and enable other countries with fewer resources to adopt them as well. It's exactly the leadership role the United States has needed to assume.

Now we have the opportunity to rally the rest of the world and get other countries to commit to more ambitious decarbonization goals, and to build practical programs that take advantage of the investable pathways we're going to create for public and private actors. But that alone won't get us there—money is still a huge problem, especially in emerging markets and developing countries. And I don't think the institutions we rely on to help these countries fund infrastructure—energy and everything else—are adequately funded. Nor do these institutions have the right structures, incentives, and staffing to fund low-carbon development in these countries rapidly enough or on the necessary scale. I'm talking about the World Bank, for instance, but the other multilateral organizations have similar issues. I frankly don't think the multilaterals can be reformed or sufficiently redirected on a short enough timeframe. We definitely need new leadership for these organizations, and I think we probably need to quickly establish new multilaterals with new people, more money, and a clarity of purpose that is likely beyond what can be achieved incrementally. I don't know if this is going to be an active public discussion at COP27, but I hope it takes place somewhere soon. Given the strong role our government plays in financing and selecting the leadership of these institutions, perhaps this is another opportunity for the United States to demonstrate courage and leadership.

Q What "investable pathways" are you talking about?

A Well, the pathways we're implicitly trying to pursue with the Infrastructure Act and IRA are pretty clear, and I'll come back to them. But first let me describe the landscape: There are three main sources of demand for energy in the economy—industry (meaning chemical production, fuel for electricity generation, cement production, materials and manufacturing, and so on), transportation (cars, trucks, ships, planes, and trains), and buildings (for heating and cooling mostly). That's about it, and these three sectors account for 75% of our total greenhouse gas emissions. So the pathways are all about how to decarbonize these three end-use sectors. There are a lot of technologies—some that exist, some that don't—that will have to be brought to bear. And so it can be a little overwhelming to try to imagine how it will all transpire, but it's pretty clear at a high level what our options are:

- First, generate a lot of low-carbon electricity and electrify as many industrial processes, vehicles, and building heating systems as we can.
- Second, develop and deploy at massive scale technologies that can capture carbon dioxide from smokestacks, or the air, and put it somewhere that it

can never escape from—in other words, carbon capture and sequestration, or CCS.

- Third, for end uses like aviation that really need to use fuels because of their extraordinary energy density, develop low-carbon alternatives to fossil fuels.

- And fourth is energy efficiency across the board—but I don't really count that as a separate pathway per se.

So, by "investable pathways" I mean specific ways to pursue these options that will attract investors. What the Infrastructure Act and the IRA do is deploy carrots (in the form of subsidies) in a variety of ways to close the gap between what it costs to deploy technologies like CCS that aren't yet at a commercial stage because they're immature, and what energy markets will tolerate.

A similar situation occurs for low-carbon production of hydrogen, one of the leading low-carbon fuel candidates. We can make it by splitting water with electricity (electrolysis), but that costs too much with present day technology; or we can make it more cheaply by separating it from methane (which is what natural gas mainly is), but that creates CO_2 that has to be transported and sequestered somewhere. And then we have to store the hydrogen until we're ready to use it, and transport it by pipeline to the industrial facilities where it will be used. That requires infrastructure that doesn't exist—pipelines, compression stations, big tanks! Come to think of it, the demand for all that hydrogen doesn't exist either—at least not if industry has to pay what it actually costs.

So, one very important thing these new acts do is subsidize production of hydrogen in various ways—and subsidize the creation of a CCS industry. The other thing they do is subsidize the deployment at enormous scale of low-carbon energy technologies. Some of them are already pretty cheap, like solar and wind, but they need to be supported by a lot of storage on the grid (which we don't yet have) and by other sorts of grid infrastructure that, again, don't exist. So, they now get subsidized, too, along with other carbon-free and low-carbon generation technologies—basically all of them.

The idea is that by stimulating at-scale deployment of all these established and emerging technologies, and funding demonstrations of novel infrastructure—effectively lowering the cost of supply of low-carbon energy in the form of electricity and fuels—we will draw out the private sector to build out much more of the connective infrastructure and invest in new industrial processes, new home heating systems, and low-carbon transportation. This subsidized build-out will take place over a decade and then phase out as costs fall—hopefully, leaving the foundation for a thriving low-carbon energy economy in its wake, along with crucial technologies and knowledge that will benefit the whole world.

Q Is all of the federal investment in energy infrastructure in the United States relevant to the energy crisis in Europe right now?

A Not in a direct way—Europe is a near-term catastrophe with a long-term challenge that is in many ways more difficult than ours because Europe doesn't have the level of primary energy resources like oil and gas that we have in abundance. Energy costs more in Europe, especially absent Russian pipelines. In a way, the narrowing of Europe's options creates an impetus to invest in low-carbon technologies sooner than otherwise. The result either way will be expensive energy and quite a lot of economic suffering for years.

The near-term challenge is to protect people from high energy prices. The big spikes in electricity prices we see now are driven by the natural gas market disruption, which will eventually dissipate as new sources of electricity come online (Sweden, for example, just announced a plan to develop new nuclear, and we're seeing other countries like Germany soften their stance on nuclear)—and gas markets will sort themselves out. Meanwhile governments are trying to shield their people with electricity price caps and other subsidies, but that's enormously burdensome. The EU recently announced gas price caps for imported gas to try to eliminate price-gouging by importers and reduce the subsidy burden. That may help to lower downstream prices, or it may make matters worse by reducing the flow of gas into the EU and fueling scarcity pricing, and ultimately adding to the subsidy burden.

A lot people are quite reasonably suggesting that if electricity prices are subject to crazy behavior in gas markets, then why not disconnect from the grid and self-generate? Wouldn't that also help reduce demand for gas overall and also reduce CO_2 emissions? It would. But it's expensive to put solar panels on your roof and batteries in your basement—so for those rich enough to do this, it would lead to higher average electricity costs that would live on far into the future, even when grid prices eventually come down.

So, an interesting idea is taking hold, with considerable encouragement from national governments—the idea of "energy communities," basically, towns or cities that encourage local firms and homeowners to install solar and batteries, and make some sort of business arrangement with the local utility to allow the community to disconnect from the national grid at times of high prices and self-supply—in other words, use the utility's wires to sell locally generated power locally. It's interesting to think about—it takes less battery storage to handle the intermittency of solar when you have a lot of generators and consumers, so forming a community helps lower costs, and with a good deal from the utility for using their wires, it might not be that much more expensive. And of course, when the national grid is working well and prices are normal, the community would reconnect and buy power cheaply, while selling back its self-generated power to the grid. There are also potentially important social benefits that might accrue in these energy communities, too. It's not a dumb idea, and we'll see some interesting experimentation in this area in the coming years—as usual, the Germans are enthusiastic!

Tom Melville, MITEI

3 Questions: Janelle Knox-Hayes on producing renewable energy that communities want

MIT professors Janelle Knox-Hayes and Donald Sadoway call for a new approach to wind-power deployment, one that engages communities in a process of "co-design" and adapts solutions to local needs. Image: Jose-Luis Olivares, MIT

Wind power accounted for 8% of U.S. electricity consumption in 2020, and is growing rapidly in the country's energy portfolio. But some projects, like the now-defunct Cape Wind proposal for offshore power in Massachusetts, have run aground due to local opposition. Are there ways to avoid this in the future?

MIT professors Janelle Knox-Hayes and Donald Sadoway think so. In a perspective piece published on September 21, 2022, in the journal Joule, *they and eight other professors call for a new approach to wind-power deployment, one that engages communities in a process of "co-design" and adapts solutions to local needs. That process, they say, could spur additional creativity in renewable energy engineering, while making communities more amenable to existing technologies. In addition to Knox-Hayes and Sadoway, the paper's co-authors are Michael J. Aziz of Harvard University; Dennice F. Gayme of Johns Hopkins University; Kathryn Johnson of the Colorado School of Mines; Perry Li of the University of Minnesota; Eric Loth of the University of Virginia; Lucy Y. Pao of the University of Colorado; Jessica Smith of the Colorado School of Mines; and Sonya Smith of Howard University. Find the paper online at doi.org/10.1016/j.joule.2022.08.014.*

Knox-Hayes is an associate professor of economic geography and planning in MIT's Department of Urban Studies and Planning, and an expert on the social and political context of renewable energy adoption; Sadoway is the John F. Elliott Professor of Materials Chemistry in MIT's Department of Materials Science and Engineering, and a leading global expert on developing new forms of energy storage. MIT News spoke with Knox-Hayes about the topic.

Q What is the core problem you are addressing in this article?

A It is problematic to act as if technology can only be engineered in a silo and then delivered to society. To solve problems like climate change, we need to see technology as a socio-technical system, which is integrated from its inception into society. From a design standpoint, that begins with conversations, values assessments, and understanding what communities need. If we can do that, we will have a much easier time delivering the technology in the end.

What we have seen in the Northeast, in trying to meet our climate objectives and energy efficiency targets, is that we need a lot of offshore wind, and a lot of projects have stalled because a community was saying "no." And part of the reason communities refuse projects is because they've never been properly consulted. What form does the technology take, and how would it operate within a community? That conversation can push the boundaries of engineering.

Q The new paper makes the case for a new practice of "co-design" in the field of renewable energy. You call this the "STEP" process, standing for all the socio-technical-economic-political issues that an engineering project might encounter. How would you describe the STEP idea? And to what extent would industry be open to new attempts to design an established technology?

A The idea is to bring together all these elements in an interdisciplinary process, and engage stakeholders. The process could start with a series of community forums where we bring everyone together and do a needs assessment, which is a common practice in planning. We might see that offshore wind energy needs to be considered in tandem with the local fishing industry, or servicing the installations, or providing local workforce training. The STEP process allows us to take a step back, and start with planners, policy makers, and community members on the ground.

It is also about changing the nature of research and practice and teaching, so that students are not just in classrooms, they are also learning to work with communities. I think formalizing that piece is important. We are starting now to really feel the impacts of climate change, so we have to confront the reality of breaking through political boundaries, even in the United States. That is the only way to make this successful, and that comes back to how can technology be co-designed.

At MIT, innovation is the spirit of the endeavor, and that is why MIT has so many industry partners engaged in initiatives like MITEI [the MIT Energy Initiative] and the Climate Consortium. The value of the partnership is that MIT pushes the boundaries of what is possible. It is the idea that we can advance and we can do something incredible, we can innovate the future. What we are suggesting with this work is that innovation isn't something that happens exclusively in a laboratory, but something that is very much built in partnership with communities and other stakeholders.

Q How much does this approach also apply to solar power, as the other leading type of renewable energy? It seems like communities also wrestle with where to locate solar arrays, or how to compensate homeowners, communities, and other solar hosts for the power they generate.

A I would not say solar has the same set of challenges, but rather that renewable technologies face similar challenges. With solar, there are also questions of access and siting. Another big challenge is to create financing models that provide value and opportunity at different scales. For example, is solar viable for tenants in multi-family units who want to engage with clean energy? This is a similar question for micro-wind opportunities for buildings. With offshore wind, a restriction is that if it is within sightlines, it might be problematic. But there are exciting technologies that have enabled deep wind, or the establishment of floating turbines up to 50 kilometers offshore. Storage solutions such as hydro-pneumatic energy storage, gravity energy storage, or buoyancy storage can help maintain the transmission rate while reducing the number of transmission lines needed.

In a lot of communities, the reality of renewables is that if you can generate your own energy, you can establish a level of security and resilience that feeds other benefits.

Nevertheless, as demonstrated in the Cape Wind case, technology may be rejected unless a community is involved from the beginning. Community involvement also creates other opportunities. Suppose, for example, that high school students are working as interns on renewable energy projects with engineers at great universities from the region. This provides a point of access for families and allows them to take pride in the systems they create. It gives a further sense of purpose to the technology system, and vests the community in the system's success. It is the difference between, "It was delivered to me," and "I built it." For researchers the article is a reminder that engineering and design are more successful if they are inclusive. Engineering and design processes are also meant to be accessible and fun.

Peter Dizikes, MIT News Office

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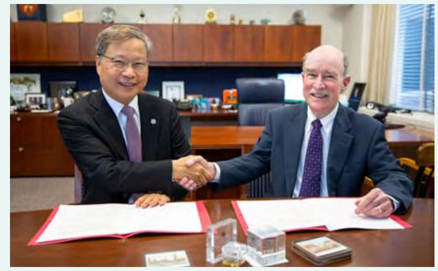
The MIT Energy Initiative creates joint framework to educate students with South Korean energy university KENTECH

The MIT Energy Initiative (MITEI) has forged an agreement with the Korea Institute of Energy Technology (KENTECH) to establish a joint framework to educate students of MIT and KENTECH in pursuit of the energy transition. The agreement was signed on the MIT campus on November 29, 2022, by MITEI Director and Chevron Professor of Chemical Engineering Robert C. Armstrong and KENTECH Founding President Euijoon Yoon.



Euijoon Yoon (left), the founding president of KENTECH, and Robert C. Armstrong, director of the MIT Energy Initiative, sign an agreement to establish a joint framework to educate students of MIT and KENTECH in pursuit of the energy transition. Photo: Kelley Travers, MITEI

The three-year agreement initiates a collaboration between MIT and KENTECH in research and education, beginning with student exchange programs, student internships, and expanding to joint research and cooperative seminars and workshops. Under the agreement, the first students from KENTECH will arrive on the MIT campus in the summer of 2023. Students from MIT will be able to participate in internships at KENTECH, Korean energy research institutions, and regional energy companies.

KENTECH was founded in 2021 by the Korean National Assembly. It is the first global university focused solely on energy research and technology and climate change. Its campus, which relies on zero-carbon energy and eco-friendly technology, is currently under construction in Naju, outside Gwangju, South Korea.

"Given MITEI's position as MIT's hub for energy education, research, and outreach, this collaboration with KENTECH is a welcome and natural development," said Armstrong. "We welcome KENTECH as an important collaborator in the energy transition and in achieving net-zero greenhouse gas emissions. We look forward to engaging with KENTECH in this rich intellectual and educational exchange."

"KENTECH expects that all activities under this agreement will enable students from both institutions to enhance their knowledge to mitigate climate change and achieve carbon neutrality," said President Yoon, who earned his PhD in Electronic Materials at MIT in 1990. "Together with MITEI we will create innovative academic programs to design the future together."

The agreement with KENTECH is part of MITEI's growing Energy and Climate Education Alliance with universities around the world. "In education we seek to give our students knowledge, skills, as well as the courage to jump into action," said Antje Danielson, MITEI director of education. "The MITEI-KENTECH effort will give students practical, hands-on experience in the energy transition—experience they will then share with the world." Faculty affiliated with the Energy and Climate Education Alliance are developing in-person and online education strategies to bridge work in the classroom with practical experience in the field. Both the Alliance and the MITEI-KENTECH agreement will engage with undergraduate, graduate, and postdoctoral students.

Tom Melville, MITEI

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To expedite the trip to net-zero, plug in electric vehicles—and reverse the flow

As the electric vehicle (EV) fleet continues to grow, new charging loads will pose a significant challenge to the electric grid, requiring new infrastructure and scheduled charging schemes to support both EVs and renewables growth. But those same EVs—or more specifically, their batteries—can also provide much-needed services back to the grid: When not on the road, EVs can be plugged in and send electricity back to the grid during periods of peak demand. MIT researchers analyze this idea of "energy storage on wheels," also known as vehicle-to-grid (V2G), and find that, in a theoretical New England power system, using EVs as a storage resource can significantly reduce the need to build stationary energy storage facilities and additional "always-on" natural gas power plants in pursuit of a low-carbon future. Read more on page 23. Image: Ehsan Faridi and Ehsan Keshavarzi, Inmywork Studio