Energy Futures

MIT ENERGY INITIATIVE MASSACHUSETTS INSTITUTE OF TECHNOLOGY SPRING 2020

Meet the team of postdocs working to expand MITEI's novel energy assessment tool p. 17

New approach to capturing CO_2 from exhaust or ambient air p. 9

Energy economics class inspires clean energy careers p. 21

Startup with MITEI roots develops lightweight solar panels p. 28

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Brian Anderson, the director of the U.S. Department of Energy's National Energy Technology Laboratory, on what the lab is doing in carbon capture, materials, hydrogen, and more.

Mobility of the Future
Randall Field and Joanna Moody, MIT researchers, on how environmental policies, urban regulations, and consumer behaviors will affect the future of personal mobility.

The age of living machines
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Scott Burger, former MITEI Energy Fellow and researcher, on rooftop solar economics, net metering, energy poverty, and electricity costs.

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On the cover
Meet the interdisciplinary team of postdocs who came to MIT to work on MITEI's novel energy assessment tool—the Sustainable Energy System Analysis Modeling Environment (SESAME). Left to right: Tapajyoti Ghosh, Naga Srujana Goteti, Emre Gençer (a MITEI research scientist and the SESAME team leader), and Maryam Arbabzadeh. Their story begins on page 17. Photo: Kelley Travers, MITEI

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A letter from the director

Dear friends,

As I write, there have been significant changes in how we work and interact with colleagues across MIT and around the world as we attempt to slow the spread of Covid-19 and keep our communities safe. It has been heartening to see the MIT community's camaraderie in action as we figure out how to work, teach, and learn remotely and to temporarily adjust our research activities. Our daily operations may look different, but MITEI remains committed to developing the solutions that will decarbonize our global energy systems and address climate change.

Within this issue, you will meet some of the passionate individuals working with us to accelerate this transition. Our cover story introduces you to members of the MITEI research team working on a novel energy assessment tool that can be used to evaluate the carbon footprint of today's evolving global energy system (page 17).

You will also learn about a new methodology that can identify cities with similar profiles to aid urban decision makers seeking role models for new transportation policies (page 3), as well as an examination of the impact that decreasing production costs and electricity prices have on the economics of solar generation (page 13). On page 9, you will read about a device that can capture carbon dioxide not only from various exhaust streams, but also from ambient air. The researchers have started a company, Verdox, Inc., that will develop a pilot plant within a few years.

It is imperative that we develop scalable solutions if we are to make meaningful progress on the climate crisis. Like Verdox, many startup companies that were conceptualized at MIT are working on promising technologies for widespread deployment. Swift Solar, a startup with roots at MITEI, makes lightweight, highly efficient, and affordable solar panels that have the potential to greatly increase the use of solar power as an energy source (page 28). Another startup, Khethworks, which launched out of the Tata Center, has developed a solar-powered water pump to increase the crop irrigation period in India. After years of work, the company founders are ready to scale up deployment, enabling more farmers and villages to benefit from this life-changing device (page 30).

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

Many of our energy students have gone on to successful energy-based careers after graduation. On page 23, we highlight two: Abigail Ostriker, who completed MITEI's Energy Studies Minor and is now pursuing her PhD in economics while studying issues related to climate resilience; and Addison Stark, whose graduate work with MITEI led him to a career in energy policy. MIT students are also inspired to pursue clean energy careers by classes such as Jing Li's energy economics course, which gives students a look into real-life electricity market scenarios (page 21).

MIT has now hosted four of the six planned Climate Action Symposia, a series that brings together our community with researchers, policymakers, and industry leaders to share the current state of climate science and policy and to generate new ideas and solutions to address the urgent challenge of climate change. On page 32, you will read about the fourth symposium, which looked beyond the electricity sector to address other areas of our economy that contribute greenhouse gas emissions, including transportation, industry, and agriculture.

I would like to thank former U.S. Secretary of State George P. Shultz for his 12 years of service as MITEI's inaugural External Advisory Board chairman. While he is stepping down from this role, he continues to serve on our board and remains an influential figure in the fight against climate change—notably with his recent leadership in developing an ambitious bipartisan climate plan that would introduce a progressive carbon price to halve U.S. carbon emissions from 2005 levels by 2035. We welcome clean energy advocate Norman Augustine, retired chairman and CEO of Lockheed Martin Corporation, as our External Advisory Board's incoming chairman.

Thank you, as always, for reading *Energy Futures* and for joining us in our efforts to achieve a low-carbon future. We at MITEI wish you and your loved ones health and safety during this difficult time.

Warm regards,

Robert C Armstrong

Professor Robert C. Armstrong
MITEI Director
April 2020

Transportation policymaking in Chinese cities

A new framework for learning from each other

Nancy W. Stauffer, MITEI

IN BRIEF

Transportation experts at MIT have developed new insights into how decision makers in hundreds of Chinese cities design and adopt policies relating to transportation—policies that could together curtail the rapidly growing demand for personal vehicles in China. Based on a mathematical analysis of historical data plus text analysis of policy reports, the team concludes that Chinese cities that have experienced similar urban development and motorization trends over time prioritize the same types of transportation policies to deal with their local conditions. Such a pattern is of interest to urban decision makers seeking role models for developing transportation policies. In addition to looking to Beijing and Shanghai—the trendsetters for innovative policymaking—decision makers can now learn by working with cities that face transportation challenges more similar to their own. The researchers' novel methodology combining data and text analysis can be applied in other rapidly developing countries with heterogeneous urban areas.

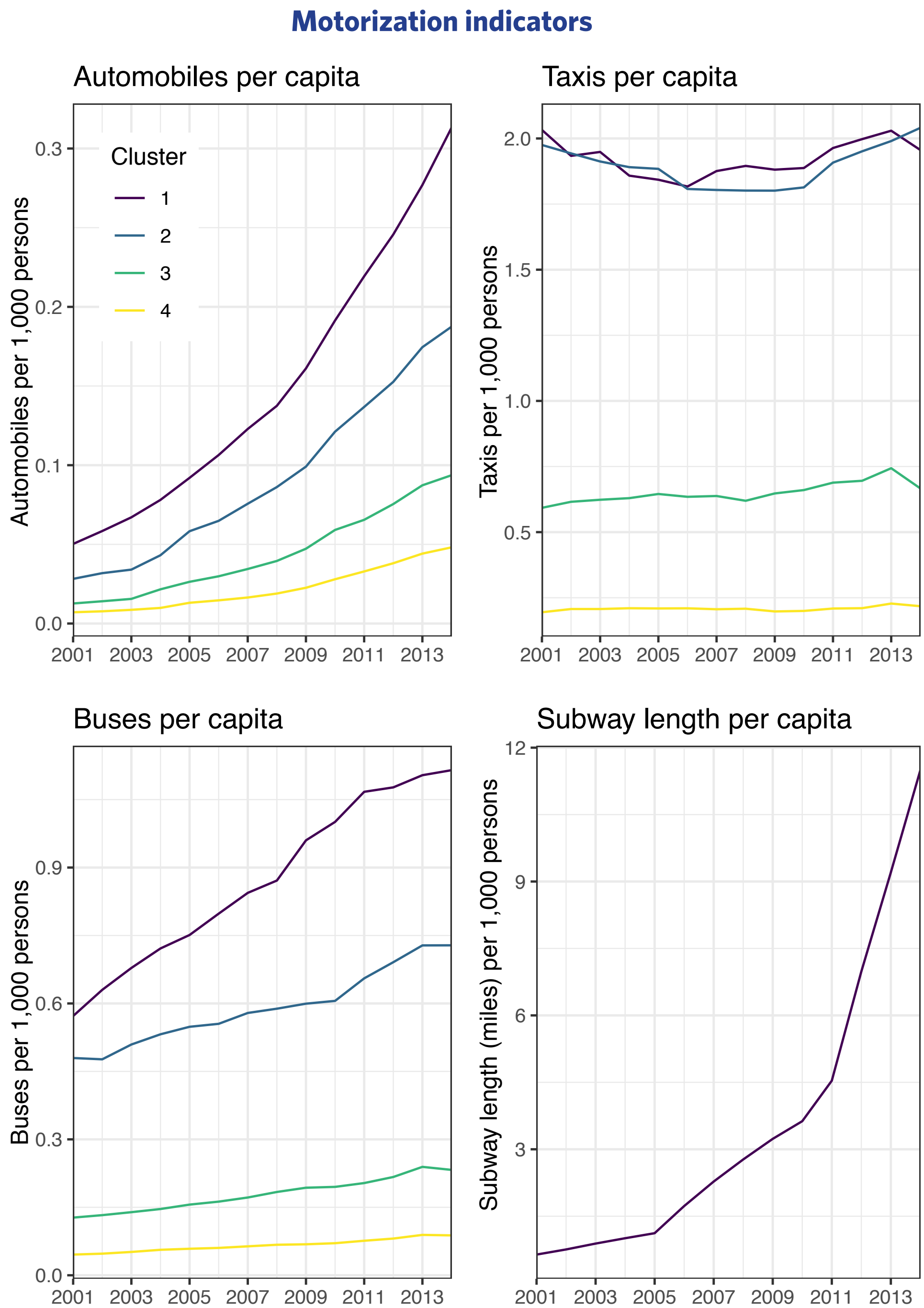
In recent decades, urban populations in China's cities have grown substantially, and rising incomes have led to a rapid expansion of car ownership. Indeed, China is now the world's largest market for automobiles. The combination of urbanization and motorization has led to an urgent need for transportation policies to address urban problems such as congestion, air pollution, and greenhouse gas emissions.

For the past three years, an MIT team led by Joanna Moody PhD '19, research program manager of the MIT Energy Initiative's Mobility Systems Center, and Jinhua Zhao PhD '09, the Edward H. and Joyce Linde Associate Professor in

Above Using a novel methodology, MITEI researcher Joanna Moody PhD '19 and Associate Professor Jinhua Zhao PhD '09 uncovered patterns in the development trends and transportation policies of China's 287 cities—including Fengcheng, shown above—that may help decision makers learn from one another. Photo: "Fengcheng, China," by blake.thornberry, via Flickr under the CC BY-NC-ND 2.0 license: bit.ly/fengcheng the Department of Urban Studies and Planning (DUSP) and director of MIT's JTL Urban Mobility Lab, has been examining transportation policy and policy-making in China. "It's often assumed that transportation policy in China is dictated by the national government," says Zhao. "But we've seen that the national government sets targets and then allows individual cities to decide what policies to implement to meet those targets."

Many studies have investigated transportation policymaking in China's megacities like Beijing and Shanghai, but few have focused on the hundreds of small- and medium-sized cities located throughout the country. So Moody, Zhao, and their team wanted to consider the process in these overlooked cities. In particular, they asked: How do municipal leaders decide what transportation policies to implement, and can they be better enabled to learn from one another's experiences? The answers to those questions might provide guidance to municipal decision makers trying to address the different transportation-related challenges faced by their cities.

The answers could also help fill a gap in the research literature. The number and diversity of cities across China has made performing a systematic study of urban transportation policy challenging, yet that topic is of increasing importance. In response to local air pollution and traffic congestion, some Chinese cities are now enacting policies to restrict car ownership and use, and those local policies may ultimately determine whether the unprecedented growth in nationwide private vehicle sales will persist in the coming decades.



Trajectories of the eight motorization and urbanization indicators used in the clustering analysis These curves show the average time series trajectories of the four city clusters on the four motorization indicators (this page) and four urbanization indicators (facing page) that the researchers used in their clustering analysis for the 287 Chinese cities. The "Subway length per capita" display shows data for only Cluster 1 cities; the other three clusters had no subway systems by 2014 so would all appear at zero. Images courtesy of the researchers

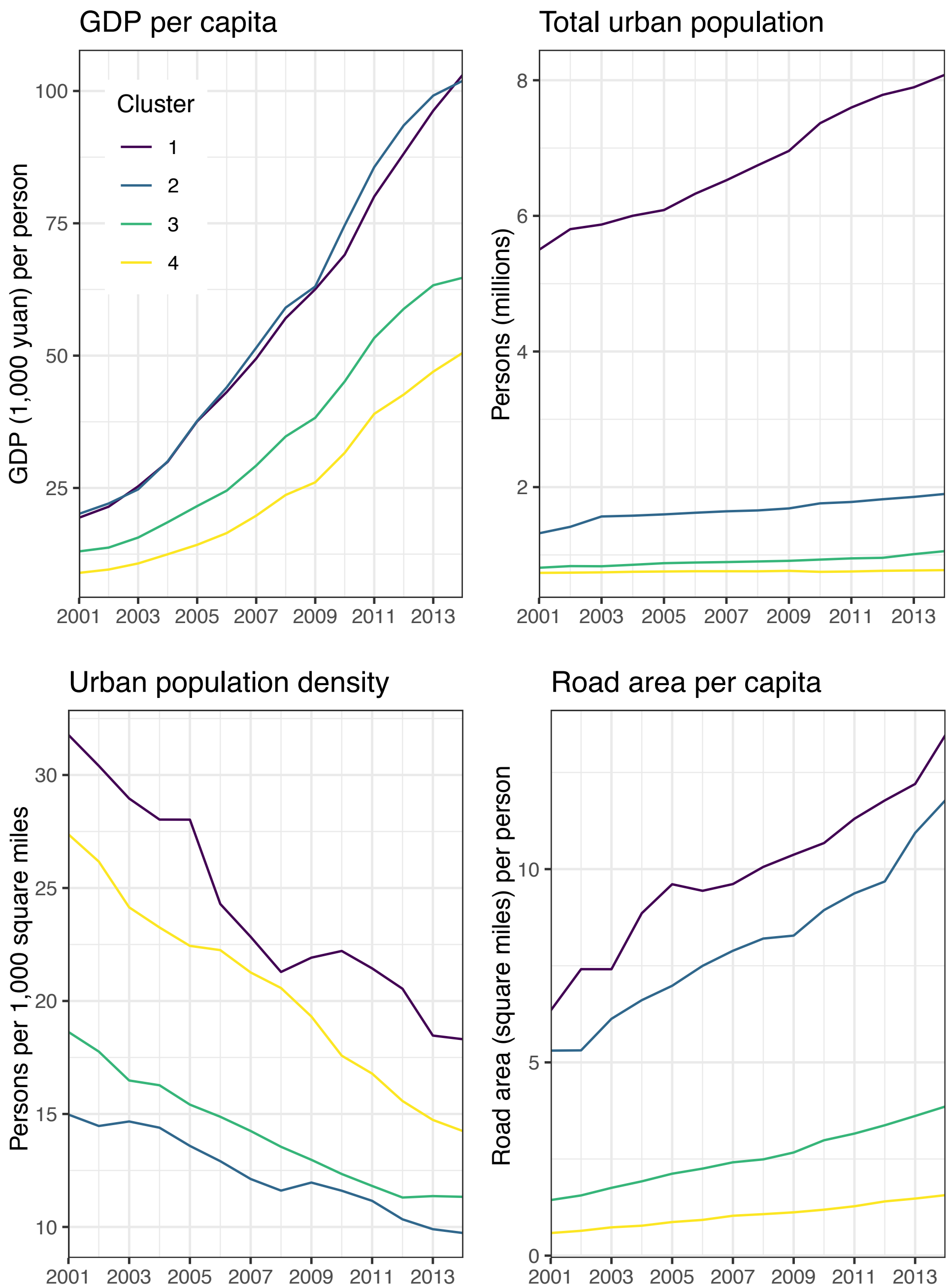
Policy learning

Transportation policymakers worldwide benefit from a practice called policy-learning: Decision makers in one city look to other cities to see what policies have and haven't been effective. In China, Beijing and Shanghai are usually viewed as trendsetters in innovative transportation policymaking, and municipal leaders in other Chinese cities turn to those megacities as role models.

But is that an effective approach for them? After all, their urban settings and transportation challenges are almost certainly quite different. Wouldn't it be better if they looked to "peer" cities with which they have more in common?

Moody, Zhao, and their DUSP colleagues—postdoc Shenhao Wang

Urbanization indicators



PhD '20 and graduate students Jungwoo Chun and Xuenan Ni MCP '19, all in the JTL Urban Mobility Lab—hypothesized an alternative framework for policy-learning in which cities that share common urbanization and motorization histories would share their policy knowledge. Similar development of city spaces and travel patterns could lead to the same transportation challenges and therefore to similar needs for transportation policies.

To test their hypothesis, the researchers needed to address two questions. To start, they needed to know whether Chinese cities have a limited number of common urbanization and motorization histories. If they grouped the 287 cities in China based on those histories, would they end up with a moderately small number of meaningful groups of peer cities? And second, would the cities in each group have similar transportation policies and priorities?

Grouping the cities

Cities in China are often grouped into three "tiers" based on political administration, or the types of jurisdictional roles the cities play. Tier 1 includes Beijing, Shanghai, and two other cities that have the same political powers as provinces. Tier 2 includes about 20 provincial capitals. The remaining cities—some 260 of them—all fall into Tier 3. These groupings are not necessarily relevant to the cities' local urban and transportation conditions.

Moody, Zhao, and their colleagues instead wanted to sort the 287 cities based on their urbanization and motorization histories. Fortunately, they had relatively easy access to the data they needed. Every year, the Chinese government requires each city to report well-defined statistics on a variety of measures and to make them public.

Among those measures, the researchers chose four indicators of urbanization—gross domestic product (GDP) per capita, total urban population, urban population density, and road area per capita—and four indicators of motorization—the number of automobiles, taxis, buses, and subway lines per capita. They compiled those data from 2001 to 2014 for each of the 287 cities.

The next step was to sort the cities into groups based on those historical data sets—a task they accomplished using a clustering algorithm. For the algorithm to work well, they needed to select parameters that would summarize trends in the time series data for each indicator in each city. They found that they could summarize the 14-year change in each indicator using the mean value and two additional variables: the slope of change over time and the rate at which the slope changes (the acceleration).

Based on those data, the clustering algorithm examined different possible numbers of groupings, and four gave the best outcome. "With four groups, the cities were most similar within each cluster and most different across the clusters," says Moody. "Adding more groups gave no additional benefit."

The four groups of similar cities are as follows.

Cluster 1: 23 large, dense, wealthy megacities that have urban rail systems and high overall mobility levels over all modes, including buses, taxis, and private cars. This cluster encompasses most of the government's Tier 1 and Tier 2 cities, while the Tier 3 cities are distributed among Clusters 2, 3, and 4.

Cluster 2: 41 wealthy cities that don't have urban rail and therefore are more sprawling, have lower population density, and have auto-oriented travel patterns.

Cluster 3: 134 medium-wealth cities that have a low-density urban form and moderate mobility fairly spread across different modes, with limited but emerging car use.

Cluster 4: 89 low-income cities that have generally lower levels of mobility, with some public transit buses but not many roads. Because people usually walk, these cities are concentrated in terms of density and development.

The figures on pages 4 and 5 plot the central trajectories for the four clusters on each of the eight urbanization and motorization indicators used in the analysis. For every indicator, there are clear differences in the trajectories of the four clusters.

City clusters and policy priorities

The researchers' next task was to determine whether the cities within a given cluster have transportation policy priorities that are similar to each other—and also different from those of cities in the other clusters. With no quantitative data to analyze, the researchers needed to look for such patterns using a different approach.

First, they selected 44 cities at random (with the stipulation that at least 10% of the cities in each cluster had to be represented). They then downloaded the 2017 mayoral report from each of the 44 cities.

Those reports highlight the main policy initiatives and directions of the city in the past year, so they include all types of policymaking. To identify the transportation-oriented sections of the reports, the researchers performed keyword searches on terms such as transportation, road, car, bus, and public transit. They extracted any sections highlighting transportation initiatives and manually labeled each of the text segments with one of 21 policy types. They then created a spreadsheet organizing the cities into the four clusters. Finally, they examined the outcome to see whether there were clear patterns within and across clusters in terms of the types of policies they prioritize.

"We found strikingly clear patterns in the types of transportation policies adopted within city clusters and clear differences across clusters," says Moody. "That reinforced our hypothesis that different motorization and urbanization trajectories would be reflected in very different policy priorities."

Here are some highlights of the policy priorities within the clusters. (For a detailed listing, see the table above).

The cities in Cluster 1 have urban rail systems and are starting to consider policies around them. For example, how can they better connect their rail systems with other transportation modes—for instance, by taking steps to integrate them with buses or with walking infrastructure? How can they plan their land use and urban development to be more transit-oriented, such as by

City clusters and their transportation policy priorities in 2017

Cluster	Transportation policy priorities
Cluster 1	Expanding existing urban rail Improving and expanding bus services Improving multimodal connectivity through transfer hubs and nonmotorized forms of transport Connecting land-use and transport planning with transit-oriented development Continuing to invest in urban expressways
Cluster 2	Developing new urban rail Improving and expanding bus service Providing public transport discounts (to encourage greater ridership)
Cluster 3	Improving and expanding bus service Emphasizing clean energy (electric) buses Continuing significant investment in additional parking spaces as well as in urban and rural roads
Cluster 4	Expanding road development to connect the urban core to rural areas on the periphery Prioritizing interconnection with other cities in the region (via road, rail, and air)

MITEI's Joanna Moody shares results from MIT's multi-year Mobility of the Future study during a launch event at MIT in November 2019. Her talk centered on the outlook for vehicle ownership, with a focus on consumer adoption of new mobility technologies and services. Photos: Kelley Travers, MITEI

providing mixed-use development around the existing rail network?

Cluster 2 cities are building urban rail systems, but they're generally not yet thinking about other policies that can come with rail development. They could learn from Cluster 1 cities about other factors to take into account at the outset. For example, they could develop their urban rail with issues of multi-modality and of transit-oriented development in mind.

In Cluster 3 cities, policies tend to emphasize electrifying buses and providing improved and expanded bus service. In these cities with no rail networks, the focus is on making buses work better.

Cluster 4 cities are still focused on road development, even within their urban areas. Policy priorities often emphasize connecting the urban core to rural areas and to adjacent cities—steps that will give their populations access to the region as a whole, expanding the opportunities available to them.

Benefits of a "mixed method" approach

Results of the researchers' analysis thus support their initial hypothesis. "Different urbanization and motorization trends that we captured in the clustering analysis are reflective of very different transportation priorities," says Moody. "That match means we can use this approach for further policymaking analysis."

At the outset, she viewed their study as a "proof of concept" for performing transportation policy studies using a mixed method approach. Mixed method research involves a blending of quantitative and qualitative approaches. In their case, the former was the mathematical analysis of time series data, and the latter was the in-depth review of city government reports to identify transportation policy priorities. "Mixed method research is a growing area of interest, and it's a powerful and valuable tool," says Moody.

She did, however, find the experience of combining the quantitative and qualitative work challenging. "There weren't many examples of people doing something similar, and that meant that we had to make sure that our quantitative work was defensible, that our qualitative work was defensible, and that the combination of them was defensible and meaningful," she says.

Associate Professor Jinhua Zhao speaks at the November 2019 Mobility of the Future study launch event at MIT. In his talk, he focused on the role of public policy in shaping the future of personal mobility in urban areas.

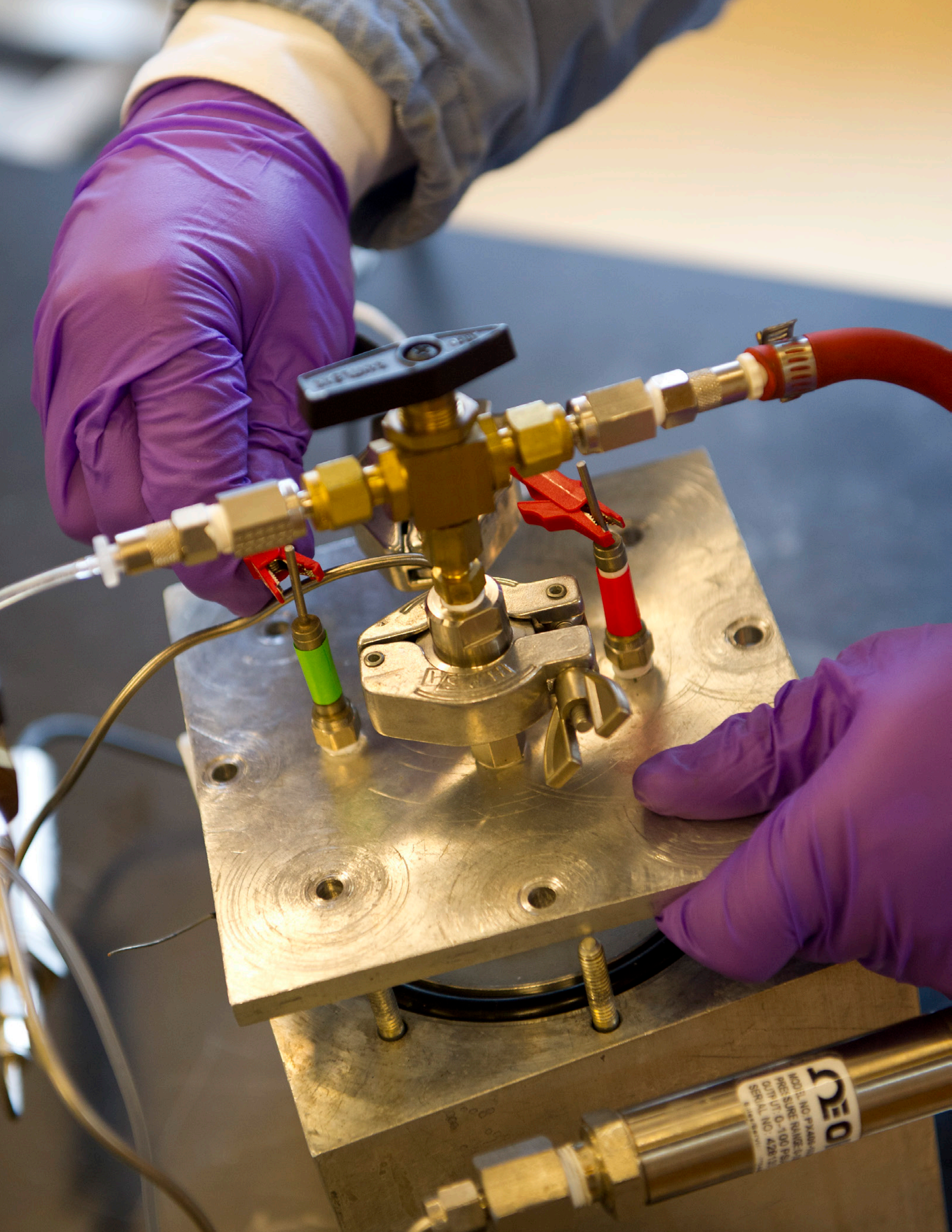
The results of their work confirm that their novel analytical framework could be used in other large, rapidly developing countries with heterogeneous urban areas. "It's probable that if you were to do this type of analysis for cities in, say, India, you might get a different number of city types, and those city types could be very different from what we got in China," says Moody. Regardless of the setting, the capabilities provided by this kind of mixed method framework should prove increasingly important as more and more cities around the world begin innovating and learning from one another how to shape sustainable urban transportation systems.

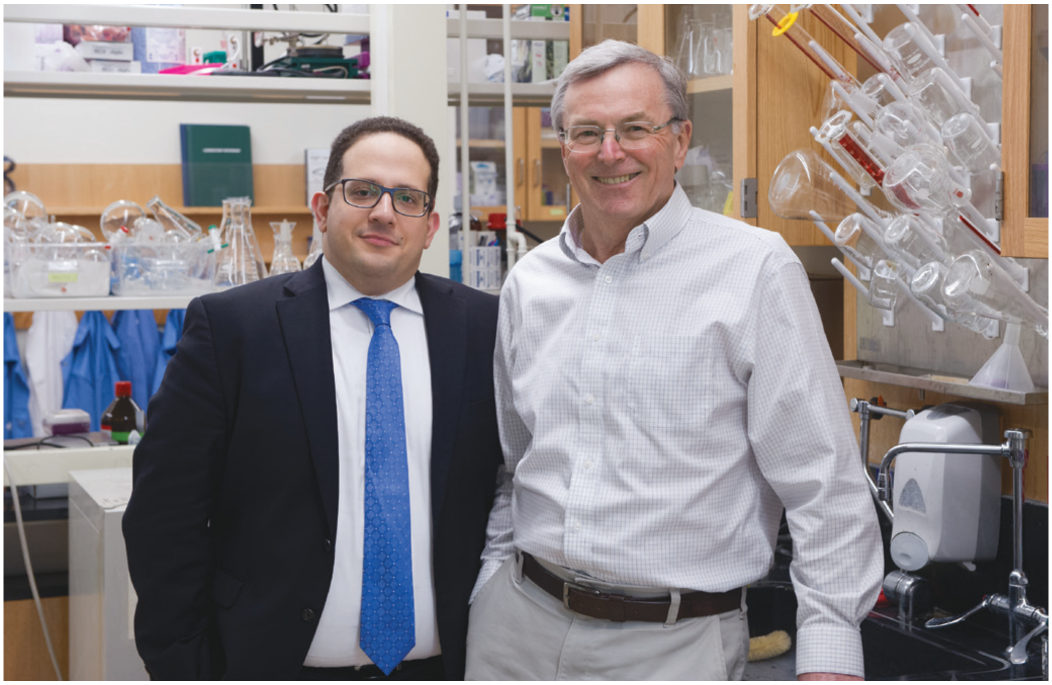
NOTES

This research was supported by the MIT Energy Initiative's Mobility of the Future study. Information about the study, its participants and supporters, and its publications is available at energy.mit.edu/research/mobilityofthefuture. For more information about the research described above, see the following:

J. Moody, S. Wang, J. Chun, X. Ni, and J. Zhao. "Transportation policy profiles of Chinese city clusters: A mixed methods approach." *Transportation Research Interdisciplinary Perspectives*, vol. 2, November 2019. Online: doi.org/10.1016/j.trip.2019.100053.

J. Chun, J. Moody, and J. Zhao. "Transportation policymaking in Beijing and Shanghai: Contributors, obstacles, and process." *Case Studies on Transport Policy*, vol. 7, issue 4, December 2019, pp. 718–731. Online: doi.org/10.1016/j.cstp.2019.09.003.





A new approach to CO_2 capture

Effective treatment for both exhaust and ambient air

Nancy W. Stauffer, MITEI

IN BRIEF

MIT researchers have demonstrated a system that promises to capture carbon dioxide (CO_2) in various exhaust streams—from power plants to home furnaces—and even retrieve it from ambient air. At the core of their device is an electrode made of a material that grabs CO_2 when the material is negatively charged and releases it the instant that charge goes away. In the device, small changes in voltage activate the electrode to capture CO_2 from a passing gas stream and then release it into a subsequent stream as pure CO_2 for industrial use or disposal. Tests show that the small, simple system is durable and efficient at targeting any level of CO_2 in any volume of exhaust. The researchers plan to develop a pilot-scale plant within a few years.

An essential component of any climate change mitigation plan is cutting carbon dioxide (CO_2) emissions from human activities. Some power plants now have CO_2 capture equipment that grabs CO_2 out of their exhaust. But those systems are each the size of a chemical plant, cost hundreds of millions of dollars, require a lot of energy to run, and work only on exhaust streams that contain high concentrations of CO_2. In short, they're not a solution for airplanes, home heating systems, or automobiles.

Facing page To test the performance of their CO_2-capture device, the researchers place it inside this pressure-sealed box, fill the space above it with a controlled concentration of CO_2, and monitor the pressure. As CO_2 is captured and released, the pressure decreases and increases. Photos: Stuart Darsch

Above Sahag Voskian SM '15, PhD '19 (left) and Professor T. Alan Hatton have developed an electrochemical cell that can capture and release CO_2 with just a small change in voltage. Results in the system shown at left and in full-scale capture units confirm the effectiveness of CO_2 removal over a range of concentrations.

To make matters worse, capturing CO_2 emissions from all anthropogenic sources may not solve the climate problem. "Even if all those emitters stopped tomorrow morning, we would still have to do something about the amount of CO_2 in the air if we're going to restore preindustrial atmospheric levels at a rate relevant to humanity," says Sahag Voskian SM '15, PhD '19. And developing a technology that can capture the CO_2 in the air is a particularly hard problem, in part because the CO_2 occurs in such low concentrations.

The CO_2 capture challenge

A key problem with CO_2 capture is finding a "sorbent" that will pick up CO_2 in a stream of gas and then release it so the sorbent is clean and ready for reuse and the released CO_2 stream can be utilized or sent to a sequestration site for long-term storage. Research has mainly focused on sorbent materials present as small particles whose surfaces contain "active sites" that capture CO_2—a process called adsorption. When the system temperature is lowered (or pressure increased), CO_2 adheres to the particle surfaces. When the temperature is raised (or pressure reduced), the CO_2 is released. But achieving those temperature or pressure "swings" takes considerable energy, in part because it requires treating the whole mixture, not just the CO_2-bearing sorbent.

In 2015, Voskian, then a PhD candidate in chemical engineering, and T. Alan Hatton, the Ralph Landau Professor of Chemical Engineering and co-director of the MIT Energy Initiative's Low-Carbon Energy Center for Carbon Capture, Utilization, and Storage, began to take a closer look at the temperature- and pressure-swing approach. "We wondered if we could get by with using only a renewable resource—like renewably sourced electricity—rather than heat or pressure," says Hatton. Using electricity to elicit the chemical reactions needed for CO_2 capture and conversion had been studied for several decades, but Hatton and Voskian had a new idea about how to engineer a more efficient adsorption device.

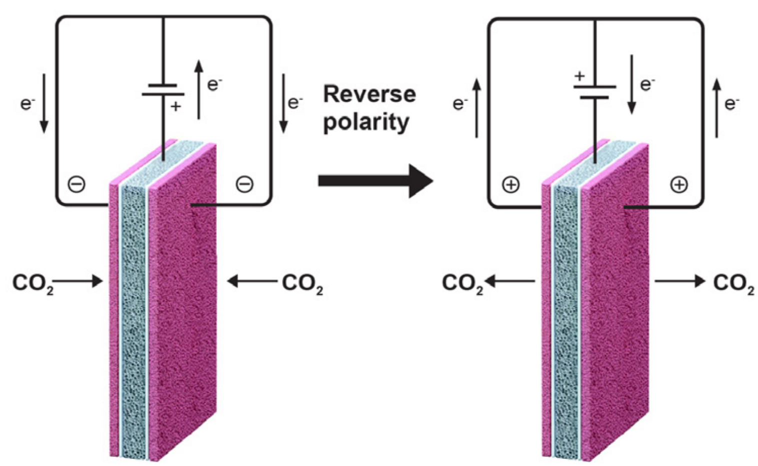
Their work focuses on a special class of molecules called quinones. When quinone molecules are forced to take on extra electrons—which means they're negatively charged—they have a high chemical affinity for CO_2 molecules and snag any that pass. When the extra electrons are removed from the quinone molecules, the quinone's chemical affinity for CO_2 instantly disappears, and the molecules release the captured CO_2.

Others have investigated the use of quinones and an electrolyte in a variety of electrochemical devices. In most cases, the devices involve two electrodes—a negative one where the dissolved quinone is activated for CO_2 capture, and a positive one where it's deactivated for CO_2 release. But moving the solution from one electrode to the other requires complex flow and pumping systems that are large and take up considerable space, limiting where the devices can be used.

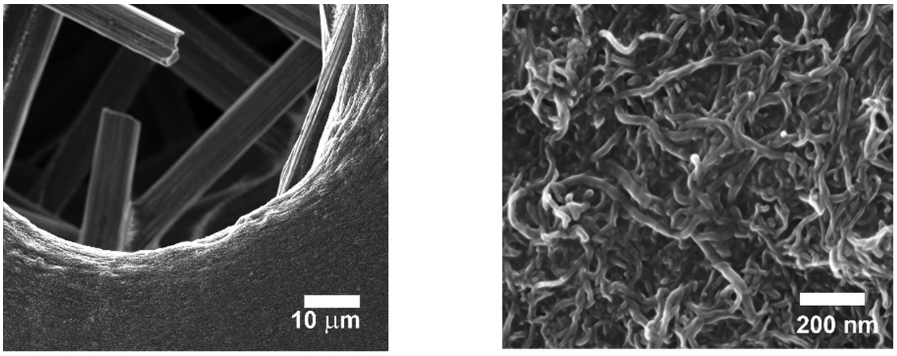
As an alternative, Hatton and Voskian decided to use the quinone as a solid electrode and—by applying what Hatton calls "a small change in voltage"—vary the electrical charge of the electrode itself to activate and deactivate the quinone. In such a setup, there would be no need to pump fluids around or to raise and lower the temperature or pressure, and the CO_2 would end up as an easy-to-separate attachment on the solid quinone electrode. They deemed their concept "electro-swing adsorption."

The electro-swing cell

To put their concept into practice, the researchers designed the electrochemical cell shown in the two diagrams below. To maximize exposure, they put two quinone electrodes (shown in pink) on the outside of the cell, thereby doubling its geometric capacity for CO_2 capture. To switch the quinone on and off, they needed a component that would supply electrons and then take them back. For that job, they used a single ferrocene electrode (shown in gray), sandwiched between the two quinone electrodes but isolated from them by electrolyte membrane separators (in white) to prevent short circuits. They connected both quinone electrodes to the ferrocene electrode using the circuit of wires at the top, with a power source along the way (indicated by the horizontal bars).



Electrochemical cell design and operation These diagrams show the electro-swing cell as it charges (left) and discharges (right). During charging, a voltage on the system causes electrons to flow from the ferrocene electrode (gray) to the quinone electrodes (pink) through the external wires. The quinone is negatively charged and captures CO_2 molecules. During discharging, the voltage is reversed, and electrons flow from the quinone back to the ferrocene. The quinone is no longer electrically charged, so it releases the captured CO_2. Images courtesy of the researchers



Scanning electron microscope (SEM) images of quinone electrode Left: This SEM micrograph shows individual uncoated fibers at the top and a region fully coated with quinone at the bottom. Right: This highly magnified view shows individual quinone-covered nanotubes.

The left-hand diagram shows the system being charged. The power source creates a voltage that causes electrons to flow from the ferrocene to the quinone through the wires. The quinone is now negatively charged. When CO_2-containing air or exhaust is blown past these electrodes, the quinone will capture the CO_2 molecules until all the active sites on its surface are filled up.

The right-hand diagram shows the discharge cycle. The direction of the voltage on the cell is reversed, and electrons flow from the quinone back to the ferrocene. The quinone is no longer negatively charged, so it has no chemical affinity for CO_2. The CO_2 molecules are released and swept out of the system by a stream of purge gas for subsequent use or disposal. The quinone is now regenerated and ready to capture more CO_2.

Two additional components are key to successful operation. First is an electrolyte, here a liquid salt, that moistens the cell with positive and negative ions (electrically charged particles). Since electrons only flow through the external wires, those charged ions must travel within the cell from one electrode to the other to close the circuit for continued operation.

The second special ingredient—not visible in the diagrams—is carbon nanotubes. In the electrodes, the quinone and ferrocene are both present as coatings on the surfaces of carbon nanotubes. Nanotubes are both strong and highly conductive, so they provide good support and serve as an efficient conduit for electrons traveling into and out of the quinone and ferrocene.

To fabricate a cell, researchers first synthesize a quinone- or ferrocene-based polymer, specifically, polyanthraquinone or polyvinylferrocene. They then make an "ink" by combining the polymer with carbon nanotubes in a solvent. The polymer immediately wraps around the nanotubes, connecting with them on a fundamental level.

To make the electrode, they use a non-woven carbon fiber mat as a substrate. They dip the mat into the ink, allow it to dry slowly, and then dip it again, repeating the procedure until they've built up a uniform coating of the composite on the substrate. The left-hand scanning electron microscope (SEM) image above shows a mat with uncoated fibers near the top and an area at the bottom that's coated with the quinone ink. The right-hand SEM image provides a highly magnified view of a coated area, with the individual, worm-like, quinone-covered nanotubes visible. The result of the process is a porous mesh that provides a large surface area of active sites and easy pathways for CO_2 molecules to move in and out.

Once the researchers have prepared the quinone and ferrocene electrodes, they assemble the electrochemical cell by laminating the pieces together in the correct order—the quinone electrode, the electrolyte separator, the ferrocene electrode, another separator, and the second quinone electrode. Finally, they moisten the assembled cell with their liquid salt electrolyte.

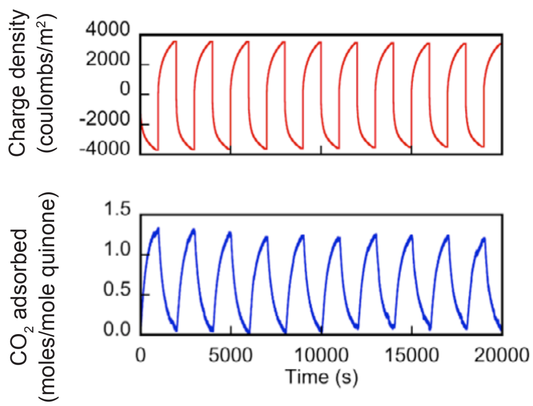
Experimental results

To test the behavior of their system, the researchers placed a single electrochemical cell inside a custom-made, sealed box and wired it for electricity input. They then cycled the voltage and measured the key responses and capabilities of the device.

The diagram on page 12 shows results from 10 cycles of voltage change. The top curve shows the charge density put into the cell, and the bottom curve shows how much CO_2 was adsorbed per mole of quinone. The simultaneous trends show that when the quinone electrode is negatively charged, the amount of CO_2 adsorbed goes up. And when that charge is reversed, CO_2 adsorption declines.

For experiments under more realistic conditions, the researchers also fabricated full capture units—open-ended modules in which a few cells were lined up, one beside the other, with gaps between them where CO_2-containing gases could travel, passing the quinone surfaces of adjacent cells.

In both experimental systems, the researchers ran tests using inlet streams with CO_2 concentrations ranging from 10% down to 0.6%. The former is typical of power plant exhaust, the latter closer to concentrations in ambient indoor air. Regardless of the concentration, the efficiency of capture was essentially constant at about 90%. (An efficiency of 100% would mean that one molecule of CO_2 had been captured for every electron transferred—an outcome that Hatton calls "highly unlikely" because other parasitic processes could be going on simultaneously.) The system used about 1 gigajoule of energy per ton of CO_2 captured. Other methods consume between 1 and 10 gigajoules per ton,



Charge density and CO_2 adsorption over time These charts show results from 10 charge-discharge cycles in the single test cell. The top panel shows charge density put into the cell, and the bottom panel shows measurements of how much CO_2 was adsorbed. The consistent alignment of the peaks and valleys confirms that inputting charge causes CO_2 capture, and reversing the polarity of that charge causes CO_2 release.

depending on the CO_2 concentration of the incoming gases. Finally, the system was exceptionally durable. Over more than 7,000 charge-discharge cycles, its CO_2 capture capacity dropped by only 30%—a loss of capacity that can readily be overcome with further refinements in the electrode preparation, say the researchers.

The remarkable performance of their system stems from what Voskian calls the "binary nature of the affinity of quinone to CO_2." The quinone has either a high affinity or no affinity at all. "The result of that binary affinity is that our system should be equally effective at treating fossil fuel combustion flue gases and confined or ambient air," he says.

Practical applications

The experimental results confirm that the electro-swing device should be applicable in many situations. The device is compact and flexible; it operates at room temperature and normal air pressure; and it requires no large-scale, expensive ancillary equipment—only the direct current power source. Its simple design should enable "plug-and-play" installation in many processes, say the researchers.

It could, for example, be retrofitted in sealed buildings to remove CO_2. In most sealed buildings, ventilation systems bring in fresh outdoor air to dilute the CO_2 concentration indoors. "But making frequent air exchanges with the outside requires a lot of energy to condition the incoming air," says Hatton. "Removing the CO_2 indoors would reduce the number of exchanges needed." The result could be large energy savings. Similarly, the system could be used in confined spaces where air exchange is impossible—for example, in submarines, spacecraft, and aircraft—to ensure that occupants aren't breathing too much CO_2.

The electro-swing system could also be teamed up with renewable sources, such as solar and wind farms, and even rooftop solar panels. Such sources sometimes generate more electricity than is needed on the power grid. Instead of shutting them off, the excess electricity could be used to run a CO_2 capture plant.

The researchers have also developed a concept for using their system at power plants and other facilities that generate a continuous flow of exhaust containing CO_2. At such sites, pairs of units would work in parallel. "One is emptying the pure CO_2 that it captured, while the other is capturing more CO_2," explains Voskian. "And then you swap them." A system of valves would switch the airflow to the freshly emptied unit, while a purge gas would flow through the full unit, carrying the CO_2 out into a separate chamber.

The captured CO_2 could be chemically processed into fuels or simply compressed and sent underground for long-term disposal. If the purge gas were also CO_2, the result would be a steady stream of pure CO_2 that soft-drink makers could use for carbonating drinks and farmers could use for feeding plants in greenhouses. Indeed, rather than burning fossil fuels to get CO_2, such users could employ an electro-swing unit to generate their own CO_2 while simultaneously removing CO_2 from the air.

Costs and scale-up

The researchers haven't yet published a full technoeconomic analysis, but they project capital plus operating costs at \$50 to \$100 per ton of CO_2 captured. That range is in line with costs using other, less flexible carbon capture systems. Methods for fabricating the electro-swing cells are also manufacturing-friendly: The electrodes can be made using standard chemical processing methods and assembled using a roll-to-roll process similar to a printing press.

And the system can be scaled up as needed. According to Voskian, it should scale linearly: "If you need 10 times more capture capacity, you just manufacture 10 times more electrodes." Together, he and Hatton, along with Brian M. Baynes PhD '04, have formed a company called Verdox, Inc., and they're planning to demonstrate that ease of scale-up by developing a pilot plant within the next few years.

NOTES

This research was supported by an MIT Energy Initiative (MITEI) Seed Fund grant and by Eni S.p.A. through MITEI. Sahag Voskian SM '15, PhD '19 was an Eni-MIT Energy Fellow in 2016–2017 and 2017–2018. He is now co-founder and chief technology officer at Verdox, Inc. Further information about the research can be found in:

S. Voskian and T.A. Hatton. "Faradaic electro-swing reactive adsorption for CO_2 capture." *Energy & Environmental Science*, issue 12, 2019. Online: doi.org/10.1039/c9ee02412c.

Solar photovoltaics

The benefits outweigh the costs

Nancy W. Stauffer, MITEI

IN BRIEF

During the past decade, both the cost of utility-scale solar arrays and the value of the electricity they provide have dropped. MIT researchers examined the net impact of those two trends on the economics of solar photovoltaic (PV) generation at more than 10,000 locations across the United States from 2010 to 2017. At each location, they balanced the cost of solar against the lifetime benefits, including revenues that potential owners would accrue and reductions in public health and climate change costs resulting from displaced emissions. Their results show that in 2017 the total benefits outweighed the cost at the majority of locations they modeled. In a follow-on analysis, they found that in California, an area with abundant solar generation, PV system owners can increase their revenues by orienting their arrays toward the west to increase power output in the evening, when prices paid for electricity are relatively high.

Over the past decade, the cost of solar photovoltaic (PV) arrays has fallen rapidly. But at the same time, the value of PV power has declined in areas that have installed significant PV generating capacity. Operators of utility-scale PV systems have seen electricity prices drop as more PV generators come online. Over the same time period, many coal-fired power plants were required to install emissions-control systems, resulting in declines in air pollution nationally and regionally. The result has been improved public health—but also a decrease in the potential health benefits from offsetting coal generation with PV generation.

Above Utility-scale photovoltaic arrays are an economic investment across most of the United States when health and climate benefits are taken into account, concludes an analysis by MITEI postdoc Patrick R. Brown PhD '16 and Senior Lecturer Francis M. O'Sullivan. Their results show the importance of providing accurate price signals to generators and consumers and of adopting policies that reward installation of solar arrays where they will bring the most benefit. Photo courtesy of SunEnergy1

Given those competing trends, do the benefits of PV generation outweigh the costs? Answering that question requires balancing the up-front capital costs against the lifetime benefits of a PV system. Determining the former is fairly straightforward. But assessing the latter is challenging because the benefits differ across time and place. "The differences aren't just due to variation in the amount of sunlight a given location receives throughout the year," says Patrick R. Brown PhD '16, a postdoc at the MIT Energy Initiative. "They're also due to variability in electricity prices and pollutant emissions."

The drop in the price paid for utility-scale PV power stems in part from how electricity is bought and sold on wholesale electricity markets. On the "day-ahead" market, generators and customers submit bids specifying how much they'll sell or buy at various price levels at a given hour on the following day. The lowest-cost generators are chosen first. Since the variable operating cost of PV systems is near zero, they're almost always chosen, taking the place of the most expensive generator then in the lineup. The price paid to every selected generator is set by the highest-cost operator on the system, so as more PV power comes on, more high-cost generators come off, and the price drops for everyone. As a result, in the middle of the day, when solar is generating the most, prices paid to electricity generators are at their lowest.

Brown notes that some generators may even bid negative prices. "They're effectively paying consumers to take their power to ensure that they are dispatched," he explains. For example, inflexible coal and nuclear plants may bid negative prices to avoid frequent shutdown and startup events that would result in extra fuel and maintenance costs. Renewable generators may also bid negative prices to obtain larger subsidies that are rewarded based on production.

Health benefits also differ over time and place. The health effects of deploying PV power are greater in a heavily populated area that relies on coal power than in a less-populated region that has access to plenty of clean hydropower or wind. And the local health benefits of PV power can be higher when there's congestion on transmission lines that leaves a region stuck with whatever high-polluting sources are available nearby. The social costs of air pollution are largely "externalized," that is, they are mostly unaccounted for in electricity markets. But they can be quantified using statistical methods, so health benefits resulting from reduced emissions can be incorporated when assessing the cost-competitiveness of PV generation.

The contribution of fossil-fueled generators to climate change is another externality not accounted for by most electricity markets. Some markets, particularly in California and the Northeast, have implemented cap-and-trade programs, but the carbon dioxide (CO_2) prices in those markets are much lower than estimates of the social cost of CO_2, and other markets don't price carbon at all. A full accounting of the benefits of PV power thus requires determining the CO_2 emissions displaced by PV generation and then multiplying that value by a uniform carbon price representing the damage that those emissions would have caused.

Calculating PV costs and benefits

To examine the changing value of solar power, Brown and his colleague Francis M. O'Sullivan, the senior vice president of strategy at Ørsted Onshore North America and a senior lecturer at the MIT Sloan School of Management, developed a methodology to assess the costs and benefits of PV power across the U.S. power grid annually from 2010 to 2017.

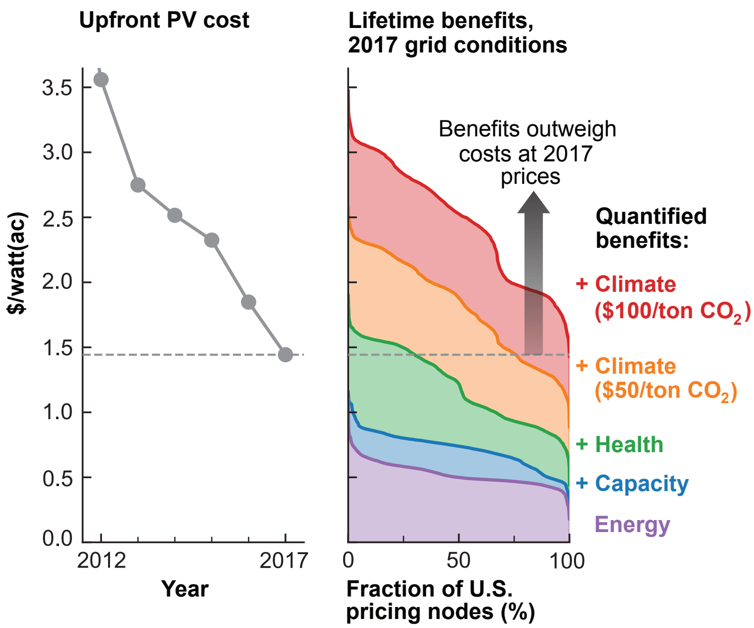
The researchers focused on six "independent system operators" (ISOs) in California, Texas, the Midwest, the Mid-Atlantic, New York, and New England. Each ISO sets electricity prices at hundreds of "pricing nodes" along the transmission network in their region. The researchers performed analyses at more than 10,000 of those pricing nodes.

For each node, they simulated the operation of a utility-scale PV array that tilts to follow the sun throughout the day. They calculated how much electricity it would generate and the benefits that each kilowatt would provide, factoring in energy and "capacity" revenues as well as avoided health and climate change costs associated with the displacement of fossil fuel emissions. (Capacity revenues are paid to generators for being available to deliver electricity at times of peak demand.) They focused on emissions of CO_2, which contributes to climate change, and of nitrogen oxides (NO_x), sulfur dioxide (SO_2), and particulate matter called $PM_{2.5}$—fine particles that can cause serious health problems and can be emitted or formed in the atmosphere from NO_x and SO_2.

Analytical results, policy implications

The results of the analysis showed that the wholesale energy value of PV generation varied significantly from place to place, even within the region of a given ISO. For example, in New York City and Long Island, where population density is high and adding transmission lines is difficult, the market value of solar was at times 50% higher than across the state as a whole.

The public health benefits associated with SO_2, NO_x, and $PM_{2.5}$ emissions reductions declined over the study period but were still substantial in 2017. Monetizing the health benefits of PV generation in 2017 would add almost 75% to energy revenues in the Midwest and New York and fully 100% in the Mid-Atlantic, thanks to the large amount of coal generation in the Midwest and Mid-Atlantic and the high population density on the Eastern Seaboard.



Break-even capital costs for PV arrays at the analyzed pricing nodes The curve on the left shows the declining upfront capital cost of PV arrays over time. The diagram on the right shows the "value stack" of calculated benefits—energy, capacity, health, and climate benefits at two carbon prices—over the lifetime of the system under 2017 grid conditions and (on the X axis) their distribution across the roughly 10,000 pricing nodes analyzed. The horizontal line marks the capital cost of PV arrays in 2017 in dollars per watt of alternating current. Assuming energy and capacity revenues plus health benefits, an investment in a PV installation at that capital cost would be paid back over the system's lifetime at 30% of the nodes. Add in the carbon price at $100 per ton, and the PV investment would break even at 100% of the nodes. Figure adapted from Brown and O'Sullivan, 2020

Based on the calculated energy and capacity revenues and health and climate benefits for 2017, the researchers asked: Given that combination of private and public benefits, what upfront PV system cost would be needed to make the PV installation "break even" over its lifetime, assuming that grid conditions in that year persist for the life of the installation? In other words, says Brown, "At what capital cost would an investment in a PV system be paid back in benefits over the lifetime of the array?"

Their findings are summarized in the chart above. Assuming 2017 values for energy and capacity market revenues alone, an unsubsidized PV investment at 2017 costs doesn't break even. Add in the health benefit, and PV breaks even at 30% of the pricing nodes modeled. Assuming a carbon price of $50 per ton, the investment breaks even at about 70% of the nodes, and with a carbon price of $100 per ton (which is still less than the price estimated to be needed to limit global temperature rise to under 2°C), PV breaks even at all of the modeled nodes.

That wasn't the case just two years earlier: At 2015 PV costs, PV would only have broken even in 2017 at about 65% of the nodes counting market revenues, health benefits, and a $100 per ton carbon price. "Since 2010, solar has gone from one of the most expensive sources of electricity to one of the cheapest, and it now breaks even across the majority of the U.S. when considering the full slate of values that it provides," says Brown.

Based on their findings, the researchers conclude that the decline in PV costs over the studied period outpaced the decline in value, such that in 2017 the market, health, and climate benefits outweighed the cost of PV systems at the majority of locations modeled. "So the amount of solar that's competitive is still increasing year by year," says Brown.

The findings underscore the importance of considering health and climate benefits as well as market revenues. "If you're going to add another megawatt of PV power, it's best to put it where it'll make the most difference, not only in terms of revenues but also health and CO_2," says Brown.

Unfortunately, today's policies don't reward that behavior. Some states do provide renewable energy subsidies for solar investments, but they reward generation equally everywhere. Yet in states such as New York, the public health benefits would have been far higher at some nodes than at others. State-level or regional reward mechanisms could be tailored to reflect such variation in node-to-node benefits of PV generation, providing incentives for installing PV systems where they'll be most valuable. Providing time-varying price signals (including the cost of emissions) not only to utility-scale generators but also to residential and commercial electricity generators and customers would similarly guide PV investment to areas where it provides the most benefit.

Time-shifting PV output to maximize revenues

The analysis provides some guidance that may help would-be PV installers maximize their revenues. For example, it identifies certain "hot spots" where PV generation is especially valuable. At some high-electricity-demand nodes along the East Coast, for instance, persistent grid congestion has meant that the projected revenue of a PV generator has been high for more than a decade. The analysis also shows that the sunniest site may not always be the most profitable choice. A PV system in Texas would generate about 20% more power than one in the Northeast, yet energy revenues were greater at nodes in the Northeast than in Texas in some of the years analyzed.

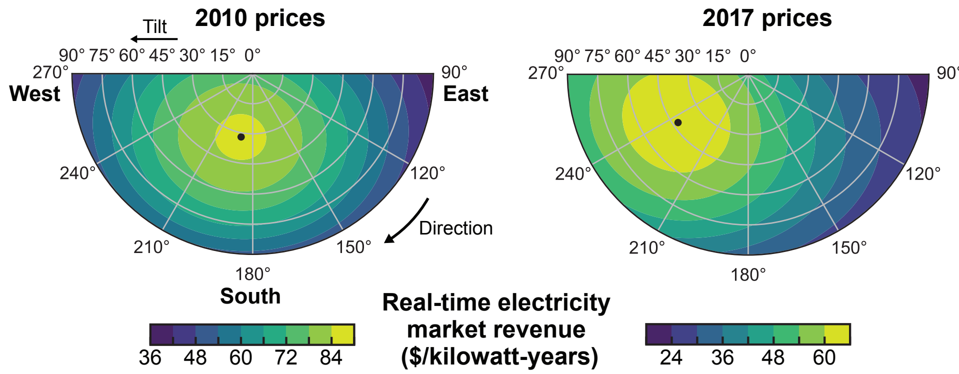
To help potential PV owners maximize their future revenues, Brown and

O'Sullivan performed a follow-on study focusing on ways to shift the output of PV arrays to align with times of higher prices on the wholesale market. For this analysis, they considered the value of solar on the day-ahead market and also on the "real-time market," which dispatches generators to correct for discrepancies between supply and demand. They explored three options for shaping the output of PV generators, with a focus on the California real-time market in 2017, when high PV penetration led to a large reduction in midday prices compared to morning and evening prices.

Curtailing output when prices are negative: During negative-price hours, a PV operator can simply turn off generation. In California in 2017, curtailment would have increased revenues by 9% on the real-time market compared to "must-run" operation.

Changing the orientation of "fixed-tilt" (stationary) solar panels: The general rule of thumb in the Northern Hemisphere is to orient solar panels toward the south, maximizing production over the year. But peak production then occurs at about noon, when electricity prices in markets with high solar penetration are at their lowest. Pointing panels toward the west moves generation further into the afternoon. On the California real-time market in 2017, optimizing the orientation would have increased revenues by 13%, or 20% in conjunction with curtailment.

Using 1-axis tracking: For larger utility-scale installations, solar panels are frequently installed on automatic solar trackers, rotating throughout the day from east in the morning to west in the evening. Using such 1-axis tracking on the California system in 2017 would have increased revenues by 32% over a fixed-tilt installation, and using tracking plus curtailment would have increased revenues by 42%.



Contour plots showing yearly energy revenues as a function of PV array orientation These plots show the orientation of a fixed-tilt array located at a pricing node in California and optimized for maximum yearly energy revenues assuming 2010 prices (left) and 2017 prices (right). The degrees marked around the circumference show which way the array is facing. The degrees across the top indicate grid lines showing how much it's tilted, with 0° pointing straight up. The black dot indicates the optimal orientation. In 2010, an array facing 10° west of south brings maximum revenues. In 2017, maximum revenues come from an array facing 55° west of south—an adjustment that reflects changes on electricity markets with increased PV penetration. Figure adapted from Brown and O'Sullivan, 2019

The researchers were surprised to see how much the optimal orientation changed in California over the period of their study (see the figure above). "In 2010, the best orientation for a fixed array was about 10 degrees west of south," says Brown. "In 2017, it's about 55 degrees west of south." That adjustment is due to changes in market prices that accompany significant growth in PV generation—changes that will occur in other regions as they start to ramp up their solar generation.

The researchers stress that conditions are constantly changing on power grids and electricity markets. With that in mind, they made their database and computer code openly available so that others can readily use them to calculate updated estimates of the net benefits of PV power and other distributed energy resources.

They also emphasize the importance of getting time-varying prices to all market participants and of adapting installation and dispatch strategies to changing power system conditions. A law set to take effect in California in 2020 will require all new homes to have solar panels. Installing the usual south-facing panels with uncurtailable output could further saturate the electricity market at times when other PV installations are already generating.

"If new rooftop arrays instead use west-facing panels that can be switched off during negative price times, it's better for the whole system," says Brown. "Rather than just adding more solar at times when the price is already low and the electricity mix is already clean, the new PV installations would displace expensive and dirty gas generators in the evening. Enabling that outcome is a win all around."

NOTES

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The computer code and data repositories are available at https://zenodo.org/record/3562896 and https://zenodo.org/record/3368397. Further information can be found in:

P.R. Brown and F.M. O'Sullivan. "Shaping photovoltaic array output to align with changing wholesale electricity price profiles." *Applied Energy*, vol. 256, December 15, 2019. Online: doi.org/10.1016/j.apenergy.2019.113734.

P.R. Brown and F.M. O'Sullivan. "Spatial and temporal variation in the value of solar power across United States electricity markets." *Renewable and Sustainable Energy Reviews*, vol. 121, April 2020. Online: doi.org/10.1016/j.rser.2019.109594.

Open SESAME

Meet the team of postdocs working to expand MITEI's novel energy assessment tool

Kathryn Luu, MITEI

For Naga Srujana Goteti, a postdoc at the MIT Energy Initiative (MITEI), finding a meaningful career has required starting from scratch—three times. She first worked as a software engineer after earning a bachelor's degree in electrical engineering, but after just one year in the role, she felt like something was missing. Her father, a civil engineer, encouraged her to look for meaning and opportunity in the energy space.

Goteti dropped her software engineering position to perform energy audits on buildings as an intern at a small startup, where a visiting professor inspired her to move from India to Thailand to pursue a master's degree in energy. After completing her graduate program, she still wasn't quite sure where she could best apply her interdisciplinary background. She ended up joining an oil and gas company to work on pipelines.

"I really enjoyed the salary, of course, but after one year, I went back to my original question of, 'What's the purpose of this?' I wasn't finding any meaning in the work I was doing," she says.

She quit her oil and gas job, desperately seeking leads on research opportunities in clean energy. At one point, she was cold-emailing "at least 30 professors per day." Her efforts paid off when a team at the Rochester Institute of Technology (RIT) informed her that it was seeking someone with an electrical engineering background, plus experience with energy and sustainability, to join a special project. Goteti fit the bill and came to the United States to pursue her PhD in sustainability.

"After getting my PhD at RIT, I really wanted to work on an interdisciplinary team that was focused on reducing carbon dioxide emissions by looking at multiple renewable energy pathways instead of just one," she says. This quest led her to MITEI.

Goteti has teamed up with Tapajyoti "TJ" Ghosh, a chemical engineer from India, and Maryam Arbabzadeh, a lifecycle assessment (LCA) practitioner from Iran—an interdisciplinary group

Above Left to right: Emre Gençer, a MITEI research scientist, is working with postdocs Naga Srujana Goteti, Maryam Arbabzadeh, and Tapajyoti Ghosh to expand MITEI's new energy lifecycle assessment tool. Photo: Kelley Travers, MITEI of postdocs who came to MIT to work on a novel energy assessment tool called the Sustainable Energy System Analysis Modeling Environment (SESAME).

Many of the energy assessment tools that exist today zero in on only one slice of the energy pie. They offer a granular analysis of solar, wind, or nuclear, but rarely look at multiple pathways together, which limits the ability of policymakers and industry professionals to see the real-time impacts of various technologies across the energy landscape as a whole.

"Today, we are facing a dual challenge: satisfying growing energy demand while reducing emissions," says Emre Gençer, a research scientist at MITEI and leader of the SESAME project. "The composition and operation of energy systems determine our ability to meet this challenge. We developed SESAME to study all energy sectors at the pathway and system levels."

SESAME, which has been under development at MIT since 2017, enables users to understand the impact of all relevant technological, operational, temporal, and geospatial variables to the evolving energy system. Several existing LCA models require expert help in order to parse the data in a way that is useful for policymakers and industry. The SESAME tool aims to bridge that divide, so that experts and laypeople alike can understand today's energy landscape and make informed decisions about the best paths forward.

Gençer spent almost a year assembling the perfect team of postdocs to help expand the tool. MITEI's SESAME team is now about 20 people strong, including postdocs Arbabzadeh, Ghosh, and Goteti, plus a mix of undergraduates, graduate students, research scientists, and PhD candidates from across MIT.

"The multidisciplinary nature of this project requires a strong mix of research backgrounds," says Gençer. "We weren't just looking within one specific discipline to build the SESAME team. We were very intentional about bringing together researchers with experience in different areas such as engineering, environmental studies and sustainability, and economics."

MITEI's goal is to develop SESAME as an open-source web application—one that incorporates energy case studies from around the globe and takes into account the heterogeneity of data across regions. These expansion directions are where Arbabzadeh, Ghosh, and Goteti come in.

Pathways to MITEI

As a child, Tapajyoti Ghosh visited oil fields and gas facilities across India with his father—"an oil and gas man." He remembers wondering, "What's going to happen when all the oil is gone?" His interest in the environmental impacts of society's dependence on fossil fuels and finding sustainable alternatives came later.

Ghosh earned his bachelor's degree in chemical engineering in 2014 from Jadavpur University in Kolkata, India, after which he came to the United States for a PhD program at Ohio State University.

"I had no idea what research direction I was interested in," he says. "I spent the first semester of my PhD program deciding what I wanted to focus on." But then a conversation with his professor set Ghosh down the energy path by introducing him to sustainable engineering.

"Sustainable engineering focuses on trying to reduce negative environmental impacts that are caused by engineering processes not considering the external impacts of their activities," he says. "I was interested in figuring out how we can make our engineering processes take environmental impacts into account during the design process while also helping industry make profits."

He came to MITEI for the opportunity to work on SESAME, which he sees as a groundbreaking environmental impact assessment tool that will help industry and policymakers. He hopes to return to India someday to become a faculty member at a university there.

"Completing my postdoctorate at MIT will have a huge impact on my future," he says. "I received several offers from other universities and research centers, but for me, the lure was getting to be at MIT. I feel like I'm in the Hollywood of academia."

Ghosh's role at MITEI is to literally "open SESAME"—he is working to convert the tool from a MATLAB application, which is a proprietary programming language developed by MathWorks, to an open-source web application, which will make SESAME available for all to use. This is a Herculean effort; the SESAME platform was designed with a modular structure to allow the analysis of a very large number of conventional and novel pathways—more than 1,000 energy pathways are embedded in the framework, capturing about 90% of energy-related emissions data. SESAME's framework provides multiple functionalities for various energy stakeholders in a single tool. For example, those working in industry or policy can compare technology options, perform technology and system scenario analyses, or explore the impacts of market and policy dynamics; or energy experts can see comprehensive cross-technology comparisons. Ghosh needs to translate all of this into Python coding language for the open-source version of the tool.

"I'm also working with an undergraduate student to gather additional environmental impact data that we can add to the tool, and adding new pathways for analysis," he says. Some of those new pathways include the production of ammonia, cement, iron, and steel.

Maryam Arbabzadeh received her bachelor's in electrical engineering, with a focus on power systems, from Amirkabir University of Technology (formerly Tehran Polytechnic) in Iran.

"That's where I started learning about renewable energy. I did my undergraduate thesis on wind energy and developing tools so users could suggest the most effective locations for installing wind turbines," she says.

When it came time for her master's degree, Arbabzadeh knew she wanted to continue studying electrical engineering, with a focus on energy systems. She came to the United States to attend the State University of New York at Buffalo (SUNY Buffalo), which sparked her interest in finding ways to reduce the negative environmental impacts of power generation.

"At SUNY Buffalo, I took classes on sustainable energy systems and climate change, and that's where I first discovered that one of the main sources for environmental emissions is the electricity sector/power grid. I became really interested in learning about that aspect of electricity production," she explains.

From there, she applied to multidisciplinary programs for her PhD, landing at the University of Michigan's School for Environment and Sustainability to work on an energy storage project.

"My PhD advisors were looking for someone with a background in electrical engineering who was also interested in learning about energy and lifecycle analysis, so it was perfect for me," she says. "My dissertation mainly focused on energy storage and technologies but at a high level—all about the optimization of the power grid and how the addition of emerging technologies such as energy storage would affect the grid."

She was drawn to the SESAME project because, during her experiences as an LCA practitioner and power systems modeler, she faced a number of challenges when it came to gathering all the disparate pieces of data she needed in order to form a comprehensive energy picture.

"It is interesting for me to develop a tool that can bring together all of these pieces from different sectors—power, transportation, et cetera—and that will allow policymakers and energy modelers to use the tool to do a system analysis for themselves," she says.

SESAME currently contains data from North American case studies. Arbabzadeh's portion of the project, which is funded by the International Energy Agency Gas and Oil Technology Collaboration Program, involves identifying international case studies that can be incorporated into SESAME to help the tool expand beyond the United States. "Emre asked me to focus specifically on examining global perspectives, so it has been fascinating for me to see how our analysis might apply to other locations." So far, Arbabzadeh has focused her efforts on identifying potential case studies, including Norway/Northwest Europe and Singapore.

"In contrast to the United States, Norway's energy sector is already clean because a huge amount of its power generation comes from hydro, with some support from wind and thermal," she says. Norwegian exports to continental Europe can enable displacement of coal with natural gas and reduce greenhouse gas emissions.

"Oil and gas production is the main contributor to greenhouse gas emissions in Norway, followed by industry and transportation," Arbabzadeh says. She is working with an undergraduate student to examine the production activities and their associated emissions from about 90 oil and gas fields across Norway. These emissions can be more than offset by planned innovative offshore CO_2 capture and sequestration projects that will permanently store CO_2 captured from various sources across Europe.

This information could help Norway and other oil and gas producers from around the world to learn about how they can reduce greenhouse gas emissions in their processes and associated systems.

Arbabzadeh's interest in contributing to the SESAME tool spans beyond professional motivation: "Personally, I want to make an impact. I was very interested in coming to MITEI to work on this tool because when it becomes available, it will really make a difference in various sectors and will be so useful for stakeholders working across the energy space."

Her work on the tool complements that of Goteti, who has been charged with capturing the heterogeneity of the data from across the United States, starting with power systems. "This is a major challenge, because it requires cross-linking all of the databases across the country so that they can be integrated into the SESAME platform," says Goteti. "I'm aiming to automate this process so that it can be used in SESAME as part of our analysis to show, for example, how California is different from Texas."

Arbabzadeh and Goteti use similar research models for their respective parts of the project.

"There is a weird disconnect between different types of energy researchers. LCA people look at energy models differently from complex energy system modelers. Complex energy system models typically examine one area in minute detail, while LCA looks across the spectrum," says Goteti. "SESAME fills the operations versus lifecycle gap in many of today's models by offering all energy experts a holistic approach to analyzing all of the systems together."

Collaborating to "open SESAME"

When asked how their roles work together, Arbabzadeh offers a deceptively simple explanation: "TJ is working on the framework and gives us direction in terms of what specific data the tool needs, and that's what Srujana and I try to collect."

The reality of the scope of the work with which they've each been charged, and the level of collaboration that is required to meet those goals, is much more complex. The interdependent nature of their work requires that they check in with each other daily, as progress on the project relies on results from each person. The information Ghosh receives from Goteti and Arbabzadeh is integral to the SESAME expansion; and, in turn, Goteti and Arbabzadeh rely on direction from Ghosh in order to procure the data and to ensure it is in a SESAME-compatible format.

The team is also working to incorporate other environmental impact categories in the model—beyond just greenhouse gas emissions, which is the tool's current focus. They are hoping to include factors such as water impacts, air pollutants, and land use.

Although they have different research backgrounds, Goteti explains, "We have a common thread of experience with LCA, so we have a basic understanding of what the SESAME team is doing across the board, even though we may not know what each other is working on at a granular level."

In addition to supporting each other as they bring their various areas of expertise to bear on their work at MITEI, the team members say they have found support from MITEI and from the MIT postdoc community as a whole.

"MITEI is a unique center where people talk to each other about what they are working on, even to others outside their project. Research scientists, postdocs, and students sit together to discuss our research, and we actually provide each other with valuable input," remarks Goteti. "There's not a tunnel view of your own projects; everyone is open to helping others, which is not the case at more corporate places, where it's a spirit of 'my project versus your project.'"

Arbabzadeh concurs: "In addition to collaboration on research, I was surprised to learn how postdocs are acknowledged here at MIT. There are a lot of professional development resources and even a career advisor specifically for postdocs! It was unique for me to see how postdocs are treated here."

Both Goteti and Ghosh also value the proximity to leading faculty, within MITEI and across MIT. "Getting inside access to faculty is a big deal for me, coming from India," says Goteti.

"I feel fortunate to have a peek into this very exclusive world. These kinds of opportunities—being able to engage with the world's leading researchers, CEOs, et cetera—were just not available to me at my previous institutions," says Ghosh. "The founder of Zipcar sits right across from my cubicle! There is a Nobel Prize–winning lab on the floor below ours."

Each member of the trio will present results from their portions of the SESAME tool expansion at various conferences. The team has also contributed to a series of journal articles about the tool, which they anticipate will be published over the coming year.

Contributing to the low-carbon energy transition

Coming from different backgrounds, Arbabzadeh, Ghosh, and Goteti are united by their desire to devote their expertise to pushing forward cutting-edge clean energy solutions.

Ghosh would like to answer the questions he's had since his childhood, first sparked by his visits to oil fields with his dad. "What's going to replace the world's dependence on fossil fuels? What is the cleanest form of energy that humans can depend on for a long amount of time? Is it going to be Tony Stark's arc reactor or some nuclear fusion reactor like a tokamak, or just solar and wind, or some other miracle solution? I'm interested in answering futuristic questions like these," says Ghosh.

Arbabzadeh is focused on using her experience to solve environmental challenges for the benefit of our planet and its future inhabitants. "During my master's degree work, I learned about the negative environmental impacts of electricity production and wondered: 'How can we improve this? I have the skills and knowledge, but how can I do more?'" adds Arbabzadeh. "Trying to solve these challenges is exciting for me. I think the energy sector is very important in terms of climate change, and the decarbonization of power production is an area where we can truly make a positive impact for future generations."

In energy, Goteti has found the meaningful work that she craved for all those years; there will be no more starting over. "Governments collapse because of energy; economies are driven by energy—I think energy is the backbone for so many things that we don't realize," says Goteti. "That excites me a lot. As a kid, I was never into politics, but now I watch the news all the time and understand that everything is related. At the end of the day, it's all about energy."

NOTES

Support for the SESAME tool has been provided by ExxonMobil and the International Energy Agency Gas and Oil Technology Collaboration Program. The SESAME online beta is expected in mid-2020. Sign up to become a beta user at sesame.mit.edu.

Energy economics class inspires students to pursue clean energy careers

Jing Li, an assistant professor of applied economics in the MIT Sloan School of Management, stands at the front of the classroom and encourages her undergraduate students to dig deeper. "Why was this a good idea?" she prompts. "How did people come up with these numbers?"

It's the second-to-last day of class, and the students in Economics of Energy, Innovation, and Sustainability are discussing their teams' results and the logic behind the decisions they made in the Electricity Strategy Game—a main feature of this course.

"[With] so much magic," a student quips in response to Li's question, to a chorus of laughter.

The real magic, they all know, is in Li's approach to teaching: She holds her students accountable for their conclusions and throws them head-first into challenging problems to help them confidently engage with the complexities of energy economics.

"She didn't baby us with tiny data sets. She gave us the real deal," says Wilbur Li, a senior computer science major and mechanical engineering minor (no relation to Jing Li). He initially took the class to round out his fall semester schedule, unsure if he would keep it due to a rigorous class load. However, just a couple of weeks into the semester, he was sold on the class.

"It's one of those classes at MIT that isn't really a requirement for anyone, but it's a class that only draws people who are genuinely interested in the subject area," he says. "That made for really good discussions. You could tell that people were interested beyond an academic sense."

Jing Li, an assistant professor of applied economics, engages with her students during the Electricity Strategy Game debrief. Photo: Kelley Travers, MITEI

15.0201/14.43, a part of MITEI's interdisciplinary Energy Studies Minor, is a relatively new course. The class, which is also offered as graduate-level course 15.020, made its debut in the spring 2019 semester and was developed to expand the energy economics offerings at MIT. Part of the motivation for creating 15.0201/14.43 stemmed from the fact that Professor Christopher Knittel's course 15.037/15.038 Energy Economics and Policy is consistently in high demand, without enough supply to accommodate interested students.

"Professor Knittel and I have positioned our two courses so that someone who wants to get a taste of energy economics could take either one and come away with a good mental map of the field, but also that someone who is very serious about a future career in energy would find it useful to take both," says Li.

Li's class focuses on innovation and employs environmental economics principles and business cases to explore the development and adoption of new technology and business strategies related to sustainability.

"The class has been particularly attractive to students who are interested in the energy landscape, such as how energy markets impact and relate to local environmental issues and how to provide energy to parts of the globe that currently lack access to affordable or reliable energy," she says. "It has also appealed to students interested in applied microeconomics."

In addition to crunching large data sets and bringing in guest speakers, such as Paul Joskow, the Elizabeth and James Killian Professor of Economics Emeritus and former chair of MIT's Department of Economics, a major element of the class—and a runaway favorite of many of the students—is the Electricity Strategy Game. The game was created by Professors Severin Borenstein and James Bushnell for the University of California at Berkeley's Haas School of Business.

The game is designed to replicate the world of deregulated wholesale electricity markets. Players are divided into firms and utilize electricity generation portfolios, based on actual portfolios of the largest generation firms in the California

Students share how they drew on business case studies and other course materials to inform their actions throughout the Electricity Strategy Game. Photos: Kelley Travers, MITEI

market, to compete in a sequence of daily electricity spot markets, in which commodities are traded for immediate delivery. Each portfolio contains differing generation technologies (thermal, nuclear, and hydro), with varying operating costs. Spot market conditions vary from hour to hour and day to day. Players must develop strategies to deploy their assets over a sequence of spot markets while accounting for the cost structure of their portfolio, varying levels of hourly electricity demand, and the strategies of other players. The game is conducted in six rounds, with the second half of the game taking into account carbon permits. Winners are determined by the financial performance of their firm and an evaluation of the logic of the firm's actions, which the teams describe in a series of memos to the professor.

"I *loved* the Electricity Strategy Game! It was really fun to have to figure out how to predict demand and then how to price supply accordingly," says Anupama Phatak, a junior mechanical engineering major and economics minor. "The bid for portfolios was also a really cool process. I put a lot of time and effort into understanding the game and developing a strategy, so it made the process all the more rewarding when my team won."

Wilbur Li echoed Phatak's enthusiasm. "My favorite part of the game was definitely the auction—it was the most exciting part," he says. "Every single group did research on their own to figure out what sort of bidding prices they wanted for each piece of property [power plants]—and when we showed up, every single group had wildly different final prices for what we bid on the plants."

For Isaac Perper, a senior mechanical engineering and computer science double major and economics minor, the value of the game was in getting a glimpse of how energy portfolios might play out in real-life auctions. "We all had different portfolios, so I think that was the most interesting part. We got to see differences between coal, hydro, and gas plants and the different price points at which they are profitable. I think the auction mirrored what you would expect in a real market," he says.

Many of the students who took 15.0201/14.43 are making it their mission to apply the lessons learned from the class to their career goals. The class helped inspire Wilbur Li to pursue a career in cleantech product development, such as working on smart meters or more efficient transportation for wind turbine blades.

"A class like 14.43 definitely helps with understanding how the products that are being worked on can be scaled in terms of figuring out which players in the economy would want to pick up and utilize a product," he says. "It has given me a deeper understanding of how technology scales on a market level, as well as how to understand and account for the target impact of those technologies."

Anupama Phatak, a junior mechanical engineering major and economics minor, details her team's winning strategy.

Phatak says that the class has made her more conscious of the adverse environmental consequences of products such as palm oil. "I now understand that even the smallest ingredient in our everyday products can have negative impacts around the world that I might not even see," she says. Because of the topics covered in Li's course, Phatak is now actively pursuing internships in sustainability.

Perper shared that the class opened his eyes to a lot of inefficiencies that exist in the energy market today. Indeed, he says that his life's goal is to help to address some of those inefficiencies. "Going into this class, I had kind of thought that we have our different electricity producers and some pollute more than others, but in terms of the actual market structure and how electricity is distributed, paid for, and expanded into developing areas, all of those things were more complicated and inefficient than I had expected," he says. When he returns to MIT in the fall to pursue his master's degree in computer science and electrical engineering, Perper says he will be thinking more about the bigger questions in terms of energy policy and technology.

Professor Li says she hopes that students come away from 14.43 with "more questions than answers," as well as a honed sense of which questions are worth spending time to answer. She also aims for her students to leave with the knowledge that sustainability and energy touch every organization in some way.

"Whatever kind of organization you are a part of and the role you take in that organization—investor, manager, employee, customer, voter—you can contribute to the sustainability goals of your organization with your ideas, voice, and actions," she says.

Kathryn Luu, MITEI

Energy alumni: Where are they now?

Addison Stark SM '10, Mechanical Engineering and Technology and Public Policy, PhD '15, Mechanical Engineering

Addison Stark is the associate director for energy innovation at the Bipartisan Policy Center (in Washington, D.C.), which focuses on implementing effective policy on important topics for American citizens, regardless of party affiliation. He also serves as an adjunct professor at Georgetown University, where he teaches a course on clean energy innovation. Prior to these roles, he was a fellow and acting program director at the U.S. Department of Energy's Advanced Research Projects Agency-Energy.

Q What experiences did you have that inspired you to pursue energy studies?

A I grew up on a farm in rural Iowa, surrounded by a growing biofuels industry and bearing witness to the potential impacts of climate change on agriculture. I then went to the University of Iowa as an undergrad. While there, I was lucky enough to serve as one of the student representatives on a committee that put together a large decarbonization plan for the university. I recognized at the time that the university not only needed to put together a policy, but also to think about what technologies they had to procure to implement their goals. That experience increased my awareness of the big challenges surrounding climate change. I was fortunate to have attended the University of Iowa because a large percentage of the students had an environmental outlook, and many faculty members were involved with the Intergovernmental Panel on Climate Change (IPCC) and engaged with climate and sustainability issues at a time when many other science and engineering schools hadn't to the same degree.

Q How did your time at MIT inform your eventual work in the energy space?

A Completing my master's in the Technology and Policy Program (TPP) and in mechanical engineering at MIT was invaluable. The focus on systems thinking that was being employed in TPP and at the MIT Energy Initiative (MITEI) has been very important in shaping my thinking around the biggest challenges in climate and energy.

While pursuing my master's degree, I worked with Daniel Cohn, a research scientist at MITEI, and Ahmed Ghoniem, a professor of mechanical engineering (who later became my PhD advisor). We looked at a lot of big questions about how to integrate advanced biofuels into today's transportation and distribution infrastructures: Can you ship it in a pipeline? Can you transport it? Are people able to put it into infrastructure that we've already spent billions of dollars building out? One of the critical lessons that I learned while at MITEI—and it's led to a lot of my thinking today—is that in order for us to have an effective energy transition, there need to be ways that we can utilize current infrastructure.

Being involved with and becoming a co-president of the MIT Energy Club in 2010 truly helped to shape my experience at MIT. When I came to MIT, one of the first things that I did was attend the MIT Energy Conference. In the early days of the club and of MITEI—in '07—there was a certain "energy" around energy at MIT that really got a lot of us thinking about careers in the field.

Q How do you think we can make the shift toward a clean energy–based economy a more pressing issue for people across the political spectrum?

A If we are serious about addressing climate change as a country, we need to recognize that any policy has to be bipartisan; it will need to hit 60 votes in the Senate. Very quickly—within the next few years—we need to develop a set of robust bipartisan policies that can move us toward decarbonization by mid-century. If the IPCC recommendations are to be followed, our ultimate goal is to hit net-zero carbon emissions by 2050. What that means to me is that we need to frame up all of the benefits of a large clean energy program to address climate change. When we address climate change, one of the valuable things that's going to happen is major investment in technology deployment and development, which involves creating jobs—which is a bipartisan issue.

As we are looking to build out a decarbonized future, one thing that needs to happen is reinvesting in our national infrastructure, which is an issue that is recognized in a bipartisan sense. It's going to require more nuance than just the pure Green New Deal approach. In order to get Republicans on board, we need to realize that investment can't be based only on renewables. There are a lot of people whose economies depend on the continued and smart use of fossil resources. We have to think about how we develop and deploy carbon capture technologies, as these technologies are going to be integral in garnering more support from rural and conservative communities for the energy transition.

The Republican Party is embracing the role of nuclear energy more than some Democrats are. The key thing is that today, nuclear is far and away the most prevalent source of zero-carbon electricity that we have. So, expanding nuclear power is a critically important piece of decarbonizing energy, and Republicans have identified that as a place where they would like to invest along with carbon capture, utilization, and storage—another technology with less enthusiasm on the environmental left. Finding ways to bridge party lines on these critical technologies is one of the biggest pieces that I think will be important in bringing about a low-carbon future.

Photo of Addison Stark:
Greg Gibson, Bipartisan Policy Center

Photo of Abigail Ostriker:
Thomas Dattilo

Abigail Ostriker SB '16, Applied Mathematics

Abigail Ostriker, who completed MIT's Energy Studies Minor, is now pursuing a PhD in economics at MIT, where she is conducting research into whether subsidized flood insurance causes over-development. Prior to her graduate studies, she conducted two years of research into health economics with Amy Finkelstein, the John and Jennie S. MacDonald Professor of Economics at MIT.

Q How did the Energy Studies Minor lead you to your current work in economics?

A I took my first economics class in my freshman fall, but I didn't really understand what economics could do until I took Energy Economics and Policy [course 14.44J/15.037] with Professor Christopher Knittel at the Sloan School the following year. That class turned the field from a collection of unrealistic maximizing equations into a framework that could make sense of real people's decisions and predict how incentives affect outcomes. That experience led me to take a class on econometrics. The combination made me feel like economics was a powerful set of tools for understanding the world—and maybe tweaking it to get a slightly better outcome.

Q What was your most memorable experience during your time as an Energy Studies Minor?

A My most memorable experience was probably the time we read an article for class about how the Waxman-Markey bill—a bipartisan attempt to introduce cap-and-trade for greenhouse gases—fell apart in Congress due to political pressures. It made me realize how many different interests are at play in the U.S. energy setting and also that economists' favored solutions are not necessarily going to appeal to the right mix of interests to get implemented.

That was a little discouraging, but it also made me realize the importance of studying not just the theoretical best-case scenario but also the best thing to do when you face the constraints of the real world. For example, in the context of flood insurance, people might not want to buy insurance because they know the government will provide aid after a disaster. Maybe the most efficient thing for the government to do is commit to withholding help after a disaster, so that people buy the insurance beforehand—but that's not how the social contract works. So, we have to figure out the efficient thing to do, given that the government can't make that commitment.

Q How does your current research connect to energy, and in what ways do the fields of economics and energy connect?

A Along with my classmate Anna Russo, I am currently studying whether subsidized flood insurance causes over-development. In the U.S., many flood maps are out of date and backward-looking: Flood risk is rising due to climate change, so in many locations, insurance premiums now cost less than expected damages. This creates an implicit subsidy for risky areas that distorts price signals and may cause a high number of homes to be built. We want to estimate the size of the subsidies and the effect they have on development. It's a challenging question because it's hard to find a way to compare areas that seem exactly the same except for their insurance premiums. We are hoping to get there by looking at boundaries in the flood insurance maps—areas where true flood risk is the same but premiums are different. We hope that by improving our understanding of how insurance prices affect land use, we can help governments to create more efficient policies for climate resilience.

Many economists are studying issues related to both energy and the environment. One definition of economics is the study of trade-offs—how to best allocate scarce resources. In energy, there are questions such as: How should we design electricity markets so that they automatically meet demand with the lowest-cost mix of generation? As the generation mix moves from almost all fossil fuels to a higher penetration of renewables, will that market design still work, or will it need to be adapted so that renewable energy companies still find it attractive to participate?

In addition to theoretical questions about how markets work, economists also study the way real people or companies respond to policies. For example, if retail electricity prices started to change by the hour or by the minute, how would people's energy use respond to that? To answer this question convincingly, you need to find a situation in which everything is almost identical between two groups, except that one group faces different prices. You can't always do a randomized experiment, so you must find something almost like an experiment in the real world. This kind of toolkit is also used a lot in environmental economics. For instance, we might study the effect of pollution on students' test scores. In that setting, economists' tools of causal inference make it possible to move beyond an observed correlation to a statement that pollution had a causal effect.

Turner Jackson, MITEI correspondent

Energy undergrad named 2020 Rhodes Scholar

Claire Halloran '20

Energy Studies Minor undergraduate Claire Halloran was one of five MIT students selected for the 2020 cohort of the prestigious Rhodes Scholarship program. All will begin postgraduate studies at Oxford University in the United Kingdom in fall 2020.

Hailing from Wauwatosa, Wisconsin, Halloran is a senior majoring in materials science and engineering with minors in energy studies and public policy. At Oxford, Halloran will pursue an MSc in energy systems and a Master of Public Policy. She aspires to become a policy leader who will advocate for legislature that is both technically sound and appropriate for wider social contexts.

Halloran is dedicated to creating clean-energy technologies, advocating for strong climate policy, and disseminating knowledge about climate change. Her research has focused on solar energy technologies, including a project on solar-to-fuel conversion reactors for concentrated solar systems with the Electrochemical Materials Laboratory in the MIT Department of Materials Science and Engineering, and an independent research project on silicon and perovskite photovoltaics. During a spring 2019 study abroad semester at Oxford, Halloran worked on high-energy-density battery design with the Faraday Institution SOLBAT Project, and in summer 2019 she interned at Form Energy, a startup focused on creating low-cost, long-lasting batteries.

Halloran has interned with the Environmental Defense Fund and held climate policy fellowships with Our Climate and the Better Future Project. On campus, she founded and directs the MIT Climate Action Team, which works to organize the MIT community in support of policies to mitigate climate change. Halloran also holds an executive position and serves as a peer educator with the MIT Violence Prevention and Response team, facilitating peer conversations about sexual violence and healthy relationships.

Julia Mongo, MIT Distinguished Fellowships
Photo: Ian MacLellan

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Nestor Sepulveda: Zeroing in on decarbonization

To avoid the most destructive consequences of climate change, the world's electric energy systems must stop producing carbon by 2050. It seems like an overwhelming technological, political, and economic challenge—but not to doctoral candidate Nestor Sepulveda.

"My work has shown me that we do have the means to tackle the problem, and we can start now," he says. "I am optimistic."

Sepulveda's research, first as a master's and now as a doctoral student in nuclear science and engineering (NSE), involves complex simulations that describe potential pathways to decarbonization. In work published last year in the journal *Joule*, Sepulveda and his co-authors made a powerful case for the use of a mix of renewable and "firm" electricity sources such as nuclear energy as the least costly, and most likely, route to a low- or no-carbon grid.

These insights, which flow from a unique computational framework blending optimization and data science, operations research, and policy methodologies, have attracted interest from *The New York Times* and *The Economist*, as well as from such notable players in the energy arena as Bill Gates. For Sepulveda, the attention could not come at a more vital moment.

"Right now people are at extremes—on the one hand worrying that steps to address climate change might weaken the economy, and on the other advocating a Green New Deal to transform the economy [to one] that depends solely on solar, wind, and battery storage," he says. "I think my data-based work can help bridge the gap and enable people to find a middle point where they can have a conversation."

Wielding complex algorithms, nuclear science and engineering doctoral candidate Nestor Sepulveda spins out scenarios for combating climate change. Photo: Gretchen Ertl

An optimization tool

The computational model Sepulveda is developing to generate this data, the centerpiece of his dissertation research, was sparked by classroom experiences at the start of his NSE master's degree.

"In courses like Nuclear Technology and Society [22.16], which covered the benefits and risks of nuclear energy, I saw that some people believed the solution for climate change was definitely nuclear, while others said it was wind or solar," he says. "I began wondering how to determine the value of different technologies."

Recognizing that "absolutes exist in people's minds, but not in reality," Sepulveda sought to develop a tool that might yield an optimal solution to the decarbonization question. His inaugural effort in modeling focused on weighing the advantages of utilizing advanced nuclear reactor designs against exclusive use of existing light water reactor technology in the decarbonization effort.

"I showed that in spite of their increased costs, advanced reactors proved more valuable to achieving the low-carbon transition than conventional reactor technology alone," he says. This research formed the basis of Sepulveda's master's thesis in 2016, for a degree spanning NSE and the Technology and Policy Program (TPP). It also informed the MIT Energy Initiative's report, *The Future of Nuclear Energy in a Carbon-Constrained World*.

The right stuff

Sepulveda comes to the climate challenge armed with a lifelong commitment to service, an appetite for problem-solving, and grit. Born in Santiago, he enlisted in the Chilean navy, completing his high school and college education at the national naval academy.

"Chile has natural disasters every year, and the defense forces are the ones that jump in to help people, which I found really attractive," he says. He opted for the most difficult academic specialty, electrical engineering, over combat and weaponry. Early in his career, the climate change issue struck him, he says, and for his senior project, he designed a ship powered by hydrogen fuel cells.

After he graduated, the Chilean navy rewarded his performance with major responsibilities in the fleet, including outfitting a $100 million amphibious ship intended for moving marines and for providing emergency relief services. But Sepulveda was anxious to focus fully on sustainable energy and petitioned the navy to allow him to pursue a master's at MIT in 2014.

It was while conducting research for this degree that Sepulveda confronted a life-altering health crisis: a heart defect that led to open heart surgery. "People told me to take time off and wait another year to finish my degree," he recalls. Instead, he decided to press on: "I was deep into ideas about decarbonization, which I found really fulfilling."

After graduating in 2016, he returned to naval life in Chile but "couldn't stop thinking about the potential of informing energy policy around the world and making a long-lasting impact," he says. "Every day looking in the mirror I saw the big scar on my chest that reminded me to do something bigger with my life or at least try."

Convinced that he could play a significant role in addressing the critical carbon problem if he continued his MIT education, Sepulveda successfully petitioned naval superiors to sanction his return to Cambridge, Massachusetts.

Simulating the energy transition

Since his resumption of studies here in 2018, Sepulveda has wasted little time. He is focused on refining his modeling tool to play out the potential impacts and costs of increasingly complex energy technology scenarios on achieving deep decarbonization. This has meant rapidly acquiring knowledge in fields such as economics, math, and law.

"The navy gave me discipline, and MIT gave me flexibility of mind—how to look at problems from different angles," he says.

With mentors and collaborators such as Richard Lester, associate provost and Japan Steel Industry Professor, and Juan Pablo Vielma and Christopher Knittel, both professors at the MIT Sloan School of Management, Sepulveda has been tweaking his models. His simulations, which can involve more than a thousand scenarios, factor in existing and emerging technologies, uncertainties such as the possible emergence of fusion energy, and different regional constraints, to identify optimal investment strategies for low-carbon systems and to determine what pathways generate the most cost-effective solutions.

"The idea isn't to say we need this many solar farms or nuclear plants, but to look at the trends and value the future impact of technologies for climate change, so we can focus money on those with the highest impact and generate policies that push harder on those," he says.

Sepulveda hopes his models won't just lead the way to decarbonization but do so in a way that minimizes social costs. "I come from a developing nation, where there are other problems like healthcare and education, so my goal is to achieve a pathway that leaves resources to address these other issues."

As he refines his computations, with the help of MIT's massive computing clusters, Sepulveda has been building a life in the United States. He has found a vibrant Chilean community at MIT and discovered local opportunities for venturing out on water, such as summer sailing on the Charles.

After graduation, he plans to leverage his modeling tool for the public benefit through direct interactions with policymakers (U.S. congressional staffers have already begun to reach out to him), and with businesses looking to bend their strategies toward a zero-carbon future.

It is a future that weighs even more heavily on him these days: Sepulveda is expecting his first child. "Right now we're buying stuff for the baby, but my mind keeps going into algorithmic mode," he says. "I'm so immersed in decarbonization that I sometimes dream about it."

Leda Zimmerman, Nuclear Science and Engineering

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Swift Solar: Startup with MITEI roots develops lightweight solar panels

Joel Jean PhD '17 spent two years working on *The Future of Solar Energy*, a report published by the MIT Energy Initiative (MITEI) in 2015. Today, he is striving to create that future as CEO of Swift Solar, a startup that is developing lightweight solar panels based on perovskite semiconductors.

It hasn't been a straight path, but Jean says his motivation—one he shares with his five co-founders—is the drive to address climate change. "The whole world is finally starting to see the threat of climate change and that there are many benefits to clean energy. That's why we see such huge potential for new energy technologies," he says.

Max Hoerantner, co-founder and Swift Solar's vice president of engineering, agrees. "It's highly motivating to have the opportunity to put a dent into the climate change crisis with the technology that we've developed during our PhDs and postdocs."

The company's international team of founders—from the Netherlands, Austria, Australia, the United Kingdom, and the United States—has developed a product with the potential to greatly increase the use of solar power: a very lightweight, super-efficient, inexpensive, and scalable solar cell.

Jean and Hoerantner also have experience building a solar research team, gained working at GridEdge Solar, an interdisciplinary MIT research program that works toward scalable solar and is funded by the Tata Trusts and run out of MITEI's Tata Center for Technology and Design.

"The inventions and technical advancements of Swift Solar have the opportunity to revolutionize the format of solar photovoltaic technology," says Vladimir Bulović, the Fariborz Maseeh (1990) Professor of Emerging Technology in MIT's Department of Electrical Engineering and Computer Science, director of MIT.nano, and a science advisor for Swift Solar.

Joel Jean PhD '17, co-founder of Swift Solar, stands in front of the company's sign at its permanent location in San Carlos, California. Photo courtesy of Joel Jean

Tandem photovoltaics

The product begins with perovskites—a class of materials that are cheap, abundant, and great at absorbing and emitting light, making them good semiconductors for solar energy conversion.

Using perovskites for solar generation took off about 10 years ago because the materials can be much more efficient at converting sunlight to electricity than the crystalline silicon typically used in solar panels today. They are also lightweight and flexible, whereas crystalline silicon is so brittle it needs to be protected by rigid glass, making most solar panels today about as large and heavy as a patio door.

Many researchers and entrepreneurs have rushed to capitalize on those advantages, but Swift Solar has two core technologies that its founders see as their competitive edge. First, they are using two layers of perovskites in tandem to boost efficiency. "We're putting two perovskite solar cells stacked on top of each other, each absorbing different parts of the spectrum," Hoerantner says. Second, Swift Solar employs a proprietary scalable deposition process to create its perovskite films, which drives down manufacturing costs.

"We're the only company focusing on high-efficiency all-perovskite tandems. They're hard to make, but we believe that's where the market is ultimately going to go," Jean says.

"Our technologies enable much cheaper and more ubiquitous solar power through cheaper production, reduced installation costs, and more power per unit area," says Sam Stranks, co-founder and lead scientific advisor for Swift Solar as well as an assistant professor in the Department of Chemical Engineering and Biotechnology at the University of Cambridge in the United Kingdom. "Other commercial solar photovoltaic technologies can do one or the other [providing either high power or light weight and flexibility], but not both."

Bulović says technology isn't the only reason he expects the company to make a positive impact on the energy sector.

"The success of a startup is initiated by the quality of the first technical ideas but is sustained by the quality of the team that builds and grows the technology," he says. "Swift Solar's team is extraordinary."

Indeed, Swift Solar's six co-founders together have six PhDs, four *Forbes* 30 Under 30 fellowships, and more than 80,000 citations. Four of them—Tomas Leijtens, Giles Eperon, Hoerantner, and Stranks—earned their doctorates at Oxford University in the United Kingdom, working with one of the pioneers of perovskite photovoltaics, Professor Henry Snaith. Stranks then came to MIT to work with Bulović, who is also widely recognized as a leader in next-generation photovoltaics and an experienced entrepreneur. (Bulović is a co-inventor of some of the patents the business is licensing from MIT.)

Stranks met Jean at MIT, where Hoerantner later completed a postdoc working at GridEdge Solar. And the sixth co-founder, Kevin Bush, completed his PhD at Stanford, where Leijtens did a postdoc with Professor Michael McGehee, another leading perovskite researcher and advisor to Swift. What ultimately drew them all together was the desire to address climate change.

"We were all independently thinking about how we could have an impact on climate change using solar technology, and a startup seemed like the only real direction that could have an impact at the scale the climate demands," Jean says. The team first met in a Google Hangouts session spanning three time zones in early 2016. Swift Solar was officially launched in November 2017.

MITEI study

Interestingly, Jean says it was his work on *The Future of Solar Energy*—rather than his work in the lab—that most contributed to his role in the founding of Swift Solar. The study team of more than 30 experts, including Jean and Bulović, investigated the potential for expanding solar generating capacity to the multi-terawatt scale by mid-century. They determined that the main goal of U.S. solar policy should be to build the foundation for a massive scale-up of solar generation over the next few decades.

"I worked on quantum dot and organic solar cells for most of my PhD, but I also spent a lot of time looking at energy policy and economics, talking to entrepreneurs, and thinking about what it would take to succeed in tomorrow's solar market. That made me less wedded to a single technology," Jean says.

Jean's work on the study led to a much-cited publication, "Pathways for Solar Photovoltaics" in *Energy & Environmental Science* (2015), and to his founding leadership role with GridEdge Solar. "Technical advancements and insights gained in this program helped launch Swift Solar as a hub for novel lightweight solar technology," Bulović says.

Swift Solar has also benefited from MIT's entrepreneurial ecosystem, Jean says, noting that he took 15.366 MIT Energy Ventures, a class on founding startups, and got assistance from the Venture Mentoring Service. "There were a lot of experiences like that that have really informed where we're going as a company," he says.

Stranks adds, "MIT provided a thriving environment for exploring commercialization ideas in parallel to our tech development. Very few places could combine both so dynamically."

Swift Solar raised its first seed round of funding in 2018 and moved to the Bay Area of California last summer after incubating for a year at the U.S. Department of Energy's National Renewable Energy Laboratory in Golden, Colorado. The team is now working to develop its manufacturing processes so that it can scale its technology up from the lab to the marketplace.

The founders say their first goal is to develop specialized high-performance products for applications that require high efficiency and light weight, such as unmanned aerial vehicles and other mobile applications. "Wherever there is a need for solar energy and lightweight panels that can be deployed in a flexible way, our products will find a good use," Hoerantner says.

Scaling up will take time, but team members say the high stakes associated with climate change make all the effort worthwhile.

"My vision is that we will be able to grow quickly and efficiently to realize our first products within the next two years, and to supply panels for rooftop and utility-scale solar applications in the longer term, helping the world rapidly transform to an electrified, low-carbon future," Stranks says.

Kathryn O'Neill, MITEI correspondent

Khethworks: Startup deploys solar-powered pumps to help irrigate crops all year long

Toward the end of 2019, startup Khethworks began selling what the team refers to internally as "version one" of its 320-watt solar-powered water pump. The pump allows farmers in India who rely on crop harvests to feed their families to farm year-round instead of being limited to the four-month monsoon season. In just a couple of months, the product has started to change the fortunes of underserved farmers in India, lifting up families and impacting entire villages.

The Khethworks system includes a submersible centrifugal solar pump, a controller, and two solar panels. To get the pump running, farmers connect the panels, pump, and controller, then connect the pump to the piping in the field, drop the pump into the water, and flip the "on" switch. Images courtesy of Khethworks

But getting to version one was neither quick nor easy. For Khethworks co-founder and CEO Katie Taylor SM '15, the first product release is the culmination of an uncompromising journey, begun in 2014, to create a product that fits the lifestyles of farmers and minimizes risk for vulnerable communities.

That approach has forced Khethworks to reject easier paths to commercialization. But now that the pump is available and production processes are in place, the founders, which also include Kevin Simon SM '15, PhD '19 and Victor Lesniewski SM '15, are excited to scale the deployment of a product they know can change lives.

A long journey

Many farmers in rural areas of eastern India have limited access to electricity, making it difficult to use the groundwater they need to grow crops outside of monsoon season, which runs from June to September. One way to farm during dry months is to rent pumps that run on diesel or kerosene, but Taylor says that option leaves farmers with hardly any profit after the high costs of the rental and fuel.

The situation forces many farmers to leave their villages each year to pursue physically demanding migrant work after monsoon season—separating families at a time when crop prices are at their highest because supply is lower.

Taylor learned all of this during trips to eastern India as an MIT graduate student and Tata Fellow in 2013. At the time, she was working with smallholder farmers to design an inexpensive, low-pressure drip irrigation system. She quickly learned the bigger problem was accessing groundwater, so she partnered with Simon, Lesniewski, and Marcos Esparza '15 (a co-founder who is no longer with the company), who were classmates of hers in 2.760 Global Engineering. The students began working nights and weekends to develop a groundwater pump that ran on the most reliable, abundant resource available to farmers during dry months: the sun.

From the start, the founders made a point of becoming intimately familiar with the existing practices and preferences of smallholder farmers.

"We didn't create this fancy technology at MIT and then think about where it was applicable," Taylor says. "We were taking input from farmers from day one."

Taylor estimates she traveled to India eight times while attending classes at MIT and credits GEAR Lab Director Amos Winter, the Robert N. Noyce Career Development Assistant Professor at MIT, for encouraging students to pursue ideas outside of the classroom.

The trips made for some insightful, if difficult, moments for the founders. Taylor remembers putting the final touches on a prototype at MIT in the middle of a blizzard with a flight scheduled for later that day. The typical route to the villages where the founders conducted testing included a flight to Mumbai, another flight to Kolkata, a seven-hour train ride, and a two-hour car ride. Things rarely went as planned.

"Kevin and I had worked nights and weekends for years leading up to a launch [in February 2015]," Taylor remembers. "We'd spent so much time in the machine shop…and we finally get to this village, all the farmers are very excited—and it didn't work the whole first day. I remember that hour-and-a-half jeep ride back from the village to our hotel being the most sad and angry I've ever been in my life. Since then I've had plenty of those 'fun' moments."

From then on, the founders traveled prepared. On another occasion, when they needed to make a change to their pump, they set up a soldering machine in their hotel room with an open door for ventilation. The hotel staff, perplexed, simply pulled up chairs and watched.

After going through delta v, the summer accelerator run out of the Martin Trust Center for MIT Entrepreneurship, Taylor and Lesniewski moved to India in the beginning of 2016, while Simon stayed at MIT to pursue his PhD. Although the challenges didn't stop when they got to India, Taylor thinks moving was a hugely beneficial decision for the company.

"The whole point of moving to India was so we could spend more time with farmers, get more feedback, manufacture in the country, build up a local team," Taylor says. "It would be shortsighted to do all that from afar."

Indeed, the founders have achieved a series of key milestones since moving, including securing early funding, obtaining a patent from the Indian government for their pump design, and setting up a manufacturing base in the west Indian city of Pune. Khethworks is also planning to raise more funding this year.

As the founders prepared to start selling their product, they were careful to go to market in a way that aligns with the company's mission.

"We've had organizations over the years say, 'This sounds good, give me 10,000 pumps and we'll take care of the rest,'" Taylor says. "But sometimes, people willing to do that might not care about the execution or the follow-up for repairs and things like that. We care so much about it being done responsibly that we refuse to have any risks we take fall upon the backs of the farmers. Perhaps we could have gone faster, but I'm glad we're proceeding ethically."

A tool for impact

From a distance, you might guess someone carrying Khethworks' pump is going to the beach. Up closer, you'd see a farmer with a small tote bag, a controller that looks like a lunch box, and two solar panels, each roughly a quarter of a ping pong table in size.

The tote bag holds what is called a submersible centrifugal solar pump—the key to the system's portability, low price point, and efficiency. Solar power drives the rotation of the pump's curved, triangular channels. When the pump is dropped into water, fluid is pushed from the center axis to the ends of the channels, driving water above ground. Compared to other locally available pumps, Taylor says Khethworks' solution is two to three times more efficient, allowing it to work with smaller, less expensive solar panels.

To get the pump running, farmers connect the panels, pump, and controller, then connect the pump to the piping in the field, drop the pump into the water, and flip the "on" switch.

A woman carries a Khethworks solar panel. The efficiency of Khethworks' groundwater pump enables it to be powered by smaller panels, making the system portable.

The pump weighs under 10 pounds, and Taylor has seen elderly women carrying the solar panels with ease. Portability is essential because, in many villages, farmers sleep with their valuables to avoid theft.

About 60 farmers used the pump during trials, and Khethworks is on track to sell 100 pumps to farmers in the states of Jharkhand and West Bengal by the end of the first quarter of 2020.

For now, the company is only selling to farmers in a few areas of eastern India, where Taylor says early adopters are using the pumps to make thousands more rupees each year, a transformative amount of money for many families. Farmers also often split the cost of the pump with neighbors and share it throughout the dry season, multiplying Khethworks' impact.

Not bad for version one. The truth is Taylor has lost track of how many versions her team has designed, but she puts it somewhere in the 30 to 40 range. Even while acknowledging the hard times, she wouldn't have it any other way.

"We've always had more demand than we could handle, so it's been exciting getting this to people who have been asking for it for years," Taylor says. "We just want to help farmers make more money. It's simple. Now we want to make that happen at greater scales."

Zach Winn, MIT News Office

Reprinted with permission of MIT News (news.mit.edu). Khethworks was the first startup to emerge from MIT's Tata Center for Technology and Design, which is part of the MIT Energy Initiative. Since then, more than a dozen new ventures have launched based on research supported through the Tata Center.

MIT Climate Symposium: Deep cuts in greenhouse emissions are tough but doable, experts say

How can the world cut its greenhouse gas emissions in time to avert the most catastrophic impacts of global climate change? It won't be easy, but there are reasons to be optimistic that the problems can still be solved if the right kind of significant actions are taken within the next few years, according to panelists at the latest MIT symposium on climate change.

The symposium, the fourth in a series of six [originally scheduled for] this academic year, was titled "Economy-wide deep decarbonization: Beyond electricity." Symposium co-chair Ernest Moniz explained in his introductory remarks that while most efforts to curb greenhouse gas emissions tend to focus on electricity generation, which produces 28% of the total emissions, "72% of the emissions we need to address are outside the electricity sector." These sectors include transportation, which produces 29%; industry, which accounts for 22%; commercial and residential buildings, at 12%; and agriculture, at 9%; according to 2017 figures.

While many commitments have been made by nations, states, and cities to zero out or drastically cut their electricity-related emissions, Moniz pointed out that in recent years many places, including Boston, have expanded those commitments beyond electricity. "We're now seeing economy-wide net-zero goals in cities, including Boston," said Moniz, who is the Cecil and Ida Green Professor of Physics and Engineering Systems Emeritus at MIT and a former U.S. Secretary of Energy.

As the generation of electricity continues to get cleaner, he said, the next step will be to extend electrification to other sectors such as home heating and heavy transport. Then, to deal with the remaining sources that are too difficult or expensive to decarbonize, technologies to remove carbon from power plant emissions or directly out of the air will be needed. Such carbon dioxide removal technology will be essential, he said, to provide enough flexibility in planning for climate change mitigation.

Ernest Moniz, former U.S. Secretary of Energy and founding director of the MIT Energy Initiative, introduced the fourth MIT symposium on climate change. Photos: Jake Belcher

The symposium, held on February 25, 2020, in MIT's Wong Auditorium and webcast live, was divided into three panels, addressing decarbonization of the transportation system and industry, development of low-carbon fuels, and large-scale carbon management including carbon removal from the air.

While electrification of passenger cars has been accelerating in recent years and is expected to increase dramatically over the coming decade, other parts of the transportation system such as aircraft and heavy trucks will be more difficult and take longer to address.

MIT professor of mechanical engineering Yang Shao-Horn described progress in increasing the amount of energy that can be stored in batteries of a given weight, a technology that will be crucial to enabling solar and wind power to produce an increasingly large share of electricity. With many new models of electric vehicles entering the market now, that industry "is experiencing explosive growth," she said; the number of electric vehicles on the road is expected to grow a hundredfold over the next decade.

Lithium-ion batteries have become today's standard for energy storage, and the amount of power they can store per pound has improved tenfold over the last 10 years, Shao-Horn said. But further progress will require new battery chemistries, which are being pursued in many labs, including her own. Researchers are exploring a variety of promising avenues, including metal-air batteries using Earth-abundant metals. For some applications such as aircraft, however, batteries may never be sufficient. Instead, cost-effective ways of using carbon-free technology to make a liquid or gas fuel, such as hydrogen, will be needed. "Development of such fuels is still in its infancy," she said, and requires more research.

John Wall, former chief technology officer for Cummins, one of the world's leading makers of diesel engines for heavy vehicles, said that after 100 years in business, that company last year introduced its first electric truck. But what's really needed, at least in the near term, he said, are carbon-neutral "drop-in" fuels that can be used in existing vehicles with little or no modification.

Wall said that battery technology has reached or will soon reach a point where electrification of heavy vehicles "is credible up to urban class-7 trucks," which encompasses most vehicles smaller than 18-wheeler tractor-trailers and heavy dump trucks. But there are limitations, he said, such as the fact that city buses must be able to complete their daily scheduled routes without needing to be recharged, which at this point means many of them would require a backup power source such as a fuel cell.

Symposium co-chair Kristala Prather, the Arthur D. Little Professor of Chemical Engineering at MIT, addressed what is needed to develop low-carbon alternative fuels from biomass. She pointed out that biofuels have been controversial, and many pilot programs for biofuels, such as incentives for ethanol made from corn, have had disappointing results and fallen well short of their production goals. Given that poor track record, "Why are we still talking about biofuels?" she asked.

She is still optimistic about the potential of biofuels, she said, even though there remain many challenges. For one thing, the raw materials to produce fuels from biomass are abundant and widely distributed. "We have the biomass to be able to make this transition" away from petroleum-based fuel, she said. "You can't make something out of nothing, but we have the something."

She said that the tools of biotechnology can be applied to improving or developing new processes for harnessing microbes to generate fuel from agricultural products. These products can be grown on marginal lands that would not be suitable for food crops and thus would not be in competition with food production.

But there are still challenges to be worked out, such as the fact that many of these processes produce toxic byproducts that require disposal or that may interfere with the production process itself. Nevertheless, with active research ongoing around the world, she said, "I do remain optimistic that we will be able to produce biofuels at scale, but it's going to take a lot of ingenuity."

Francis M. O'Sullivan, a senior lecturer at MIT's Sloan School of Management and senior vice president for strategy at the wind energy company Ørsted Onshore North America, said hydrogen could provide an important bridge fuel as the United States and the world work to decarbonize transportation. But he pointed out that not all hydrogen is created equal. Most of what's produced currently is made from fossil fuels through a process that releases carbon dioxide. Efficient, scalable electrolysis systems will be needed to produce hydrogen using just water and electricity produced from clean sources.

In the power sector, he said, "there is a significant role for hydrogen, in concert with renewables," for example in transportation and in industrial processes. Though there are many issues to be solved in terms of efficient storage and transportation of hydrogen, "it does allow us a lot of flexibility, and therefore is a pathway worth exploring." And there is progress in that direction, O'Sullivan said. For example, the U.K. is currently building a 100-megawatt electrolysis plant to produce hydrogen, powered by offshore wind turbines. But currently such projects would not be feasible without government subsidies.

Howard Herzog, a senior research engineer at the MIT Energy Initiative, said that about 30% of the world's total greenhouse gas emissions comes from sources that can be classified as "difficult to eliminate." Therefore, developing ways to capture and store carbon, either at the emissions source or directly out of the air, will be essential for meeting decarbonization targets. The easiest way to do that is at the emissions-producing plants themselves, where the gas is much more highly concentrated.

But direct air capture may be the only way to clean up those emissions that come not from energy sources themselves but from certain production processes. For example, cement production releases as much carbon dioxide from the limestone being heated as it does from the power to provide that heating. But though direct air capture is "a very seductive concept," he said, achieving it "is not that easy."

"The question is not whether we can get carbon dioxide out of air—we do it today. The real question is the cost," Herzog said. While estimates vary, he says the true cost today is around $1,000 per ton of carbon dioxide removed, and to be truly

A panel on decarbonization of transportation featured, from left to right, MIT professor Yang Shao-Horn, former Cummins CTO John Wall, and professor emeritus and former U.S. Secretary of Energy Ernest Moniz.

competitive it would need to be about a tenth of that. Still, some pilot plants have been built, including one in Texas that can capture 1.6 million tons of carbon dioxide per year.

Ruben Juanes, a professor of civil and environmental engineering at MIT, discussed ways of dealing with the carbon dioxide that gets captured by these methods. A number of different processes have been proposed and some have been implemented, including the use of depleted oil and gas wells, and deep underground saline aquifers—formations deep enough and salty enough that nobody would ever want to use them as water sources.

"They are ubiquitous. They provide a gigantic capacity that is available at scale," he said.

But because the scale of the problem is so big, there still remain challenges, such as getting the carbon dioxide from its source to the underground storage location. The amount of carbon dioxide involved is comparable to the total amount of petroleum currently distributed worldwide through pipelines and supertankers, and so would require an enormous creation of new infrastructure to move.

While that may not be an ultimate solution, "we can think of this as a bridge technology" to use until better systems are developed, he said. "If we want to make good on our efforts" to eliminate global greenhouse gas emissions, "we need to have that bridge."

David L. Chandler, MIT News Office

Excerpt reprinted with permission of MIT News (news.mit.edu); see full text at bit.ly/ghgcuts. MITEI has been providing programming and logistics support for the series of MIT Climate Action Symposia, working with the MIT Office of the Vice President for Research. For more on the symposia, visit climate.mit.edu/symposia. Note that the final two symposia have been postponed until next academic year.

PERSPECTIVES

3 Questions: Emre Gençer on hydrogen in the energy system

As the world increasingly recognizes the need to develop more sustainable and renewable energy sources, low-carbon hydrogen has reemerged as an energy carrier with the potential to play a key role in sectors from transportation to power. MIT Energy Initiative research scientist Emre Gençer shares his thoughts on the history of hydrogen and how it could be incorporated into our energy system as a tool for deep decarbonization to address climate change.

Q How has public perception of hydrogen changed over time?

A Hydrogen has been in the public imagination since the 1870s. Jules Verne wrote that "water will be the coal of the future" in his novel *The Mysterious Island.* The concept of hydrogen has persisted in the public imagination for over a century, though interest in hydrogen has changed over time.

Initial conversations about hydrogen focused on using it to supplement depleting fuel sources on Earth, but the role of hydrogen is evolving. Now we know that there is enough fuel on Earth, especially with the support of renewable energy sources, and that we can consider hydrogen as a tool for decarbonization.

The first "hydrogen economy" concept was introduced in the 1970s. The term "hydrogen economy" refers to using hydrogen as an energy carrier, mostly for the transportation sector. In this context, hydrogen can be compared to electricity. Electricity requires a primary energy source and transmission lines to transmit electrons. In the case of hydrogen, energy sources and transmission infrastructure are required to transport protons.

In 2004, there was a big initiative in the U.S. to involve hydrogen in all energy sectors to ensure access to reliable and safe energy sources. That year, the National Research Council and National Academy of Engineering released a report titled *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*. This report described how hydrogen could be used to increase energy security and reduce environmental impacts. Because its combustion yields only water vapor, hydrogen does not produce carbon dioxide [CO_2] emissions. As a result, we can really benefit from eliminating CO_2 emissions in many of its end-use applications.

Today, hydrogen is primarily used in industry to remove contaminants from diesel fuel and to produce ammonia. Hydrogen is also used in consumer vehicles with hydrogen fuel cells, and countries such as Japan are exploring its use in public transportation. In the future, there is ample room for hydrogen in the energy space. Some of the work I completed for my PhD in 2015 involved researching efficient hydrogen production via solar thermal and other renewable sources. This application of renewable energy is now coming back to the fore as we think about deep decarbonization.

Q How can hydrogen be incorporated into our energy system?

A When we consider deep decarbonization, or economy-wide decarbonization, there are some sectors that are hard to decarbonize with electricity alone. They include heavy industries that require high temperatures, heavy-duty transportation, and long-term energy storage. We are now thinking about the role hydrogen can play in decarbonizing these sectors.

Hydrogen has a number of properties that make it safer to handle and use than the conventional fuels used in our energy system today. Hydrogen is nontoxic and much lighter than air. In the case of a leak, its lightness allows for relatively rapid dispersal. All fuels have some degree of danger associated with them, but we can design fuel systems with engineering controls and establish standards to ensure their safe handling and use. As the number of successful hydrogen projects grows, the public will become increasingly confident that hydrogen can be as safe as the fuels we use today.

To expand hydrogen's uses, we first need to explore ways of integrating it into as many energy sectors as possible. This presents a challenge because the entry points can vary for different regions. For example, in colder regions like the northeastern U.S., hydrogen can help provide heating. In California, it can be used for energy storage and light-duty transportation. And in the southern U.S., hydrogen can be used in industry as a feedstock or energy source.

Once the most strategic entry points for hydrogen are identified for each region, the supporting infrastructure can be built and used for additional purposes. For example, if the northeastern U.S. implements hydrogen as its primary source of residential heating, other uses for hydrogen will follow, such as for transportation or energy storage. At that point, we hope that the market will shift so that it is profitable to use hydrogen across all energy sectors.

Q What challenges need to be overcome so that hydrogen can be used to support decarbonization, and what are some solutions to these challenges?

A The first challenge involves addressing the large capital investment that needs to be made, especially in infrastructure. Once industry and policymakers are convinced that hydrogen will be a critical component for decarbonization, investing in that infrastructure is the next step. Currently, we have many hydrogen plants—we know how to produce hydrogen. But in order to move toward a semi-hydrogen economy, we need to identify the sectors or end users that really require or could benefit from using hydrogen. The way I see it, we need two energy vectors for decarbonization. One is electricity; we are sure about that. But it's not enough. The second vector can be, and should be, hydrogen.

Emre Gençer discusses hydrogen at the MIT Energy Initiative's 2019 Spring Symposium.
Photo: Kelley Travers, MITEI

Another key issue is the nature of hydrogen production itself. Though hydrogen does not generate any emissions directly when used, hydrogen production can have a huge environmental impact. Today, close to 95% of its production is from fossil resources. As a result, the CO_2 emissions from hydrogen production are quite high.

There are two ways to move toward cleaner hydrogen production. One is applying carbon capture and storage to the fossil fuel–based hydrogen production processes. In this case, usually a CO_2 emissions reduction of around 90% is feasible.

The second way to produce cleaner hydrogen is by using electricity to produce hydrogen via electrolysis. Here, the source of electricity is very important. Our source of hydrogen needs to produce very low levels of CO_2 emissions, if not zero. Otherwise, there will not be any environmental benefit. If we start with clean, low-carbon electricity sources such as renewables, our CO_2 emissions will be quite low.

Nafisa Syed, MITEI correspondent

At MITEI's 2019 Spring Symposium, Emre Gençer gave a presentation titled "Hydrogen Towards Deep Decarbonization" (bit.ly/hydrogen0619), where he elaborated on how hydrogen can be used across all energy sectors. Other themes discussed by experts at the symposium included industry's role in promoting hydrogen, public safety concerns surrounding the hydrogen infrastructure, and the policy landscape required to scale hydrogen around the world. Read about the symposium: bit.ly/miteispring19.

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STARTUP NEWS

E25Bio, a startup with Tata Center ties, produces rapid tests for Covid-19

E25Bio, a Cambridge, Massachusetts-based biotech startup that develops diagnostic tests for infectious diseases like dengue and Zika, has a new rapid antigen test for Covid-19. The company's technologies grew out of an MIT lab led by Lee Gehrke, the Hermann L.F. von Helmholtz Professor at the Institute for Medical Engineering and Science (IMES), and Irene Bosch, then a research scientist at IMES. The team's early research was funded by the MIT Energy Initiative's Tata Center for Technology and Design. The startup recently raised $2 million from investors to specifically develop and manufacture testing kits for Covid-19.

E25Bio's rapid diagnostic test resembles an over-the-counter pregnancy test and provides visual results within 15 minutes by detecting the presence of the virus in the patient sample. As a point of comparison, hospitals across the country are currently using polymerase chain reaction (PCR)-based tests that typically take 24 hours or more in some cases to provide results. Given the exponential rate of spread of the virus, there is a critical need to deploy fast, reliable, affordable, and easy-to-use point-of-care tests in order to flatten the curve by quickly detecting and isolating patients who need immediate care. Having identified a Massachusetts-based manufacturing partner, the startup is in the process of obtaining clearance under FDA's Emergency Use Authorization model. If approved, the test would give medical professionals an opportunity not to just test patients at the onset of coronavirus symptoms, but also to track the progression of the disease by testing the same patient over time.

[…]

Bosch, who serves as E25Bio's CTO, and Gehrke have worked closely with the Tata Center on implementation pathways for their research in rapid diagnostics. With the help of the center's Translational Research program, Bosch and Gehrke were able to move their early-stage technology toward commercialization. "The Tata Center and the Tata Trusts believed in us and funded our early research before anyone else. Together with our manufacturing partner, High Media in India, we're very grateful for all their support," says Bosch.

Shivangi Misra, MITEI

Read the full article at bit.ly/MITE25Bio. The Tata Center at MIT is supported by the Tata Trusts, one of India's oldest philanthropic organizations.

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Khethworks: Startup deploys solar-powered pumps to help irrigate crops all year long

In India, millions of smallholder farmers are able to irrigate the crops they need to feed their families only during the four-month monsoon season. A new, low-cost, solar-powered pumping system developed by the startup Khethworks is now enabling them to access groundwater for irrigation so they can farm year-round. The lightweight, submersible pump at the core of the system is so efficient that running it requires only small, easily carried solar panels, as shown in the photo above. Khethworks has set up a manufacturing base in western India and is now on track to sell hundreds of systems to early adopters. Khethworks was the first startup to emerge from MIT's Tata Center for Technology and Design, which is part of the MIT Energy Initiative. Image courtesy of Khethworks