Energy Futures

MIT ENERGY INITIATIVE

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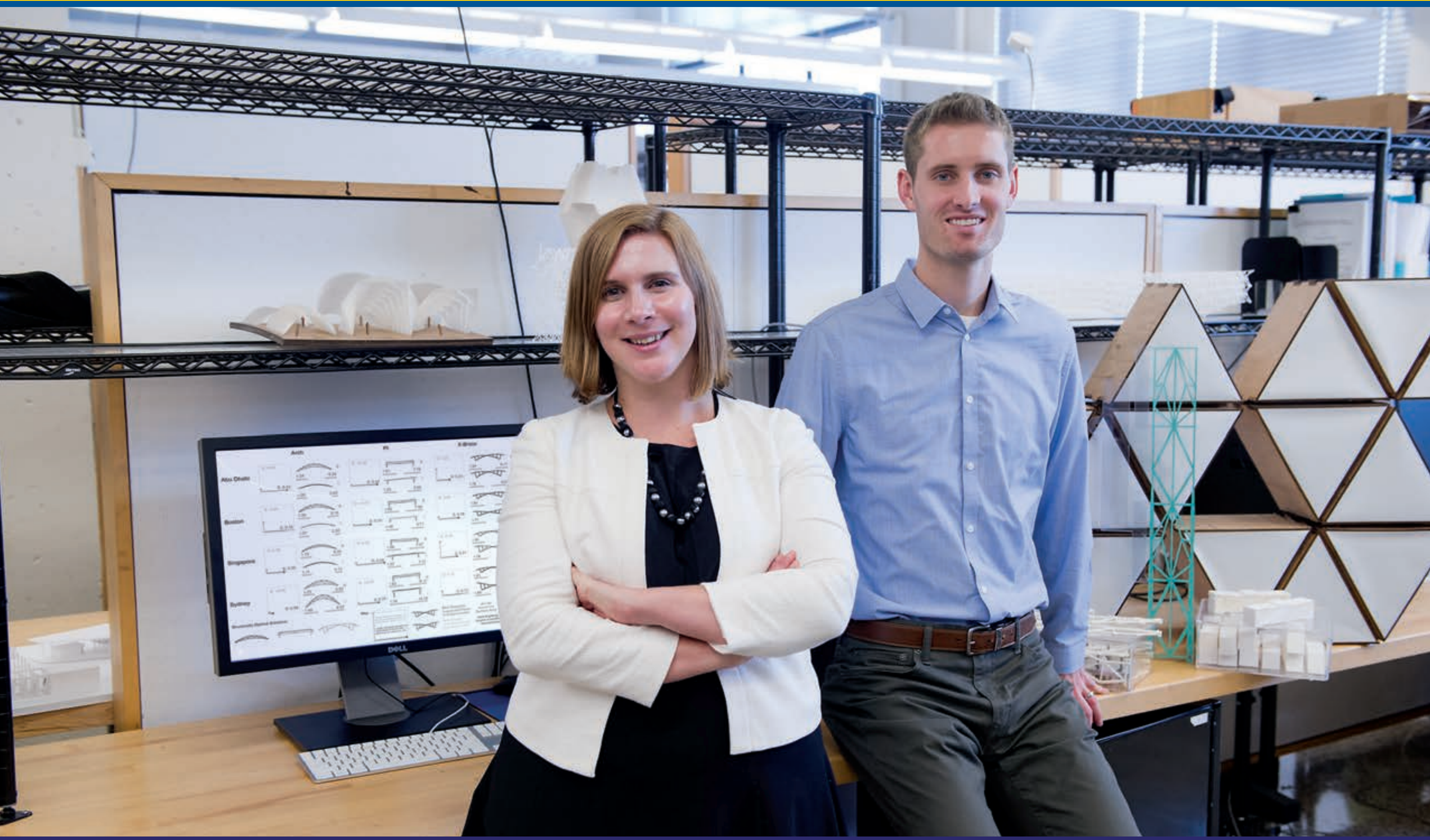

Energy-efficient design: Helping architects weigh their options

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Energy Futures

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MIT Energy Initiative

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A letter from the director

Photo: Webb Chappell

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

Dear Friends,

As I write, we have just concluded MITEI's 2016 Annual Research Conference, where MIT energy researchers, our industry members, public officials, and other experts shared their perspectives on how to accelerate the global transition to a low-carbon energy system.

In his keynote speech, Jonathan Pershing, the US special envoy for climate change, highlighted successes since the Paris Agreement, such as the recent agreement in Kigali to phase down hydrofluorocarbons (HFCs), while also outlining the massive challenges of implementing and ratcheting up the commitments from Paris—most notably, mobilizing the necessary investment in research, development, and deployment of technologies to address climate change.

At the conference, faculty co-directors of MITEI's eight Low-Carbon Energy Centers shared research, innovations, and grand challenges in those areas, from energy storage to nuclear fusion. In this issue of *Energy Futures*, three of the centers' co-directors discuss their visions for advancing research in center efforts (see page 2).

You'll also read about how MIT researchers in different disciplines are approaching carbon emissions reductions. Our cover story describes a tool to help architects design energy-efficient buildings by considering trade-offs between operational and embodied structural energy (page 6). Additional research reports include new methods for detecting and preventing defects in solar cells (page 18), an analysis of how aggressive policy action could be the only route to low-carbon energy sources (page 13), and advances on a device that could turn carbon dioxide emissions into high-quality fuels (page 23). MIT's newest energy faculty members are also working to make the world a better place with their energy research, from advanced materials development to urban planning for sustainability (page 33).

Students conducting energy research have also been hard at work addressing energy and climate challenges: Graduate student research assistants are the driving force behind many of the breakthroughs coming out of MIT laboratories (page 38); and in summer 2016, a new group of undergraduates experienced hands-on research and mentoring through the Energy Undergraduate Research Opportunities Program (UROP), which provided problem-solving skills they can use throughout their careers (page 40). Now, undergraduates can gather, work on projects, attend events, and socialize in a new space: the Undergraduate Energy Commons, completed this fall (page 42).

In the year since the release of MIT's Plan for Action on Climate Change, MITEI has been taking a lead role in implementing the aspects of the plan focused on accelerating technology development and deployment, as the Low-Carbon Energy Centers have taken shape, as the Utility of the Future and Mobility of the Future studies have progressed, and as the Tata Center for Technology and Design has continued to address energy access issues in the developing world with low-carbon solutions.

As with last year in Paris, MIT sent a delegation of observers to the UN Climate Change Conference in Marrakech, Morocco, known as COP22. MIT thought leaders participated in events throughout the conference to demonstrate MIT's commitment to climate action. I invite you to read about our activities in Marrakech at energy.mit.edu/ news-tag/cop22.

We are also preparing to release the report from the multi-year Utility of the Future study, examining the technology, policy, and business models that are shaping the evolution of the delivery of electricity services. This widely anticipated report is designed to help regulators and policymakers prepare for and react to major changes in the electricity sector. We will share more details in the next issue of *Energy Futures*, and the full report will be available at energy.mit.edu.

Thank you for your continued interest in and support for our mission.

Robert C Armstrong

Professor Robert C. Armstrong
MITEI Director
November 2016

Q&As with Low-Carbon Energy Center co-directors

Over the past year, the MIT Energy Initiative (MITEI) has spearheaded the launch of eight Low-Carbon Energy Centers, each one dedicated to advancing research in a technology area critical to addressing climate change. The directors of three of these centers—those focused on carbon capture, utilization, and storage; energy storage; and materials in energy and extreme environments—discussed their vision for transforming the energy system.

Center for Carbon Capture, Utilization, and Storage

Photo: Patrick Gillooly, MIT

"There is a fundamental incompatibility, at least for the next several decades, between the need to improve the standard of living of people in developing countries and the desire to keep fossil fuels in the ground. We could resolve this incompatibility by using the energy stored in fossil fuels while returning the associated carbon dioxide to the subsurface. This is unlikely to happen without innovation in capturing, utilizing, and storing carbon—innovation that MIT can and should provide!"

Directors **Bradford H. Hager** (left), Cecil and Ida Green Professor of Earth Sciences, and **T. Alan Hatton** (right), Ralph Landau Professor of Chemical Engineering Practice

Photo: Stu Rosner

Why is research in carbon capture, utilization, and storage critical to meeting the world's low-carbon goals?

Every year, human activities emit more than 40 billion metric tons of carbon dioxide (CO_2) into the atmosphere, and the release of CO_2 from fossil fuel combustion is still on the rise. In the past 50 years, concentrations of CO_2 in the atmosphere have increased 25%.

Carbon capture, utilization, and storage hold great promise for ameliorating the effects of excess emissions by capturing CO_2—particularly from industrial operations and power facilities—converting some of this CO_2 into useful products, and storing what is not used safely and securely. Unfortunately, today's carbon capture techniques are energy-intensive and expensive at over $50 per metric ton of CO_2 avoided—and most carbon use and storage efforts are as yet only employed at small scales. Research is needed to discover and demonstrate more efficient capture technologies, to secure long-term storage solutions, and to identify additional carbon storage methods.

How will the new Center for Carbon Capture, Utilization, and Storage overcome the major barriers to progress?

Scaling up affordable technologies for carbon capture, utilization, and storage will require a wide range of expertise—from novel chemistry, biology, and engineering for capture to subsurface science and engineering at field scale for storage. The new MIT Energy Initiative center is developing, tracking, and assessing methods that can reduce the carbon costs of meeting the world's energy needs by tapping into MIT's extensive existing research capability in such areas as molecular simulation; materials design; separation and catalytic processes; fluid mechanics; seismic, geodetic, and electromagnetic imaging; and systems analysis.

Center faculty will also team up with representatives from a diverse set of global businesses, government entities, and organizations that face carbon capture, utilization, and storage challenges to ensure MIT's experts are engaged with the most pressing real-world needs in these areas.

What kind of research is currently under way at the center?

The Center for Carbon Capture, Utilization, and Storage supports a solutions-focused portfolio of projects ranging from molecular simulation to materials design to systems analysis.

Examples of carbon capture research under way at MIT include electrochemically mediated amine regeneration, an improved technique for capturing CO_2 from coal-fired power plant flue gas, and the development of metal oxide covalent network ultrathin films, which have the potential to separate larger quantities of carbon at much lower temperatures than membrane materials currently under consideration for scrubbing smokestack emissions.

Within the area of CO_2 reduction and utilization, the center is working on converting CO_2 into fuels using a strategy that emphasizes the bottom-up, molecular-level engineering of functional inorganic interfaces with a focus on electrochemical energy conversion. MIT researchers are also exploring ways to fix CO_2 biologically, for example by converting CO_2 into carbonates that can be used as building material.

Much of MIT's carbon storage research focuses on storing compressed CO_2 in porous underground formations such as saline aquifers. MIT experts are applying theoretical, computational, experimental, and field observation approaches to bring this option to scale and to demonstrate that storage can be accomplished safely and securely.

Energy Storage Research Center

Photo: M. Scott Brauer

Photo: Stuart Darsch

"The problems we face in energy storage are too important, the need for solutions too urgent, and the hurdles to be overcome too challenging to solve within a single research group or traditional industry-academic partnership. Sustained science and engineering is needed for this research to facilitate the transition to a carbon-neutral energy landscape. The Energy Storage Research Center at MITEI enables a truly accelerated pace of innovation through highly cross-disciplinary collaboration."

Directors **Jeffrey Grossman** (left), Morton and Claire Goulder and Family Professor in Environmental Systems and professor of materials science and engineering, and **Yang Shao-Horn** (right), W.M. Keck Professor of Energy, professor of materials science and engineering, and professor of mechanical engineering

How can improvements in energy storage help the world reach its goal of reducing carbon emissions?

There is a critical need for storage because the most abundant sources of carbon-free energy, wind and solar, generate power intermittently. Yet today, storage options are so limited that even if solar cells were free, only 10% of Americans could take advantage of them because the electric grid can't accommodate more intermittent energy. In fact, today the only carbon-free system that is cost-competitive with the grid and capable of storing energy at scale is hydropower.

Storing energy electrochemically shows enormous promise but to date has proved practical primarily at small scales. Electric vehicles, cell phones, and other consumer electronics thus remain limited by battery life (governed by energy storage density). In fact, the primary reason current power generation and transportation systems rely so heavily on fossil fuel–based technologies is because of the high-density, fuel-level energy storage that these options provide.

Making the transition to a low-carbon future therefore requires the development of new storage technology options—ones that can combine technical performance with costs low enough to make them attractive for use in renewables-heavy electricity systems and in electricity-powered transportation, communications, and other applications.

How will the new Energy Storage Research Center address the major challenges in this area?

What is needed is a game-changer—storage that works over time scales ranging from milliseconds to months, with different combinations of power delivery and energy capacity, and a full range of volumetric and gravimetric characteristics.

The Energy Storage Research Center will draw on cross-disciplinary research in engineering, science, and policy as well as real-world input from stakeholders in industry, government, and nongovernmental organizations to hasten the development of new energy storage technologies with the technical performance and cost characteristics needed to provide power sustainably at any place, at any scale, and at any time.

What kind of research is currently under way at the center?

The research portfolio at the center will mirror the wide variety of energy storage needs that must be addressed to enable greater deployment of renewables in the power sector and more extensive electrification of mobility. Examples include developing new lithium-ion and sodium-ion battery materials with increased storage capacity and fuels that can store solar energy as usable, distributable, on-demand chemical energy.

In addition, researchers are investigating myriad ways to control, synthesize, and characterize materials at the atomic and nanometer scales—work that will facilitate the design of new materials for storage applications. Work already under way at MIT includes the synthetic design of small molecules for flow batteries; the development of polymers and ceramics for new and fast ion conduction; and the design of new electrodes using self-assembly of nanomaterials by electrostatics and biological-templated assembly. Researchers are also designing new catalysts and electrodes using computational and experimental methods as well as developing solid-state batteries and model systems for energy storage using chemical vapor deposition, pulsed laser deposition, and molecular beam epitaxy.

Center researchers are also developing theories and leveraging new computational capacities to accurately describe the fundamental processes involved in energy storage—critical steps to addressing the storage challenge.

Center for Materials in Energy and Extreme Environments

Photo: Justin Knight

"Engaging with industry is our key mission, and we would love to send MIT faculty to representative companies in each sector—including oil and gas; utilities; chemicals, metals, and construction materials; automotive; and aerospace—to observe plant operations and challenges, and help define research projects."

Directors **Ju Li** (left), Battelle Energy Alliance Professor of Nuclear Science and Engineering, and **Bilge Yildiz** (right), associate professor of nuclear science and engineering and of materials science and engineering

Photo: Denis Paiste, MIT

Why are materials an important component of energy research, and how can new and advanced materials help reduce global carbon emissions?

Materials are fundamental to the success of a wide range of energy-related activities from oil and gas exploration to nuclear power generation and from wind power to synthetic fuel production. Stakeholders from virtually every industry ask the same questions: What are the performance limits of the materials? How much do they cost? How long will they last? How much do we need, and how difficult will these materials be to produce, transport, and dispose of?

Such questions are particularly critical in the extreme environments that characterize energy industries. Ball bearings in wind turbines are subjected to extreme dynamic mechanical loads; nuclear fuel cladding needs to tolerate radiation; oil and gas infrastructures are aged by corrosion and fouling; solar concentrators and fuel cells suffer damage from high temperatures; and solar fuels production suffers from dissolution or corrosion in aggressive chemical environments.

The development of low-cost, high-performance, and durable materials promises to improve the safety and economy of many energy production, conversion, and transmission activities while reducing carbon emissions and other environmental impacts.

How will the Center for Materials in Energy and Extreme Environments help move us toward a low-carbon future?

The center works to develop new materials, processes, diagnostics, and software with the goal of improving the economy and efficiency of materials while reducing their carbon emissions and other environmental impacts. One key objective is to devise innovative materials solutions to improve performance and reduce the CO_2 footprint of existing energy technologies. Another is to provide the innovative functional and structural materials needed to enable and enhance new energy technologies. Take the hydrogen economy as an example: The entire value chain, from the production of hydrogen, to storage and transportation infrastructure, to hydrogen fuel cells requires advanced materials that fall into the purview of our center.

Center research focuses on advancing technologies based on fundamental scientific breakthroughs that enhance materials performance and predict and mitigate bulk and surface damage in complex environments that include combined effects of electrochemistry, temperature, and mechanical loads. Materials selection and design is a big part of the center's activities.

Can you provide some examples of research currently under way at the center?

The center takes a three-pronged approach to research, simultaneously working to develop new materials and interfaces; characterize the chemical, mechanical, and physical behavior of materials at both the micro and macro scale; and enhance materials performance and life in a given environment.

Already, MIT researchers have made significant progress in the development of such new materials as nanocomposites and graded surfaces, which hold the promise of being stronger, tougher, and more tolerant of corrosion, radiation, and high temperature than anything now available. Center researchers are also engineering new catalysts in the hopes of emulating the reactivity of natural enzymes at milder temperatures than traditional synthetic catalysts, thus improving their activity. Another example is using elastic strain engineering to design materials structures with finite residual stress to guide interactions with ions, electrons, photons, etc., to improve (for example) the performance of superconductor cables and power electronic components for electrical energy transmission as well as fuel cells and electrolyzers for energy conversion.

At the same time, the center is investigating major materials performance issues such as hydrogen embrittlement, stress corrosion cracking, and materials fouling. In the United States alone, the trouble caused by materials fouling—such as clogged pipes and component failures—costs industry more than $15 billion a year in degraded energy system performance. MIT's research into how fouling occurs and how the process can be detected and disrupted thus holds obvious potential benefits. Such work is just the tip of the iceberg: Advances in how materials are designed and used will ultimately impact the full spectrum of energy research needed to meet low-carbon objectives.

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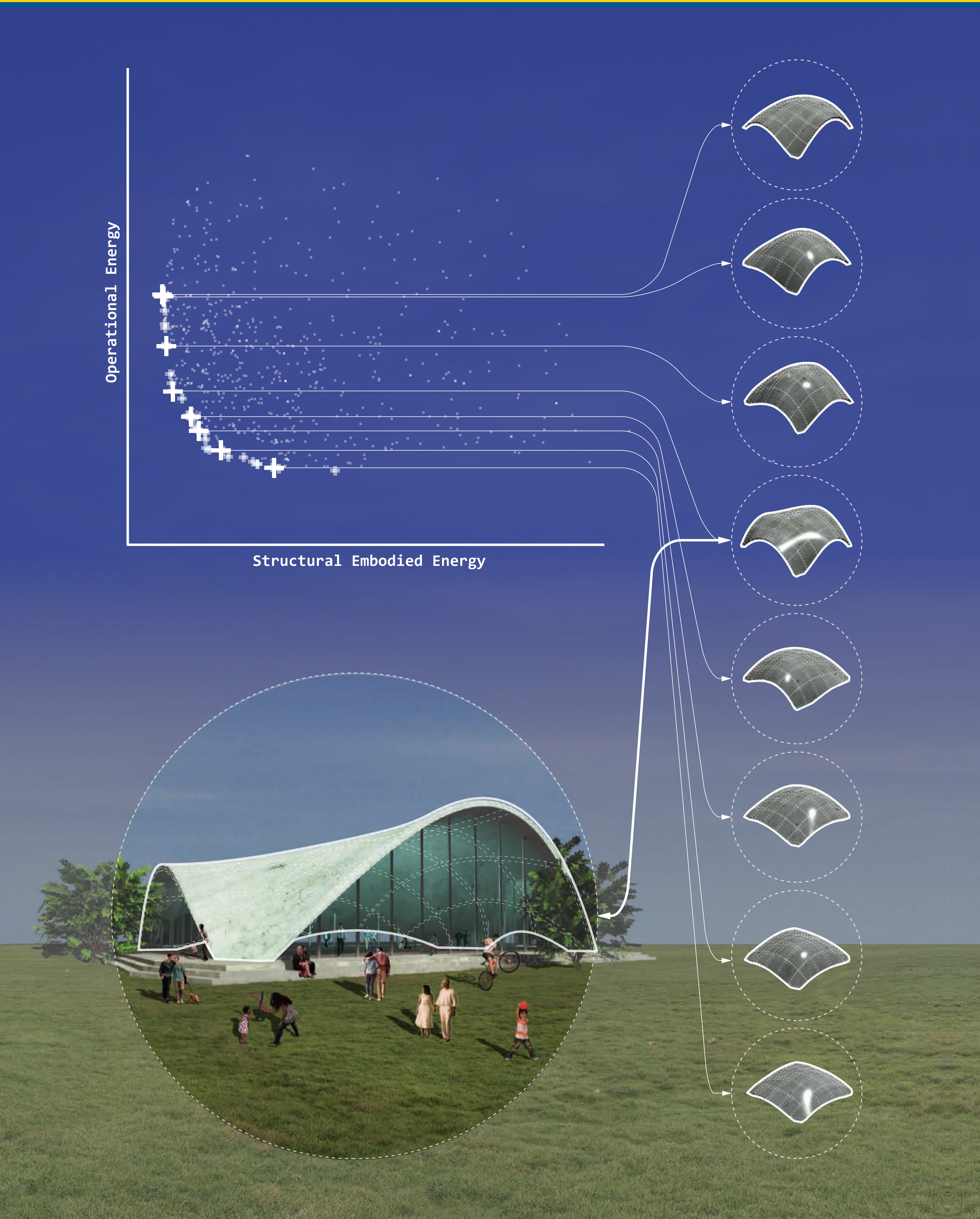
By Kathryn M. O'Neill, MITEI correspondent

Look for Q&As with the directors of additional centers—electric power systems; energy bioscience; advanced nuclear energy systems; nuclear fusion; and solar energy—in upcoming issues of Energy Futures.


Operational Energy
Structural Embodied Energy

Energy-efficient design

Helping architects weigh their options

Above: Caitlin Mueller of architecture and civil and environmental engineering (left) and Nathan Brown of architecture have performed analyses showing how a computer simulation can help architects optimize energy consumption when they're defining the shape of a building early in the design process.

Facing page: This illustration represents simulation results in which optimal design choices arise from myriad options that explore trade-offs between structural embodied energy and operational energy.

Photo: Stuart Darsch

Illustration: Nathan Brown, Caitlin Mueller, Kam-Ming Mark Tam, and Renaud Danhaive, MIT

Designing energy-efficient buildings can be challenging: Incorporating features that decrease the energy needed to run them often increases the energy-intensive materials required to build them, and vice versa. Now an MIT team has demonstrated a computer simulation that can help architects optimize their designs for both future operational energy and the initial energy required for making structural materials—at the same time. The technique rapidly generates a set of designs that offer the best compromises between those two critical energy components. The architect can then make a choice based on quantitative information as well as aesthetic preference. The demonstration produced some striking results. In one case, choosing a design that was slightly less efficient in operational energy cut energy for structural materials in half—an opportunity that would have gone undetected using a simulation that optimized operational energy alone.

In recent years, concerns about global warming and greenhouse gas emissions have prompted efforts to make buildings more sustainable, or "green." The main focus has been on reducing the energy that buildings require for heating, cooling, ventilation, and lighting. But an increasing role is being played by "structural embodied energy," that is, the energy used to extract, process, and transport the structural materials in them.

"Newly constructed buildings have become so efficient to operate that the energy embodied in the materials required to create them is becoming a larger and larger percentage of the total energy used," says Caitlin Mueller, assistant professor of architecture and of civil and environmental engineering. "Energy is embodied in building materials such as finishes, insulation, and cladding, but far more is in the building's structural system." And while benefits from more energy-efficient operation are spread over the lifetime of the building, energy savings from reducing that structural embodied energy—notably by early decisions about a building's overall shape—are reaped immediately.

When designing a building with energy in mind, therefore, architects need to consider both operational and structural embodied energy, and the two are intertwined. For example, extending the roof out beyond the edge of a building can shade windows and reduce cooling needs in hot climates, but making an overhang that's structurally sound can take a lot of energy-intensive material.

The challenge is to determine a building design that trades off the two goals—and also allows room for creativity and aesthetic decisions. Today's computer algorithms can help guide the design process, taking just seconds to generate designs that are optimized for several objectives at once. Even so, many architects and structural engineers persist in doing separate analyses, looking either to minimize operational energy consumption or to minimize the amount of energy-intensive material required. And in both cases, they tend to perform their analyses only after they have developed a conceptual design. "They use a simulation program to see if the design they've come up with is 'good enough,'" says Mueller—a process she calls "guess and check."

The changing role of simulation

Mueller and her colleague Nathan Brown SMBT '16, now a PhD candidate in building technology, are keenly aware of the importance of focusing on structural embodied energy as well as operational energy use. Both are trained in architecture and structural engineering, and both are convinced of the power of computational design. They note in particular today's "genetic" algorithms, which perform design optimization based on an evolutionary metaphor: They generate "populations" of designs that are "bred" and "mutated" over time for better performance. Given a starting set, the computer calculates the operational and structural embodied energy for each building design and then tweaks certain features or aspects to generate a set of new designs with better characteristics. By repeating the process, the computer analyzes thousands and thousands of designs to produce a limited set for the architect's consideration.

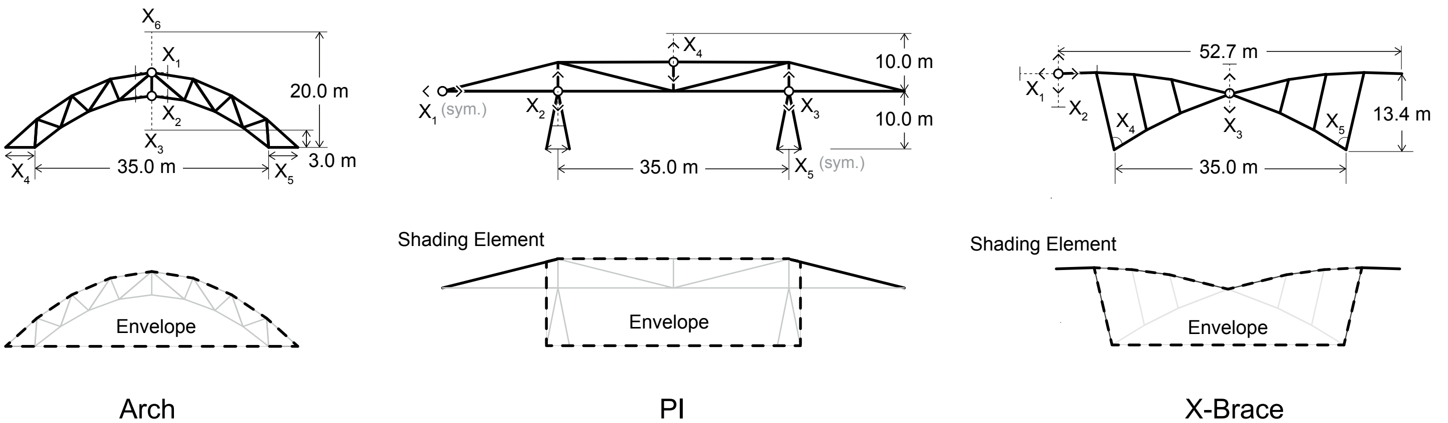
"These final designs are suggested by the computer as ones that are going to do well," says Brown. "It would be much harder to find them through trial and error, just by guessing. So I think it changes the role of simulation analysis in the design process. It's not just a checking algorithm but is a way to actually help with creative design exploration."

Challenging case studies

To demonstrate the power of this approach, Mueller and Brown performed a series of case studies focusing on "long-span buildings"—structures such as airport terminals, concert halls, and bus stations. Such buildings seemed a good subject for their analyses. For one thing, they pose a special modeling challenge: They often have large open spaces with unusual shapes and few interior columns, so they rely on systems of triangular trusses and frames working together to support the load of the building. The structural materials required for those systems make up a significant fraction of the embodied energy component, so they provide a good target for energy savings. In addition, the use of computer simulation early in the design process—when the shape of the building is determined—can have a major impact on embodied energy. Careful choice of the geometry and layout of the structure can reduce internal forces and decrease the amount of energy-intensive structural materials required for support.

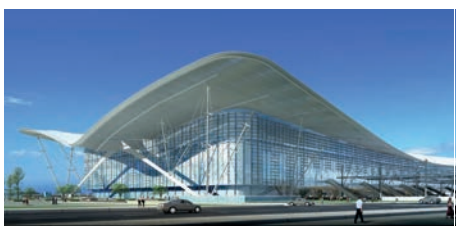
Two characteristic features of long-span buildings involve trading off operational and structural embodied energy. Already mentioned is the cantilevered overhang, a rigid surface extending out from the main part of a building, anchored only at its origin with no additional support along its length. Adding a carefully designed overhang can block sunlight and reduce cooling

Building types for case studies



Olympic Stadium
Montreal, 1976
Roger Taillibert

Suvarnabhumi International Airport
Bangkok, 2006
Murphy/Jahn Architects



Qingdaobei Station
Qingdao, China, 2014
AREP (Architect) / MaP3 (Structural Engineer)

To demonstrate multi-objective optimization, MIT researchers performed analyses of the three types of long-span buildings shown above. The upper diagrams show each building's geometry with both set and variable dimensions; the lower diagrams outline the building envelope; and the photos show representative constructed buildings. The enclosed arch involves trade-offs between operational and structural embodied energy when varying height. The PI structure and x-brace involve trade-offs associated with both height and overhang. (For complete image credits, see the *Energy and Buildings* article cited on page 12.)

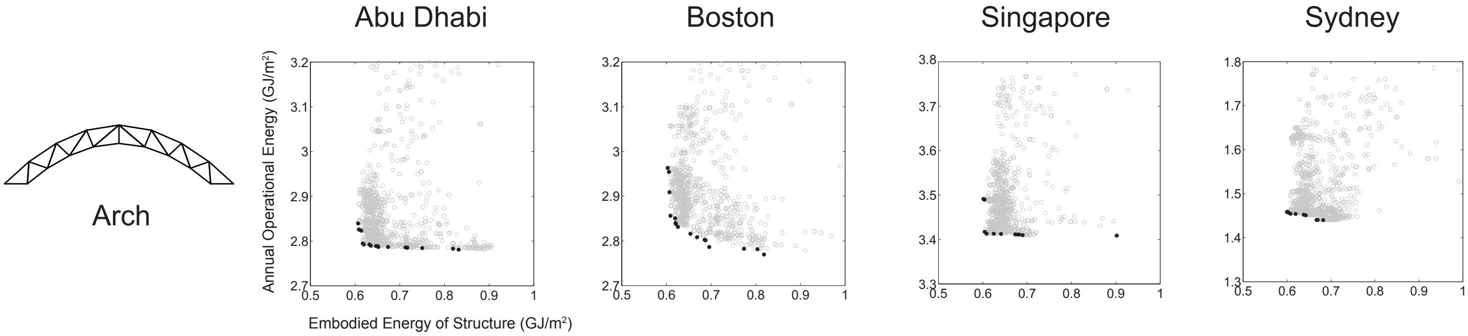
loads, but it increases embodied energy by requiring the use of extra structural material.

The other aspect of interest is building height. According to Brown, increasing the height will spread out internal forces in the structure so that support systems can be thinner and more widely spaced. Making the structure taller can—up to a point—reduce the amount of building material required, and embodied energy will decline. But a taller building has more exterior surface—the "building envelope"—and a greater volume of air to be conditioned, both of which generally increase operational energy.

To test those trade-offs in practical systems, Mueller and Brown analyzed three types of long-span structures: an enclosed, trussed arch; a "PI" structure (resembling the Greek letter); and an "x-brace." The figure above shows diagrams of the three building types along with photos of representative buildings. The upper diagrams indicate certain set dimensions along with others to be defined, while the lower diagrams include dashed outlines showing the building envelopes. Analysis of the enclosed arch demonstrates energy trade-offs involved in selecting height, while analyses of the PI structure and the x-brace show trade-offs associated with both height and overhang.

For each building type, the researchers defined a three-dimensional structure for simulation by assuming a parallel lineup of identical units to create an indoor space with a set floor area. They then ran simulations using a multi-objective genetic algorithm plus a collection of other programs to calculate

Simulation results for the analysis of the arch



These diagrams plot results for annual operational energy against structural embodied energy for the closed arch in four locations with different climates. Each dot represents a specific design generated by the computer. The dark dots on each diagram indicate a set of optimal choices where the designer can't do better on one objective without doing worse on the other.

operational and structural embodied energy. The former is based on energy flows for heating, cooling, lighting, ventilation, and so on. For the latter, they considered only the use of steel, a key structural material in long-span buildings. The amount of steel required is determined by calculating the load on each member of the structure and the smallest section size required to support it. The total steel in the design is computed and then converted (based on weight) into structural embodied energy using a standard coefficient. Based on those evaluations, the multi-objective optimization algorithm comes up with a new set of designs that should perform better—and the process repeats.

Simulation results

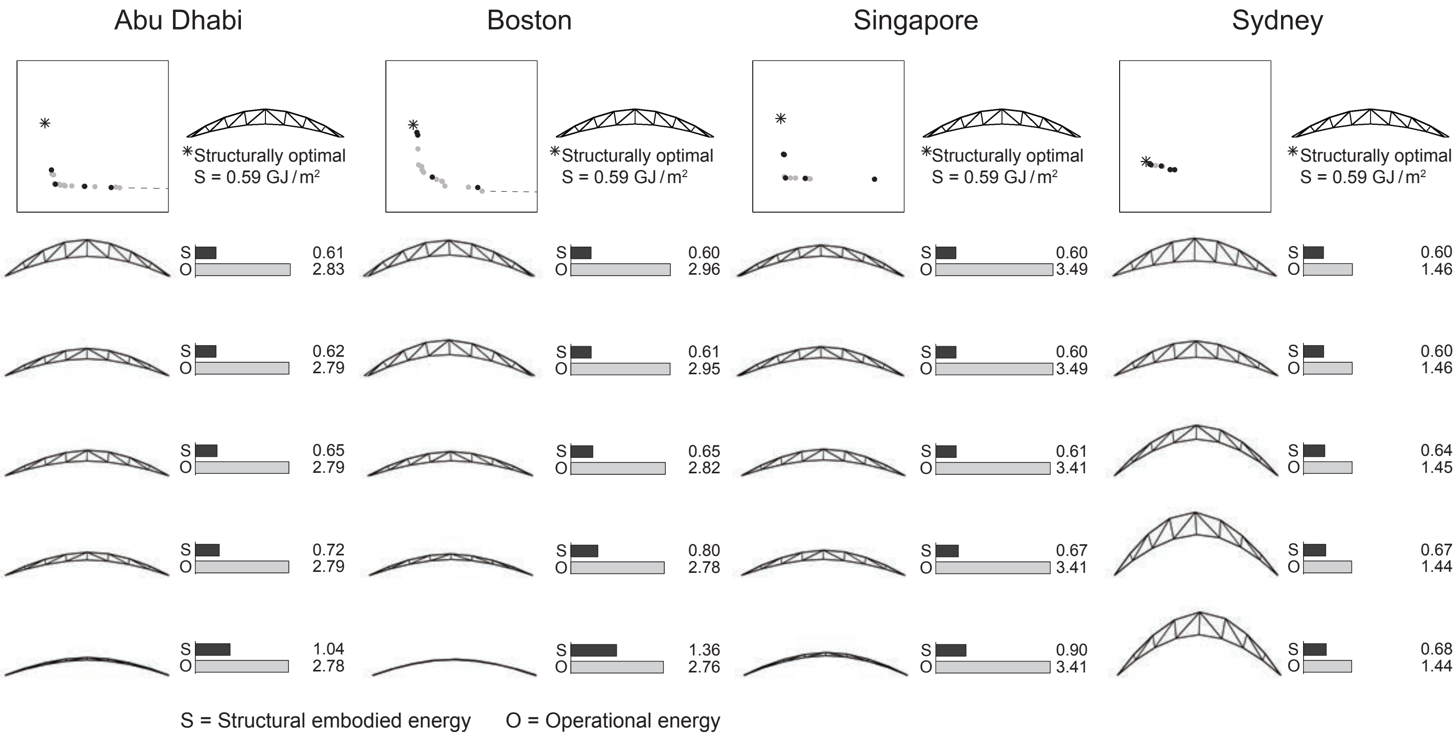
The figure above shows simulation results for the closed arch in four locations representing different climates: Abu Dhabi (arid), Boston (cool), Singapore (tropical), and Sydney (temperate). Each diagram plots annual operational energy against embodied energy of the structure, both measured in gigajoules per square meter. The individual dots on the diagrams represent specific designs generated by the computer.

The series of dark dots on each diagram forms the "Pareto front"—the best collection of compromising designs where the designer can't make one performance objective better without making the other one worse. The dark dot at the farthest left in each diagram minimizes structural embodied energy regardless of operational energy, while the dark dot at the farthest right minimizes operational energy regardless of embodied energy. Points in between represent designs that are compromises between those objectives for a given emphasis on one objective over the other (say, minimizing operational energy more than embodied energy).

Of particular interest are the shapes of the Pareto fronts. The front for Boston is the classic shape—sometimes called a banana curve. The results are on a continuum such that moving either way will enable the user to do a bit better on one objective while doing a bit worse on the other.

In contrast, the curve for Abu Dhabi contains a long, flat section and then an abrupt 90-degree turn at a point referred to as the knee. In that case, moving left along the Pareto front will enable the user to significantly reduce embodied energy without much sacrifice in operational energy—as far as the knee, when operational energy suddenly jumps up. The point at the knee is therefore likely to be a good choice, as it provides a good balance between the two variables. "A single-objective optimization for operational energy would produce the dot farthest to the right," says Mueller. "But by considering both objectives, we find that with just a small increase in operational energy, we can decrease embodied energy by about a factor of two."

Visual catalog of the optimal set of arch geometries



These arch geometries correspond to five of the dark data points representing the best compromises in the diagrams on page 10. The most structurally efficient designs are at the top, the most operationally efficient at the bottom. The solutions vary from city to city, with the set for Sydney looking markedly different from the others due to that city's mild climate.

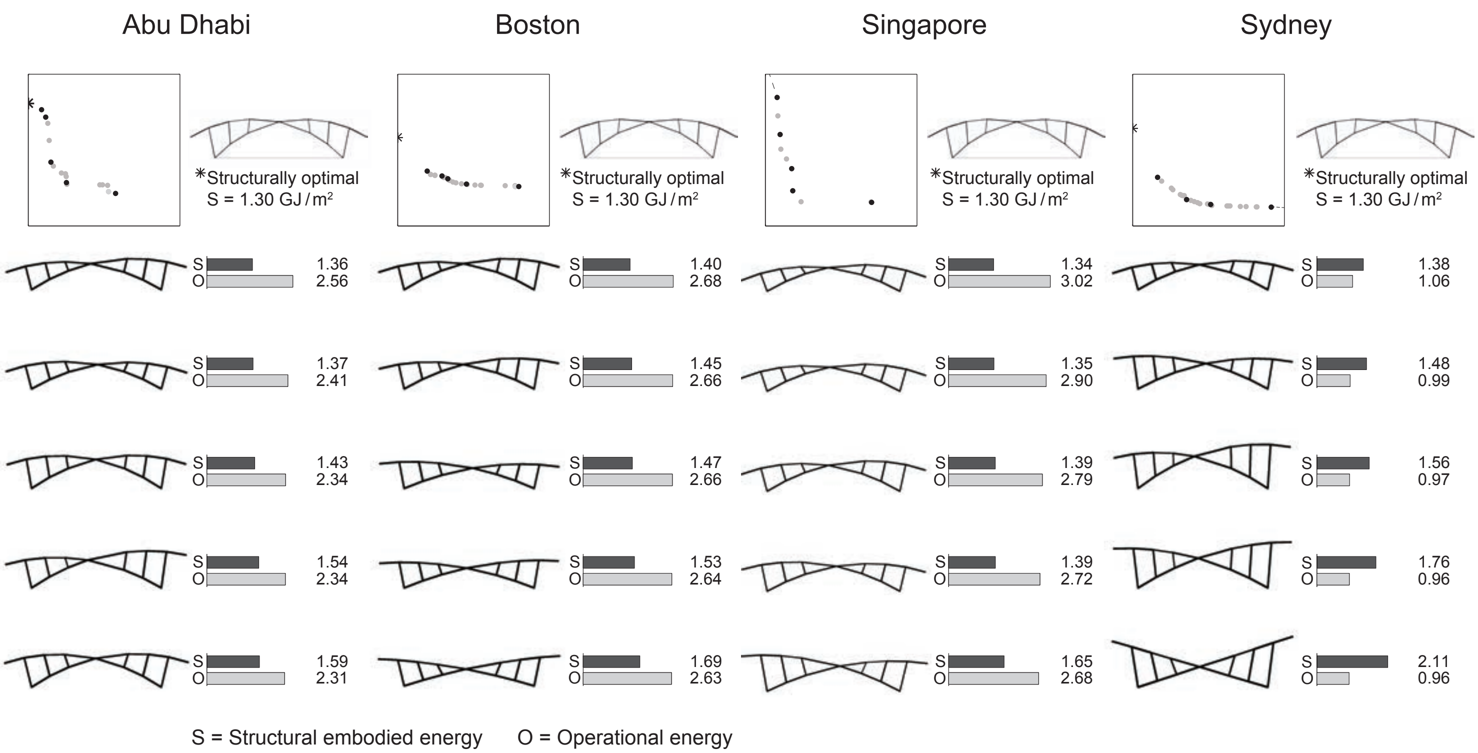
Visualizing the options

The figure above presents a "visual catalog" of the arch configurations that correspond to five selected points on the Pareto fronts on page 10. The designs range from the most structurally efficient at the top to the most operationally efficient at the bottom. Bars beside each design indicate its structural embodied energy and operational energy, both measured in gigajoules per square meter.

The structurally efficient designs don't differ dramatically from city to city, but the options with efficient operation do. In Abu Dhabi, Boston, and Singapore, efficient operation is achieved by decreasing the arch truss depth and height to reduce the interior conditioned volume and the envelope surface area—a change that also reduces structural efficiency. In contrast, the Sydney arch achieves higher operating efficiency by becoming taller to maximize its surface area. In the mild Sydney climate, exchanging more heat with the outside can stabilize temperatures inside.

The transition from embodied to operational energy efficiency is more gradual with the x-brace, as shown on page 12. In Abu Dhabi and Singapore, all the solutions are fairly shallow, with small envelope surface areas and shading edges that curve down toward the windows they protect. In Boston, the main arch members become less curved, with flatter shading elements that allow more sunlight to enter and offset heating loads. In Sydney, those elements also become flat but at a higher angle, which generates taller walls and windows—again supporting greater surface area and more extensive heat exchange with the outdoors. Interestingly, in several cases the x-brace is noticeably asymmetrical so as to more effectively block out or let in the sun.

Visual catalog of the optimal set of x-brace geometries



This figure presents the optimal set of designs for the x-brace. In Abu Dhabi and Singapore, operational energy is reduced by curving the overhangs down over the windows. In Boston, those shading elements are less curved to allow more sunlight in, and in Sydney they become flat at a higher angle to generate taller walls and windows and thus more surface area to exchange heat with the mild outdoor air. In several cases, the x-brace is slightly asymmetrical to maximize the impact on incoming sunlight.

Considering other factors

The researchers think there's more to be done with their methodology. Already they have performed a series of analyses to show how different assumptions about building lifetimes and operational efficiency can change the shape of the Pareto front. Factors such as monetary cost and constructability could also be considered and traded off. But they hope that their work to date will encourage architects and structural engineers to incorporate the MIT team's methodology early in the design process, when it can push solutions in interesting and unexpected ways and lead to new building designs that are high-performance, innovative, and architecturally expressive.

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By Nancy W. Stauffer, MITEI

This research was supported by the MIT Department of Architecture, including a one-semester Hyzen Fellowship awarded to Nathan Brown. Further information can be found in:

N.C. Brown. *Multi-Objective Optimization for the Conceptual Design of Structures*. SM thesis, MIT Department of Architecture, June 2016.

N. Brown and C.T. Mueller. "Design for structural and energy performance of long span buildings using geometric multi-objective optimization." *Energy and Buildings*, vol. 127, pp. 748–761, 1 September 2016.

Moving away from fossil fuel energy?

Not without aggressive policy action

Christopher Knittel of the MIT Sloan School of Management (above) and his collaborators Michael Greenstone and Thomas Covert of the University of Chicago have examined historical and predicted costs for fossil fuel resources and carbon-free energy technologies and concluded that policy action is needed if the world is to shift away from reliance on fossil fuels.

Data for the analyses were provided by BP, a Founding Member of the MIT Energy Initiative.

Photo: M. Scott Brauer

An analysis by MIT and University of Chicago researchers concludes that market forces alone won't reduce the world's reliance on fossil fuels for energy. Historical data suggest that as demand grows, new technologies will enable producers to tap into deposits that were previously inaccessible or uneconomic. And the recovered fuels will likely be our cheapest energy option. Without dramatic breakthroughs, widespread power generation from solar photovoltaics and wind will remain more expensive than using fossil fuels. And electric vehicles won't replace gasoline-powered vehicles unless battery costs drop and/or oil prices go up at unrealistic rates. The researchers conclude that if the world is to cut greenhouse gas emissions enough to avert a disastrous temperature rise, policymakers must put a price on carbon emissions and invest heavily in research and development to improve low-carbon energy technologies.

Experts agree that significant climate change is unavoidable unless we drastically cut greenhouse gas emissions by moving away from fossil fuels as an energy source. Some observers are optimistic that such a shift is coming. Prices of solar and wind power have been dropping, so those carbon-free renewable resources are becoming more cost-competitive. And fossil resources are by their nature limited, so readily accessible deposits could start to run out, causing costs to rise.

A study from MIT and the University of Chicago has produced results that crush the optimistic view that market forces alone will drive the transition. The analysis shows that while innovation in low-carbon energy is striking, technological advances are constantly bringing down the cost of recovering fossil fuels, so the world will continue to use them—potentially with dire climate consequences. "If we want to leave those resources in the ground, we need to put a price on carbon emissions, and we need to invest in R&D to make clean energy technologies more affordable," says Christopher Knittel, the George P. Shultz Professor at the MIT Sloan School of Management.

Knittel and his colleagues—Michael Greenstone, the Milton Friedman Professor in Economics and the College at the University of Chicago, and Thomas Covert, an assistant professor at the Booth School of Business at the University of Chicago—reached their conclusion by examining historical evidence along with possible future trends that may affect the success of fossil fuels in the marketplace. "As economists, we often focus on supply and demand for different products," says Knittel. "The goal of this project was to look at whether there's any evidence that either the supply of fossil fuels or the demand for fossil fuels will shrink in the near- or even medium-term future."

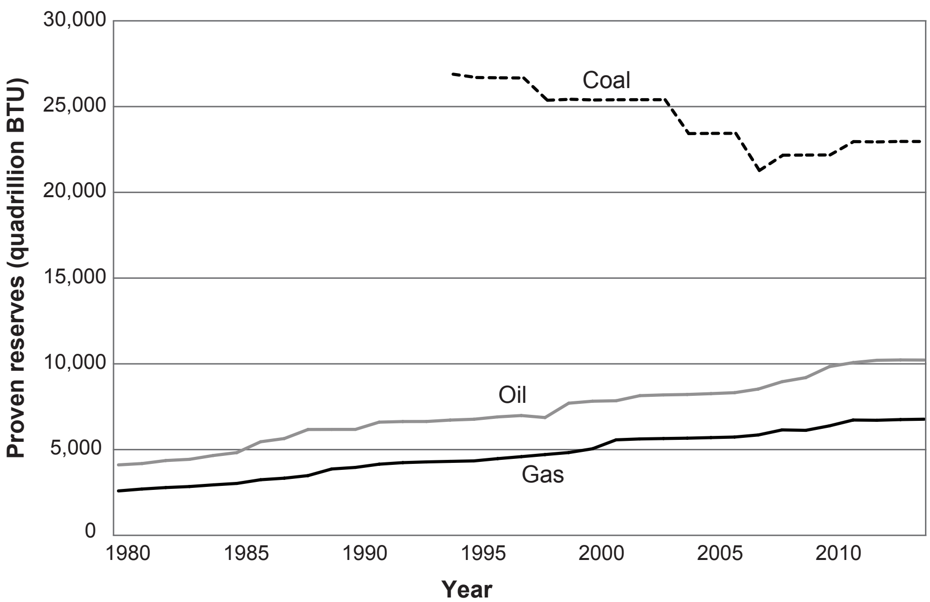
Decades of fuel supply

One source of insight into future supply is historical data on fossil fuel reserves—deposits that are known and economically viable. Using the *BP Statistical Review of World Energy*, the researchers compiled data on annual reserves of oil, natural gas, and coal back to 1950. The figure below shows those estimates for the past 34 years.

According to the data, reserves of coal declined over time and then rebounded about a decade ago at a level sufficient to meet world demand for the next 100 years. In contrast, oil and natural gas reserves have marched steadily upward at a rate of about 2.7% per year—despite their continual withdrawal and use. Indeed, at any point in the past three decades, the world has had 50 years of both oil and gas reserves in the ground.

So for oil and gas, reserves have grown at least as fast as consumption. How can that be? "It's true that there's a finite amount of oil and natural gas in the ground, so every barrel of oil we take out means there's one fewer barrel of oil left," says Knittel. "But each year we get better at finding new sources or at taking existing fossil fuels out of the ground."

Proven reserves of oil, natural gas, and coal over time

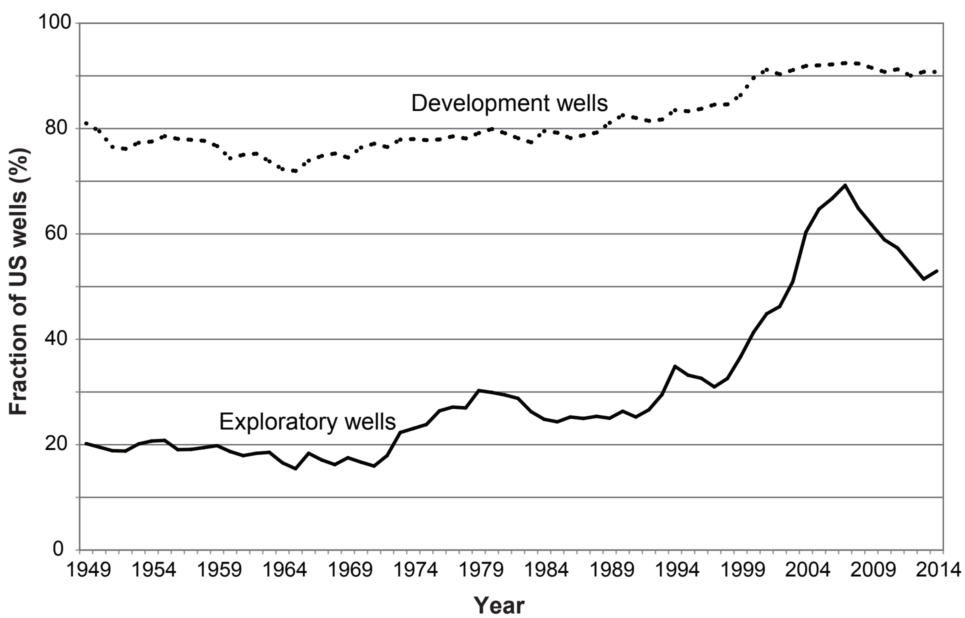


Data from the *BP Statistical Review of World Energy, 2015* show proven reserves (economically recoverable deposits) for the past 34 years. Coal reserves were in decline but leveled off in the past few years. Oil and gas reserves have steadily increased at an annual rate of about 2.7%. As oil and gas reserves are depleted, technological advances constantly make new deposits economically accessible and extractable.

Two examples illustrate how technological progress affects the level of oil and gas reserves. Both shale and bituminous sands (tar sands) were long recognized as possible sources of hydrocarbons. But the low permeability of shale made removing oil and gas difficult, and tar sands contain a mixture of heavy oil, sand, and clay that's viscous and hard to handle. In both cases, technology has made hydrocarbon recovery economically feasible. Hydraulic fracturing (fracking) and horizontal drilling enabled US operators to begin tapping oil and gas from low-permeability rock formations. As a result, US oil and gas reserves expanded 59% and 94%, respectively, between 2000 and 2014. And in Canada, advanced techniques have enabled companies to extract the heavy oil mixtures from tar sands and upgrade them to light, sweet crude oil. Taken together, those two "unconventional" sources of hydrocarbons now make up about 10% of oil and gas reserves worldwide.

Another question is whether companies are becoming less successful at locating and recovering oil and gas as more reserves are withdrawn. Historical data show the opposite. The figure on this page plots the fraction of successful exploration and development wells in each year from 1949 to 2014. The probability of a successful exploratory well has drifted downward at various periods, but it's still markedly higher than it was in much of the past. Development wells are drilled into formations known to contain oil or gas, but they still can run into technical difficulties and ultimately produce no output. Nevertheless, the fraction of successful development wells has also largely grown over time—an important indicator as 10 to 20 times more development than exploratory wells are now typically drilled.

Fraction of US exploratory and development wells that are successful



Data from the US Energy Information Administration and IHS on drilling outcomes show that companies have for the most part become increasingly successful at finding new oil and gas deposits in their exploratory wells and at recovering those deposits in their development wells. Again, advances in technology help firms sustain production despite the constant withdrawal of resources.

The fact that we always seem to have 50 years of both oil and natural gas is striking to Knittel. "It suggests that there's equilibrium between technology and demand," he says. "If demand goes up rapidly, then technological progress or R&D also goes up rapidly and counterbalances that." Because there's so much coal, there's no real need for technological progress in locating or recovering it. "But our guess is that if it ever started to get in somewhat short supply, we would also invest in R&D on the coal side," notes Knittel.

Resources waiting in the wings

A last consideration on the supply side is the availability of fossil fuel resources—deposits that are known to exist but are not currently economical to extract. While estimates of resources range widely, they're far larger than current reserves in every case: as much as four times larger for oil, 50 times larger for natural gas, and 20 times larger for coal. If technological progress continues, those resources could move into the category of economically recoverable reserves, extending the years of available oil, gas, and coal "for quite some time," says Knittel.

Two resources are known to exist in large quantities. One is oil shale, a fine-grained sedimentary rock that contains oil and gas. If oil shale became economical in the near future, it would nearly triple oil reserves. The other resource is methane hydrates, which are solid mixtures of natural gas and water that form beneath sea floors. Methane hydrates are evenly dispersed across the globe, and there's a big incentive to extract those resources in regions where natural gas is expensive.

"Given the industry's remarkably successful history of innovation, it seems more than possible that oil shale and methane hydrates will become commercially developed," says Knittel. He finds the prospect worrying. Refining oil shale would involve far higher carbon emissions than processing conventional oil does, and tapping methane hydrates would require disturbing the ocean floor and also carefully containing the recovered gas, as the climate-warming potential of methane is far higher than that of carbon dioxide.

The outlook for demand

Not surprisingly, as fossil fuel supplies have been increasing, global consumption of them has also grown. Between 2005 and 2014, consumption of oil rose by 7.5%, coal by 24%, and natural gas by 20%. But in the demand arena, the future may not look like the past. New technologies are evolving that could shift demand away from fossil fuels.

To investigate that possibility, the researchers examined carbon-free options in two major fossil fuel–consuming sectors: power generation and transportation.

One carbon-free option for generating power is nuclear fission, but over the past decade fission has become less cost-competitive, and plant construction has slowed. The researchers therefore focused on two rapidly growing options: solar photovoltaics and wind turbines. To compare costs, they used the levelized cost of energy (LCOE), that is, the average cost of generating a kilowatt of electricity, accounting for both upfront costs and operating costs over the lifetime of the installation.

Data from the US Energy Information Administration show that the LCOE of solar has fallen dramatically over time. However, on average, electricity from a solar array in the United States is still about twice as expensive as electricity from a power plant fired by natural gas—and that's not accounting for the cost of backup natural gas generation, batteries, or other storage systems needed with intermittent sources such as solar and wind.

Knittel also notes that the cited LCOEs are average costs. The LCOE for solar is far lower in sunny Arizona than it is in cloudy Seattle. "There are certainly pockets where solar can compete with natural gas, but remember that the goal here is to replace all of fossil fuel generation," he says. "That's going to require renewables or nuclear across the entire US, not just in the places best suited for them."

The LCOE for wind looks more promising. Wind is cheaper than both nuclear and coal. But again, wind is intermittent and location-dependent, so a meaningful comparison would need to include buying an electricity storage system and perhaps beefing up transmission.

The researchers' projections cover only the next 10 years. "Our crystal ball isn't any clearer than anyone else's, so we can't rule out the possibility that solar all of a sudden will cut their costs in half again 20 years from now," says Knittel. "But what these data suggest is that at least in the near term—absent incentives from policymakers—we shouldn't expect to see the market replace natural gas generation with solar and wind generation."

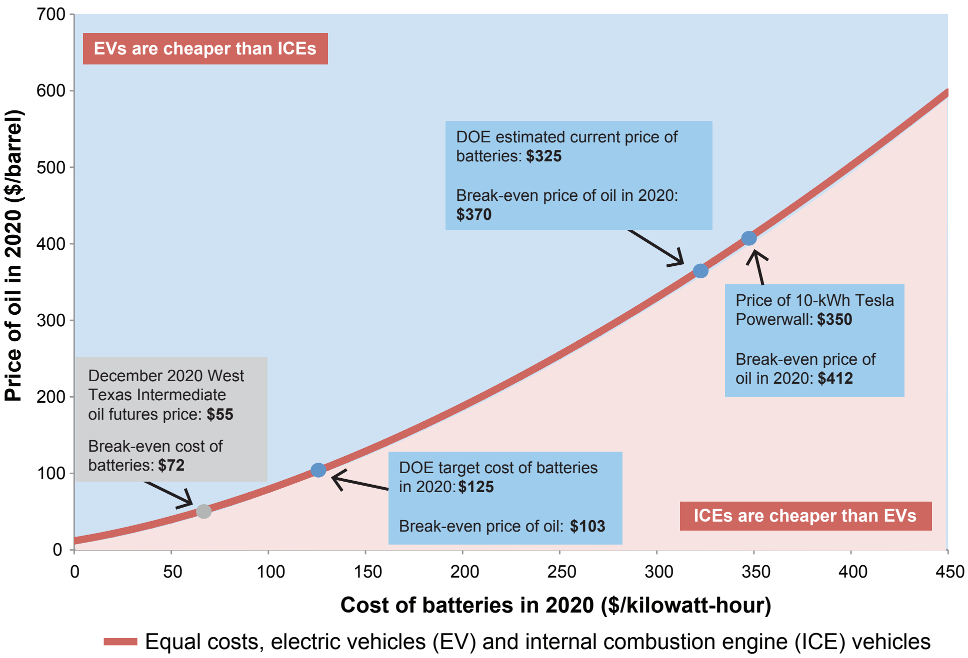
The case of transportation

Turning to the transportation sector, the researchers focused on the much-touted electric vehicle (EV) and its potential for taking market share from the petroleum-burning internal combustion engine (ICE) vehicle. Under what conditions will consumers spend less if they buy and operate an EV rather than an ICE vehicle?

To find out, the researchers developed a simple spreadsheet that calculates the lifetime cost in 2020 of owning each type of vehicle, including upfront costs and gasoline costs. (Go to bit.ly/knittel for an interactive version of the spreadsheet.) The results of their analysis—presented on page 17—show that even under optimistic targets for the price of batteries, an EV is unlikely to compete with an ICE vehicle. For example, the Department of Energy (DOE) estimates current battery costs at $325 per kilowatt-hour (kWh). At that cost, an EV is less expensive to own only if the price of oil exceeds $370 per barrel—and oil is now at just $50 per barrel. The DOE's target for battery cost in 2020 (only four years from now) is $125. At that cost, oil has to be $103 per barrel for cost-conscious consumers to choose an EV.

Knittel points out two other considerations. Their analysis assumes an EV with a range of 250 miles. Expanding that range requires adding more batteries, so batteries will have to be even cheaper for the EV to be cost-competitive. In addition, when looking to the future, it's important

Break-even oil prices and battery costs



This graph shows combinations of oil price and battery cost at which a consumer in 2020 would spend the same amount of money to buy and operate an electric vehicle as an internal combustion engine vehicle. For example, at an oil price of $55 per barrel—the current level of 2020 oil futures—batteries would need to cost $72 per kilowatt-hour (kWh), which is well below DOE's currently estimated price of $325. At DOE's 2020 target battery cost of $125 per kWh, the "indifference" oil price would be $103. (For the detailed assumptions used in the analysis, see the journal article cited on this page. To test your own assumptions, go to the interactive spreadsheet at bit.ly/knittel.)

to remember not to compare future costs of an EV with current costs of an ICE vehicle. Historical evidence suggests that ICE fuel economy improves by about 2% per year, so operating costs will continue to decline in the future—an effect included in their analysis.

A future to be avoided

To underscore the immense amount of fossil fuels in the ground and the importance of leaving them there, the researchers performed one more calculation. Using a climate model, they calculated the change in global average temperatures that would result if we burned all the fossil fuels now known to exist. The result is a temperature increase of 10°F to 15°F by 2100—a change that would alter the planet in hard-to-imagine ways and dramatically threaten human well-being in many parts of the world.

"So the final lesson is…that we need policymakers to step up to the plate and adopt the right set of policies—and economists are pretty consistent about what those policies are," says Knittel. "We need a price on carbon, and we need to subsidize research and development for alternatives to fossil fuel–based technologies." And the longer we wait to take action, the harder it will be to stop the ongoing march toward what the researchers call "a dystopian future."

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By Nancy W. Stauffer, MITEI

This research was funded by the Center for Energy and Environmental Policy Research at MIT. Data critical to the analysis were provided by BP, a Founding Member of the MIT Energy Initiative. Further information can be found in:

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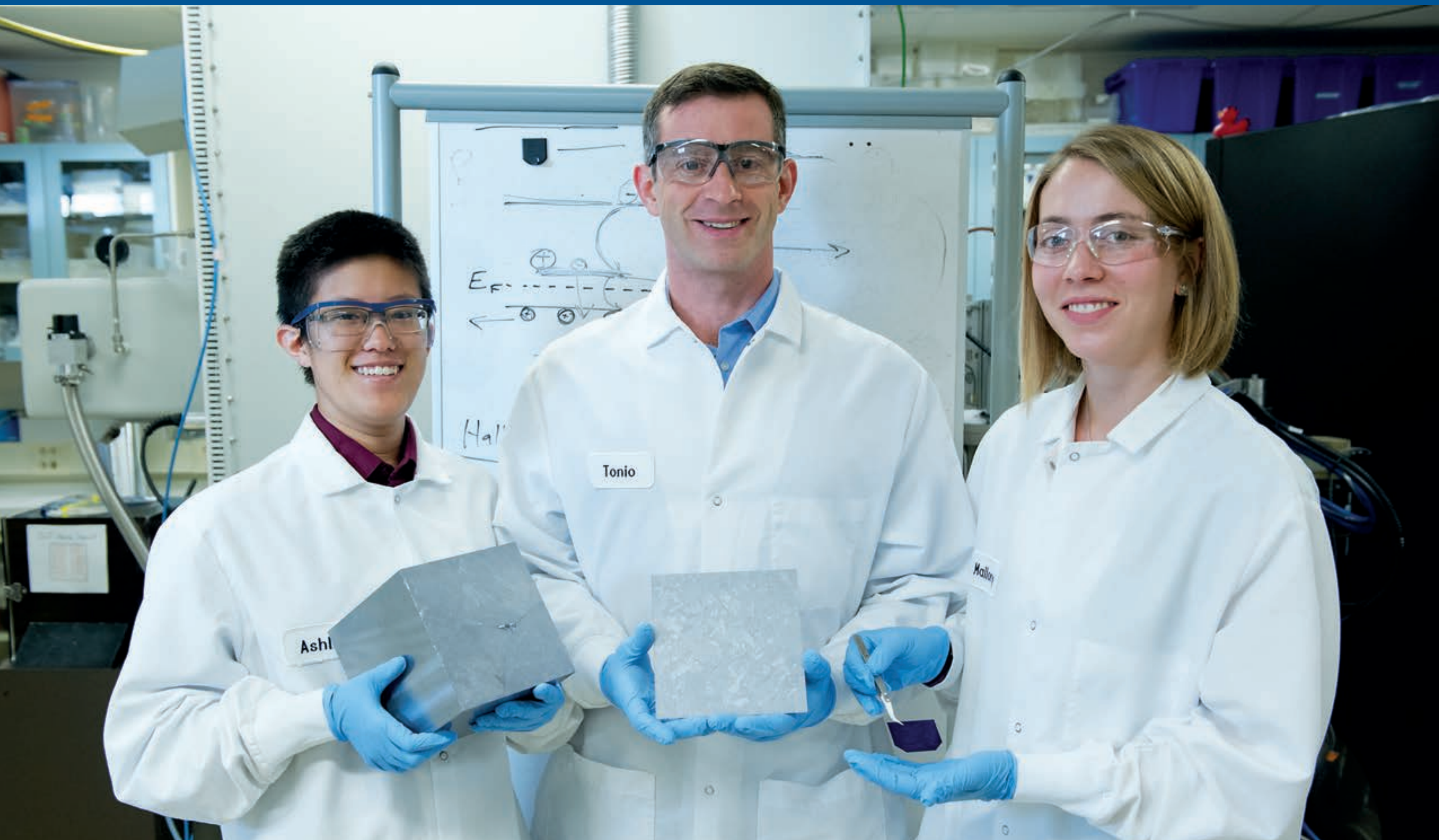


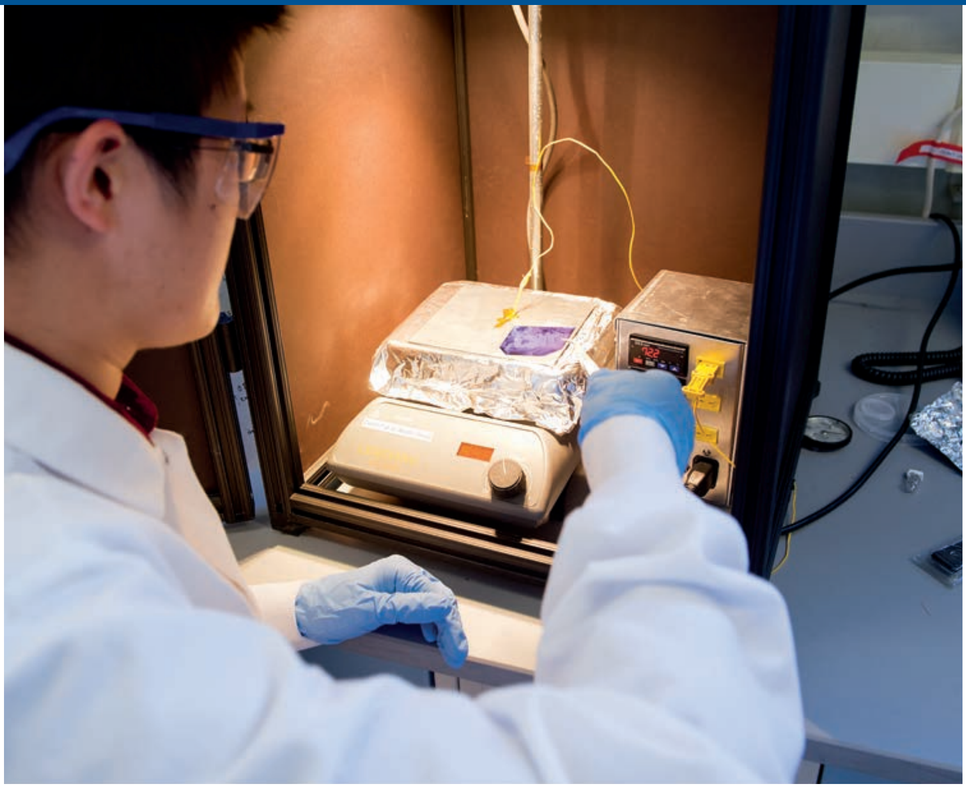
Advanced silicon solar cells

Detecting defects that reduce efficiency

From left: Ashley Morishige, Tonio Buonassisi, and Mallory Jensen of mechanical engineering have identified defects that may be causing a promising type of high-efficiency silicon solar cell to generate decreasing amounts of electricity in sunlight and have made recommendations to manufacturers that may help prevent the problem. Here the researchers display a silicon brick, a silicon wafer, and the silicon core of a partially fabricated solar cell.

Photo: Stuart Darsch

MIT research is shedding light on why some (but not all) photovoltaic modules containing a new type of high-efficiency silicon solar cell generate significantly less electricity after they've been in sunlight for just a few months. Based on studies using specialized equipment and analytical techniques, the researchers hypothesize that defects in the silicon are causing electrons that have been energized by incoming sunlight to lose their extra energy—before they can travel through external wires as current. They recommend that manufacturers fabricating these solar cells use the lowest firing temperatures they can and ensure that their silicon has low concentrations of certain impurities that the MIT team has identified as potentially contributing to the problem. The researchers hope that their final explanation of this fault and how to solve it will help encourage the rapid deployment of these promising high-efficiency solar cells.



Postdoc Ashley Morishige prepares to use a halogen lamp to "light-soak" a silicon wafer extracted from a PERC solar cell. The procedure is designed to induce the faults that have been causing the power output of some PERC modules to decline in sunlight.

As the world transitions to a low-carbon energy future, near-term, large-scale deployment of solar power will be critical to mitigating climate change by midcentury. Climate scientists estimate that the world will need 10 terawatts (TW) or more of solar power by 2030—at least 50 times the level deployed today. At the MIT Photovoltaic Research Laboratory (PVLab), teams are working both to define what's needed to get there and to help make it happen. "Our job is to figure out how to reach a minimum of 10 TW in an economically and environmentally sustainable way through technology innovation," says Tonio Buonassisi, associate professor of mechanical engineering and lab director.

Their analyses outline a daunting challenge. First they calculated the growth rate of solar required to achieve 10 TW by 2030 and the minimum sustainable price that would elicit that growth without help from subsidies. Current technology is clearly not up to the task. "It would take between $1 trillion and $4 trillion of additional debt to just push current technology into the marketplace to do the job, and that'd be hard," says Buonassisi. So what needs to change?

Using models that combine technological and economic variables, the researchers determined that three changes are required: reduce the cost of modules by 50%, increase the conversion efficiency of modules (the fraction of solar energy they convert into electricity) by 50%, and decrease the cost of building new factories by 70%. Getting all of that to happen quickly enough—within five years—will require near-term policies to incentivize deployment plus a major push on technological innovation to reduce costs so that government support can decrease over time.

Making strides on efficiency

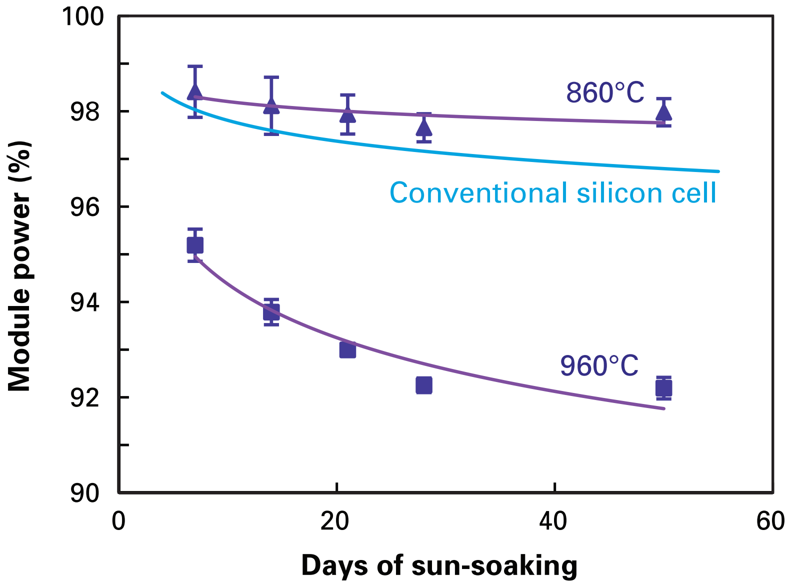
Major gains are already being made on the conversion efficiency front—both at the MIT PVLab and around the world. One especially promising technology is the passivated emitter and rear cell (PERC), which is based on low-cost crystalline silicon but has a special "architecture" that captures more of the sun's energy than conventional silicon cells do. While costs must be brought down, the technology promises to bring a 7% increase in efficiency, and many experts predict its widespread adoption.

But there's been a problem. In field tests, some modules containing PERC solar cells have degraded in the sun, with conversion efficiency dropping by fully 10% in the first three months. "These modules are supposed to last 25 years, and within just weeks to months they're generating only 90% as much electricity as they're designed for," says Ashley Morishige, postdoc in mechanical engineering. That behavior is perplexing because manufacturers thoroughly test the efficiency of their products before releasing them. In addition, not all modules exhibit the problem, and not all companies encounter it. Interestingly, it took up to a few years before individual companies realized that other companies were having the same problem. Manufacturers came up with a variety of engineering solutions to deal with it, but its exact cause remained unknown, prompting concern that it could recur at any time and could affect next-generation cell architectures.

To Buonassisi, it seemed like an opportunity. His lab generally focuses on basic materials problems at the wafer and cell level, but the researchers could equally well apply their equipment and expertise to modules and systems. By defining the problem, they could support the adoption of this energy-efficient technology, helping to bring down materials and labor costs for each watt of power generated.

Working closely with an industrial solar cell manufacturer, the MIT team undertook a "root-cause analysis"

Power loss in PERC modules: effect of cell-firing temperature



This figure shows power output as a fraction of pre-sun-soaking power output from two pairs of PERC modules during 50 days of exposure to sunlight outdoors. One pair of modules contained cells fired at a peak temperature of 860°C (triangles); the other pair contained cells fired at 960°C (squares). Power loss is significantly greater with the cells fired at the higher temperature. Power output from modules made with conventional solar cells (blue line) is included for reference.

to define the source of the problem. The company had come to them for help with the unexpected degradation of their PERC modules and reported some odd trends. PERC modules stored in sunlight for 60 days with their wires connected into a closed loop lost no more efficiency than conventional solar cells typically do during their break-in period. But modules stored in sunlight with open circuits degraded significantly more. In addition, modules made from different silicon ingots displayed different power-loss behavior. And, as shown in the figure above, the drop in efficiency was markedly higher in modules made with cells that had been fabricated at a peak temperature of 960°C than in those containing cells fired at 860°C.

Subatomic misbehavior

Understanding how defects can affect conversion efficiency requires understanding how solar cells work at a fundamental level. Within a photoreactive material such as silicon, electrons exist at two distinct energy levels. At the lower level, they're in the "valence band" and can't flow; at the higher level, they're in the "conduction band" and are free to move. When solar radiation shines onto the material, electrons can absorb enough energy to jump from the valance band to the conduction band, leaving behind vacancies called holes. If all is well, before the electrons lose that extra energy and drop back to the valence band, they travel through an external circuit as electric current.

Generally, an electron or hole has to gain or lose a set amount of energy to move from one band to the other. (Although holes are defined as the absence of electrons, physicists view both electrons and holes as "moving" within semiconductors.) But sometimes a metal impurity or a structural flaw in the silicon provides an energy "state" between the valence and conduction bands, enabling electrons and holes to jump to that intermediate energy level—a move achieved with less energy gain or loss. If an electron and hole both make the move, they can recombine, and the electron is no longer available to pass through the external circuit. Power output is lost.

The PVLab researchers quantify that behavior using a measure called lifetime—the average time an electron remains in an excited state before it recombines with a hole. Lifetime critically affects the energy conversion efficiency of a solar cell, and it is "exquisitely sensitive to the presence of defects," says Buonassisi.

To measure lifetime, the team—led by Morishige and graduate student Mallory Jensen of mechanical engineering—uses a technique called lifetime spectroscopy. It involves shining light on a sample or heating it up and monitoring electrical conductivity during and immediately afterward. When current flow goes up, electrons excited by the added energy have jumped into the conduction band. When current drops, they've lost that extra energy and fallen back into the valence band. Changes in conductivity over time thus indicate the average lifetime of electrons in the sample.

Locating and characterizing the defect

To address the performance problems with PERC solar cells, the researchers first needed to figure out where in the modules the primary defects were located. Possibilities included the silicon surface, the aluminum backing, and various interfaces between materials. But the MIT team thought it was likely to be in the bulk silicon itself.

To test that assumption, they used partially fabricated solar cells that had been fired at 750°C or at 950°C and—in each category—one that had been exposed to light and one that had been kept in the dark. They chemically removed the top and bottom layers from each cell, leaving only the bare silicon wafer. They then measured the electron lifetime of all the samples. As shown in the figure at right, with the low-temperature pair, lifetime is about the same in the light-exposed and unexposed samples. But with the high-temperature pair, lifetime in the exposed sample is significantly lower than that in the unexposed sample.

Those findings confirm that the observed degradation is largely attributable to defects that are present in the bulk silicon and—when exposed to light—affect lifetime, thus conversion efficiency, in cells that have been fired at higher temperatures. In follow-up tests, the researchers found that by reheating the degraded samples at 200°C for just an hour, they could bring the lifetime back up—but it dropped back down with re-exposure to light.

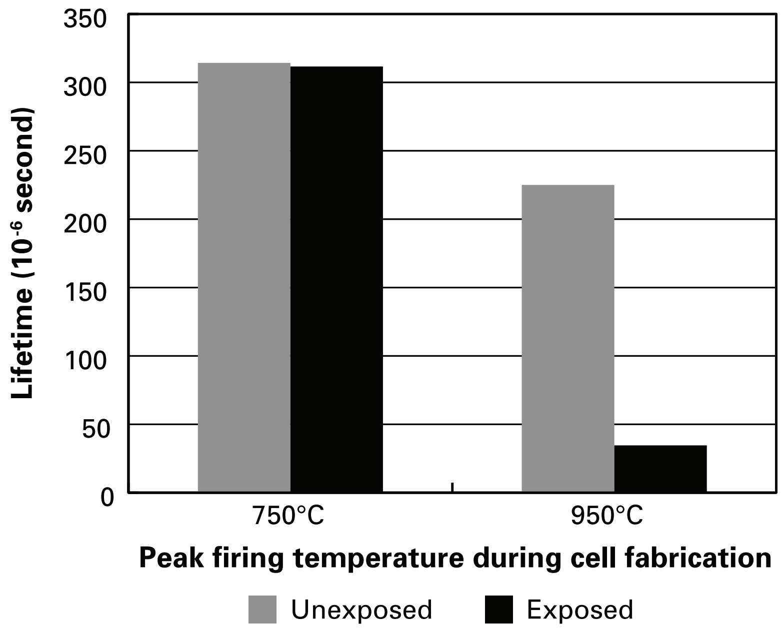
So how do those defects interfere with conversion efficiency, and what types of contaminants might be involved in their formation? Two characteristics of the defects would help the researchers answer those questions. First is the energy level of the defect—where it falls between the valence and conduction bands. Second is the "capture cross section," that is, the area over which a defect at a particular location can capture electrons and holes. (The area might be different for electrons than for holes.)

While those characteristics can't easily be measured directly in the samples, the researchers could use a standard set of equations to infer them based on lifetime measurements taken at different illumination intensities and test temperatures. Using samples that had been fired at 950°C and then exposed to light, they ran lifetime spectroscopy experiments under varying test conditions. With the gathered data, they calculated the energy level and capture cross section of the primary defect causing recombination in their samples. They then consulted the literature to see what elements are known to exhibit those characteristics, making them likely candidates for causing the drop in conversion efficiency observed in their samples.

According to Morishige, the team has narrowed down the list of candidates to a handful of possibilities. "And at least one of them is consistent with much of what we've observed," she says. In this case, a metal contaminant creates defects in the crystal lattice of the silicon during fabrication. Hydrogen atoms that are present combine with those metal atoms, making them electrically neutral so they don't serve as sites for electron-hole recombination. But under some conditions—notably, when the density of electrons is high—the hydrogen atoms dissociate from the metal, and the defects become very recombination-active.

That explanation fits with the company's initial reports on their modules. Cells fired at higher temperatures would be more susceptible to light-induced damage because the silicon in them typically contains more impurities and less hydrogen. And performance would vary from ingot to ingot because different batches of silicon contain different concentrations of contaminants as well as hydrogen. Finally, baking the silicon at 200°C—as the researchers did—could cause the hydrogen atoms to recombine with the metal, neutralizing the defects.

Lifetime measurements in silicon wafers



Results from lifetime measurements in silicon wafers fired at 750°C and 950°C and either unexposed to light (left-hand bar in each pair) or "light-soaked" by halogen lamps in the laboratory (right-hand bar). Lifetime in the wafer fired at 750°C is unchanged by light-soaking. Lifetime in the 950°C wafer starts out lower and then drops significantly after light-soaking. Those results are consistent with the power losses observed in the PERC modules exposed to sunlight outdoors.

Photos: Stuart Darsch

Graduate student Mallory Jensen performs a test to determine the spatially averaged lifetime of excited electrons in a sample silicon wafer. A high-intensity, broadband flash of light excites electrons in the wafer, inducing voltage in a sensor beneath. Inset photo: A close-up of the silicon wafer and the sensor region over which the average is taken.

Based on that possible mechanism, the researchers offer manufacturers two recommendations. First, try to adjust their manufacturing processes so that they can perform the firing step at a lower temperature. And second, make sure that their silicon has sufficiently low concentrations of certain metals that the researchers have pinpointed as likely sources of the problem.

Unintended consequences

The bottom line, observes Buonassisi, is that the very feature that makes the PERC technology efficient—the special architecture designed to capture solar energy efficiently—is what reveals a problem inherent in the fabricated material. “The cell people did everything right,” he says. “It’s the quintessential law of unintended consequences.” And if the problem is the higher density of excited electrons interacting with defects in the silicon wafer, then developing effective strategies for dealing with it will only get more important because next-generation device designs and decreasing wafer thicknesses will bring even higher electron densities.

To Buonassisi, this work demonstrates the importance of talking across boundaries. He advocates communication among all participants in the solar community—both private companies and research organizations—as well as collaboration among experts in every area—from feedstock materials to wafers, cells, and modules to system integration and module installation. “Our laboratory is taking active steps to bring together a community of stakeholders and create a vertically integrated R&D platform that I hope will enable us to more quickly address the technical challenges and help lead to 10 TW of PV by 2030,” he says.

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By Nancy W. Stauffer, MITEI

This research was funded by the National Science Foundation, the US Department of Energy, and the National Research Foundation Singapore through the Singapore-MIT Alliance for Research and Technology. Further information can be found in:

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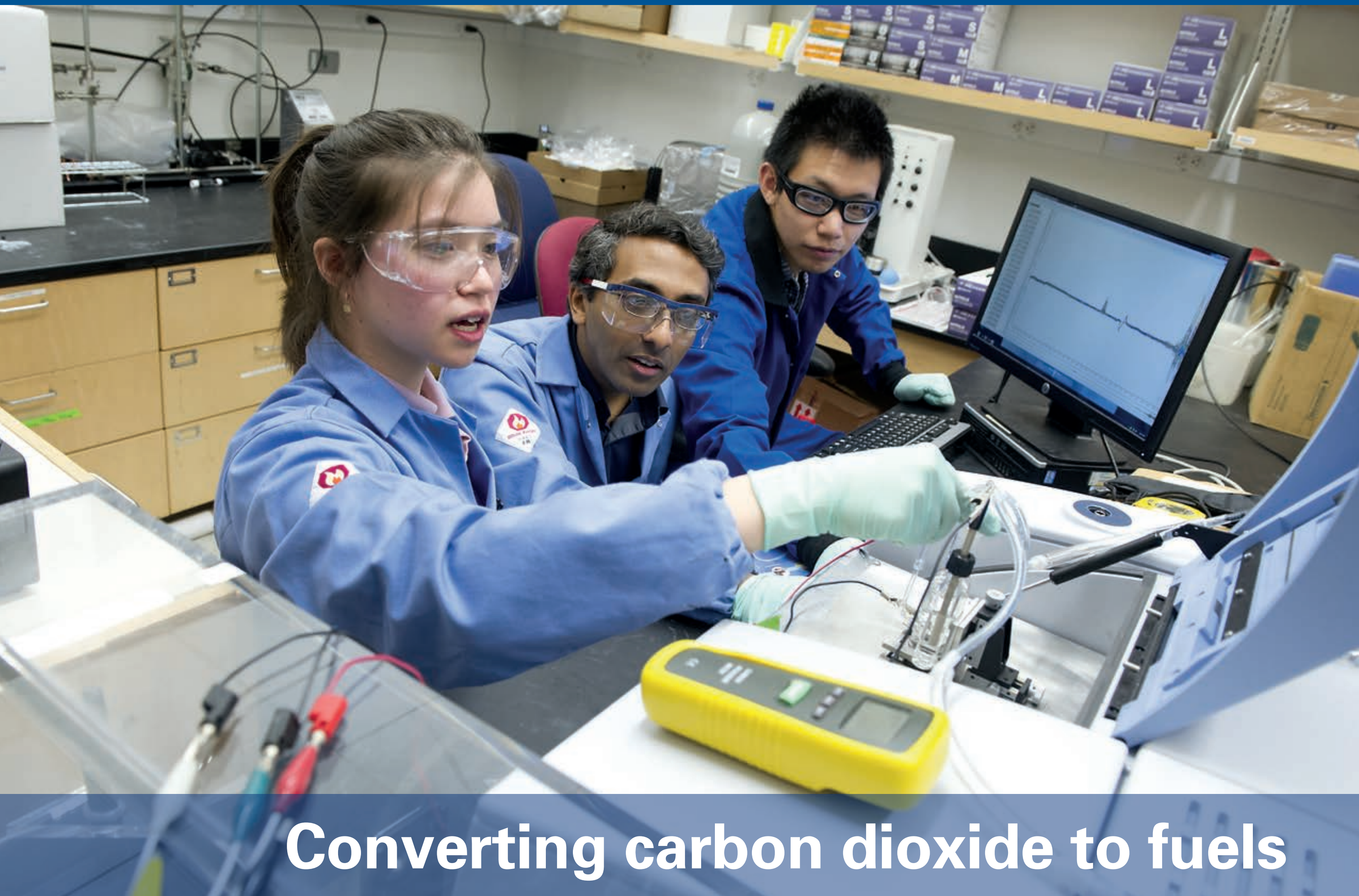


Converting carbon dioxide to fuels

A method of fossil resource recycling

From left: Anna Wuttig, Yogesh Surendranath, and Youngmin Yoon of chemistry use infrared absorption spectroscopy to analyze the chemical species adsorbed on the surface of a model catalyst—information they use to evaluate its effectiveness in converting carbon dioxide into precursors for making liquid fuels. Former MIT postdoc Anthony Shoji Hall (not pictured) was also involved in the work.

Photo: Stuart Darsch

MIT chemists have demonstrated major advances in the design of a device that could one day take carbon dioxide emissions from fossil fuel combustion and—powered by renewable energy—turn them back into high-quality fuels. By examining the individual steps that convert key chemicals inside the device, they've identified ways to redesign the catalyst they use so that it selectively encourages the formation of compounds suitable for making fuels. For example, making the catalyst thick and porous significantly increases the production of carbon monoxide, which can be converted to a variety of liquid fuels. Controlling nanoscale features on the catalyst's surface should further enhance carbon monoxide production. This work provides a compelling demonstration of how fundamental analyses can guide catalyst design—a persistent challenge in many important chemical systems.

Most of the world's energy needs are met by burning fossil fuels—a process that emits large amounts of carbon dioxide (CO_2), a major contributor to climate change. Carbon-free alternatives are now available, notably renewable sources such as solar and wind. But those sources are intermittent, so relying on them at large scale requires a means of storing the excess electricity they generate during peak production for use when the sun and wind aren't available.

Yogesh Surendranath, the Paul M. Cook Career Development Assistant Professor in the Department of Chemistry, has been working on a way to use that excess electricity to turn CO_2 emissions into new carbon-based fuels that could be used when renewable generation is interrupted. The process would provide a means of energy storage for solar and wind systems and would create a closed cycle for fossil fuels. "Right now we combust hydrocarbons, pull more out of the ground, and combust those hydrocarbons, each time making more CO_2," says Surendranath. "If we used renewable electricity to convert captured CO_2 emissions back into a fuel, we'd essentially reverse combustion and have a carbon-neutral energy cycle."

But dealing with CO_2 is difficult because it's chemically inert. One approach to getting it to react is through electrochemistry, that is, using electricity to activate chemical reactions that wouldn't otherwise happen. Dissolving CO_2 plus a salt in water and then activating the mixture with electricity—ideally from a renewable source—would generate hydrogen plus a mixture of carbon-containing molecules.

Unfortunately, that process typically produces far more hydrogen than carbon products, and hydrogen is a less

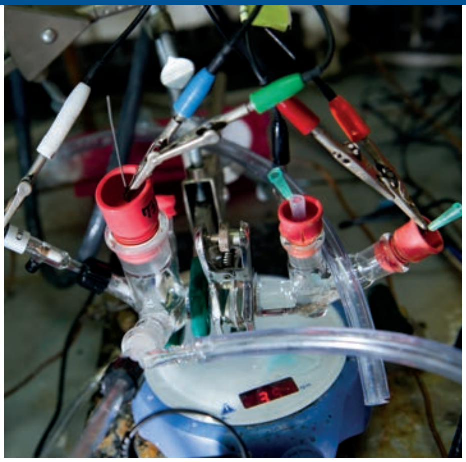


Photo: Stuart Darsch

This electrochemical cell is used for an experiment that both characterizes the gold electrode's surface and tests its impact on CO_2 conversion. The researchers bubble CO_2 into an aqueous solution and apply a constant potential to a submerged gold electrode in the left-hand glass cell and then withdraw the gaseous products formed for analysis.

desirable fuel: Gaseous hydrogen stores less energy per unit volume; the infrastructure to support its use doesn't yet exist; and it doesn't capture carbon. In addition, CO_2 electrolysis produces many different carbon compounds, and separating out the ones that are good starting materials for making fuels is both expensive and energy-intensive.

The MIT team therefore faced a dual challenge. They needed to make the electrolysis system produce more carbon-containing products than hydrogen, and they needed to make it "selective" for the specific carbon products that they wanted.

One determinant of what happens is the catalyst—a material used to speed up chemical reactions involving inert compounds without being consumed in the process. For the past three decades, researchers have been trying to develop better catalysts for CO_2 conversion, largely through trial and error and with very limited success. Given all the chemicals present and the many possible reactions among them, unraveling what's going on empirically is challenging. So Surendranath and his team decided to combine experimental and theoretical studies to develop a detailed understanding of the reactions that take place during CO_2 electrolysis.

A target compound

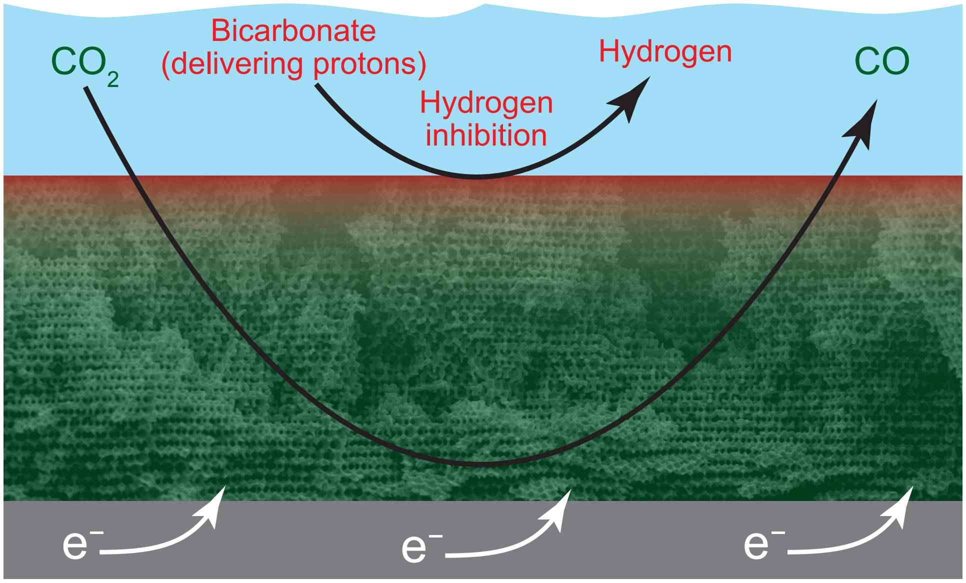
As an example, Surendranath, graduate student Anna Wuttig of chemistry, and their international collaborators focused their investigation on carbon monoxide (CO), a good starting material for making liquid fuels, including diesel. Typically, the hydrogen-forming reactions proceed faster than the CO-forming reactions. To find a way to reverse that balance, they needed to understand both reactions in detail.

To that end, they have constructed a lab-scale electrolyzer with an electrode made of gold foil—an element good at both conducting electricity and catalyzing CO_2 conversion. They fill their device with a mixture of water and bicarbonate (the salt that carries electrically charged particles through the solution), pressurize the mixture with added CO_2, and send in electricity. Products form on the electrode, bubble off, and travel to a gas chromatograph for chemical analysis.

They then use one more tool not generally used in studies of CO_2 catalysis: in situ vibrational spectroscopy. While reactions are occurring, they illuminate the catalyst with infrared light, which is absorbed by molecules bound to the surface. The light that is not absorbed is reflected to the detector, and the resulting spectrum is used to infer what molecules are present. This technique allows them to monitor reactions on the catalyst in real time. Indeed, they can "watch" how molecules interact with the surface of the catalyst as CO, hydrogen, and other products are formed.

To generate more CO than hydrogen, the researchers needed to find a way to either speed up the CO-forming reactions or slow down the hydrogen-

The porous gold electrode: structure and impacts



A scanning electron microscope image of the porous gold electrode. Electrons (e^-) enter from a metal slab at the bottom; the bulk mixture of CO_2, bicarbonate, and water is in the blue region at the top; and dark-colored pores are visible throughout the electrode. CO_2 (dissolved in water) easily flows into the electrode, while the proton-bearing bicarbonate is replenished more slowly. As a result, CO-forming reactions occur at reactive sites on the walls of all the pores (indicated in green), while hydrogen-forming reactions occur primarily on the electrode surface (indicated in red).

forming ones. They knew that the hydrogen- and CO-forming reactions both require two types of electrically charged, subatomic particles—electrons, which are delivered by the electrode, and protons, which are delivered by the bicarbonate. But when they figured out all the details of the reactions—the bonds that break and form and rearrange—they found that the electrons and protons play different roles in the two processes, providing a means of controlling the relative rates of the two reactions.

The critical difference

The rate of any chemical reaction is determined by the rate at which the slowest step in the overall process proceeds. In the CO-forming sequence, that "rate-limiting" step involves a CO_2 molecule reacting with an electron on the electrode. A proton will be needed, but not until later in the overall CO_2 reaction process. In contrast, in the hydrogen-forming reaction, the rate-limiting step requires that an electron react with a proton on the electrode. The two charged particles must therefore be transferred to the electrode surface at the same time.

"That means the rate of the hydrogen reaction on the electrode will be very sensitive to the nearby concentration of protons, whereas the CO-forming reactions won't be," notes Surendranath. Since protons are delivered by the bicarbonate, reducing the amount of bicarbonate near the electrode should slow the formation of hydrogen without affecting the conversion of CO_2 to CO.

That strategy seemed both simple and promising. But one process inside the electrolyzer could interfere. When bicarbonate mixed with CO_2 and water "donates" its protons to a chemical reaction, the CO_2 and water could react with each other to make more. If that occurs rapidly near the electrode, it will deplete the CO_2 and make more bicarbonate for proton delivery—the opposite of the researchers' intended outcome.

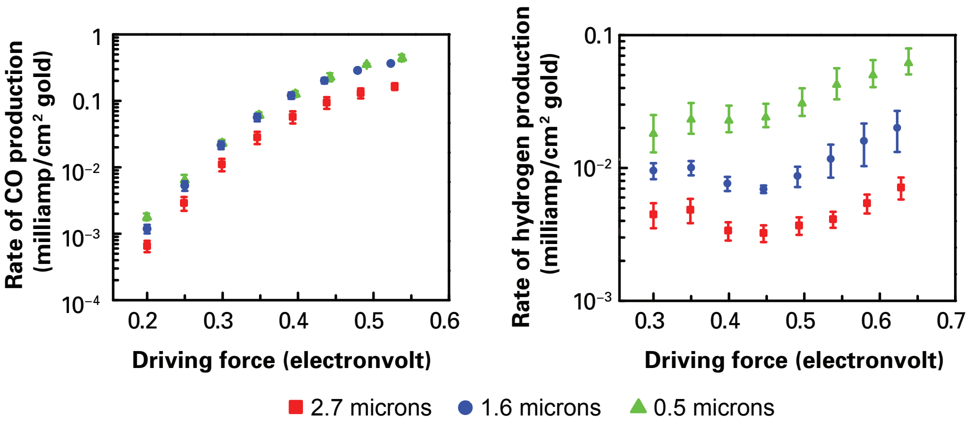
But that's not what happens in the vicinity of the electrode inside the electrolyzer. Instead, the bicarbonate concentration remains slightly lower at the electrode surface than in the rest of the mixture. The researchers' analysis explains why it's not replenished. The conversion of CO_2 to bicarbonate is a notoriously slow reaction—so slow that the CO_2 in the area is captured by the electrode and converted to CO long before it can react with water to replenish the bicarbonate concentration.

Porous electrodes

Since the bicarbonate won't be replenished near the electrode, the researchers just needed to keep fresh bicarbonate from flowing to that area to deliver protons. They've now demonstrated a simple way to achieve that goal: They make the electrode thick and porous.

On the thin electrode the researchers originally tested, reaction sites occur only on the surface of the gold electrode. With the thick, porous electrode, active sites are also available on the interior walls of all the pores throughout the volume. But the various chemicals inside the electrolyzer don't all reach those interior sites with equal ease. As indicated in the image above, CO_2 (dissolved in water) flows readily throughout the electrode, so it can react with electrons at all the interior sites. In contrast, bicarbonate diffuses less easily, so it doesn't reach the interior sites to deliver protons. As a result, CO_2 converts to CO throughout the electrode, but hydrogen forms only on the surface, where fresh bicarbonate continues to bathe active sites, delivering protons. The rate of CO formation will thus far exceed the rate of hydrogen formation.

Effect of porous electrode thickness on CO and hydrogen production



The researchers tested the impact of their porous electrode by preparing three samples of differing thicknesses: 2.7 microns (red squares), 1.6 microns (blue circles), and 0.5 microns (green triangles). Using those electrodes in their electrolyzer, they measured the rate of CO production (left) and hydrogen production (right) per unit area at increasing driving force. At any given driving force, the CO production rate is similar with the three sample electrodes. In contrast, the hydrogen production rate varies significantly, with the thickest electrode exhibiting a 10-fold decrease in hydrogen relative to the thinnest one. The thicker the porous electrode, the more hydrogen formation is suppressed.

To demonstrate that effect, Surendranath, Wuttig, former MIT postdoc Anthony Shoji Hall, and graduate student Youngmin Yoon of chemistry, a 2016–2017 ExxonMobil–MIT Energy Fellow, fabricated three porous gold electrodes of varying thicknesses and tested them in the electrolyzer. The diagrams above show the measured rates of CO production (left) and hydrogen production (right) at various driving forces with the different electrodes. As expected, the rate of CO production increases with increasing driving force. But at a given driving force, the rate is about the same in all three electrode samples. In contrast, the rate of hydrogen production at a given driving force is not the same in the three samples. The thickest sample consistently shows about a 10-fold decrease in activity relative to the thinnest sample. (The researchers are currently investigating why the curves for hydrogen don't rise smoothly as driving force increases.)

"If using a thick, porous electrode leaves the rate of one reaction unchanged but reduces the rate of the other one by an order of magnitude, that dramatically changes the selectivity," says Surendranath. "Instead of designing a catalyst to speed up a preferred reaction, we've made one that slows down the less desirable reaction so that the preferred one can compete."

Going forward

The researchers are now looking at ways to simultaneously speed up CO production. The in situ spectroscopy analyses showed that about 20% of the surface of their catalyst is covered by stuck CO. Those "spectator" molecules reduce the productivity of the device by covering up sites where other incoming CO_2 molecules could react.

While that appears to be bad news, it could actually provide insights into how to design more effective catalysts. The active sites on a catalyst have varied surface features such as terraces and edges, and they bind incoming molecules in different orientations and with varied strength. From the in situ spectroscopy, the researchers can see how the molecules of interest behave on specific sites, so they can see which ones most effectively catalyze the CO_2 reactions.

"Ultimately, we may be able to design and manufacture catalysts with surface structures that are optimized for maximum performance," says Surendranath. "We're only in the early stages of being able to systematically nanostructure electrochemical catalysts, but that could be a powerful tool for controlling surface sites to build the optimal catalysts for these reactions."

Recently, they've hit upon yet another possible way of improving the performance of their system for CO production. New analyses suggest that varying the diameters and shapes of the pores in their electrode can both reduce the rate of hydrogen formation and increase the rate of CO formation. "Our results to date are a powerful demonstration that elucidating the fundamental behavior of chemicals in a system can lead to important practical insights," says Surendranath. And he believes there are many more to come.

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By Nancy W. Stauffer, MITEI

This research was supported by the Air Force Office of Scientific Research and by the MIT Department of Chemistry. Anna Wuttig was supported by a graduate research fellowship from the National Science Foundation. Further information can be found in:

A.S. Hall, Y. Yoon, A. Wuttig, and Y. Surendranath. "Mesostructure-induced selectivity in CO_2 reduction catalysis." *Journal of the American Chemical Society*, vol. 137, pp. 14834–4837, 2015.

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Alcator C-Mod tokamak nuclear fusion reactor sets world record on final day of operation

On Friday, September 30, 2016, at 9:25 p.m. EDT, scientists and engineers at MIT's Plasma Science and Fusion Center made a leap forward in the pursuit of clean energy. The team set a new world record for plasma pressure in the Institute's Alcator C-Mod tokamak nuclear fusion reactor. Plasma pressure is the key ingredient to producing energy from nuclear fusion, and MIT's new result achieves over 2 atmospheres of pressure for the first time.

Alcator leader and senior research scientist Earl Marmar [presented] the results at the International Atomic Energy Agency Fusion Energy Conference in Kyoto, Japan, on October 17.

Nuclear fusion has the potential to produce nearly unlimited supplies of clean, safe, carbon-free energy. Fusion is the same process that powers the sun, and it can be realized in reactors that simulate the conditions of ultrahot miniature "stars" of plasma—superheated gas—that are contained within a magnetic field.

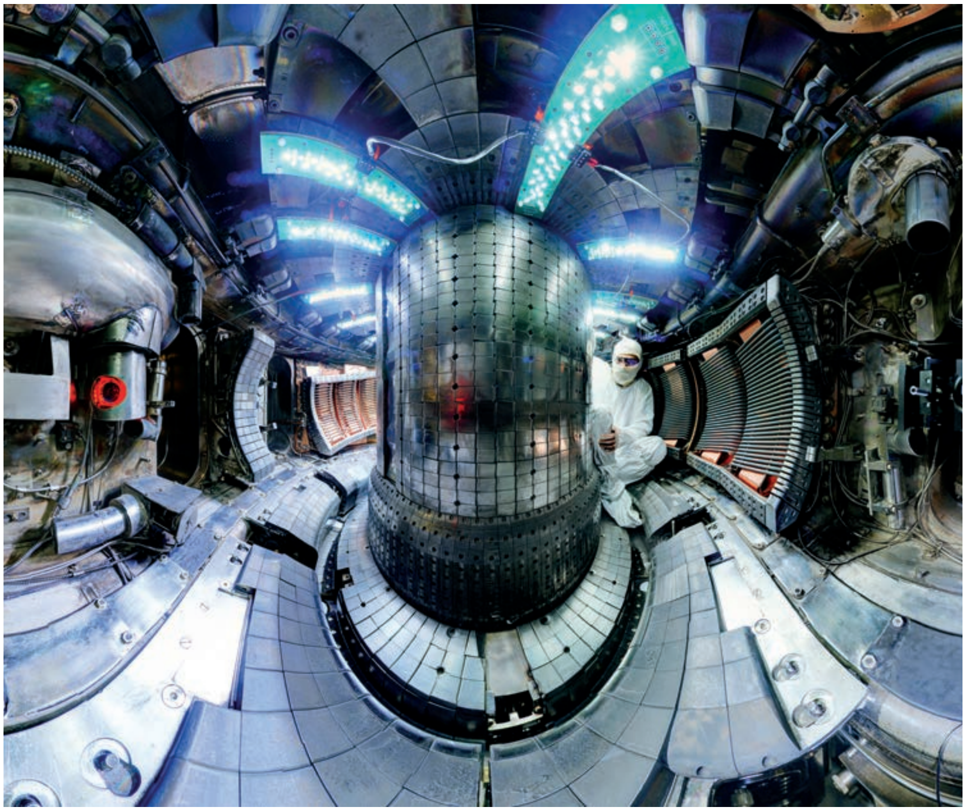

Photo: Bob Mumgaard/Plasma Science and Fusion Center

In September 2016, the interior of the fusion experiment Alcator C-Mod at MIT broke the plasma pressure record for a magnetic fusion device. The interior of the donut-shaped device confines plasma hotter than the interior of the sun using high magnetic fields. Postdoc Ted Golfinopoulos, shown here, is performing maintenance between plasma campaigns.

For over 50 years it has been known that to make fusion viable on the Earth's surface, the plasma must be very hot (more than 50 million degrees), it must be stable under intense pressure, and it must be contained in a fixed volume. Successful fusion also requires that the product of three factors—a plasma's particle density, its confinement time, and its temperature—reaches a certain value. Above this value (the so-called "triple product"), the energy released in a reactor exceeds the energy required to keep the reaction going.

Pressure, which is the product of density and temperature, accounts for about two-thirds of the challenge. The amount of power produced increases with the square of the pressure—so doubling the pressure leads to a fourfold increase in energy production.

During the 23 years Alcator C-Mod has been in operation at MIT, it has repeatedly advanced the record for plasma pressure in a magnetic confinement device. The previous record of 1.77 atmospheres was set in 2005 (also at Alcator C-Mod). While setting the new record of 2.05 atmospheres, a 15% improvement, the temperature inside Alcator C-Mod reached over 35 million degrees Celsius, or approximately twice as hot as the center of the sun. The plasma produced 300 trillion fusion reactions per second and had a central magnetic field strength of 5.7 tesla. It carried 1.4 million amps of electrical current and was heated with over 4 million watts of power. The reaction occurred in a volume of approximately 1 cubic meter (not much larger than a coat closet), and the plasma lasted for two full seconds.

Other fusion experiments conducted in reactors similar to Alcator have reached these temperatures, but at pressures closer to 1 atmosphere; MIT's results exceeded the next highest pressure achieved in non-Alcator devices by approximately 70%.

While Alcator C-Mod's contributions to the advancement of fusion energy have been significant, it is a science research facility. In 2012 the Department of Energy (DOE) decided to cease funding to Alcator due to budget pressures from the construction of the major international project ITER. Following that decision, the US Congress restored funding to Alcator C-Mod for a three-year period, which ended on September 30.

"This is a remarkable achievement that highlights the highly successful Alcator C-Mod program at MIT," says Dale Meade, former deputy director at the Princeton Plasma Physics Laboratory, who was not directly involved in the experiments. "The record plasma pressure validates the high-magnetic-field approach as an attractive path to practical fusion energy."

"This result confirms that the high pressures required for a burning plasma can be best achieved with high-magnetic-field tokamaks such as Alcator C-Mod," says Riccardo Betti, the Robert L. McCrory Professor of Mechanical Engineering and Physics and Astronomy at the University of Rochester.

Alcator C-Mod is the world's only compact, high-magnetic-field fusion reactor with advanced shaping in a design called a tokamak (a transliteration of a Russian word for "toroidal chamber"), which confines the super-heated plasma in a donut-shaped chamber. C-Mod's high-intensity magnetic field—up to 8 tesla, or 160,000 times the Earth's magnetic field—allows the device to create the dense, hot plasmas and keep them stable at more than 80 million degrees. Its magnetic field is more than double what is typically used in other designs, which quadruples its ability to contain the plasma pressure.

C-Mod is third in the line of high-magnetic-field tokamaks, first advocated by MIT physics professor Bruno Coppi, to be built and operated at MIT. Ron Parker, a professor of electrical engineering and computer science, led its design phase. Professor Ian Hutchinson of the Department of Nuclear Science and Engineering led its construction and the first 10 years of operation through 2003.

Unless a new device is announced and constructed, the pressure record just set in C-Mod will likely stand for the next 15 years. ITER, a tokamak currently under construction in France, will be approximately 800 times larger in volume than Alcator C-Mod, but it will operate at a lower magnetic field. ITER is expected to reach 2.6 atmospheres when in full operation by 2032, according to a recent DOE report.

Alcator C-Mod is also similar in size and cost to non-tokamak magnetic fusion options being pursued by private fusion companies, though it can achieve pressures 50 times higher. "Compact, high-field tokamaks provide another exciting opportunity for accelerating fusion energy development, so that it's available soon enough to make a difference to problems like climate change and the future of clean energy—goals I think we all share," says Dennis Whyte, the Hitachi America Professor of Engineering, director of the Plasma Science and Fusion Center, and head of the Department of Nuclear Science and Engineering at MIT.

These experiments were planned by the MIT team and collaborators from other laboratories in the United States—including the Princeton Plasma Physics Laboratory, the Oak Ridge National Laboratory, and General Atomics—and conducted on the Alcator C-Mod's last day of operation. The Alcator C-Mod facility, which officially closed after 23 years of operation on September 30, leaves a profound legacy of collaboration. The facility has contributed to more than 150 PhD theses and dozens of inter-institutional research projects.

To understand how Alcator C-Mod's design principles could be applied to power generation, MIT's fusion group is working on adapting newly available high-field, high-temperature superconductors that will be capable of producing magnetic fields of even greater strength without consuming electricity or generating heat. These superconductors are a central ingredient of a conceptual pilot plant called the Affordable Robust Compact (ARC) reactor, which could generate up to 250 million watts of electricity.

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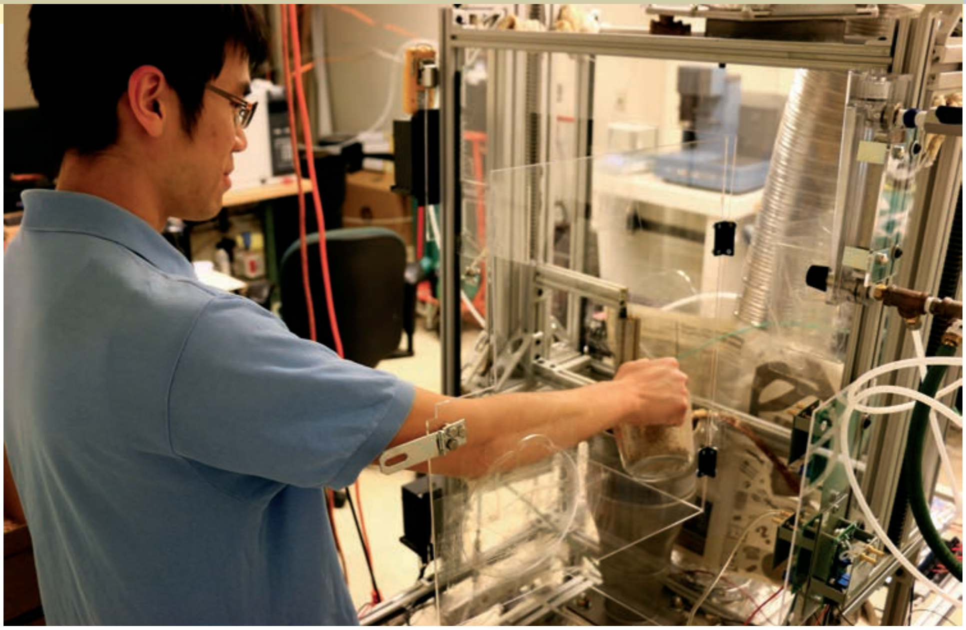
Courtesy of the MIT Plasma Science and Fusion Center

A version of this article first appeared on MIT News at bit.ly/mitfusionrecord. A related article can be found at bit.ly/mitfusionlegacy. Researchers at the Plasma Science and Fusion Center (www.psfc.mit.edu) are now playing key roles in developing and leading MITEI's new Low-Carbon Energy Center for Fusion Research.

Biomass torrefaction: Tapping the hidden value of farm waste



Photos: Ben Miller, MIT

Kevin Kung, a Tata Fellow and PhD candidate in biological engineering, feeds rice husks into the torrefaction reactor in his lab at MIT. A thermochemical process will convert the biomass to a more energy-dense form, making it easier to transport and use as fuel.

India has millions of small farms, many an acre or less in size, cultivating rice, wheat, sugarcane, and other staple crops. And twice a year, when the harvest is done, these farms go up in flames.

Satellite imagery of agricultural regions such as the Punjab show thousands of smoke plumes rising as farmers burn biomass waste in the form of husks, stalks, and other plant residue in order to clear the land for another crop cycle. This smoke affects air quality locally and carries as far as major cities like Delhi. In fact, the practice of burning biomass in the open is so widespread that it was found to account for about 18% of global carbon dioxide emissions in a 2014 Stanford study (bit.ly/stanfordbiomass).

There is untapped value in this waste—especially as a biofuel alternative to coal. Once, farmers would have plowed it under as a type of fertilizer, returning nutrients to the soil. But today in India, synthetic and low-cost fertilizers, often subsidized by the government, have replaced these traditional methods.

What if there were a way to reduce the environmental burden of open burning and create a new revenue source for farmers, who often live near or below the poverty line?

Ahmed Ghoniem, Ronald C. Crane (1972) Professor of Mechanical Engineering, and PhD student Kevin Kung of biological engineering, a Fellow in the MIT Tata Center for Technology and Design, are developing a technology that may help accomplish just that. Their project is a reactor that uses a process called torrefaction to densify biomass, making it transportable and increasing its shelf life. Torrefaction technology has been used at the industrial scale for more than a century, but it remains inaccessible to farmers in remote regions of the world. Ghoniem and Kung's research seeks to make it a practical solution that could facilitate a meaningful income boost for small-holder farmers.

Cooking biomass

If biomass has value, and farmers have biomass, why are they burning it instead of selling it? Ghoniem and Kung have keyed in on transportation as the missing link.

Existing large torrefaction reactors, Ghoniem says, "are not compatible with the distributed nature of biomass."

"Biomass is mostly available in rural, dispersed locations in small batches," Kung adds. "It's usually very bulky, loose, and wet. In remote areas, the waste is being burned because it doesn't make sense to haul it to a processing center."

If farmers could densify their biomass waste, this economic equation could change. Suddenly it might become an attractive proposition for biofuel producers to haul it away and add it to their energy feedstock. This cycle has the added benefit of helping meet the huge demand for affordable cooking and heating fuel in India and other developing countries.

That's where the torrefaction reactor comes in.

"Torrefaction is good for long-distance transportation," Kung says, "because for the same truckload you can carry a lot more units of energy, and people pay for the energy."

So how does torrefaction work? Kung says it's a thermochemical process a lot like cooking, and illustrates by explaining that he's a "forgetful" chef.

"I put some food in the oven, and by the time I remember half an hour later, my food is charred. What has happened is similar to torrefaction, but we do it in a much more controlled manner," he says.

In the torrefaction process, plant-based biomass containing carbon, hydrogen, and oxygen is heated to between 200°C and 300°C in an oxygen-free environment. This treatment causes it to rapidly decompose, releasing low-energy molecules first.

"The first thing to come out of the biomass is water, so you are drying the biomass," Kung says. "The next to come out is carbon dioxide, and then you start getting organic acids like ethanol and methanol. You end up with a solid fraction of biomass that's much higher in carbon content. You are essentially converting it to something more like coal, with a much higher energy density."

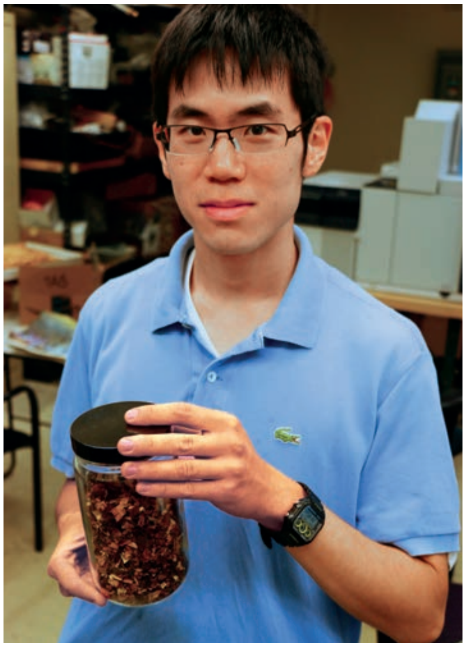
Another advantage of torrefaction is that it takes place in a closed, energy-efficient loop. The biomass releases combustible gases that are used to generate the required heat, making the process self-powering.

"Nothing blew up"

Ghoniem and Kung are wrapping up their lab-scale demonstration of the technology.

"We are working towards building an efficient small- to medium-sized reactor based on modeling the physics and chemistry of the process," Ghoniem says.

One of the main challenges has been moving from a batch process, in which one lot of biomass is torrefied at a time, to a continuous process, in which biomass is fed through continually



Here Tata Fellow Kevin Kung displays a jar of torrefied biomass—agricultural waste that has undergone thermochemical treatment in the torrefaction reactor to increase its energy density.

while conditions inside the reactor remain stable.

To be successful and economical on Indian farms, the reactor will have to be continuous, efficient, and mobile.

"Farmers have maybe one or two weeks after harvest before they feel compelled to burn the biomass and get ready for the next crop cycle," Kung says. "There's a short window in which this conversion has to take place. If it's going to work in a decentralized area, the unit has to be able to move from farm to farm, doing the conversion on site."

He says they are making progress toward the desired stability, avoiding calamitous failures so far: "We went from batch process to continuous process, and nothing blew up. In our first test it ran continuously for forty-five minutes. I'm pretty happy about that."

Kung is no stranger to implementing technologies in the field: He previously started a biochar company in Kenya. But his PhD research aims to contribute to the fundamental scientific understanding of torrefaction as well.

"I hope to demonstrate that this is a continuous process reactor and to identify the optimal conditions for maximizing energy efficiency in this process," he says.

Ultimately, they want to lay the scientific groundwork for deploying torrefaction in rural areas of developing countries. "We are starting with a lab-size system to optimize, and then we will scale it up," says Ghoniem.

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By Ben Miller, MIT Tata Center for Technology and Design

This research was supported by the MIT Tata Center for Technology and Design (tatacenter.mit.edu). More information can be found at bit.ly/tata-torrefaction.

Mapping coal's decline and renewables' rise

Even as coal-fired power plants across the United States are shutting down in response to new environmental regulations and policy mandates, defenders of the emissions-heavy fuel still have cost on their side. Coal, after all, is cheap—or so it seems. This perception makes it difficult for alternative, low-carbon energy sources like solar and wind to compete.

A new study from MIT researchers, however, shows that coal's economic edge may soon be far thinner than we think. In a working paper for the MIT Energy Initiative (MITEI), graduate students Joel Jean, David C. Borrelli, and Tony Wu show how replacing current coal-fired power plants with wind and solar photovoltaic generation facilities could provide benefits for the environment and for bottom lines in the near future.

The online tool they've created to help illustrate this argument is CoalMap (coalmap.com), a web application that compares the levelized cost of electricity (LCOE)—that is, the minimum electricity price a power plant must receive to break even on investment costs over its life cycle—of existing US coal-fired plants with the expected LCOE of potential new utility-scale solar and wind generation in the same locations. The tool draws on publicly available data sets from sources including the US Energy Information Administration and the National Renewable Energy Laboratory.

CoalMap presents users with a map of the continental United States showing the locations of current coal plants, with markers indicating each plant's nameplate capacity and relative cost. As users apply different carbon prices, deployment subsidies, and rates of cost decline for solar and wind, they can observe the effects of these changes on the cost-competitiveness of renewable energy across the country.

The results might be surprising to those arguing for coal's inherent cheapness. If levelized costs continue to decline as solar and wind technology improves, both will catch up to coal in terms of cost-competitiveness in the coming decades. The effect is even more staggering if a carbon price is

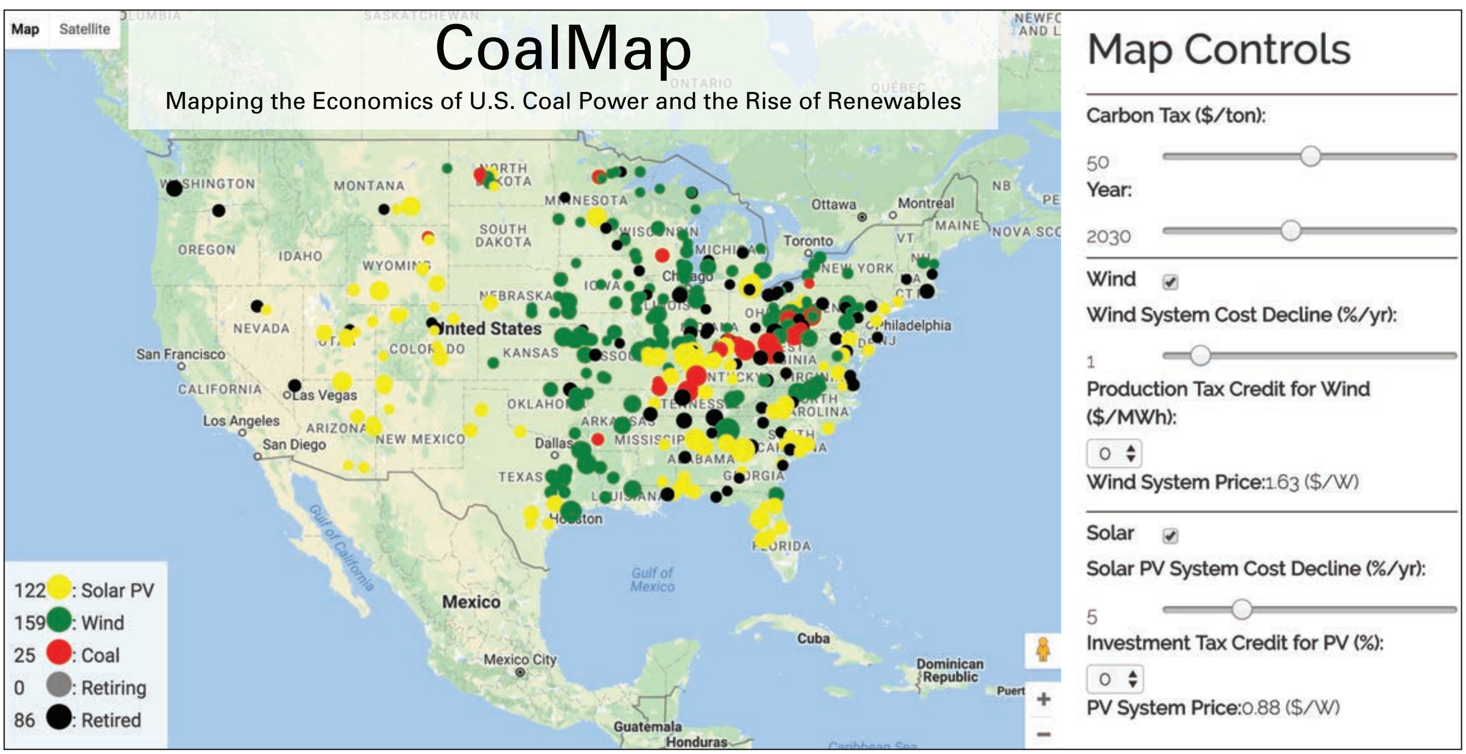

Image: Coalmap.com

CoalMap is an online tool that allows users to explore the potential effects of various market factors on the cost-competitiveness of coal versus renewable energy. Here, the variable being tested is a carbon price, set to $50 per ton CO_2-equivalent. The map shows whether coal plants (red dots), wind farms (green dots), or solar photovoltaic plants (yellow dots) are cheapest to operate at the location of each existing US coal plant at this price point. Gray dots represent coal plants that are scheduled to retire, and black dots represent those that have already been retired.

Photo courtesy of Joel Jean

The team that conceptualized CoalMap at the 2015 MIT Clean Earth Hackathon: (left to right) Joel Jean, Fanni Fan, Tony Wu, and David C. Borrelli.

implemented. Indeed, as the authors write, "Imposing a price on carbon would make new solar and wind facilities significantly more competitive with coal power, even without major cost reductions" due to technological improvement. In the event of both a carbon price and improvements in clean energy technology, the researchers say, nearly all aging coal-fired plants in the United States could be headed for retirement within the next two decades, displaced by cheap low-carbon energy generation, even without subsidies and in areas with poor solar and wind resources.

The idea for CoalMap was born at the 2015 MIT Clean Earth Hackathon, hosted by the Department of Civil and Environmental Engineering and the MIT Office of Sustainability. There, the team—made up of Wu and Jean, both of the Department of Electrical Engineering and Computer Science; Borrelli PhD '14, an alumnus of the Department of Chemical Engineering; and Fanni Fan, an MIT Sloan School of Management Master of Finance student—won in the energy category, rising to the Rocky Mountain Institute's challenge for hackathon participants to build a compelling map that could help regulators and policymakers take action against heavily polluting or uneconomic coal plants. "Everyone on our team was very interested in the scalability of renewable energy, especially solar, so we decided to take on the challenge," says Jean. According to Wu, the hackathon offered "a great opportunity to compare coal head-to-head with renewables."

The team subsequently met with researchers from the Rocky Mountain Institute and the Sierra Club to discuss potential avenues for using the map. The consensus, according to Jean: The map had potential as a climate change and energy outreach tool that "would be interesting to many people beyond MIT."

Jean and his fellow researchers hope to see CoalMap used by diverse groups—not just academics and activists, but stakeholders and policymakers as well. They want to put the information the map provides in the hands of the public, especially individuals well placed to bring about actionable change on issues of energy and climate.

With its straightforward user interface, CoalMap raises awareness about the environmental and economic costs of continuing to run legacy coal plants in the United States, while simultaneously underscoring the benefits of investing in clean energy generation.

"It's incredible to see how fast solar and wind costs have dropped and how soon they can become competitive with even the cheapest legacy coal if historical rates of cost decline are maintained," says Jean.

Jean emphasizes that CoalMap uses just one metric—LCOE in dollars per kilowatt-hour—and that coal plants can run continuously, independent of time of day, while wind and solar are intermittent generation sources, making direct comparison between the technologies difficult. Even so, Jean says, CoalMap can help people visualize a low-carbon future, instilling in them "intuition about the importance of continuing to innovate in solar and wind and setting a price on carbon."

Sponsors of the Clean Earth Hackathon (cleanearthhack.mit.edu) provided support that initiated the project. Francis O'Sullivan, director of research and analysis at MITEI, and John Parsons, senior lecturer at MIT Sloan and former executive director of the MIT Center for Energy and Environmental Policy Research, provided feedback on the team's working paper.

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By Francesca McCaffrey, MITEI

The MITEI working paper—*Mapping the Economics of U.S. Coal Power and the Rise of Renewables* (March 2016)—is available at bit.ly/coal-map.

New faculty strengthen, broaden MIT's energy expertise

Gabriela Schlau-Cohen: What photovoltaics can learn from photosynthesis

Photo: Justin Knight

Unlike human-made electric grids, the natural world's energy-harvesting systems never experience blackouts. Gabriela Schlau-Cohen, assistant professor of chemistry at MIT, is trying to learn from this natural talent for energy-making so she can change our energy systems for the better.

For Schlau-Cohen, this means starting with plants. Plants are the ultimate energy-users. The average global rate of photosynthesis is 130 terawatts—a level of energy capture more than six times worldwide energy consumption. "Leaves absorb light throughout the visible spectrum, and they basically funnel all of that energy to a dedicated protein where electricity is generated," Schlau-Cohen says. Plants' ability to convert sunlight into electricity is two- to three-fold higher than that of a typical solar photovoltaic (PV) system.

With this in mind, Schlau-Cohen and her colleagues set out to unlock plants' energy secrets. They began by studying the basic physics of plants, with the eventual goal of mimicking these natural characteristics in a man-made system. Through the MIT Center for Excitonics (www.rle.mit.edu/excitonics), Schlau-Cohen and her team are able to experiment with cutting-edge technology for bio-inspired artificial light-harvesting systems.

One of the most important takeaways from her study of plants isn't the discovery of a single plant structure or chemical that makes natural energy processing so efficient, Schlau-Cohen says. It's the economic choices represented by the operation of the system as a whole.

"I think that the big picture here is that nature has solved the intermittency problem," says Schlau-Cohen. One of the major challenges for renewable energy is that two of its key sources—wind and sunlight—are intermittent. That variability proves a challenge for those who are trying to develop technology for harvesting energy from those sources. Schlau-Cohen gives the example of building solar PV systems. "Build a system to handle just the maximum amount of sunlight, and it's going to sit idle for most of the time," says Schlau-Cohen. "But build it to work best at the lowest level of sunlight, and in high-sun situations much of the light is unused."

To deal with this challenge, the energy-harvesting pathways in plants are designed to strike a balance between being hardy enough to operate in full sunlight and finely tuned enough to make the most of low sunlight conditions. Increasing the amount of time the system can be active has economic advantages as well. Natural systems optimize by making sure their most energy-expensive machinery is always in use so that they can get the most out of it. "Through complicated feedback loops implemented in its molecular machinery, the system responds to changes in solar intensity," says Schlau-Cohen. This responsiveness addresses the intermittency problem, while also ensuring that the plant structures that take the most energy to develop are used to their full potential.

Based on their new understanding of plants' energy-harvesting pathways, Schlau-Cohen and her team are finding ways to control for different variables—creating biomass, for example, rather than protecting the system against too much sunlight. "If we rewire those pathways for optimizing biomass, we can get a fifteen percent increase in biomass, or even thirty percent under some conditions," she says.

As Schlau-Cohen tackles these issues at the forefront of energy knowledge, she finds a source of inspiration in her research community. When she made the decision to come to MIT, the students were a particular draw. "I think MIT students are the best of the best, not just in terms of their smarts, but in terms of their excitement about science," she says. "That was something I could not turn down, because I felt like they would make me the best scientist I could be." The students have not disappointed, providing both inspiration and fun—Schlau-Cohen's very own source of renewable energy.

Rafael Jaramillo: Making new materials to energize today's technologies

Photo: Claudio Cambon

Rafael Jaramillo studied physics as an undergrad and graduate student, but at MIT—first as a postdoc and now as an assistant professor—his work has taken him in a slightly different direction. He's now developing new materials and teaching materials science and engineering. During his career in engineering, one important lesson he's learned is how to see new pathways for scientific discoveries that transcend, and often connect, research fields.

"I try to find where the connections are between the scope of science, what you're capable of at a university, and what matters for energy applications such as solar photovoltaics," Jaramillo says. As a postdoc, he worked with Tonio Buonassisi, an MIT professor in mechanical engineering who is an expert in solar photovoltaics (PV). "I really appreciate the real-world education I got in Tonio's group," Jaramillo says. "It taught me how to be opportunistic—how to define projects where all of those factors come together, and you can find a way to help."

Though photovoltaics isn't Jaramillo's only focus now, he's carried this skill for finding opportunities for discovery throughout his studies and his early professorship. On the energy front, he now specializes in the study of semiconductors and their use as new materials for improved energy devices, from batteries and microelectronics to photovoltaic systems.

Jaramillo knows that his interest in semiconductors is something of a departure from his training in fundamental physics. "Physics has in a way moved on," he says. "It's been several decades since departments have really taught semiconductors." This well-studied class of materials, however, is seeing the dawn of a new era. In the low-carbon energy arena, scientists are constantly experimenting with new materials that will improve the economics and energy footprint of existing technologies, permitting critically needed increases in manufacturing along with cost reductions from economies of scale.

Different materials will address different scaling challenges in areas ranging from solar PV to computing to sustainable global development, but the fact that new materials are needed remains a constant, Jaramillo says. "We're butting up against the limitations of the tried and true materials. That's exciting because it means you get to dive in and think about new materials. And they're all semiconductors."

As Jaramillo works to develop new materials, he is also seeking new ways to inspire students to study one of the most classic (and deceptively basic) topics in science: thermodynamics, the subject of an introductory course he teaches to undergraduates.

"Thermodynamics is almost the core of materials science," he says. "It allows you to make predictions about how to process materials and get desired products." This importance, though, is sometimes lost in traditional ways of teaching the subject. "There are canonical examples, like the invention of steel and the invention of stainless steel, but I tend to focus more on microelectronics and semiconductors," he says. "You can find great canonical examples of thermodynamics in action from not just 60, 70, 80 years back, but in the last 10 years, 20 years, and today. I like to reach for those."

According to Jaramillo, it all comes down to being open to new ways of looking at the world, and the applied sciences are a critical part of that. "I think a lot of the great, deep insights have come out of applied research throughout history," he says. "Einstein came up with relativity by looking at train tables and asking very practical questions about how you synchronize train arrival and departure times across Europe. That sounds pretty boring in the wrong hands. So I think that use-inspired research and going in multiple directions from there is the most rewarding way to do science."

David Hsu: Planning cities for sustainable living

Photo: Katherine Shozawa

"Climate change, climate change, climate change." Assistant Professor David Hsu of urban studies and planning has no hesitation naming what he considers the most significant challenge facing urban planners today. Threats to cities range from sea level rise to extreme weather events. But for Hsu, the immediate challenge is to address climate change itself by finding ways to make cities and their inhabitants consume resources like energy and water more efficiently.

Tackling particular sectors can affect climate on a global scale. Hsu says, "If you take just US buildings as a single country, it would be the third-biggest carbon emitter on the planet after the rest of the US economy and China." Accordingly, a number of Hsu's current projects involve how to make built environments, both urban and rural, more sustainable. He's collaborating with fellow researchers at MIT and elsewhere on a wide range of projects including smart infrastructure embedded in physical systems, regulatory policies that promote renewables, and deployment of experimental microgrids in India.

One of the most effective ways to cut down on building energy use, though, is to target the behavior of those inhabiting the buildings. In order to understand humans' energy behavior and how to change it, researchers need data. One of Hsu's new projects involves integrating programs, policies, and technologies to enable the monitoring of energy flows between buildings and the grid. This setup would enable greater grid stability—a prospect that Hsu and his fellow researchers hope will attract the attention of today's utilities. That information would also enable researchers to map out energy distribution and consumption, which in turn would help them understand better how to shape that consumption to minimize carbon emissions and energy use, he says. Sometimes, one of the most direct ways to encourage people to consume less is simply to share such data with them. Once consumers see how they're using energy, they can make informed decisions about where they could make changes.

Hsu took a self-described "long, tortuous educational path," one that he laughingly tells students never to replicate. This path led from undergraduate and master's degrees in physics to a PhD in urban planning and design. His post-graduation jobs ranged from green building engineering to real estate finance, and eventually brought him to city government. His first job in city planning was in New York City working to rebuild Lower Manhattan after September 11. Since then, Hsu has worked in cities from Philadelphia to Seattle to London. This rich, varied experience with city living has led Hsu to his current focus on human interaction with infrastructure, as well as the challenges involved in adapting infrastructure to emerging climate constraints. Last spring he taught a course called Theories of Infrastructure, which compared alternative theories of how people interact with technological systems. Hsu enjoyed the students as much as the course content. "I had a diverse bunch of students who were really into the topic," he says. "They were curious, interested, and we had great debates."

Hsu's membership on MITEI's Energy Education Task Force demonstrates his commitment to training leaders in all aspects of energy. But he especially focuses on preparing the urban planners of tomorrow to grapple with humans' relationship with energy—a remarkably varied one, depending on where you live. "In many places, people have never had cheap, safe, and reliable electricity. One or two out of the three, maybe, but never all three," Hsu says. Providing all three while also encouraging people worldwide to build sustainable ways of life is—in Hsu's view—one of the great challenges facing city planners today.

Nuno Loureiro: In search of a more perfect fusion reactor


Photo: Susan Young

Nuno Loureiro, an assistant professor in nuclear science and engineering at MIT, is particularly attuned to the inner movement of complex systems. Much of his research on plasma theory and modeling concerns turbulence and magnetic reconnection, two phenomena that disrupt the operation of nuclear fusion reactors.

To Loureiro, MIT itself represents a fascinating system—one he's been exploring since he joined the faculty in January 2016. "It's great to be in an environment where the system will respond at the level you want," he says. "Sometimes it's hard to find an institution where there is a perfect resonance between what you want, the rhythm you want for your own research, and the institution itself. And MIT does this. MIT will basically respond to whatever you throw at it."

What drew Loureiro to plasma physics, he says, was energy. "If one is not naïve about today's world and today's society, one has to understand that there is an energy problem. And if you're a physicist, you have the tools to try and do something about it."

Fusion reactors, with their potential to provide continuous, greenhouse gas emissions–free energy, are one answer to the problem. A working fusion reactor gleans its energy from the organized movement of plasma, a hot ionized gas, along tracks formed by magnetic bands within the reactor, similar to the way the solar plasma on the surface of the sun moves along paths dictated by the sun's magnetic field. Loureiro, who specializes in plasma as it relates to both reactor physics and astrophysics, knows the details of this parallel well. Sometimes the magnetic field lines on the sun's surface rearrange themselves, and the resulting "violent phenomenon" of energy release is a solar flare, Loureiro says.

Something similar can take place within fusion reactors. A reactor's plasma occasionally will spontaneously reconfigure the prescribed magnetic field, inducing instabilities that may abruptly terminate the experiment. In addition, fusion reactor plasmas tend to be in a turbulent state. Both effects hinder the reactor's ability to operate.

Loureiro uses theoretical calculations and supercomputer modeling to try to figure out what causes those phenomena and what can be done to avoid them in future experiments. He says, "When someone proposes a new concept for a fusion reactor, or when one is planning new experiments on existing machines, one of the things you have to think about is, how will the plasma in it behave?" His simulations use several theoretical approaches to tackle such questions. He notes that his simulations are not meant to be prescriptive, which would require a high level of complexity and realism. "My approach is at a more fundamental level," he says. "I take very complex phenomena and try to understand them by reducing them to the simplest possible system that still captures the essential physics of those phenomena."

Loureiro looks forward to continuing to involve more students in his research. In his lab and in the classroom, he already works with both undergraduate and graduate physics students. He is currently teaching a numerical methods class for graduate students in nuclear science and engineering, and an undergraduate introductory seminar on plasma physics and fusion energy. "One of the things that has impressed me most about MIT is how talented the students are," Loureiro says. "People told me, 'Oh, the students are just amazing.' But I don't think I expected just how amazing they are."

He feels the same esteem for his fellow researchers. "It's inspirational to be on the same campus as people in completely different areas from mine who are world leaders in their fields," he says. "That's something that is unique to MIT and that I find incredibly motivating."

He's also inspired by the vibrant environment of the Plasma Science and Fusion Center (PSFC). "I feel that some of the most interesting ideas in fusion right now are being explored at the PSFC," he says. "It's great to be an active part of that excitement."

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By Francesca McCaffrey, MITEI

Energy Fellows, 2016–2017

The Society of Energy Fellows at MIT welcomed 28 new members in fall 2016. Twenty-five of the fellows are listed below. Three additional ExxonMobil-MIT Energy Fellows are now being named. The Energy Fellows network now totals more than 375 graduate students and postdoctoral fellows and spans 20 MIT departments and divisions and all five MIT schools. Fellows include incoming graduate students and graduate student researchers, teaching fellows, and postdoctoral associates. This year's fellowships are made possible through the generous support of eight MITEI member companies.

Photo: Kelley Travers, MITEI

Bosch

Eric Fadel
Materials Science and Engineering

BP

Christoph Tries
Institute for Data, Systems, and Society
Assignment in Joint Program on the Science and Policy of Global Change

Nathan Yee
Chemical Engineering

Chevron

Michela Geri
Mechanical Engineering

Eni

Francesca Freyria, PhD
Chemistry

Ryan Gillis
Chemical Engineering

Kehang Han
Chemical Engineering

Paul Rekemeyer
Materials Science and Engineering

Yi Song
Electrical Engineering and Computer Science

Constantin Voll
Chemistry

Sahag Voskian
Chemical Engineering

Zheng Wang
Aeronautics and Astronautics

Ella Wassweiler
Electrical Engineering and Computer Science

ExxonMobil

Josimar Alves da Silva Junior
Earth, Atmospheric and Planetary Science

Eugene Cho
Materials Science and Engineering

Daisy Hikari Green
Electrical Engineering and Computer Science

Adeel Jamal, PhD
Chemical Engineering

Brent Keller
Materials Science and Engineering

Alan Long
Chemical Engineering

Youngmin Yoon
Chemistry

Lockheed Martin

David Whyte
System Design and Management
Assignment in Civil and Environmental Engineering

Shell

Justin Chen, PhD
Civil and Environmental Engineering

Qing Liu
Chemistry

David Wang
Earth, Atmospheric and Planetary Science

Total

Rachel Chava Kurchin
Materials Science and Engineering
Assignment in Mechanical Engineering

Fellows as of November 7, 2016

Research assistants gain skills and advance knowledge at energy's cutting edge

MIT graduate students working in energy conduct widely varied research projects—from experiments in fundamental chemistry to surveys of human behavior—but they share the common benefit of gaining hands-on work experience while helping to move the needle toward a low-carbon future.

"You learn about a lot of wonderful things in theory, in reference books, but you never really get a feel for [research] unless you're actually involved in it," says Srinivas Subramanyam, a PhD candidate in materials science and engineering whose work as a research assistant (RA) focuses on developing a lubricant-impregnated surface that may one day keep oil and gas pipelines free of clogs. "Having a research assistantship has been a very good experience."

"I see this as a first step in a long-term research agenda that I hope to continue in my academic career," says J. Cressica Brazier, a PhD candidate in urban studies and planning who is developing a mobile carbon footprinting tool to gauge personal energy consumption. Brazier says this RA work has given her a variety of skills—from statistical modeling to team building—that will help her continue to research low-carbon urban development in the years ahead.

The academic track isn't the only option for well-trained RAs, however. Qing Liu, a PhD candidate in chemistry and a 2016–2017 Shell-MIT Energy Fellow, says he also feels qualified to work as a data scientist, energy analyst, or consultant. "I think the expertise I've gained from the research assistantship definitely helped broaden my career choices," says Liu, whose research centers on a catalytic process that converts airborne pollutants to fuels.

Photo: Justin Knight

Srinivas Subramanyam, a graduate student in materials science and engineering, uses an instrument called a contact angle goniometer to measure interactions at the interface between one of his novel coatings and various types of fluids. Such measurements are critical for characterizing the new coatings and for testing their potential performance in icing and fouling environments.

Research assistants are paid to conduct research under the supervision of a faculty advisor, and they often pursue novel investigations of their own design—in many cases leading to doctoral theses and other peer-reviewed publications at the cutting edge of their fields. For this reason, RAs play a crucial role in moving the world toward a low-carbon energy system, says Antje Danielson, director of education at the MIT Energy Initiative (MITEI).

"RAs are the worker bees of the research projects, and they are the people who produce the data and the prototypes that will then lead to discovery and innovation, so they're very valuable members of the energy innovation ecosystem. They are the future," says Danielson, noting that Brazier, Liu, and Subramanyam were all supported by MITEI funding. "Meanwhile, they learn lab skills, analytical skills, and if this is their thesis project, they really learn how to analyze a specific topic and write up their findings."

Making a difference

For Brazier, Liu, and Subramanyam—just three of the more than 2,500 graduate students who work as research assistants and research trainees at MIT—making progress toward a low-carbon energy system is a significant motivator.

"The only way I get motivated is if I know this is something that has the potential to make a difference. Abstract problems don't really drive me," Subramanyam says. Therefore, he focuses his research on addressing the range of problems caused by the deposition of materials on surfaces—for example, ice buildup on airplane wings, wind turbine blades, overhead powerlines, etc., and scale buildup in gas pipelines, geothermal power plants, water heaters, etc. "Having that end goal in mind—especially being aware that this is a product that's important to MITEI—that keeps me working on the problem."

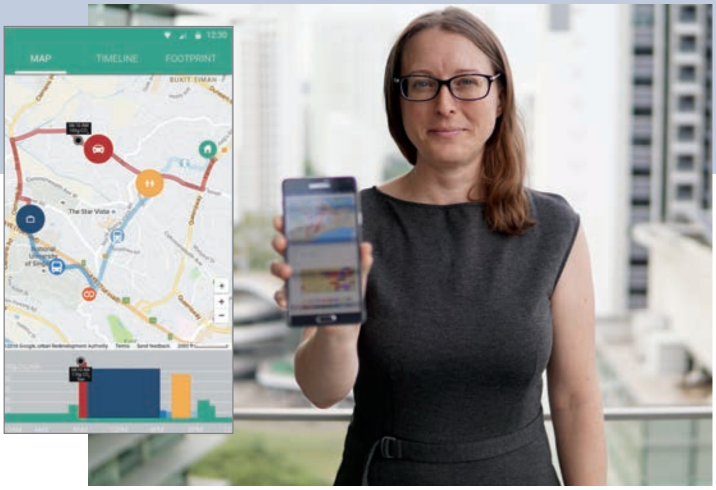

Photo: Daniel Palencia

Above: Graduate student J. Cressica Brazier of urban studies and planning displays a tool she's developing to provide users with feedback on their personal energy consumption and carbon emissions. Inset screenshot: The Mobile Carbon Footprinting application displays a day-by-day timeline of estimated emissions for each participant, derived from activity and travel data that the Future Mobility Sensing (FMS) platform collects. FMS is a smartphone-based activity logging system developed by the Singapore-MIT Alliance for Research and Technology.

Photo: Justin Knight

Graduate student Qing Liu of chemistry prepares for an experiment examining fundamental chemical reactions that occur on a crystal designed to catalyze fuel gasification in a Fischer-Tropsch system. Here he performs a routine check of the connection between the thermocouple leads and the sample crystal to ensure reliable readings of reaction temperatures during the tests.

During his research assistantship, Subramanyam succeeded in developing a surface treatment that significantly reduces scale buildup by combining two strategies—changing the morphology of the surface material and adding a coating. The resulting lubricant-impregnated surface promises to improve efficiency in the oil and gas industry by addressing productivity losses due to scale fouling, Subramanyam says.

Improving the efficiency of existing energy systems is also central to Liu's research, which examines the fundamental catalytic chemistry behind the production of natural gas and liquid fuels using greenhouse gases and airborne pollutants. Liu's work holds promise for the development of more efficient Fischer-Tropsch catalysts, a critical step in the attainment of carbon neutrality. "I definitely feel I'm helping to make the planet greener," Liu says.

Brazier takes a different approach to energy research: She explores how human behavior impacts the greenhouse gas emissions that are contributing to climate change. "We need tools to moderate or mitigate how people use the increasing convenience and comfort that comes with new technologies," Brazier says. She says she hopes the mobile application she is developing will provide individuals with feedback that will motivate greener lifestyle choices.

Gaining practical skills

Whatever specific research RAs focus on, along the way they learn to collaborate, communicate, and persuade others about the validity of their ideas. They also learn project management and how to think systematically about open-ended problems, says Kripa Varanasi, associate professor of mechanical engineering and Subramanyam's advisor. "They learn a lot of practicalities of how to work in the real world," he says.

"The scientific method, you first experience it once you start working in the lab yourself, confirming and rejecting potential solutions," Subramanyam says. "You are pushing the boundaries of knowledge, trying to do things no one has ever done."

Teamwork is critical, says Liu, noting that his research involves complex and specialized instrumentation that is very tough to operate alone. "There are two to three people on the same machine, working very closely with each other... so it's really important to us to have good teamwork," he says. "That's something I couldn't learn from class."

Working with diverse researchers—including faculty members, postdocs, and fellow RAs from a variety of disciplines—rounds out the RAs' educational experience, the students say. "In terms of really applying statistical tools, I learned more from one RA than I ever did from my sequence of quantitative methods courses," Brazier says.

Ultimately, the RA experience can be transformative. "They come out of undergrad exposed to many subjects, but they haven't really gotten their hands wet in a lab," Varanasi says, noting that within a few years he sees major changes. "They become professionals."

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By Kathryn M. O'Neill, MITEI correspondent

A piece of the action: Students find niche in low-carbon energy research

MIT undergraduates engaged in energy research during summer 2016 received a double benefit: They broadened and deepened their own academic experience, and at the same time they supported the Institute's five-year commitment to addressing climate change.

Announced just over a year ago, the MIT Plan for Action on Climate Change enhances the Institute's efforts in key areas of climate action, including accelerating research and development of low-carbon energy technologies and expanding related educational programs.

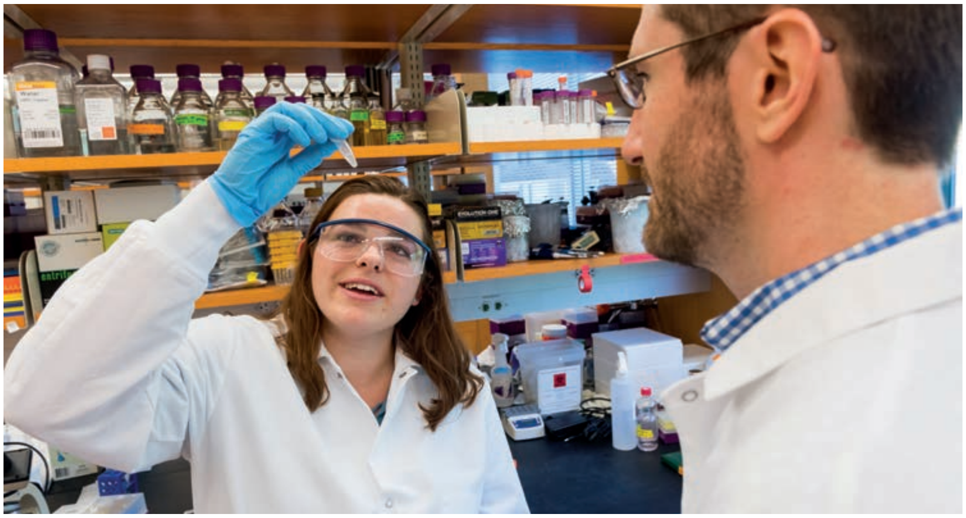
Many MIT students are eager for MIT to make ambitious strides in tackling climate change, notes Antje Danielson, director of education at the MIT Energy Initiative (MITEI). Participating in MIT's Undergraduate Research Opportunities Program (UROP) through MITEI provides a direct means for them to make a difference. By taking part in MIT research, students can "contribute to a huge change that needs to happen," says Danielson. "Even though students may be working on a small part of the puzzle, they can know that they are part of something much larger."

A green, high-octane alternative to gasoline

Among those students is Allison Shepard '19, a chemical engineering major who spent her summer developing a promising new biofuel. "The work we're doing now is really exciting, because when it becomes optimized, it could be used right away, not 50 years from now," she says.

Shepard's research took place in the lab of Kristala Jones Prather, associate professor of chemical engineering, who

Photos: Justin Knight



Allison Shepard '19 (left) and her supervisor, chemical engineering postdoc Jason Boock, examine a sample of an *E. coli* culture mixed with the substrate that will be converted to high-energy-density biofuel. The *E. coli* genes encode enzymes needed to set in motion the conversion pathway.

leads the project on metabolic engineering for biofuel production.

With support from MITEI Founding Member Shell, Shepard worked on tweaking enzymatic pathways to speed the conversion of glucose to 4-methyl-1-pentanol, a high-energy-density biofuel. "This fuel, because of its carbon chain branches, has an ideal use in engines now," says Shepard, who describes herself as "passionate" about finding energy solutions and sits on the executive board of the undergraduate MIT Energy Club. "We're trying to get to industrial standards so we can produce it at great enough levels and low enough cost to be competitive with conventional vehicle fuels."

Shepard found herself deeply immersed in synthetic biology, learning bacterial cloning techniques as well as high-performance liquid and gas chromatography. "I've learned so much here in only a few months, and I can already see so many ways to go with this work," she says.

An electric grid to go

A critical element of MIT's climate plan involves integrating low-carbon energy approaches into the curriculum. As part of this thrust, Juan De Jesus '17, majoring in electrical and electronics engineering, spent his summer with a team developing a portable, laboratory-scale model of a power plant for classroom use. The device has an on-board battery bank feeding a DC motor, which is controlled to mimic the dynamics of, for example, the rotor of a wind turbine and drives a generator that produces AC electricity. Several such devices and others representing loads and transmission lines will be connected together to resemble the structure of a mini power system that can demonstrate multiple modes of electricity generation and consumption.

"In some electrical engineering classes, there is a disconnect because they are very theoretical and lacking a hands-on approach," says De Jesus. With support from the S.D. Bechtel, Jr. Foundation,

Left to right: UROP students Daniel Vignon '17, Taylor V'Dovec '19, and Juan De Jesus '17, and MITEI postdoc Claudio Vergara adjust a torque and angular speed sensor, which is mounted on a shaft between electrical machines operated as a motor and a generator in their lab-scale model of a power system. The sensor will be used to estimate the electro-mechanical parameters of the machines.

he became part of a team that was led by James Kirtley, professor of electrical engineering, and included UROP students Daniel Abiola Vignon '17 and Taylor V'Dovec '19, both of mechanical engineering. "Our portable system will be the first of its kind, so students will have a physical setup they can experiment on that shows how a grid behaves when use shifts and when power comes from different sources," says De Jesus.

This research provided De Jesus with his first experience manipulating electric hardware, batteries, power conversion, and programming. "I've been craving just this kind of practical hands-on work," he says. De Jesus also learned to write software enabling the system to simulate inputs such as natural gas, wind, and hydroelectric turbines.

Readying this laboratory microgrid system for a multitude of classroom applications was a major challenge. "Juan, Daniel, and Taylor had to learn a lot of new concepts quickly," says Claudio Vergara, a MITEI postdoc supervising the summer research.

Vergara says he believes the new classroom tool will "provide students with hands-on research experiences that will complement their conceptual learning and prepare them to tackle the real-world challenges of integrating renewable energy technologies into future power systems."

Securing nuclear plants at sea

For his very first foray into research, Jared Conway '19, a nuclear science and engineering major, played a key role in an ongoing project in his department. Conway's task: defending an ocean-based nuclear power plant against a range of threats.

"By marrying the well-established floating structure of the oil and gas industry with a nuclear plant, we've created a new paradigm, which means developing new safety configurations," says Neil Todreas, professor emeritus of nuclear science and engineering, who leads security strategy development on the project and serves as Conway's direct supervisor.

"There are threats such as subsurface attacks that a land-based nuclear plant wouldn't have to worry about," says Conway, who used a commercial computer program that permits simulating different security scenarios. It's a "video game approach," he says, but with real-world stakes attached.

Conway found that biggest benefit of his summer UROP—which was supported by MITEI Affiliate Member John Hardwick '86, SM '88, PhD '92—involved building his communication skills.

Jared Conway '19 (left) and his advisor, Professor Neil Todreas of nuclear science and engineering, discuss possible solutions to the special security challenges facing floating nuclear power plants.

"I was in close touch with the security software company and worked with their chief scientist to figure out some challenging bugs in the program," he says. These are the types of skills Conway feels sure will come in handy as he applies to and prepares for a naval nuclear officer program this year or for a potential career assessing security and training employees in the nuclear power industry.

Expanding opportunities

Like many MIT students, MITEI is playing an active role in the Institute's climate plan. As detailed in the plan, MITEI is now establishing eight Low-Carbon Energy Centers to advance and deploy specific technologies needed to meet growing global energy needs in a carbon-constrained world (for more details, see page 2). With the establishment of the new centers, Danielson anticipates a wealth of research possibilities opening up to undergraduates. "We will be connecting our education programs to these centers, providing an amazing opportunity for students to be part of research that incubates and accelerates innovation," she says. "MIT is a great place for learning how to change the world."

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By Leda Zimmerman, MITEI correspondent

Students celebrate opening of MITEI Undergraduate Energy Commons

After more than a year of planning and construction, the new Undergraduate Energy Commons was unveiled on October 6, 2016, to an energetic crowd of MIT students, faculty, and staff. "We're really excited about this space as a way to provide convenient opportunities for undergraduates to get together—and to think together—about what you can do to change the world for the better," said MIT Energy Initiative (MITEI) Director Robert Armstrong as he welcomed the students who now have access to the Commons.

"We really needed a space where students can come together," said MITEI Education Director Antje Danielson, thanking the MIT community members who worked to make the Commons a reality. "Now, energy students across all majors and disciplines will be able to gather, host events, and pursue shared projects to build a sense of community among energy undergraduates."

After cutting the ceremonial ribbon to officially open the Commons, sophomore Rebecca Eisenach of materials science and engineering, vice president of the Undergraduate Energy Club, said she looks forward to holding meetings there. "It will be valuable to get all of the energy students together," she said.

"If we want to start a conversation about energy, then it can easily be started right here with people we feel are interested," added Emmanuel Havugimana, an MIT freshman who participated in the 2016 MITEI energy-focused Freshman Pre-Orientation Program (FPOP). Havugimana and fellow FPOP student Anthony Hernandez both said they look forward to using the space to reconnect with others from the program.

Photo: Chelsey Meyer, MITEI

MITEI Director Robert Armstrong (left) addresses the crowd gathered at the MITEI Undergraduate Energy Commons Open House.

Located underneath MIT's iconic dome in Room 10-063, the Energy Commons serves both to foster community and to fill an educational need. The space has three small study/meeting rooms with conference tables and audiovisual equipment; open space for group work, meetings, and presentations; a student lounge area; and a kitchen. It is reserved for undergraduate students in energy, including Energy Studies Minors, active members of the Undergraduate Energy Club, Energy FPOP participants, and students who have participated in the Energy Undergraduate Research Opportunities Program.

"Having a space like this, in this location, really signals to everyone on campus and off that energy is something that's important, even for undergraduates," said Sam Shames '14, who was instrumental in the planning and development of the Commons and has gone on to co-found EMBR Labs. "I think that's really exciting, and I think this is going to be a great catalyst to help the energy community to continue to grow."

Professor Amy Glasmeier of urban studies and planning, who co-chaired the Energy Education Task Force while the project was being developed, encouraged the students to take advantage of the space. "Dream up great ideas," she said. "Enjoy it, and we will see great things from it."

Funding for the renovation and furnishing of the Undergraduate Energy Commons was provided by a generous donation from the S.D. Bechtel, Jr. Foundation, which shares MITEI's vision to build opportunities for multidisciplinary, applied learning in energy education at MIT.

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By Kelley Travers, MITEI

Energy Studies Minor graduates, June 2016

Joshua Acosta
Mechanical Engineering

Mohammed Alsobay
Chemical Engineering

David D'Achiardi
Mechanical Engineering, Economics

Aaron Downward
Materials Science and Engineering

Olivia Massey
Civil and Environmental Engineering

Abigail Ostriker
Mathematics

Carolena Ruprecht
Nuclear Science and Engineering

Conrad Sanborn
Mechanical Engineering

Leah Schmitz
Chemical Engineering

Energy orientation introduces freshmen to low-carbon technologies on campus and in the region

In one of the last weeks before the official start of classes, 25 incoming MIT freshmen learned about their new undergraduate home—both on- and off-campus—in a preorientation program with a special focus on energy that ran from August 24–28, 2016. The MIT Energy Initiative (MITEI)-led program, called Discover Energy: Learn, Think, Apply (DELTA-FPOP), was designed as an interactive introduction to topics from wind energy to nuclear power and climate policy—with group bonding activities throughout the week.

Students began the program by exploring the MIT campus on a scavenger hunt to find campus landmarks and sustainable energy features such as solar-powered trash compactors. That afternoon, they built their own direct-current (DC) motors in an activity led by Steven Leeb, a professor of electrical engineering and computer science. "It's a small project," said freshman Melissa Meloche, "but it's the first time you get to do engineering." Meloche, who grew up with a nuclear power plant visible through the windows of her home in Germany, developed her interest in energy amid her country's debates about nuclear power. The DC motor lab was one of her first "hands-on opportunities."

The next day, the group learned about how wind turbine blades are tested to improve technology development from George Blagdon, a senior engineer at the Massachusetts Clean Energy Center's Wind Technology Testing Center in Charlestown. On a tour of the immense facility, students saw prototype turbine blades, learned about the technology used to test their integrity, and peered into the interior of an old blade outside the building.

The students lunched together in the town of Hull before learning about the wind energy project there from two of the people who helped make it a success: Community clean energy leader Andrew Stern took students inside the wind turbine to see the controls at the tower's base; and Panos Tokadjian, operations manager at Hull Wind, answered student questions about the technology and its impact on the town.

Another technology the students learned about was nuclear fission. They visited MIT's own nuclear research reactor, which is unique in the United States for involving students in the development and implementation of nuclear engineering experimental programs.

The preorientation program also included two energy policy exercises: an activity led by five MIT alumni that prompted students to consider emissions problems specific to Germany, and another led by Antje Danielson, MITEI education director, that made use of a simulator where students adjusted details such as carbon tax or land use to see how these small changes would impact carbon dioxide emissions overall.

These collaborative exercises encouraged the group to think about how they as MIT students can help solve the world's energy and climate challenges.

Students were enthusiastic about their energy preorientation experience. Eden Bensaid, a freshman from Israel, said, "The program felt really balanced between being with friends and learning new things."

For freshman Hamed Mounla, talking with faculty and fellow students during the program confirmed what had originally attracted him to MIT: "I was drawn to the people, and the vibe, and how excited everyone was about what they were doing."

MITEI academic coordinator Ann Greaney-Williams said, "We hope the preorientation program is just the first of many opportunities the class of 2020 will have to explore energy with us at MITEI, whether it's through our Energy Studies Minor, an undergraduate summer research project, or other involvement with our programs and events."

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By Chelsey Meyer, MITEI

Photo: Chelsey Meyer, MITEI

While participating in Professor Steven Leeb's direct-current motor lab activity, freshmen Dylan Lewis (left) and Jose Domingo Soto Rivera (center) compare rotors made using magnet wire with counselor Rebecca Eisenach '19 of materials science and engineering.

MIT to neutralize 17% of carbon emissions through purchase of solar energy

MIT, Boston Medical Center, and Post Office Square Redevelopment Corporation have formed an alliance to buy electricity from a large new solar power installation, adding carbon-free energy to the grid and demonstrating a partnership model for other organizations in climate-change mitigation efforts.

The agreement, announced October 19, 2016, will enable the construction of a roughly 650-acre, 60-megawatt solar farm on farmland in North Carolina. Called Summit Farms, the facility, the largest renewable-energy project ever built in the United States through an alliance of diverse buyers, is expected to be completed and to begin delivering power into the grid by the end of this year.

MIT's purchase of power from this facility's 255,000 solar panels is equivalent to 40% of the Institute's current electricity use; the purchase will neutralize 100% of electricity consumption for both Boston Medical Center (BMC), a 496-bed academic medical center in Boston's South End, and Post Office Square Redevelopment Corporation (POS), which manages an underground parking garage and a park in downtown Boston.

MIT has committed to buying 73% of the power generated by the new array, with BMC purchasing 26% and POS purchasing the remainder. MIT's purchase of 44 megawatts is among the largest publicly announced purchases of solar energy by any American college or university, and the largest among academic institutions in the eastern United States.

The partnership that enabled this project was managed by the Boston-based organization A Better City, of which MIT, BMC, and POS are all members; CustomerFirst Renewables designed, structured, and led the negotiation of the energy solution. The design, construction, and operation of Summit Farms will be handled by Dominion, a Virginia-based energy company, which will own the facility and assume responsibility for the project's full cost—with financing made possible by the guaranteed power purchase.

The project takes the form of a 25-year power purchase agreement (PPA) between the three Boston-area institutions and Dominion. In aggregate, the expected 146 gigawatt-hours of emissions-free power per year will result in the abatement of 119,500 metric tons of carbon dioxide emissions—the equivalent of removing 25,250 cars from the road.

"It is this integrative and collaborative approach that will enable us to reach our goals," says Israel Ruiz, MIT's executive vice president and treasurer. "It represents our collective commitment and is a small step to solving these immense challenges together."

The agreement to purchase energy from Summit Farms comes as MIT reaches the one-year anniversary of its Plan for Action on Climate Change. That plan included a pledge of a 32% reduction in the Institute's carbon emissions from 2014 levels, to be achieved by 2030.

"Today's agreement not only enables us to address a substantial portion of MIT's campus carbon emissions, but it also enables us to demonstrate the feasibility of large-scale renewable-energy projects to other potential purchasers, developers, and financiers," says Maria Zuber, MIT's vice president for research, who is leading implementation of the Plan for Action on Climate Change. "We believe our experience can help catalyze similar investments in clean energy, which will be vital to achieving a zero-carbon global energy system within this century."

Real-time performance data from the site will be made available to MIT researchers, along with access to some identical solar panels that will be

Photo courtesy of SunEnergy1

Summit Farms, an array of 255,000 solar panels, will occupy an area in North Carolina four times the size of MIT's campus and is projected to generate 146 gigawatt-hours of carbon-free power per year. This aerial view shows a similar solar farm in North Carolina, using the same type of solar panels, illustrating what the new project will look like when it is completed by the end of this year.

installed on the MIT campus to compare their performance under local conditions, says Julie Newman, director of MIT's Office of Sustainability.

While 41 potential renewable-energy projects were evaluated by MIT, BMC, and POS—some of which were much closer to the Boston area—this installation had a number of significant advantages: It uses a larger contiguous area than was available in the Northeast, and the local companies handling the design and installation of the solar panels have a proven track record of building and operating similar facilities, minimizing uncertainties about the facility's cost and output.

In addition, the existing power grid in North Carolina has significantly higher greenhouse-gas emissions: More of that region's energy comes from coal-fired plants than in New England. This means that more emissions will be displaced for a given amount of solar power than for a similar facility built in the Northeast.

Progress on MIT's climate action plan

The impact of this initial PPA on MIT's carbon footprint is equivalent to more than half (17%) of the total emissions reductions that MIT committed to in its Plan for Action on Climate Change, announced on October 21, 2015—a 32% reduction from 2014 levels, to be achieved by 2030.

In addition to the 17% reduction from this PPA, MIT is targeting an 8% to 12% reduction in emissions through planned improvements in building efficiency—such as through building retrofits and installation of better windows—and could achieve a further reduction of at least 1% through aggressive installation of solar panels on campus rooftops.

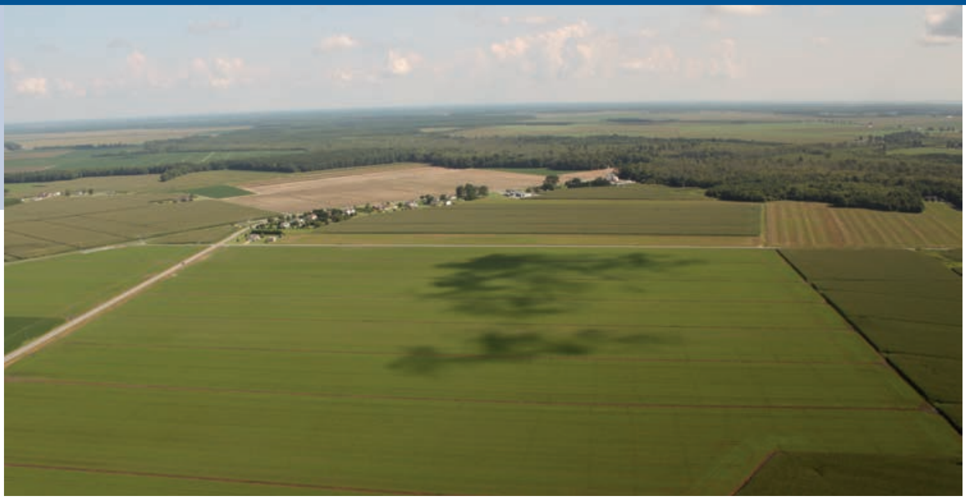

Photo: Joe Higgins, MIT

Summit Farms, a 650-acre parcel in Moyock Township, North Carolina, where the new solar installation will be built, is shown as it appeared before the beginning of construction.

In addition, the Institute plans to offset an expected 10% demand growth from new buildings through an efficiency upgrade of its existing cogeneration plant, which currently provides 50% of the Institute's power.

Together, even at the low end of these projections, these measures would yield roughly a 26% emissions reduction from 2014 emissions levels. Since last October, when the Plan for Action on Climate Change was announced, Zuber has emphasized that the 32% target is a minimum, and that MIT aims to achieve full carbon neutrality as rapidly as it feasibly can. A number of other climate-mitigation projects to help realize this goal, both on campus and beyond, are actively being studied.

"Our focus is on looking beyond the 32% goal," Newman says, "recognizing that that is an interim milestone, and this agreement greatly contributes to a portfolio of reduction strategies."

The on-site design and construction of Summit Farms will be handled by SunEnergy1 under contract to Dominion, and the power produced by the plant will be transmitted by PJM, the mid-Atlantic regional grid operator. Meanwhile, MIT, BMC, and POS will receive the benefits of a predictable fixed price for electricity and the environmental benefits of the emissions mitigation, in the form of Renewable Energy Certificates.

As the largest such project ever enabled by a group of buyers acting together, the agreement could set an example for other institutions and companies to follow, Newman says.

"This is a model where we're thinking of solutions that are beyond the scale of the capabilities of the individual partners, but that demonstrate positive global benefits," she says. "By banding together, the partnership enables the parties to join in on a large-scale project that they couldn't have done individually. Many thousands of organizations around the country that are too small to initiate their own power purchase agreements could potentially follow this cooperative model."

This agreement, as significant as it is, is just one step in the process, Newman says. "MIT is looking at all its opportunities for reduction of emissions, on campus and beyond," she says. "The progress toward that goal represented by this one contract, within one year, is remarkable."

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Excerpted from an article by David L. Chandler, MIT News Office

To read the complete article, go to bit.ly/mitsolar.

MIT, French colleagues renew research pact on multiscale materials

MIT President L. Rafael Reif joined a high-level delegation of French officials at MIT on September 9, 2016, to sign an agreement extending the research partnership behind MultiScale Material Science for Energy and Environment, or MSE2 (umi.mit.edu), an international joint unit or UMI (reflecting the French term "unité mixte internationale") that has produced groundbreaking research into such complex materials as concrete and shale rocks.

Photo: L. Barry Hetherington

Left to right: MIT Professor Franz-Josef Ulm, Aix-Marseille University President Yvon Berland, MIT President L. Rafael Reif, French National Center for Scientific Research (CNRS) President Alain Fuchs, and CNRS research director and MIT senior research scientist Roland Pellenq at a signing ceremony extending the partnership behind MultiScale Material Science for Energy and Environment (MSE2), which has produced groundbreaking research into such complex materials as concrete and shale rocks.

Reif signed the agreement with Alain Fuchs, president of the French National Center for Scientific Research (CNRS), and Yvon Berland, president of Aix-Marseille University, extending the collaboration for another seven years. The new pact also formalizes Aix-Marseille University's role as a full partner in the UMI.

"At MIT, our mission directs us to bring knowledge to bear on today's challenges to make the world better. That's a big aspiration. That obviously goes well beyond the capacity of one institution or one nation," Reif said. "We take courage from knowing we face these challenges together."

Valéry Freland, France's consul general in Boston, and Minh-Hà Pham, counselor for science and technology at the French embassy in Washington, were among the approximately 50 people who attended the ceremony in MIT's Samberg Conference Center.

"Congratulations on this French-American success story!" said France's minister of state for higher education and research, Thierry Mandon, who spoke at the ceremony. Noting that France is working to bolster its higher education and research institutions, he said, "This is a perfect example of what we want to support."

More than 50 scholars work at the MSE2 lab, which hosts French researchers at MIT for years at a time. Going forward, MIT faculty and students will also have the opportunity to conduct research at a parallel lab centered at Aix-Marseille University: Centre Interdisciplinaire de Nanoscience de Marseille.

"We are privileged to have really top students from France here, and we're grateful Marseille is opening its doors to our students. We're delighted," said Bernd Widdig, director for international activities at MIT's Office of the Provost.

MSE2 was founded with support from the MIT Energy Initiative in 2012 to explore "bottom up" simulation and experimental verification of the properties of complex multiscale materials. Since that time, the joint lab has produced groundbreaking work—particularly in characterizing cement, the key component of concrete, the production of which accounts for 10% of carbon dioxide emissions worldwide.

"Because of its ubiquitousness, [concrete] has an enormous environmental impact," said Professor Franz-Josef Ulm, the George Macomber Professor of Civil and Environmental Engineering at MIT, who leads the lab along with Roland Pellenq, CNRS research director and an MIT senior research scientist, who emceed the day's events.

Ulm offered guests a brief summary of key MSE2 research, highlighting the lab's recent discovery that cement has the structure of glass—a finding that will enable engineers to apply the field of glass physics to concrete science and potentially reduce the environmental footprint of the material.

"UMI is driving progress in important areas of materials research," Reif said.

Speaking after the event, Pellenq said, "The UMI is the concrete expression of the will of merging engineering and science into a unified field where engineering solutions can be designed on sound fundamental scientific results. This is particularly important for complex materials such as concrete and shale rocks for which the span of complexity in texture and phenomena starts at the nanoscale. Altogether, this is an ambitious goal that encompasses education too; the UMI contributes to the annual Marseille Winterschool and the annual research workshop of the international network known as the Groupement de Recherche International Multi-scale Materials Under the Nanoscope."

MIT's partner signatories also offered remarks at the ceremony. Fuchs of CNRS thanked MIT for its collaboration and noted that the partnership succeeds because it relies on excellence. "This is the way things should be made at the international level," he said.

Berland of Aix-Marseille University in turn highlighted the lab's interdisciplinary approach to multiscale research and noted that the UMI is successful because it integrates research with education and enlists resources from industry. "I am convinced that this project is an example to follow," he said.

Reif was similarly enthusiastic. "The UMI team has demonstrated a collaboration that is both strong and sustainable, and with today's signing we know it will be enduring as well," he said.

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By Kathryn M. O'Neill, MITEI correspondent

Related articles appeared in the Spring 2016 issue of *Energy Futures*. See "Designing climate-friendly concrete—from the nanoscale up" (bit.ly/concrete-nano) and "Porous materials workshop in France focuses on nuclear industry" (bit.ly/porous-materials).

Leading the global energy sector to address climate change

As the need to address climate change becomes more and more pressing, it is more critical than ever for women to have equal opportunities to participate in all aspects and at all levels of climate and energy research, policy, business, and other areas. Since 2010, the multi-governmental Clean Energy Ministerial (CEM) has recognized this imperative with the Clean Energy, Education, and Empowerment (C3E) women's initiative. In 2012, the CEM—along with the US Department of Energy (DOE) and the MIT Energy Initiative (MITEI)—launched the C3E Women in Clean Energy Symposium and Awards as an annual conference celebrating women energy professionals, from students to mid-career and senior leaders. This year, the conference highlighted ways in which women around the world are leading and changing the energy sector to sustainably meet global energy needs while substantially reducing greenhouse gas emissions.

Hosted on May 31, 2016, in Palo Alto, California, at Stanford University's Precourt Institute for Energy—which has joined MITEI and DOE as a partner in the US C3E initiative—and held in the same week as the US-hosted meeting of the CEM in San Francisco, the 2016 C3E symposium drew leaders from across the globe. The timing with the CEM meeting also offered synergies in speakers and themes.

Photo: MITEI Office of Communications

US Secretary of Energy Ernest Moniz (right) responds to questions following his keynote address at the C3E symposium. Moniz is former director of the MIT Energy Initiative (MITEI), and his energy counselor, C3E ambassador Melanie Kenderdine (left), is former executive director of MITEI.

"This year's C3E symposium presented a special opportunity to engage with the Clean Energy Ministerial, where our ambassadors, awardees, and other members of the C3E network helped shape the global dialogue on deploying clean, affordable, and plentiful energy sources that meet the world's needs while curbing climate change," said Martha Broad, executive director of MITEI, who is also one of C3E's US ambassadors.

This year, eight clean energy leaders received awards in specific categories, and Sarah Kurtz of the National Center for Photovoltaics and the National Renewable Energy Laboratory, a world-renowned solar photovoltaics expert, won the C3E lifetime achievement award (details at c3eawards.org/winners).

C3E ambassador Sally Benson, co-director of the Precourt Institute and director of Stanford's Global Climate and Energy Project, said, "The nine women honored today represent nearly every facet of clean energy, from policy and finance to technology and entrepreneurship. Their remarkable accomplishments are a clear sign that the gender gap is finally beginning to narrow for women in clean energy and other professions related to sustainability."

• • •

By Francesca McCaffrey, MITEI

To read the full article about the 2016 C3E symposium, go to bit.ly/C3E-2016.

MITEI Founding and Sustaining Members

MITEI's Founding and Sustaining Members support "flagship" energy research programs and projects at MIT to advance energy technologies to benefit their businesses and society. They also provide seed funding for early-stage innovative research projects and support named Energy Fellows at MIT. To date, members have made possible 151 seed grant projects across the campus as well as fellowships for more than 375 graduate students and postdoctoral fellows in 20 MIT departments and divisions.

MITEI FOUNDING MEMBERS

MITEI SUSTAINING MEMBERS

MITEI Associate Members

MITEI's Associate Members support a range of MIT research consortia, education programs, and outreach activities together with multiple stakeholders from industry, government, and academia. In general, these efforts focus on near-term policy issues, market design questions, and the impact of emerging technologies on the broader energy system. Specific programs include the Utility of the Future study, the MITEI Low-Carbon Energy Centers, the Associate Member Symposium Program, and the MITEI Seminar Series.

MITEI ASSOCIATE MEMBERS

Symposium Program and Seminar Series

Cummins
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Low-Carbon Energy Centers

Eni S.p.A.
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Eversource
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NEC Corporation
PSE&G
Siemens
Statoil

Observers

Paul and Matthew Mashikian

MITEI Affiliates

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

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Members as of November 1, 2016

MITEI member news

On August 30, 2016, the MIT Energy Initiative (MITEI) announced that GE has joined MITEI as a Sustaining Member to fund advanced technology solutions to help transform global energy systems. GE is committing a total of $7.5 million over a five-year period ($1.5 million annually) and will play an active role in MITEI's research and project priorities. Specifically, GE will participate in four of MITEI's Low-Carbon Energy Centers: solar energy; energy storage; electric power systems; and carbon capture, utilization, and storage.

"The world will need 50 percent more power in the next 20 years," said Steve Bolze, president and CEO of GE Power. "GE and MITEI are proud to be working together to find new solutions to develop cleaner, more affordable, and accessible energy solutions that will address this need."

ExxonMobil

On October 13, 2016, MITEI announced that ExxonMobil is expanding its support for MITEI's research and development of low-carbon technologies, building on the company's 2014 commitment as a Founding Member of MITEI to support faculty and student research. Specifically, ExxonMobil will join MITEI's Center for Carbon Capture, Utilization, and Storage, one of MITEI's eight Low-Carbon Energy Centers.

"Advancing economic and sustainable technologies to capture carbon dioxide is one component of ExxonMobil's research into lower-emissions solutions," said Vijay Swarup, vice president of research and development at ExxonMobil Research and Engineering Company. "This effort expands our continuing collaboration with MIT to advance the scientific fundamentals needed to deliver low-carbon energy solutions."

MIT Energy Initiative
Massachusetts Institute of Technology
77 Massachusetts Avenue, E19-307
Cambridge, MA 02139-4307

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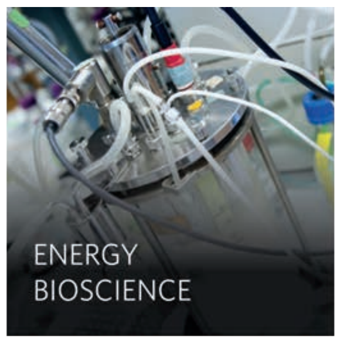
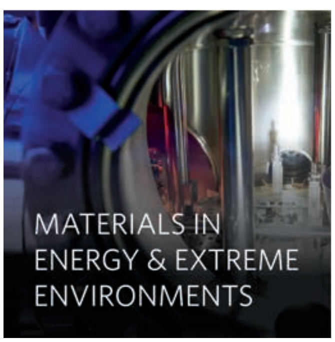
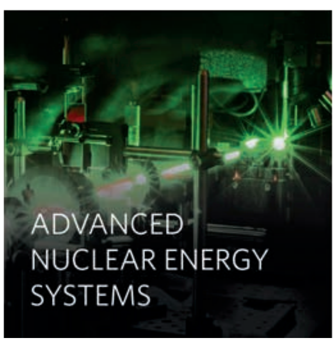
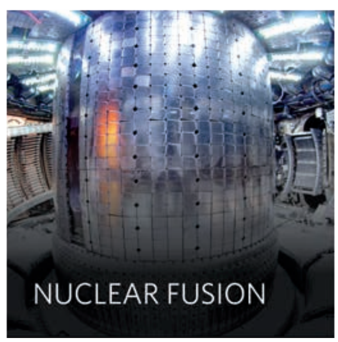
MITEI's Low-Carbon Energy Centers









Update on MITEI's Low-Carbon Energy Centers

Since the last issue of *Energy Futures*, the MIT Energy Initiative (MITEI) has made good progress on developing its eight Low-Carbon Energy Centers to advance technologies that are key to addressing climate change and expanding energy access to those who need it most. Announced in October 2015 as a core element of the Institute's Plan for Action on Climate Change, the centers are designed to facilitate interdisciplinary collaboration among MIT researchers, industry, and government in the specific energy technology areas displayed above.

Researchers from across MIT have been converging around these technology areas, and industry membership in the centers has been growing steadily. Turn to page 2 to find out what the co-directors of three of the eight centers view as key challenges and possible solutions in their research areas, and watch for low-carbon energy as a recurring theme throughout this issue.

Illustration: Jenn Schlick and Elizabeth Boxer, MITEI