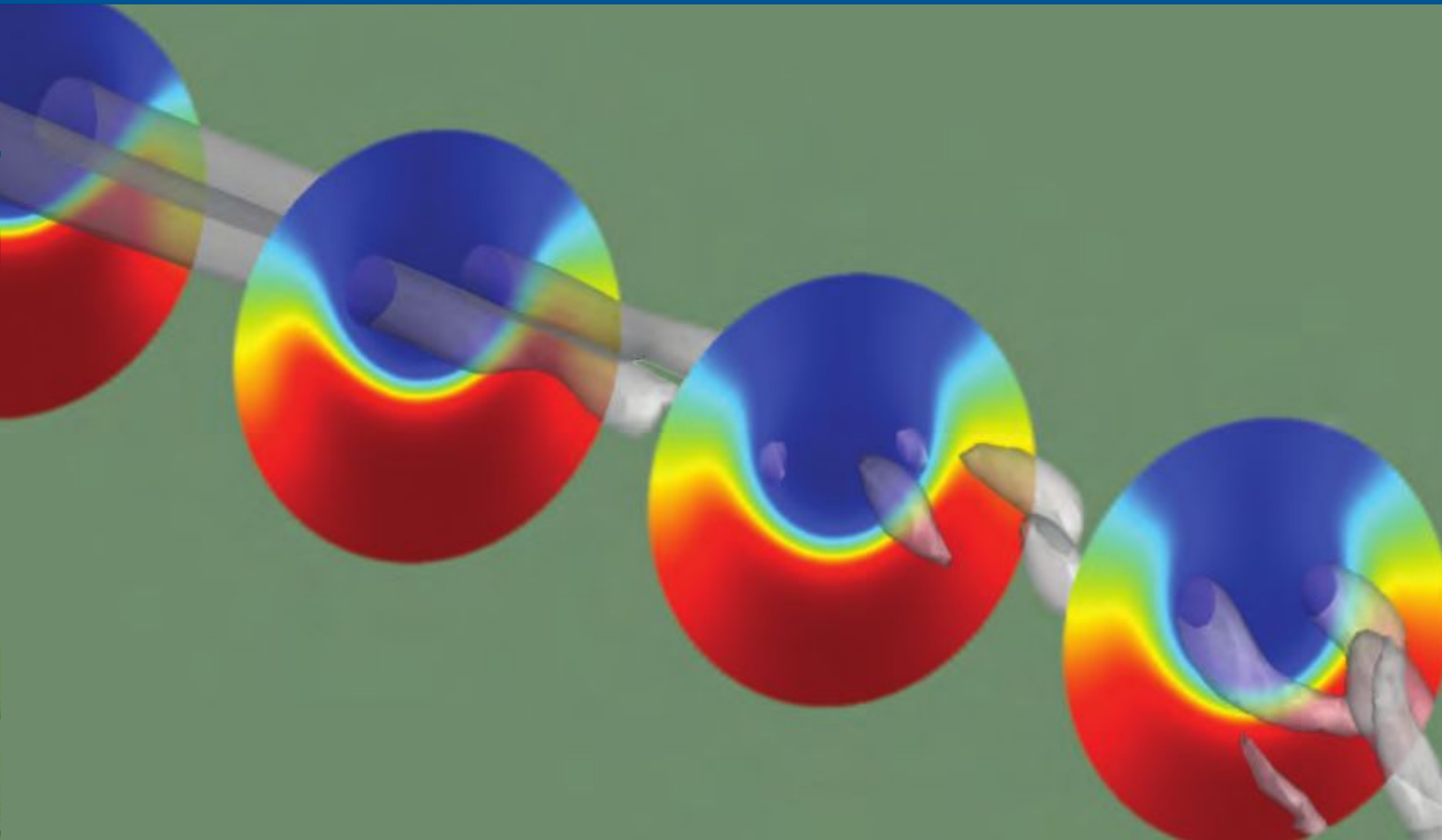


Energy Futures

MIT ENERGY INITIATIVE

MIT

SPRING 2015



Making clean, high-quality fuels from low-quality oil

IN THIS ISSUE



Ruben Juanes: Exploring subsurface energy, from academics to industry

Changing the game:
Building MIT's capacity for a sustainable future



Carbon emissions in China:
Can new policies curtail their growth?

Sustainable Energy class cultivates
critical thinking

Energy Futures

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MIT Energy Initiative

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A letter from the director

Dear Friends,

These are interesting and challenging times for energy. There are signs of emerging global action on climate change as we move toward the Paris meeting in December. In a joint announcement issued last November, China committed to capping CO₂ emissions growth by 2030, and the United States pledged to reduce greenhouse gas emissions 26–28% below 2005 levels by 2025. In addition, in late February, India committed to a major scale-up of both solar and wind power by 2022.

At the same time, existing businesses are being stressed. Oil prices are severely depressed relative to a year ago, in part due to industry success in bringing new technology to bear on producing shale oil. The electric utility industry is working hard to understand what business models will be like 10 or 15 years from now as distributed generation continues to grow, distributed storage begins to emerge, and the “internet of energy” provides new ways of increasing efficiency and reducing emissions. As we tackle such challenges, we find that the MITEI model of partnering closely with the energy industry and bringing together all of MIT’s schools is more valuable than ever.

I see the energy challenge before us as having two parts: By midcentury, we must meet a projected doubling in energy demand—the result of growing global population and increasing standards of living. At the same time, we must dramatically lower the carbon emissions of our energy systems to mitigate climate change.

How can we double energy output while slashing emissions? I believe that five key technologies can help—and MIT is working on all of them.

Solar is a vast resource for the world to utilize, and it will almost surely be critical to a sustainable future. We will have much more to say about solar in the next issue of *Energy Futures* when we report on “The Future of Solar Energy,” a comprehensive, multidisciplinary MIT assessment scheduled for release this spring after this issue goes to press (see mitei.mit.edu/futureofsolar).

Energy storage is of interest for uses ranging from consumer electronics and vehicles to residential and commercial equipment. But perhaps most important is large-scale energy storage, which is critical for the successful incorporation of solar and wind generation into the power grid—the subject of a recent MITEI symposium, which gathered experts to discuss promising grid-scale storage technologies and related issues of regulation and market design.

The **power grid** itself is clearly critical to our energy future. Research is needed to reimagine the architecture, size, reliability, security, adaptability, and resiliency of our current power system. Such issues are being addressed in our “Utility of the Future” study, an ongoing analysis that involves MIT researchers and a consortium of industrial and other stakeholders.

Nuclear fission is the only at-scale, zero-carbon energy-production technology we have ever used, but some countries are now limiting and even cutting back its use. It is hard to imagine a low-carbon future without nuclear, so we must address concerns about cost, public safety, security, and waste disposal. An article on page 9 of this issue reports on a novel MIT concept that tackles those concerns by floating a nuclear power plant at sea, where it is away from people, unaffected by



Photo: Webb Chappell

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

earthquakes and tsunamis, and surrounded by an abundant, passive source of cooling water.

Finally, we will need **carbon capture and sequestration (CCS)**. According to most projections, fossil fuels will continue to dominate the energy supply mix for the coming three or more decades. To protect the environment, therefore, we must capture the carbon released as those fuels are produced and used and sequester it deep underground. MIT researchers have been leaders in this critical area, developing new, low-cost capture systems, modeling processes that will trap injected CO₂ underground, analyzing public policy designed to incentivize CCS, and more.

Taking full advantage of these and other promising technologies will require collaboration not only among researchers across the MIT campus but also among experts and stakeholders worldwide.

To that end, in February, I traveled to New Delhi, India, on behalf of MITEI to speak about clean coal technologies and natural gas-derived fuels at the 5th World PetroCoal Congress. India is the world’s third largest emitter of CO₂; its main energy source is coal; and its population and economy are growing rapidly. Therefore, we cannot have a conversation about global energy solutions without India’s voice present.

Meanwhile, MIT researchers continue the long-standing tradition of working with collaborators around the world. Two projects involving international cooperation are described in this issue.

In one, teams led by faculty from architecture are working with a nonprofit in India to create energy-efficient, earthquake-resilient, low-cost housing for rural regions of that country (see page 27). The work takes place through MIT's Tata Center for Technology and Design, which tackles a variety of challenges faced by resource-constrained communities in India and elsewhere in the developing world (see tatacenter.mit.edu).

The second project involves collaboration between researchers at MIT and Tsinghua University in Beijing through the Tsinghua-MIT China Energy and Climate Project (see globalchange.mit.edu/CECP). China is now the largest emitter of CO₂ in the world, and its emissions continue to increase. In a project described on page 14, a CECP team has examined how new Chinese energy and climate policies can reverse the constant upward growth of those emissions—without a major impact on national economic growth.

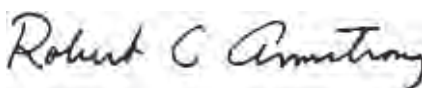
Two other articles in this issue focus on MIT projects that take novel approaches to ensuring the continued availability of clean-burning fossil fuels or of non-fossil replacement fuels. Researchers in mechanical and chemical engineering are working on a promising approach to converting heavy, sulfur-laden crude oil into clean, high-quality fuels including gasoline and diesel (page 19), and teams from MIT and the Whitehead Institute have demonstrated a simple but effective approach that could dramatically increase the productivity of yeast-based

systems for making valuable biofuels such as ethanol and butanol (page 4).

On campus, I'm pleased to report that we received a terrific response from faculty throughout the Institute to our call for proposals for undergraduate energy curriculum development, under a multi-year grant from the S.D. Bechtel, Jr. Foundation. MITEI is pleased to support the development of five new classes and the significant revision of four others, with work starting this summer (see page 34). The curriculum grants will build on the strength of the core domains of the Energy Studies Minor—energy science, technology, and social science—and will add important new content in the study of electrical grids from both technical and regulatory perspectives.

Finally, I was delighted to deliver the opening remarks at the 10th annual MIT Energy Conference in late February (page 43). Organized by the MIT Energy Club, this major event gathers the world's energy leaders to share their expertise, and it always adds to the overwhelming sense of enthusiasm and responsibility felt across the MIT campus to solve the world's energy challenges.

I hope you find this issue of *Energy Futures* informative and inspiring. MIT is special in the way it tackles society's grand challenges. I am deeply indebted to all of you—our industrial partners, donors, alumni, and friends—for your support in this enterprise.



Professor Robert C. Armstrong
MITEI Director

May 2015



Photo: Themistocles Resvanis, MIT

Over the past decade, MIT's Kim Vandiver, professor of mechanical and ocean engineering, and his collaborators have developed a leading modeling tool for predicting vortex-induced vibrations (VIV), which can damage long cylinders deployed in ocean currents. Now, two of MITEI's Sustaining Members—Lockheed Martin and Statoil—are jointly supporting new towing-tank experiments that will improve predictions of VIV response and fatigue in ocean risers and other equipment critical to deep-sea oil operations. Above: Vandiver (left) and Don Spencer, chief engineer at Oceanic Consulting Inc., prepare a heavily instrumented cylinder for tests in the National Research Council of Canada's towing tank in St. John's, Newfoundland.



Photo courtesy of IHS Energy CERAWEEK

Left to right: At this year's IHS Energy CERAWEEK, Daniel Yergin of IHS and Professor Robert Armstrong of MITEI led a special session at which MIT Professors Donald Sadoway, Sanjay Sarma, Kripa Varanasi, and Dennis Whyte shared their insights on game-changing technologies that will reshape the energy future. MITEI led a delegation including more than 80 MIT alumni to this preeminent international gathering of industry, policy, technology, and financial leaders. More at ceraweek.com/2015.



Boosting biofuel production

Supplements help yeast survive

Left to right: Gregory Stephanopoulos of chemical engineering, Gerald Fink of biology and the Whitehead Institute, and Felix Lam of chemical engineering are developing new insights and techniques that could one day dramatically increase the amount of ethanol, butanol, and other biofuels that yeast can produce from raw materials such as corn and sugar cane.

This research was supported in part by the MIT Energy Initiative Seed Fund Program. See page 8 for other sponsors and a publication resulting from this research.

Photo: Stuart Darsch

Chemical engineers and biologists at MIT have found a simple way to make yeast produce more ethanol from sugars: Spike the mixture they're growing on with two common chemicals. Adding potassium and an acidity-reducing compound helps the yeast tolerate higher concentrations of the ethanol they're making without dying. Aided by those "supplements," traditionally underperforming laboratory yeast made more ethanol than did industrial strains genetically evolved for ethanol tolerance. The supplements also enabled lab yeast to tolerate higher doses of high-energy alcohols such as butanol, a direct gasoline substitute. In other "firsts," the researchers described the mechanism by which alcohols poison yeast; they defined two genes that control ethanol tolerance; and they modified those genes in lab yeast to make them out-produce the industrial strains—even without the supplements.

Manufacturers worldwide rely on yeast to convert sugars from corn or sugar cane into ethanol, a biofuel now blended with gasoline in cars and trucks. But there's a problem: At certain concentrations, the ethanol kills the yeast that make it. As a result, a given batch of yeast can produce only so much ethanol.

"The biggest limitation on cost-effective biofuels production is the toxic effect of alcohols such as ethanol on yeast," says Gregory Stephanopoulos, the Willard Henry Dow Professor of Chemical Engineering. "Ethanol is a byproduct of their natural metabolic process, as carbon dioxide is a byproduct of ours. In both cases, high doses of those byproducts are lethal."

Five years ago, Stephanopoulos; Gerald Fink, MIT professor of biology and a member of the Whitehead Institute for Biomedical Research; and Felix Lam, postdoctoral associate in chemical engineering, began looking at this problem. How could they make yeast resistant to higher concentrations of ethanol?

Previous efforts involving genetic engineering had proved unsuccessful. "Ethanol tolerance is one of those traits that's sort of mysterious," says Lam. He offers the analogy of diabetes. "People know that it's not one gene that says you'll be susceptible to diabetes or not. It's a multitude of genes," he says. "Altering a single gene has not prevented diabetes—or made yeast more ethanol-tolerant."

Results from those earlier genetic engineering efforts did, however, give the researchers an idea. Certain yeast that were somewhat ethanol-tolerant showed high activity in genes related to phosphate utilization. So they tried

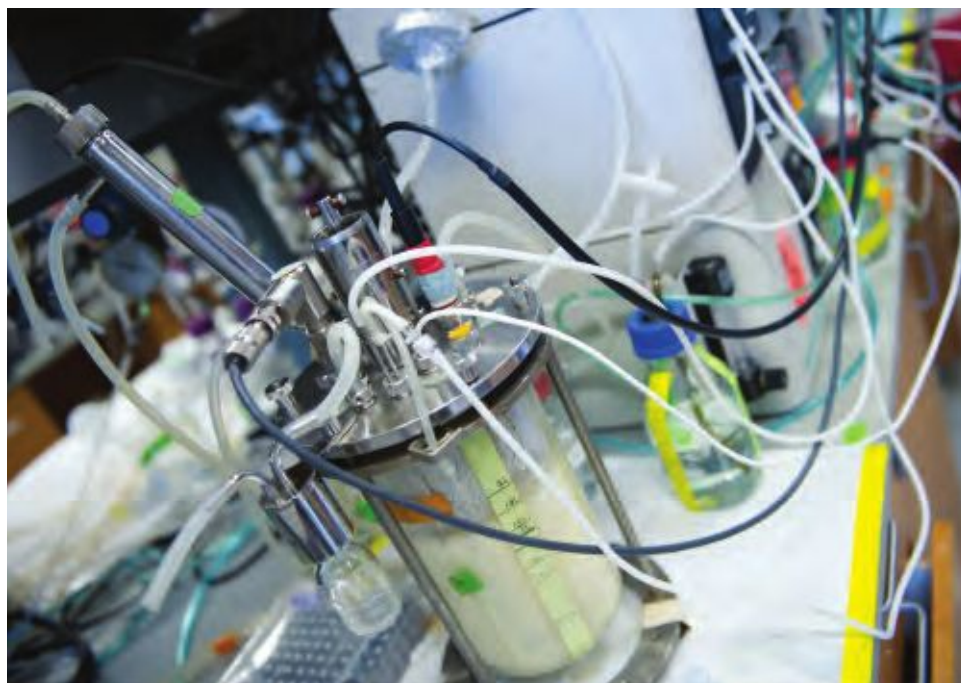


Photo: Stuart Darsch

To explore their novel concept, the researchers ran many parallel experiments in which they cultured laboratory yeast on defined glucose media, some with no supplements and others with supplements added, either singly or in various combinations. They then replicated the most promising combinations in this laboratory-scale bioreactor, a device that mimics the conditions inside industrial-scale fermenters.

growing yeast on the standard lab medium, but to some cultures they added potassium phosphate, a compound readily available in their lab. The jump in ethanol production was dramatic.

Figuring out why proved challenging. Initially, the researchers focused on the phosphate. After all, phosphate is an essential micronutrient for all living things; and Lam knew well the importance and workings of phosphate metabolism from previous research. But the boost in ethanol production persisted even when they used genetic methods to disable phosphate metabolism in the yeast. In contrast, when they replaced the potassium in the potassium phosphate with sodium, calcium, or ammonium, the positive impact essentially disappeared.

Both outcomes were surprising. Potassium, calcium, and ammonium are all critical to the nutrition and functioning of living cells, so what made the potassium special? And what about the phosphate? After much testing, they realized that the change wasn't due to metabolic processes—or any processes—occurring inside the cell. The impact of the potassium on ethanol tolerance occurred too quickly for cells to be mounting a biological response. And further testing showed that the role of the phosphate, a natural pH buffer, was simply to reduce the acidity of the mixture. "It had little to do with the biology inside the cell but rather more with the chemistry outside it," says Lam. Experiments confirmed their reinterpretation: Just adding potassium and reducing acidity—with no phosphate present—gave the same remarkable boost in ethanol production.

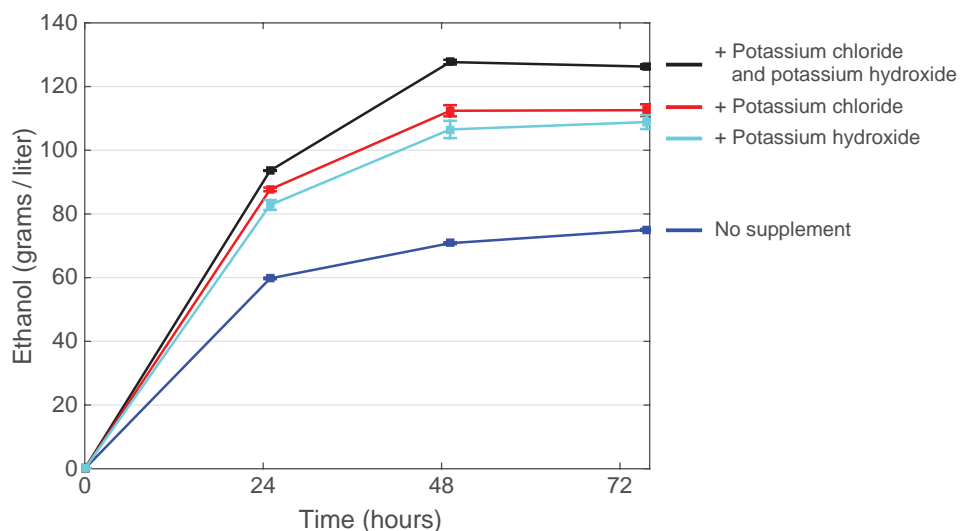
Effect of adding potassium chloride and potassium hydroxide on ethanol output

Experimental evidence

A series of experiments demonstrated the effectiveness of this approach. To retain commercial relevance, the researchers mimicked conditions typically seen inside industrial biofuel fermenters: They used a high density of yeast cells growing on a high concentration of glucose—the simple sugar extracted from corn or sugar cane. As their supplement, they used potassium chloride to add more potassium and potassium hydroxide to alter the acidity. And to challenge their method, they used an inbred laboratory strain of yeast known to be particularly sensitive to ethanol.

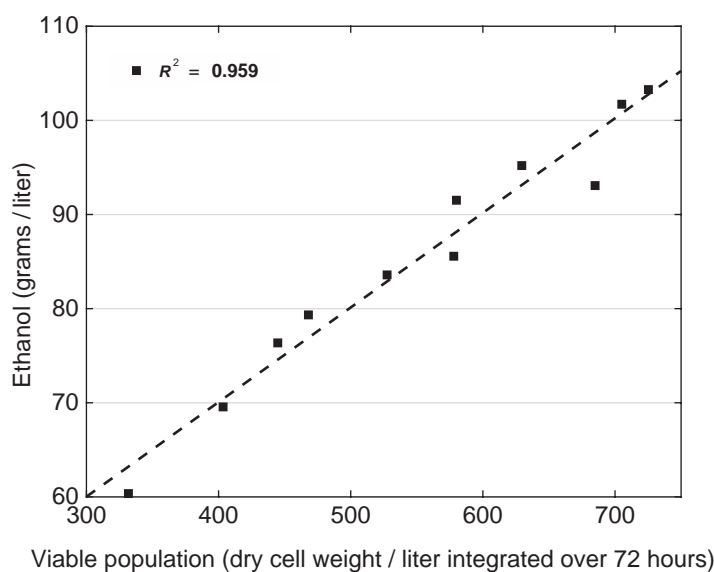
The curves in the top figure on this page show ethanol production from a single culture growing for 72 hours under four conditions: on the standard laboratory medium with no supplement (blue); with added potassium chloride (red); with added potassium hydroxide (light blue); and with both potassium chloride and potassium hydroxide (black). Each supplement pushed up ethanol output significantly, and adding the two together brought an increase of 80%. Moreover, in the latter case, the yeast consumed essentially all of the available glucose.

Further examination showed that the elevated potassium plus reduced acidity results in an increase in cell viability and thus in ethanol productivity. Indeed, raising potassium and reducing acidity gradually brings about increases in the viable cell population—changes that lead to corresponding increases in ethanol production, as shown in the bottom figure on this page. “So the ability to endure toxicity is a principle determinant of ethanol output—and it’s the primary trait strengthened by our supplements,” says Fink.



These curves show ethanol production from laboratory yeast growing on glucose for 72 hours. Adding either potassium chloride (to increase potassium) or potassium hydroxide (to reduce acidity) pushes up ethanol output significantly from the baseline with no supplements. Adding both chemicals together boosts ethanol output by 80%.

Relationship between viable yeast cell population and ethanol production



This diagram shows the amount of ethanol produced as a function of the viable population of yeast cells over the course of fermentation. The data show a direct correlation between total viable population and ethanol production. Different combinations of supplements enable yeast to resist ethanol longer, and the greater the viable population, the greater the ethanol output from a given culture.

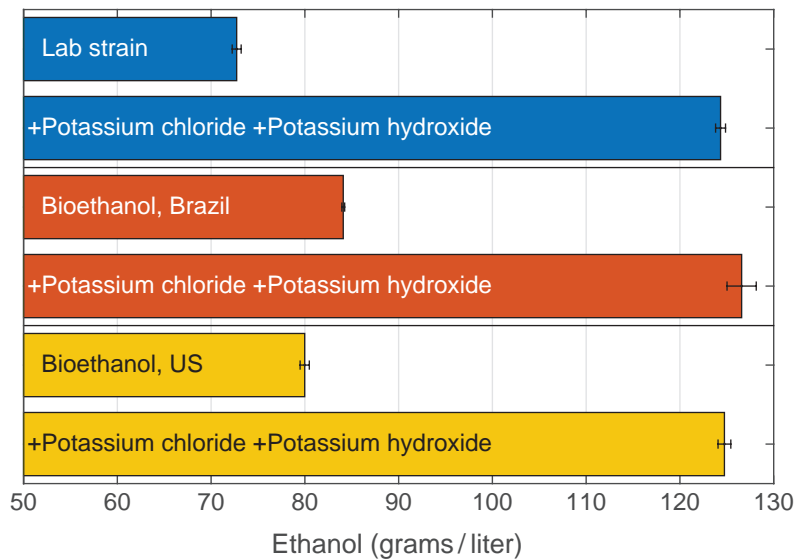
Impact of supplements on ethanol production from various yeast strains

The researchers note that adding the supplements slightly stimulates the growth of the initial batch of yeast so that there are actually more cells in the culture over the three days. But the largest boost—by far—comes from individual cells being able to withstand higher levels of ethanol. “The per-cell production rate hardly changes, but the cells stay alive much longer; and the longer they live, the more ethanol they make,” says Lam.

Other challenges

The tests described so far involve the ethanol-sensitive lab strain of yeast. But yeast strains used commercially are carefully selected for their genetic predisposition toward ethanol tolerance. So the researchers decided to see how the performance of their lab yeast compared with that of several commercial strains—and how adding the supplements would affect the productivity of the commercial strains.

The results are presented in the figure on this page. The top two bars show production from the basic lab strain, without and with the supplements. The next pairs of bars show results from cultures involving yeast strains used in bioethanol production in Brazil (middle pair) and the United States (bottom pair). Not surprisingly, the baseline ethanol production from those strains is higher than that from the basic lab strain. But production from the lab strain with the supplements is significantly greater than the baseline production from the two commercial strains. In addition, assisting the commercial strains with the supplements pushes their ethanol yields up to roughly the same level as yields from the lab strain with supplements. Thus, the combination of high potassium and reduced acidity in



This table shows ethanol production from standard lab yeast and from yeast strains used in bioethanol production in Brazil and in the United States. In cultures grown under unsupplemented conditions, the commercial strains produce more ethanol than the lab strain does. However, when assisted by the supplements, the lab strain produces far more ethanol than the commercial strains do. When all three receive the supplements, the ethanol yields are comparable. Thus, adding the supplements to the growth medium influences ethanol output more than do any genetic differences among these yeast strains.

the growth medium can “override” genetic differences between strains.

Encouraged by their results, the researchers decided to apply their methods to other issues encountered in biofuels production. For example, commercial yeast are good at fermenting glucose; but they cannot deal with xylose, an important constituent in cellulosic sources such as corn stover and switchgrass. When they grew a specially engineered lab strain on pure xylose and added the supplements, the ethanol yield jumped by more than 50%—a result consistent with the complete consumption of xylose.

Another challenge is to make fuels that are better suited than ethanol to today’s transportation needs. “Everyone knows that ethanol is ultimately a pretty lousy fuel,” says Lam. “Butanol, for example, has a higher energy content

per liter; and unlike ethanol, it can be used as a direct substitute for gasoline in today’s cars.” Such high-energy alcohols are even more toxic to yeast than ethanol is, but the researchers found that the boost in tolerance extended to such alcohols as well. Both the lab and industrial strains were able to withstand higher concentrations of butanol when aided by the supplements.

Explaining the mechanism

The researchers believe that their findings reveal the mechanism by which ethanol and other alcohols kill yeast at levels relevant to biofuel production. Critical to the survival of any living cell is an electric potential across its external membrane, which gives it the energy it needs to bring in nutrients and expel wastes. That potential is created by electrochemical

gradients, which are differences in concentrations of ions (electrically charged particles) inside and outside the cell.

A yeast cell maintains two primary gradients: Concentrations of potassium ions are high inside the cell and low outside; and concentrations of protons—the hydrogen ions that determine acidity—are low inside and high outside. Two “pumps” in the membrane move those materials in opposite directions: One pulls in potassium ions, and the other pushes out protons. Since both potassium ions and protons are positively charged, the gradients are coupled. The interior of the cell must be electrically neutral and remain that way; thus, when a potassium ion comes in, a proton goes out.

Based on their experimental evidence, the researchers propose the following “toxicity mechanism.” At concentrations achieved in biofuel production, alcohols do not dissolve the yeast’s cell membrane but rather make it porous. The small holes in the membrane allow potassium to leak out and protons to leak in, thereby dissipating the critical gradients. The potassium and proton pumps work hard to maintain the gradients; but as leakage increases, the pumps can’t keep up, the gradients collapse, and the cell dies.

Adding chemicals that increase the concentration of potassium ions and decrease the concentration of protons outside the cell helps the pumps do their job. Having more potassium ions outside the cell makes it easier to bring potassium in, and having fewer protons outside makes it easier to send protons out. Perhaps just as important, when the inside and outside concentrations are more in balance, fewer ions flow through any holes in the membrane. So

while adding the two supplements may actually reduce the gradients, the net result helps the cell to better maintain sufficient gradients for its own viability at higher alcohol concentrations.

If that toxicity mechanism is correct, then increasing the strength of the two pumps by genetic engineering should help. Indeed, using yeast with genetically augmented pumps but no added supplements pushed ethanol production up by 27%—not as high as the level reached with unaltered yeast plus the supplements, but still higher than the levels reached with the Brazil and US commercial strains.

Thus, their targeted genetic changes worked better than the “survival of the fittest” genetics that typify commercial strains. Moreover, the effectiveness of the genetic modifications alone—in the absence of the physical supplements—supports the researchers’ hypothesized toxicity mechanism and suggests that they have for the first time isolated genes responsible for ethanol tolerance in yeast.

Next steps

The researchers already have pushed up ethanol productivity from the levels reported here. In addition, they have promising initial results showing production increases from samples of mixed raw materials actually used in industrial fermentations. And they are looking more closely at the impacts of combining their two approaches—chemical supplementation and genetic modification.

The technical and economic effectiveness of the supplementation strategy will, of course, depend on its performance at large scale and in an industrial

setting. If larger-scale laboratory or pilot-plant tests take place and are successful, Lam notes that it should be relatively easy to implement the approach at existing bioethanol plants: Just increase potassium levels and control acidity inside the bioreactor. Given the already high performance of certain industrial yeast strains, making those changes could bring even more dramatic increases in the production of ethanol—and perhaps second-generation biofuels such as butanol—than have been demonstrated in the lab.

• • •

By Nancy W. Stauffer, MITEI

This research was supported by the MIT Energy Initiative Seed Fund Program, the US Department of Energy, and the National Institutes of Health. Further information can be found in:

F.H. Lam, A. Ghaderi, G.R. Fink, and G. Stephanopoulos. “Engineering alcohol tolerance in yeast.” *Science*, vol. 346, issue 6205, pp. 71–75, 3 October 2014.



A new look for nuclear power

Floating on the deep sea

Left to right: Michael Golay and Jacopo Buongiorno of nuclear science and engineering (NSE) and Neil Todreas of NSE and mechanical engineering are designing a floating nuclear plant that could provide enhanced safety, easier siting, and centralized construction—and could be deployed in time to play a critical role in a low-carbon energy future.

See page 13 for information on funding and publications.

Photo: Justin Knight

A novel nuclear power plant that will float eight or more miles out to sea promises to be safer, cheaper, and easier to deploy than today's land-based plants. In a concept developed by MIT researchers, the floating plant combines two well-established technologies—a nuclear reactor and a deep-sea oil platform. It is built and decommissioned in a shipyard, saving time and money at both ends of its life. Once deployed, it is situated in relatively deep water well away from coastal populations, linked to land only by an underwater power transmission line. At the specified depth, the seawater protects the plant from earthquakes and tsunamis and can serve as an infinite source of cooling water in case of emergency—no pumping needed. An analysis of potential markets has identified many sites worldwide with physical and economic conditions suitable for deployment of a floating plant.

The Offshore Floating Nuclear Plant

Many experts cite nuclear power as a critical component of a low-carbon energy future. Nuclear plants are steady, reliable sources of large amounts of power; they run on inexpensive and abundant fuel; and they emit no carbon dioxide (CO₂).

“More than 70 new nuclear reactors are now under construction, but that’s not nearly enough to make a strong dent in CO₂ emissions worldwide,” says Jacopo Buongiorno, professor of nuclear science and engineering (NSE). “So the question is, why aren’t we building more?”

He cites several challenges. First, while the fuel is cheap, building a nuclear plant is a long and expensive process often beset by delays and uncertainties. Second, siting any new power plant is difficult. Land near sources of cooling water is valuable as residential property, and local objection to construction may be strenuous. And third, the public in several important countries has lost confidence in nuclear power. Many people still clearly remember the 2011 accident at the Fukushima nuclear complex in Japan, when an earthquake created a tsunami that inundated the facility. Power to the cooling pumps was cut, fuel in the reactor cores melted, radiation leaked out, and more than 100,000 people were evacuated from the region.

In light of such concerns, Buongiorno and his team—Michael Golay, professor of NSE; Neil Todreas, the KEPCO Professor of Nuclear Science and Engineering and Mechanical Engineering; and their NSE and mechanical engineering students—have been investigating a novel idea: mounting a conventional nuclear reactor on a floating platform similar to those used



This illustration shows the researchers’ vision of the Offshore Floating Nuclear Plant. In this design, the structure is about 45 meters in diameter, and the plant will generate 300 MW of electricity. An alternative design for a 1,100 MW plant calls for a structure about 75 meters in diameter. In both cases, the structures include living quarters and helipads for transporting personnel—just as offshore oil drilling platforms do.

in offshore oil and gas drilling, and mooring it about 10 miles out to sea.

The Offshore Floating Nuclear Plant (OFNP) integrates two well-established technologies with already robust global supply chains. “There are shipyards that build large cylindrical platforms of the type we need and companies that build nuclear reactors of the type we need,” says Buongiorno. “So we’re just combining those two. In my opinion, that’s a big advantage.” By sticking with known technologies, the researchers are minimizing costly and time-consuming development tasks and licensing procedures. Yet they are making changes they think could revolutionize the nuclear option.

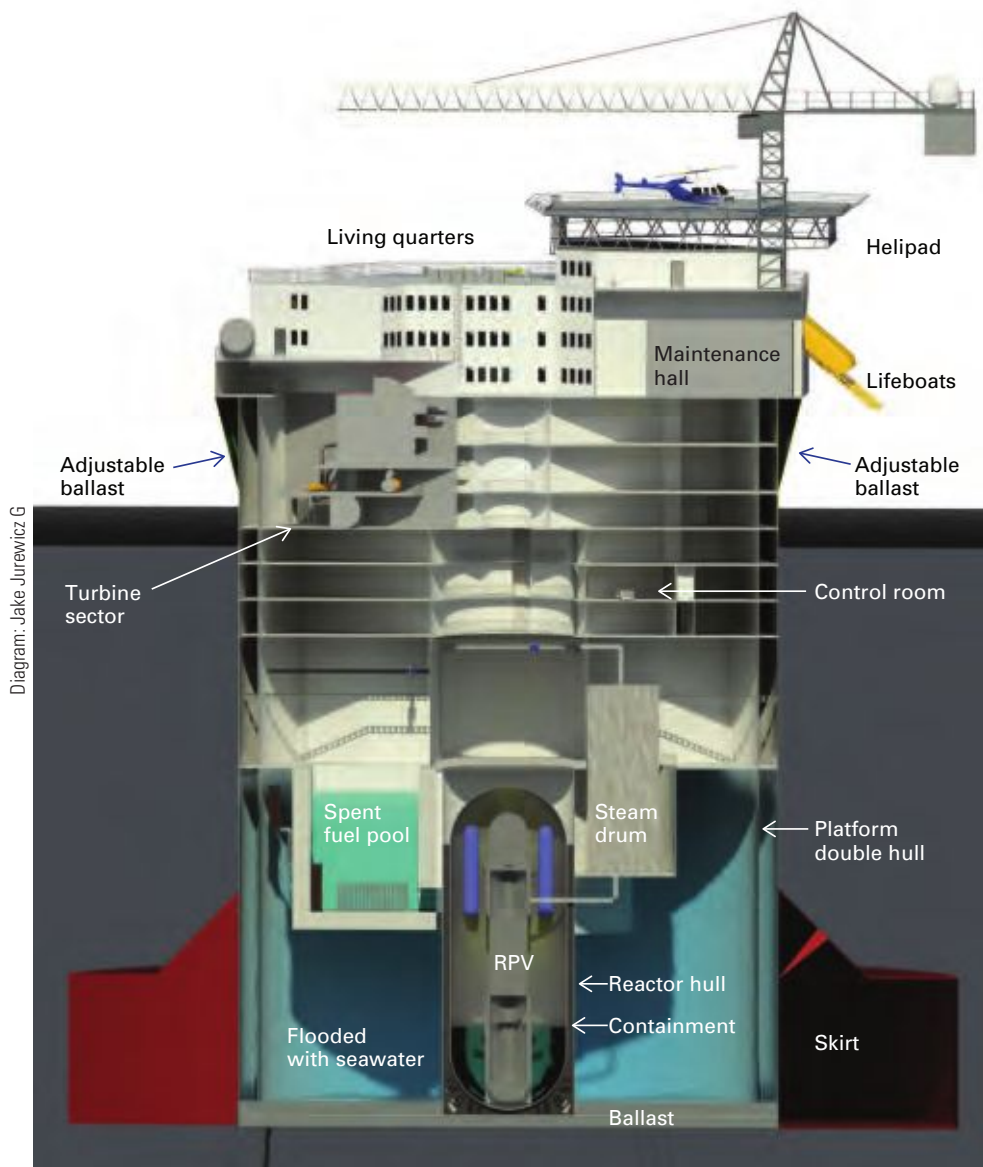
Advantages of shipyard construction, offshore siting

According to the researchers’ plan, OFNPs will be built entirely in shipyards, many of which already regularly deal with both oil and gas platforms and large nuclear-powered vessels. The OFNP structure (platform and all) will be built upright on movable skids, loaded onto a transportation ship, and carried

out to its site. There, it will be floated off the ship, moored to the seafloor, and connected to the onshore power grid by an underwater power transmission cable. At the end of its life, it will be towed back to the shipyard to be decommissioned—just as nuclear-powered submarines and aircraft carriers are now.

Compared to deploying terrestrial nuclear plants, this process should provide enhanced quality control, standardization, and efficiency. There’s no need to transport personnel, materials, and heavy equipment to a building site—or to clean up after the plant has been retired. The plan also reduces the need for site evaluation and preparation, which contribute uncertainty and delays. Finally, the OFNP is made mostly of steel, with virtually no need to deal with structural concrete, which—according to Buongiorno—is typically responsible for significant cost overruns and construction delays as well as the emission of substantial quantities of CO₂. Taken together, these factors mean that the OFNP can be deployed with unprecedented speed—an important benefit for a project that is highly capital-intensive. “You don’t want to

Details of the Offshore Floating Nuclear Plant design



This cutaway view shows key features of the OFNP. The nuclear reactor and related safety systems are located in watertight compartments deep in the structure. The reactor pressure vessel (RPV) is inside a containment structure, which is itself inside a dry compartment surrounded by seawater—a passive, continuous source of cooling when needed. Steam from steam generators immersed in the heated water inside the RPV passes to electricity-generating turbines located higher in the structure. Every 12 to 48 months, spent fuel assemblies are lifted up through the opening above the containment, and fresh fuel is inserted into the reactor. The removed assemblies are transferred to the spent fuel pool, which contains freshwater, is passively cooled by seawater, and has storage capacity to handle all the fuel removed from the plant over its lifetime.

have a large investment lingering out there for eight or ten years without starting to generate electricity,” says Buongiorno.

The planned site of the floating plant offers other benefits. The OFNP will be situated eight to 12 miles offshore—within the limit of territorial

waters—and in water at least 100 meters deep. Thus, it will be far from coastal populations (its only onshore presence will be a small switchyard and a staff and materials management facility), and the deep water beneath it will reduce threats from earthquakes and tsunamis: At that depth, the water absorbs any motion of the ocean floor

during earthquakes, and tsunami waves are small. Tsunamis become large and destructive only when they hit the shallow water at the coastline—a concern for nuclear plants built on the shore.

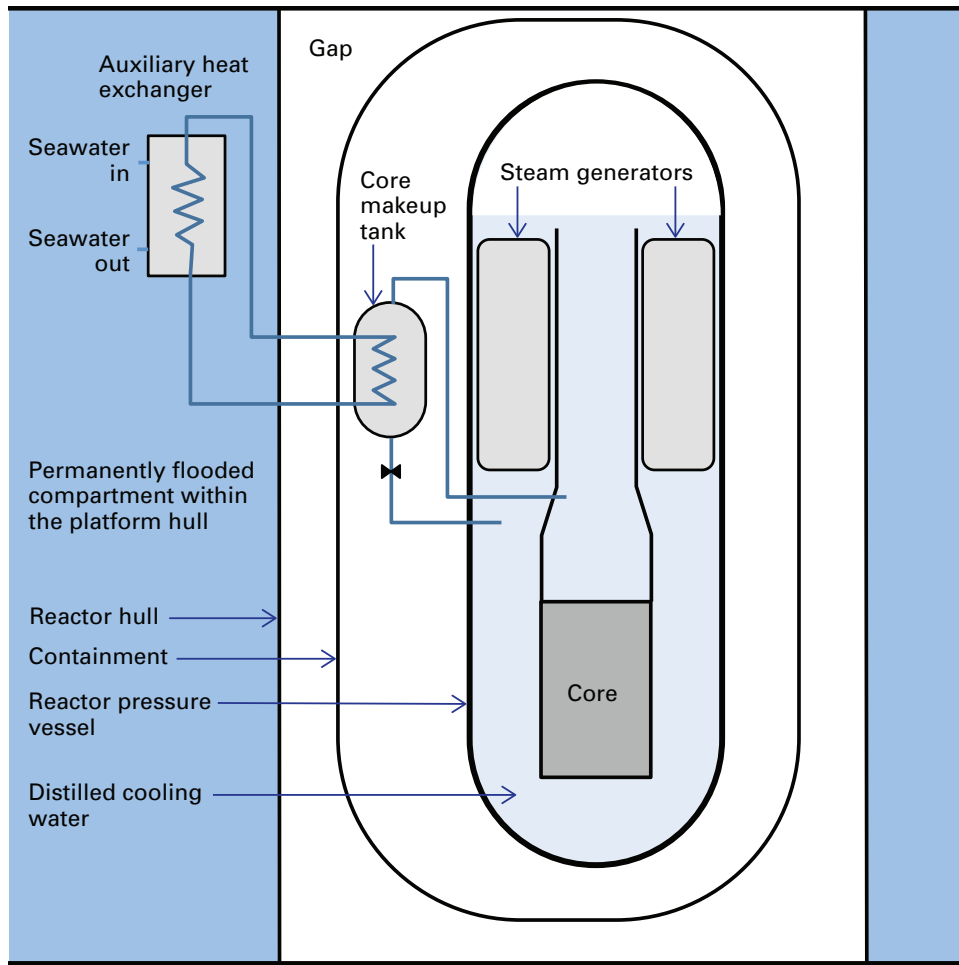
Finally, the open ocean will provide the OFNP with an endless supply of cooling water. If accident conditions arise, seawater can be used to remove heat from the reactor: Because the plant is well below the water line, the necessary flows will occur passively, without any pumping and without any seawater contamination. “We won’t lose the ultimate heat sink,” says Buongiorno. “The decay heat, which is generated by the nuclear fuel even after the reactor is shut down, can be removed indefinitely.”

The OFNP thus addresses the three main takeaways from Fukushima cited by Buongiorno: Stay away from dense populations, protect against earthquakes and tsunamis, and never lose cooling to the fuel.

Designed for efficient operation, enhanced safety

The illustration on page 10 presents a view of the OFNP in its ocean setting. The cutaway diagram on this page shows the plant’s key features. The overall structure is upright, cylindrical in shape, and divided into many floors, most of them split into compartments separated by watertight bulkheads. The upper levels house noncritical components such as the living quarters and a helipad. As on oil and gas platforms, workers are brought out by boat or helicopter for three- or four-week shifts. Food, fuel, and equipment and materials for minor maintenance activities are brought out by supply boat, and heavy loads are lifted off by crane.

OFNP decay heat removal system



This diagram shows the reactor core and steam generators immersed in fresh, distilled cooling water inside the reactor pressure vessel (RPV). If operation of the cooling pumps is interrupted, the cooling water can flow passively through an auxiliary heat exchanger immersed in seawater. If a more serious problem such as a pipe break occurs, the cooling water is released from inside the RPV into the containment structure, and seawater can be allowed to enter the normally empty space around the containment. Heat from the cooling water will pass through the containment wall to the seawater. The seawater flows naturally through the structure, so it is constantly renewed, providing an infinite source of cooling when necessary.

The nuclear reactor (either a 300 MW or a 1,100 MW unit) and its related safety systems are located in watertight compartments low in the structure to enhance security and safety, provide easy access to ocean water, and give the overall structure a low center of gravity for increased stability. The reactor core

and associated critical components are housed within a reactor pressure vessel (RPV), and the RPV is located inside a compact structure called the containment. Surrounding the containment—but separated by a gap—is a large chamber that extends to the edge of the cylindrical structure and is constantly

flooded with seawater, which enters and exits freely through ports.

Specific design features allow for response to various types of interruptions in normal cooling operations. Generally, pumps bring in cool water from the low ocean layers and discharge the used, heated water to the warm surface layers, thereby preventing “thermal pollution” that can threaten the local ecosystem. If that cooling process is temporarily disrupted, heated water from the reactor is allowed to circulate naturally to a special heat exchanger within the flooded chamber (see the figure at left). If a more serious problem (for example, a pipe break) threatens the core, distilled cooling water from inside the RPV is released into the containment (always keeping the core submerged), and seawater from the outside compartment fills the gap around the containment. Heat is efficiently transferred through the containment wall to the seawater, which is constantly and passively renewed. At all times, the cooling water and seawater are kept separate so that contaminants cannot flow from one to the other.

In the unlikely event that—despite continuous heat removal—pressure inside the containment builds up to dangerous levels, gases from within the containment can be vented into the ocean. However, the gases would first pass through filters to capture cesium, iodine, and other radioactive materials, minimizing their release. Current research is tracking the likely dispersion and dilution of such materials to ensure that any radioactivity in the water remains below acceptable limits even under such extreme circumstances.

Promising economics, abundant potential markets

The MIT team believes that the OFNP may be “a potential game changer” as far as the economics of nuclear power is concerned. It provides the economic advantage of “factory” production of multiple units, yet the units can be large enough to benefit from economies of scale. In addition, unlike any type of terrestrial plant, the OFNP is mobile. “If you build a power plant on land, it remains at the construction location for 40 or 50 years,” says Buongiorno. “But with the OFNP, if after a decade or two you need the generating capacity 100 miles farther up the coast, you can unmoor your floating power plant and move it to the new location.”

The viability of the researchers’ idea depends, of course, on whether there are locations with the necessary physical attributes—deep water relatively near shore but away from busy shipping lanes and frequent massive storms—as well as economic and other incentives for adopting the OFNP.

A detailed analysis identified many potential sites. For example, regions of East and Southeast Asia have limited indigenous resources, a high risk for both earthquakes and tsunamis, and coastal populations in need of power. Countries in the Middle East could use OFNPs to fulfill their domestic needs, freeing up their valuable oil and gas resources for selling. Some countries in coastal Africa and South America rely on power supplied by generators running on imported diesel fuel—an expensive and highly polluting way to go. “Bringing in an OFNP, mooring it close to the coast, and setting up a small distribution system would make a lot of sense—with minimal need for infrastructure development,” says Buongiorno.

Continuing research

The researchers are continuing to work on various aspects of the OFNP. For example, they are developing optimal methods of refueling, a detailed design of the mooring system, and a more thorough model of the plant’s hydrodynamic response in storm waves. In addition, they are establishing a cohesive OFNP protection plan. The plant design provides considerable security: The reactor is deep in the structure within multiple hulls; the high upper decks permit an unimpeded 360-degree view; and the physical layout minimizes approaches for attackers. Working with security experts, the researchers are now investigating additional strategies involving state-of-the-art sonar and radar systems, submarine netting and booms, and a team of armed security guards.

While much work remains, Buongiorno says, “We anticipate that the first OFNPs could be deployed in a decade and a half—in time to assist the massive growth in nuclear energy use required to combat climate change.”

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By Nancy W. Stauffer, MITEI

This research was supported by the MIT Research Support Committee. Further information can be found in:

J. Buongiorno, M. Golay, N. Todreas, A. Briccetti, J. Jurewicz, V. Kindfuller, D. Fadel, G. Srinivasan, R. Hannink, A. Crowle, and M. Corradini. “Offshore small modular reactor (OSMR): An innovative plant design for societally acceptable and economically attractive nuclear energy in a post-Fukushima, post-9/11 world.” *Proceedings of the ASME 2014 Small Modular Reactors Symposium*, Washington, DC, April 15–17, 2014.

J. Buongiorno, J. Jurewicz, M. Golay, and N. Todreas. “Light-water reactors on offshore floating platforms: Scalable and economic nuclear energy.” Paper 15366, *Proceedings of ICAPP ’15*, Nice, France, May 3–6, 2015.



Carbon emissions in China

Can new policies curtail their growth?

Valerie Karplus of the MIT Sloan School of Management (left) and Xiliang Zhang of Tsinghua University pose on the Tsinghua campus. In their joint research, they are using a novel model to investigate the impacts of Chinese energy and climate policies on the country's future energy use, carbon dioxide emissions, and economic activity.

This research is supported by a group of sponsors including Eni S.p.A. and Shell, both Founding Members of the MIT Energy Initiative. See page 18 for a complete list of sponsors plus a publication that resulted from this research.

Photo courtesy of the Tsinghua-MIT China Energy and Climate Project

Researchers from MIT and Tsinghua University in Beijing are collaborating to bring new insights into how China—now the world's largest emitter of carbon dioxide (CO₂)—can reverse the rising trajectory of its CO₂ emissions within two decades. They use a newly developed global energy-economic model that separately represents details of China's energy system, industrial activity, and trade flows. In a recent study, the team estimated the impact on future energy use, CO₂ emissions, and economic activity of new policies announced in China, including a price on carbon, taxes on fossil fuel resources, and nuclear and renewable energy deployment goals. The researchers conclude that by designing and implementing aggressive long-term measures now, Chinese policy makers will put the nation on a path to achieve recently pledged emissions reductions with relatively modest impacts on economic growth.

In November 2014, the presidents of the United States and China delivered a joint announcement committing their countries to new, aggressive measures to curb carbon emissions. Those pledges were seen as a breakthrough in global climate change negotiations. Until recently, binding commitments were in place only for a group of developed nations together responsible for about 15% of global carbon emissions. The new action involves a developed nation and a developing nation that together represent 45% of all emissions today. Moreover, it breaks a longstanding stalemate between the United States and China in which each has been waiting for the other to act first, and it sets the stage for other developing nations to declare their commitments to the global effort.

China's pledge represents an ambitious target for a rapidly growing country. The country pledged to turn around the constant growth in its CO₂ emissions by 2030 at the latest and to increase the fraction of its energy coming from zero-carbon sources to 20% by the same year—approximately double the share it has achieved so far. The commitment raises serious questions: Are those goals realistic, and if so, what new actions will be needed to accomplish them?

"To meet its new 2030 targets, China will need to take aggressive steps, including introducing a nationwide price on carbon emissions as well as preparing for the safe and efficient deployment of nuclear and renewable energy at large scale," says Valerie J. Karplus, assistant professor of global economics and management at the MIT Sloan School of Management and director of the Tsinghua-MIT China Energy and Climate Project

(CECP). "But with strong action, China's targets are credible and within reach."

Her assessment is based on studies that she and her CECP colleagues at MIT and Tsinghua University had been performing before the joint pledge was announced. The work was motivated by policy changes that were already occurring within China. In January 2013, an extreme episode of bad air quality and subsequent public outcry led to the adoption the following September of a new air pollution action plan. A few months later, Chinese policy makers at a major government summit pledged to tackle environmental problems by using new market-based instruments, including an emissions trading system that will put a price on CO₂ emissions as well as taxes on fossil fuel resources that will incentivize firms to conserve energy.

"So whether it was for reasons of bad air quality or greater concern about climate change or deeper interest in market reforms, the winds of change were blowing," says Karplus. "And we thought, 'Well, we need to model this!'" A theoretical analysis could produce insights into how such policies might affect China's energy system and carbon emissions, and it could shed light on the level of carbon tax that might be required to achieve a given emissions reduction—information that could help guide Chinese policy makers as they further define the details of their plans.

New model, new analyses

To perform their study, the MIT and Tsinghua collaborators used the China-in-Global Energy Model (C-GEM), which MIT researchers and Tsinghua graduate students developed while the Tsinghua students were visiting MIT

three years ago. "In our joint research we use a model that was built with methods largely contributed by MIT but with detailed data and insights largely provided by our Tsinghua colleagues," says Karplus.

Specifically, the researchers calibrated the model using domestic economic and energy data for China in both 2007 and 2010. And rather than combining all the energy-intensive industries into a single sector, they divided that group into six distinct sectors—both within China and within the 18 additional regions that represent the rest of the world in the model. That disaggregation is important for two reasons, says Karplus: Those six sectors differ in energy intensity and growth trends, and in China—unlike in many developed economies—they make up a significant share of economic activity and account for a large share of emissions. Finally, the researchers incorporated into the model changes in China's economic structure that may occur as per capita income increases over time. In particular, the main driver of economic growth gradually shifts away from investment (for example, in infrastructure development) and toward consumption.

In their analysis of China's policy initiatives, they assume two scenarios with differing levels of policy effort, plus one more scenario that assumes that no energy or climate policies are in place after 2010—an approach that is generally viewed as unsustainable but here serves as a baseline for comparison. The detailed assumptions for each scenario appear in the table on page 16.

The **Continued Effort (CE)** scenario assumes that China remains on the path of reducing CO₂ intensity (carbon emissions per dollar of GDP) by about 3% per year through 2050, consistent

Policy assumptions in each scenario

Measures	No Policy	Continued Effort	Accelerated Effort
Carbon price	No carbon price	Carbon price required to achieve ~3% per year reduction in carbon intensity	Carbon price rises to achieve ~4% per year reduction in carbon intensity
Fossil resource tax	No fossil resource tax	Crude oil/natural gas: price + 5% Coal: 4 CNY/ton (~US\$0.6/ton)	Crude oil/natural gas: price + 8% Coal: 10% of the price
Feed-in tariff (FIT) for wind, solar, and biomass electricity	No FIT	Surcharge on electricity prices to finance FIT	Surcharge on electricity prices to finance FIT; reduced scaling costs
Hydro resource development	Economic hydro resources are deployed with no policy constraint	Achieve current target of 350 GW in 2020 and increase to 400 GW by 2050	Same as the Continued Effort assumption
Nuclear power development policy	No targets or measures to promote nuclear energy development	Achieves the existing target of 58 GW in 2020 and increases to 350 GW by 2050	Same as the Continued Effort assumption in 2020 and increases to 450 GW by 2050

with an extension of commitments the country made at global climate talks in 2009. Importantly, the researchers find that a carbon price is needed to achieve such a reduction in carbon intensity; the needed improvements in energy efficiency and emissions do not result from normal equipment turnover and upgrading, as they have in the past. The CE scenario also assumes the extension of existing measures including resource taxes on crude oil, natural gas, and coal; a “feed-in tariff” that guarantees returns to renewable electricity generators; and increased deployment of hydroelectricity and of nuclear electricity (here assumed to be mandated by government).

The **Accelerated Effort (AE)** scenario is designed to achieve a more aggressive CO₂ reduction—4% per year—and includes a carbon price consistent with that target. It assumes the same feed-in tariff as under the CE scenario, but now the assumed cost of integrating intermittent renewables is lower.

It also assumes higher resource taxes on fossil fuels and greater deployment of nuclear electricity beyond 2020.

Impact on energy demand and emissions

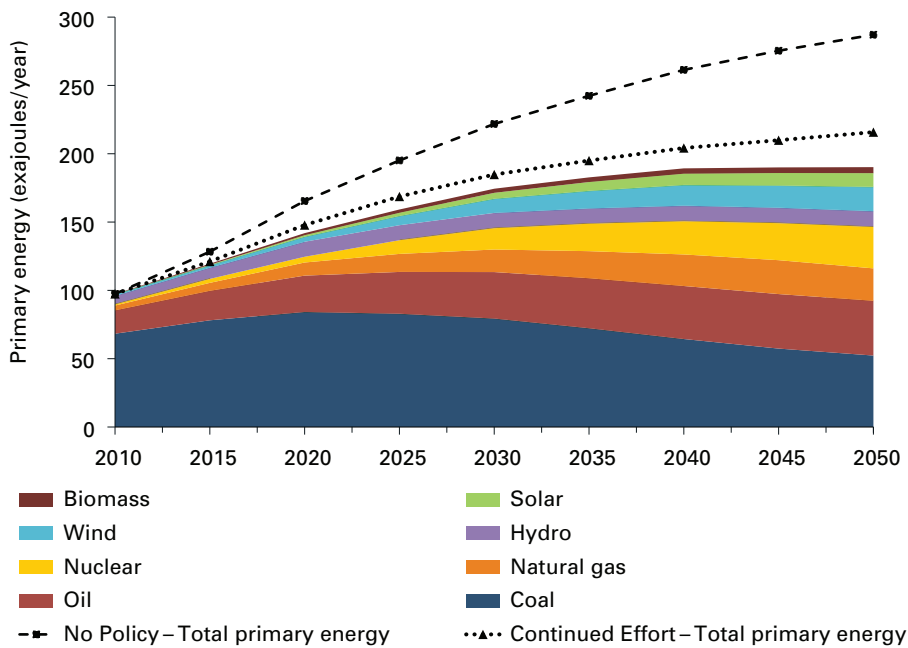
The top figure on page 17 shows total energy demand over time for the three scenarios, plus the actual breakdown of primary energy use by source in 2010 and estimates thereafter from the AE scenario only. The bottom figure shows total CO₂ emissions between 2010 and 2050 for each of those scenarios.

With no energy or climate policies in effect (the “No Policy” scenario), total CO₂ emissions continue to rise through 2050, with no peak in sight. Rising emissions are mainly due to continued reliance on China’s domestic coal resources. In 2050, more than 66% of all energy comes from coal—more than 2.8 times the current level, which is already widely viewed as untenable within China.

In the CE scenario, total energy use is well below the No Policy case, and that decline generates disproportionately high reductions in emissions. Carbon emissions level off at about 12 billion metric tons (bmt) in the 2030 to 2040 time frame. The CO₂ charge needed to achieve that outcome reaches \$26/ton CO₂ in 2030 and \$58/ton CO₂ in 2050. Deployment of non-fossil energy is significant, and its share of total energy demand climbs from 15% in 2020 to about 26% through 2050. Nuclear power expands significantly to 11% of total primary energy in 2050. Coal continues to account for a significant share of primary energy demand (39% in 2050). The share of natural gas use nearly doubles between 2030 and 2050, while the share of oil use increases slightly over the same period.

Under the AE scenario, CO₂ emissions level off in the 2025 to 2035 time frame, peaking at about 10 bmt—about 20% above current emissions levels. The carbon price rises from \$38/ton CO₂ in

Demand for energy in the three scenarios



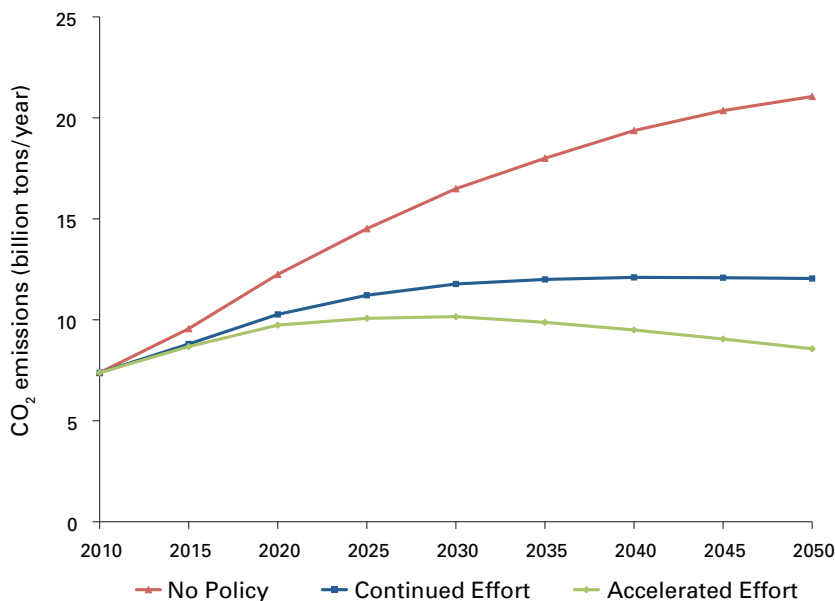
This figure shows total energy demand in the No Policy, Continued Effort, and Accelerated Effort scenarios, with the primary energy mix shown for the Accelerated Effort scenario only. Both levels of policy effort significantly decrease total energy demand relative to the baseline No Policy scenario, which assumes that no energy or climate policies are in effect after 2010.

2030 to \$115/ton CO₂ in 2050. Those prices are substantially above the levels in the CE scenario, but CO₂ emissions now peak as much as a decade earlier.

Under the AE scenario, non-fossil energy accounts for fully 39% of the primary energy mix by 2050. Wind, solar, and biomass electricity continue to increase through 2050 (as they do in the CE scenario), and nuclear is now 16% of the total energy mix. Despite its relatively low carbon content, natural gas is eventually penalized by the increasing carbon price. Between 2045 and 2050, natural gas actually starts to decline as a share in absolute terms. Coal's share drops dramatically—from 70% in 2010 to about 28% by 2050, with peak use occurring in about 2020. In contrast, oil's share of energy use continues to increase through 2050.

The differing outcomes for coal and oil are largely due to the availability and cost of substitutes. Coal is the least expensive fuel to displace; it has many substitutes, including wind, solar, nuclear, and hydro in the power sector and natural gas or biomass in industrial processes. In contrast, fewer substitutes are available for oil-based liquid fuels used in transportation; and switching to the alternatives—for example, bio-based fuels or electric vehicles—is a relatively expensive way to reduce CO₂ emissions. "As a result, oil consumption is relatively insensitive to a carbon price," says Karplus. "So China seems set to account for a significant share of global oil demand over the period being considered."

Total CO₂ emissions in China in the three scenarios



The decreases in energy demand in the Continued Effort and Accelerated Effort scenarios (shown in top figure) bring about even greater reductions in CO₂ emissions. While the Accelerated Effort scenario involves more aggressive measures than the Continued Effort scenario does, it causes CO₂ emissions to peak about a decade earlier and brings more substantial decreases thereafter.

Relevance for the new Chinese pledge

The findings of the Tsinghua-MIT analysis have direct relevance for current policy making in China. Under the new bilateral agreement with the United States, China needs to start reducing emissions at or before the year 2030. In the AE scenario, the researchers find that by starting now, China should be able to meet that 2030 target at an added cost to the economy that rises to just 2.6% of China's domestic consumption by 2050—a relatively modest impact on the country's economic development. "While we are currently working on detailed calculations, we expect that the economic cost will be offset—at least to some extent—by associated reductions in the environmental and health costs of China's coal-intensive energy system," says Karplus.

The CECP researchers are continuing to study how different energy and climate policies in China could be used to support the achievement of the China-US agreement. For example, they are looking at the carbon trading system now being tested in several regions of China, in particular, examining which provinces win or lose under the carbon price and how policy design choices can mitigate uneven impacts. And they're investigating how a carbon price affects air pollution and how air pollution policies affect carbon emissions.

Karplus stresses that their work is not meant to be a crystal ball that tells the future. "It's really intended to develop our collective intuition of the level of effort required to change China's energy system," she says. "And because the CECP involves both Chinese and US contributors, we are in a position to offer analyses and outputs that we hope

will be trusted and valued by policy makers in both countries as they work to strengthen the bilateral relationship."

Already Chinese policy makers are benefiting from the CECP, according to Professor Xiliang Zhang, CECP lead and director of the Institute of Energy, Environment, and Economy at Tsinghua University. He says, "The work of the CECP has played an important role in helping policy makers in China understand the challenges and opportunities that will accompany the country's low-carbon energy transformation."

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By Nancy W. Stauffer, MITEI

This research is supported by Eni S.p.A., the French Development Agency (AFD), ICF International, and Shell International Limited, founding sponsors of the MIT-Tsinghua China Energy and Climate Project (CECP). (Eni S.p.A. and Shell are also Founding Members of the MIT Energy Initiative.) The Energy Information Agency of the US Department of Energy and the Energy Foundation also supported this work as sustaining sponsors. Additional support came from the National Science Foundation of China, the Ministry of Science and Technology of China, the National Social Science Foundation of China, and Rio Tinto China, and from the MIT Joint Program on the Science and Policy of Global Change through a consortium of industrial sponsors and US federal grants (listed at globalchange.mit.edu/sponsors/all). Further information can be found in:

X. Zhang, V.J. Karplus, T. Qi, D. Zhang, and J. He. *Carbon Emissions in China: How Far Can New Efforts Bend the Curve?* MIT Joint Program on the Science and Policy of Global Change, Report No. 267, October 2014.



Making clean, high-quality fuels from low-quality oil

New insights into a promising approach

Left to right: William Green of chemical engineering, Ashwin Raghavan of mechanical engineering, and Ahmed Ghoniem of mechanical engineering are developing new computer models that will help energy companies implement improved processes for converting low-quality crude oil into clean-burning, high-quality fuels, including those that will be needed by the transportation sector in the coming decades.

This research was supported by Saudi Aramco, a Founding Member of the MIT Energy Initiative. See page 23 for a list of publications.

Photo: Stuart Darsch

New findings released by MIT researchers could help energy companies implement a long-recognized process for converting heavy, high-sulfur crude oil into high-value, cleaner fuels such as gasoline without using hydrogen—a change that would reduce costs, energy use, and carbon dioxide emissions. The process involves combining oil with water under such high pressures and temperatures that they mix together, molecule by molecule, and chemically react. The researchers have produced the first detailed picture of the reactions that occur and the role played by the water in breaking apart the heavy oil compounds and shifting the sulfur into easily removable gases. They also have formulated models that show how best to mix the oil and water to promote the desired reactions—critical guidance for the design of commercial-scale reactors.

More than a third of the world's energy needs are met using oil, and our reliance on that convenient, high-energy-density resource will likely continue for decades to come, especially in the transportation sector. But converting crude oil into lightweight, clean-burning, high-quality fuels such as gasoline, diesel, and jet fuel is getting harder. In the past, oil found in the ground tended to be lightweight, clean, and easily made into high-value fuels. Now, more and more of it is heavy, thick, tarry material that—when refined—yields a higher fraction of lower-value products such as asphalt along with solid chunks of waste called coke. Moreover, newly discovered oil contains ever-higher concentrations of sulfur, a contaminant that—when burned—produces gases that are now strictly regulated because they interfere with pollution-control systems in vehicles and contribute to acid rain and smog.

Processes now used to upgrade and desulfurize heavy crude oil are expensive and energy intensive, and they require hydrogen, which companies typically produce from natural gas—a high-cost process that consumes valuable gas resources and releases high levels of carbon dioxide (CO₂). “So there’s a lot of interest in finding alternative processes for converting low-quality crude oil into valuable fuels with less residual coke and for removing the sulfur efficiently and economically without using hydrogen,” says Ahmed Ghoniem, the Ronald C. Crane ('72) Professor of Mechanical Engineering.

One approach calls for using water rather than natural gas as the source of the hydrogen molecules needed for key chemical reactions in the refining process. Ordinarily, oil and water won't



Photo: Stuart Darsch

Critical to the research is this two-dimensional gas chromatograph, which uses a two-step process to separate the chemical components in an injected sample. The researchers use the device to determine the chemical makeup of their starting materials—even complex mixtures such as crude oil—and of the products that exit the reactor vessel, obtaining data such as those presented on page 21.

mix, so the molecules can't “see” one another and chemically react. But using “supercritical” water solves that problem. Under extreme conditions—specifically, at pressures and temperatures above 220 atm and 375 C—water goes into a supercritical state in which it is as dense as a liquid but spreads out to fill a confined space as a gas does. Add oil to supercritical water (SCW) and stir, and the two will mix together perfectly, setting the stage for the desired chemical reactions—without any added hydrogen from natural gas.

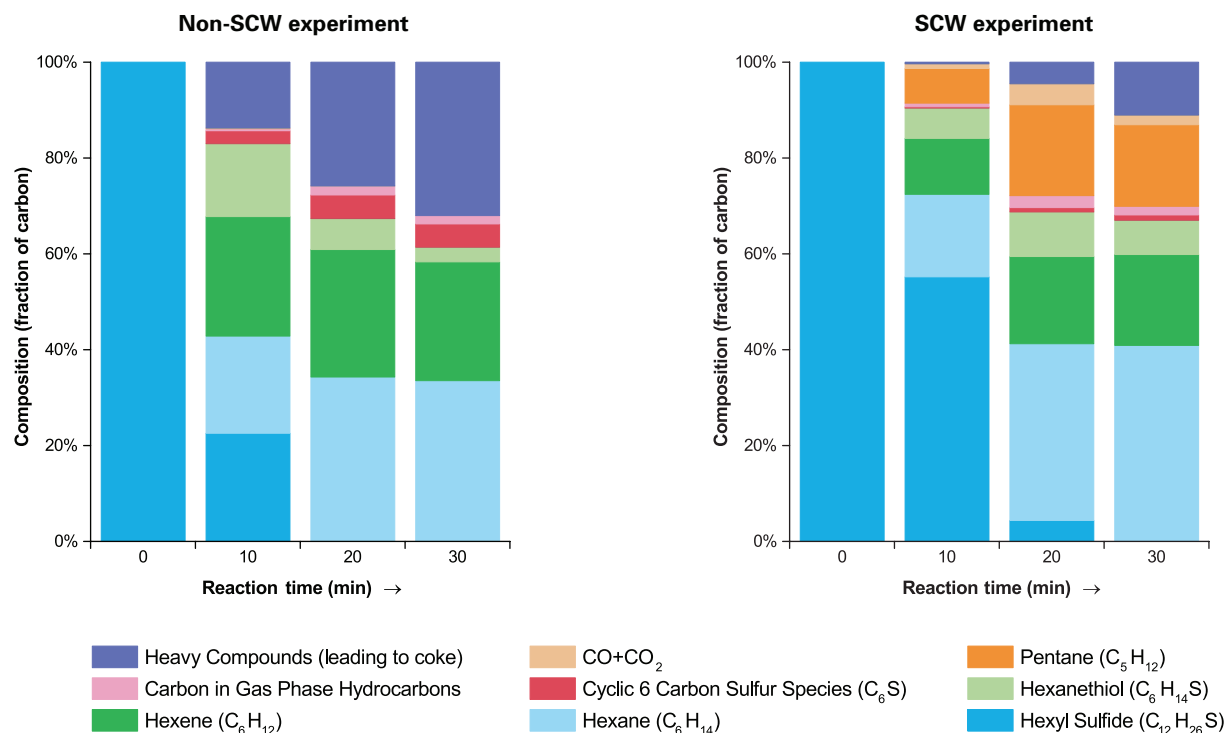
Industrial and academic researchers have demonstrated that mixing heavy oils with SCW produces lighter hydrocarbons (compounds of hydrogen and carbon atoms) containing less sulfur and forming less waste coke. But no one has understood exactly how it happens or how to optimize the process. For the past five years, Ghoniem and William Green, the Hoyt C. Hottel Professor of Chemical Engineering, have been working to close gaps in the fundamental knowledge about the chemistry involved as SCW and oil molecules react and about the flows

and mixing behaviors that will produce the desired reactions and reaction products. Combining those new insights, the researchers are developing new computational tools to help guide energy companies that want to implement the new process. “Testing designs and operating conditions at large scale and extreme pressures is almost impossible,” says Ghoniem. “Our goal is to provide computer models that companies can use to predict performance before they start building new equipment.”

Tracking the chemistry

When crude oil is mixed with SCW, the hundreds of chemical compounds present can react together in different combinations and at different rates, in some cases producing intermediate compounds that are then involved in further reactions. “The challenge with SCW processing is that you have to let the oil and SCW mix together long enough for the reactions that remove sulfur and break down large hydrocarbon molecules to happen—and then

Breakdown of hexyl sulfide, without and with supercritical water (SCW)



These results are from experiments in which hexyl sulfide—a large, sulfur-containing compound—was processed in a reactor vessel by raising the temperature without adding water (left) and by mixing it with SCW (right). In each experiment, samples were removed from the vessel at regular intervals up to 30 minutes. All of the samples taken at or after 10 minutes include smaller hydrocarbons, some with bound sulfur. But only the SCW samples include pentane, carbon monoxide (CO), and carbon dioxide (CO₂). The presence of the last two products indicates that the water (H₂O)—the only source of oxygen—must be reacting and providing the hydrogen atoms needed to remove the sulfur as hydrogen sulfide (H₂S).

stop the process to prevent further reactions that form products you don't want," says Green.

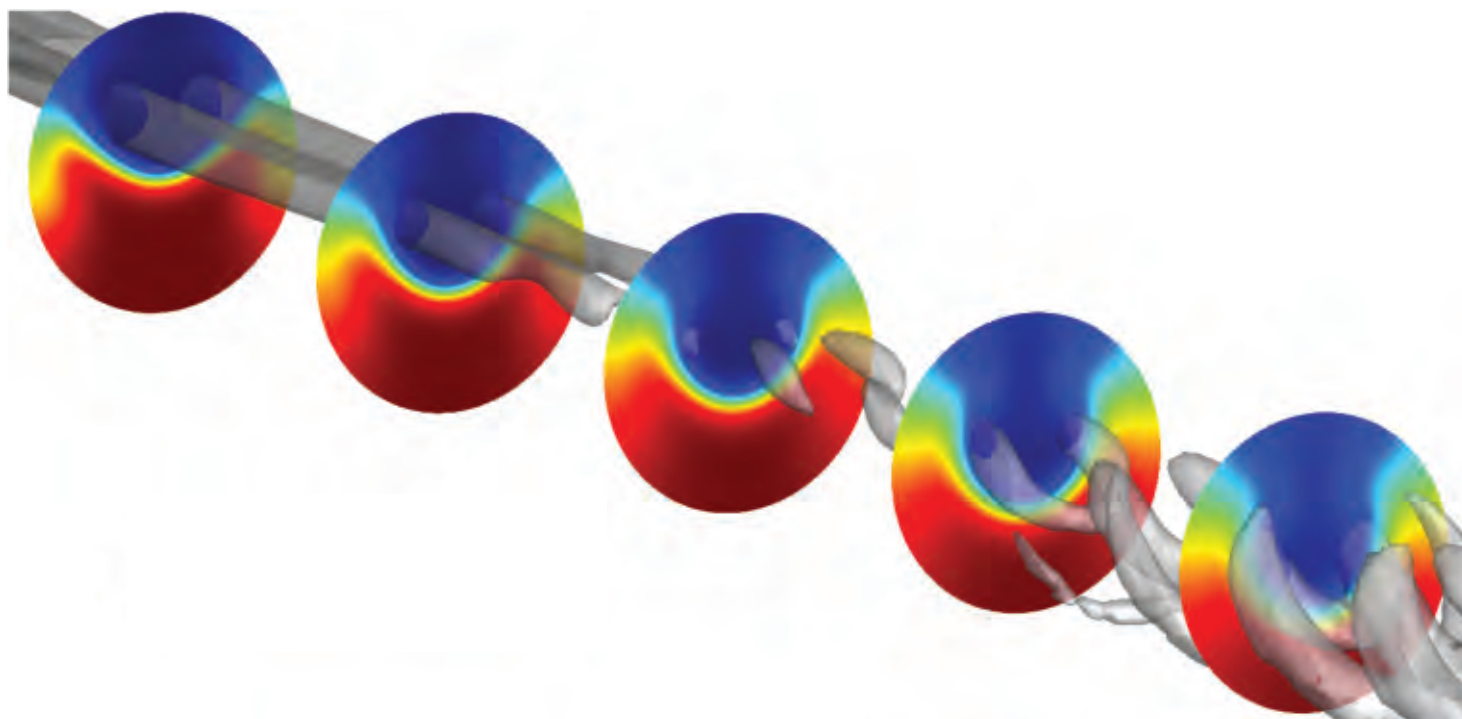
Based on a series of experiments, Green and his team have defined key chemical reactions that take place, how quickly they occur, and the intermediate products that are formed. As a sample sulfur-containing compound, they used hexyl sulfide, a large molecule made up of 12 carbon atoms, 26 hydrogen atoms, and one atom of sulfur. To test the impact of the SCW, they performed two parallel experiments. In one, they heated hexyl sulfide without adding water; in the other, they mixed the hexyl sulfide with SCW. In both cases, they removed samples from their reactor vessel at regular intervals up to 30 minutes.

Results are shown in the figure above. As expected, both sets of samples include a variety of smaller hydrocarbon compounds, some with bound sulfur. But the SCW samples (right) brought some surprises. The products include pentane—a smaller hydrocarbon not seen in the absence of SCW—and carbon monoxide and CO₂. Since water is the only source of oxygen in the mixture, it must be reacting with the carbon compounds. In addition, in the SCW experiments, less of the carbon goes into heavy compounds that are likely to lead to coke formation. The appearance of the samples supports that conclusion: The non-SCW product is dark brownish-black in color, while the SCW product is a light yellow, clear liquid consistent with coke suppression by the SCW.

To further clarify the chemical reactions and how they are affected by temperature, pressure, and SCW concentration, the researchers combined their experimental work with theoretical modeling and analysis. Based on those studies, they identified the whole series of chemical reactions by which hexyl sulfide breaks down and releases its sulfur in the presence of SCW. According to that "reaction mechanism," the sulfur-bearing hexyl sulfide is first broken apart, forming a smaller molecule with the sulfur atom in a very reactive form. In the absence of water, that highly reactive sulfur-bearing molecule would join with others like itself to form a long chain and eventually become coke. But in the presence of water, it reacts with the water, and the products ultimately include lighter hydrocarbons that are readily converted

Computational fluid dynamics analysis of flows and mixing as oil is injected into supercritical water (SCW)

Figure: Ashwin Raghavan G



These results from the computational fluid dynamics model show flows and mixing as oil is injected from above into SCW flowing down a pipe from left to right. (The sidewalls of the circular pipe are not shown.) Interaction between the two fluids causes the formation of two vortices—coherent swirls that spin in opposite directions, mixing the streams together. Those vortices—shown here as gray tubes—are initially separate structures, but they soon break down as the streams mix. The colored cross sections show concentrations of oil and SCW at five locations along the pipe. Blue indicates regions of cold oil, while red indicates regions of hot SCW. The intermediate colors where the red and blue meet are mixed layers with varying concentrations of oil and SCW. As evident in the cross sections, the two oppositely spinning vortices drive the oil downward toward the center of the pipe and the water upward along the sidewalls. Moving down the pipe, the layers between the oil and SCW become more and more diffuse as the two streams mix together.

into valuable light fuels. The sulfur combines with hydrogen atoms to form hydrogen sulfide, a gas that can easily be removed and dealt with using existing technology.

Green notes that some of those reactions came as a surprise. “People didn’t expect them,” he says. “But we were able to discover that they were occurring and how fast they proceed and how much energy is needed to start them.” By knowing those “energy barriers,” the researchers can determine the reaction rates under different operating conditions—critical information for the overall model of the process.

Those results define—for the first time—the key roles played by water in the SCW system. “We confirmed that

the hydrogen atoms needed to convert the sulfur to hydrogen sulfide can be provided by water rather than by hydrogen gas, as in the conventional process,” says Green. “And our empirical data show that the new SCW method does make less coke than the conventional process, for reasons that we’re now trying to clarify.”

Mixing without stirring

The results described thus far elucidate reactions and reaction rates under different conditions. Knowing what those conditions are inside a practical reactor is a parallel challenge. When oil is injected into flowing SCW, interactions between the two flows determine how mixing and heating proceed, first at the macroscale and then down to the

microscale at which chemical reactions occur. The trick is to encourage and control optimal mixing. Using a stirring device is impractical, given the extreme supercritical conditions. So the researchers must generate such mixing naturally. “We need to know what drives the speed and patterns of mixing so we can select equipment designs and operating conditions that will either support key features of mixing for a long time or let them decay faster,” says Ghoniem.

To understand the details of flows and mixing, the researchers are using three-dimensional computational fluid dynamics (CFD), a method of simulating fluid flows within a well-defined region. Such modeling involves equations that describe the flow, mixing, and energy transfer between streams of

fluids. But with supercritical fluids, key parameters such as viscosity and density are in ranges not seen under normal (non-supercritical) conditions. Nevertheless, the researchers were able to use powerful computers to accurately solve their CFD model, accounting for the complex changes that occur as fluids move from normal to supercritical conditions. To their surprise, they found that supercritical flows do indeed behave differently. For example, they become turbulent earlier than do comparable flows under normal conditions.

In one practical implementation of their model, they simulated mixing between SCW and oil near a “tee” junction consisting of a horizontal pipe with a smaller pipe coming into it from the top. SCW flows through the horizontal pipe, and cold oil—here a sample hydrocarbon—is injected into it through a vertical pipe. The figure on page 22 shows how the SCW and oil mix as they flow down the pipe from left to right. (The walls of the circular pipe are not shown.) Initial interaction between the two streams causes the formation of two coherent swirls called vortices—rotating structures in the fluids shown in the figure as gray tubes. At first, the vortices are separate swirls that spin in opposite directions, mixing the oil and SCW together. Moving along the pipe, the vortices break down, and mixing rates decay.

The colored circles in the figure show mixing between the two fluids at five cross sections located along the pipe. Blue regions are rich in cold oil; red regions are rich in hot SCW; and regions shown in intermediate colors have varying concentrations of the two fluids. The oil enters the cross section at the top and water at the bottom. As the spinning vortices form, the oil

is driven downward near the center of the pipe, and the water is driven upward along the walls. In the first cross section, the interface layer between the oil and SCW is thin and sharp. In subsequent cross sections, that layer expands and diffuses, showing the extent of the mixing.

The researchers conclude that most of the fluid mixing and associated heat transfer is due to the swirling action of the vortices. However, they note that the mixing rate and heating rate differ—and that both influence the chemistry that occurs in regions where the fluids are mixed. Given design and operating details—the kind of oil; pressures, speeds, and temperatures of the incoming flows; shape and size of the pipes; and so on—the CFD simulation can predict “how this natural mixing process will progress and how temperatures will change at different locations over time,” says Ghoniem.

Continuing research

The researchers are continuing to generate new knowledge that will help SCW processing become an economically viable commercial option. For example, they are clarifying the reactions whereby carbon-carbon bonds are broken in the heaviest fractions, including asphalt. They are quantifying the different rates at which various oils will diffuse and mix in SCW—an effect first discovered in their modeling analyses. They are taking a closer look at inexpensive catalysts that can help encourage the breakdown of large hydrocarbons and are stable enough to be regenerated and reused. And they are exploring the possibility of linking SCW processing with other environmentally friendly desulfurization and upgrading technologies to create a combined system that will make

it practical to continue producing high-value fuels from all kinds of oil for decades to come.

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By Nancy W. Stauffer, MITEI

This research was supported by Saudi Aramco, a Founding Member of the MIT Energy Initiative. Further information can be found in:

Y. Kida, C.A. Class, A.J. Concepcion, M.T. Timko, and W.H. Green. “Combining experiment and theory to elucidate the role of supercritical water in sulfide decomposition.” *Physical Chemistry Chemical Physics*, vol. 16, no. 20, pp. 9220–9228, 2014.

A. Raghavan and A.F. Ghoniem. “Simulation of supercritical water-hydrocarbon mixing in a cylindrical tee at intermediate Reynolds number: Formulation, numerical method and laminar mixing.” *The Journal of Supercritical Fluids*, vol. 92, pp. 31–46, 2014.

A. Raghavan and A.F. Ghoniem. “Simulation of supercritical water-hydrocarbon mixing in a cylindrical tee at intermediate Reynolds number: Impact of temperature difference between streams.” *The Journal of Supercritical Fluids*, vol. 95, pp. 325–338, 2014.

M.T. Timko, A.G. Ghoniem, and W.H. Green. “Upgrading and desulfurization of heavy oils by supercritical water.” *The Journal of Supercritical Fluids*, vol. 96, pp. 114–123, 2015.

MIT Energy Initiative announces new seed grant awards

The MIT Energy Initiative (MITEI) has announced its latest round of seed grants to support early-stage innovative energy projects. A total of \$1.65 million was awarded to 11 projects, each lasting up to two years.

Including the latest round of grants, the MITEI Seed Fund Program has supported 140 innovative, energy-focused research projects for a total of nearly \$17.4 million in funding over the past eight years. The program supports researchers from throughout MIT's five schools to collaborate in exploring new energy-related ideas, and it attracts a mix of established energy faculty as well as many who are new to the energy field. Funding is provided by MITEI's Founding and Sustaining Members and by philanthropic contributors.

"The MITEI seed fund awards build on our successful track record of support for innovative thinking around key energy challenges," says MITEI Director Robert C. Armstrong, the Chevron Professor of Chemical Engineering. "There is tremendous potential in these innovative early-stage projects. This round of grants includes important collaborative research efforts that seek to address key global energy and climate challenges."

This year, MITEI received a total of 60 proposals from across the Institute. Applications came from 82 researchers in 29 departments, labs, and centers (DLCs). Twenty-five applications represented collaborations between two or more researchers, including 21 that spanned multiple DLCs.

Each of this year's winning proposals—listed on page 26—was chosen for its potential to advance critical energy-related research. Examples of topics

addressed include improved batteries and ultracapacitors for energy storage, more efficient conversion of energy resources into valuable fuels, new approaches to desalinating brackish water, and novel methods and materials for oil and gas drilling and recovery.

Opportunities for new faculty

As in past years, the winners this year include a number of new faculty members who will pursue creative ideas that could have a significant impact in the energy field. The following five projects are being led or co-led by four faculty members who came to MIT last academic year (2013–2014).

Multi-dimensional materials for improved thermoelectric performance

When a thermoelectric material is hot on one side and cold on the other, it generates electricity—a behavior that could be useful in harnessing the energy in waste heat from, say, car engines and power plants. But so far, the conversion efficiency has been too low for widespread use of these promising materials. The problem is that high electrical and thermal conductivity generally go hand in hand, so temperatures in an electrically conductive sample will quickly equalize. Assistant Professor Joseph Checkelsky of physics will be synthesizing novel materials with nanoscale geometries that permit fine-tuning of thermal and electrical properties separately, making possible conversion efficiencies high enough to be commercially viable. His first task: to build a device that can measure the conversion efficiencies of the materials he and his group fabricate.

Scalable three-dimensional battery electrodes

Electrodes used in today's rechargeable batteries are basically flat—a design that makes them inexpensive to manufacture but vulnerable to mechanical failure and leads to a trade-off between storing a lot of energy and delivering it quickly. Associate Professor A. John Hart of mechanical engineering is leading work to develop battery electrodes with a novel structure that will provide mechanical robustness as well as high energy density and fast delivery simultaneously. The team will fabricate electrodes, explore how their geometry influences performance and durability, and conceptualize methods for their large-scale production. If successful, the new electrodes could one day be the key to improved high-performance batteries for uses ranging from portable electronics to electric vehicles.

High-speed printing of two-dimensional materials for energy systems

Atomic layer sheets of graphene and molybdenum disulfide could be used to make ultra-thin, flexible energy devices and storage materials. But current methods of growing and printing such two-dimensional layers are typically slow, wasteful, and effective on only limited types of surfaces. Hart and Professor Jeffrey Grossman of materials science and engineering are combining their expertise in precision engineering and computational methods to investigate a novel printing process that will permit the high-speed, large-area, continuous printing and stacking of two-dimensional layers onto a variety of substrates. In the final phase of their project, they hope to use their printing process to demonstrate new device concepts.

In-situ and above-ground chemical oxidation strategies for treating hazardous flowback water generated from hydraulic fracturing

During hydraulic fracturing (fracking) operations, the natural gas that emerges is accompanied by water containing potentially hazardous chemicals, some injected with the fracturing fluids and some picked up underground. Removing them before the water is recycled or discharged can be difficult and costly. Assistant Professor Benjamin Kocar of civil and environmental engineering is examining strategies for reducing the contaminants that reach the surface and for degrading those that do. One strategy calls for supplementing the injected fluids with strong oxidants that will transform natural minerals in shale surfaces into a form that will bind and retain hazardous constituents, thereby immobilizing them below ground. Other work focuses on new methods of treating complex organic mixtures above ground using inexpensive photocatalysts activated by ultraviolet light from sunshine or artificial sources.

Electrochemical methane upgrading at carbon-supported catalysts

Methane is an abundant, low-carbon fuel, but it is difficult to store and transport, so huge amounts of it are simply wasted. Converting methane gas into liquid methanol would permit the widespread use of this valuable resource, particularly for transportation. Industry performs that conversion but in a two-stage process that is both energy- and capital-intensive. Assistant Professor Yogesh Surendranath of chemistry is developing a method of converting methane into methanol in a single step inside a device operating at low temperatures. Key to the process is using a combination of catalysts

specially designed and well-tuned to work together to produce methanol efficiently and selectively. Once the process has been optimized, the research team will begin developing a prototype device for direct methane-to-methanol conversion.

Past successes

Past MITEI seed fund awards have helped launch a number of successful startups. For example, Professor of Materials Science and Engineering Donald Sadoway's work as part of a seed fund project led to the founding of Ambri, a company that is developing novel, low-cost, long-lifespan batteries for utility-scale energy storage. FastCAP Systems, under founder and CEO Riccardo Signorelli PhD '09, is commercializing breakthrough ultracapacitor technology that received early support from a seed fund grant awarded to Professors Joel Schindall and John Kassakian of the Department of Electrical Engineering and Computer Science with then-graduate student Signorelli. Associate Professor of Mechanical Engineering Kripa Varanasi's past seed fund projects have led to two startups. One, LiquiGlide, has created liquid-impregnated surfaces that are designed to be hyper-slippery to viscous fluids, ice, hydrates, and more. And Varanasi's collaboration with Karen Gleason, professor of chemical engineering and MIT's associate provost, led to the formation of DropWise, a company that is commercializing technology to make durable coatings on steam condenser surfaces that can dramatically improve efficiency in both electricity generation and desalination, thereby reducing fuel costs and greenhouse gas emissions.

"MITEI seed funding was among the early funding I received which laid the foundation for basic research that ultimately led to the startups LiquiGlide and DropWise, which I co-founded," says Varanasi. "These awards can be incredibly instrumental in helping to move projects from the research stage into the real world."

The MITEI Seed Fund Program has awarded new grants each year since it was established in 2008. For more information, go to mitei.mit.edu/research/seed-fund-program.

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By Melissa Abraham and Nancy W. Stauffer, MITEI

Recipients of MITEI seed grants, spring 2015

Multi-dimensional materials for improved thermoelectric performance

Joseph Checkelsky
Physics

Encoded hollow particles for use as proppants

Patrick Doyle
Chemical Engineering

Multi-wave imaging of subsurface heterogeneity: Characterization and monitoring of geologic hazards, infrastructure, and fluids

Michael Fehler
Earth, Atmospheric, and Planetary Sciences

Stephen Brown
Earth, Atmospheric, and Planetary Sciences

Daniel Burns
Earth, Atmospheric, and Planetary Sciences

Scalable three-dimensional battery electrodes

A. John Hart
Mechanical Engineering

High-speed printing of two-dimensional materials for energy systems

A. John Hart
Mechanical Engineering
Jeffrey Grossman
Materials Science and Engineering

High-temperature supercapacitors based on nanostructured surfactant ionic liquids

T. Alan Hatton
Chemical Engineering

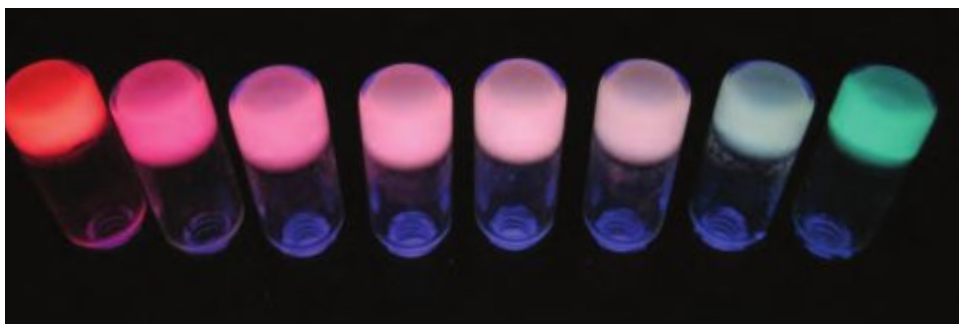


Photo: Pangkuan Chen, MIT

With support from a 2014 MITEI seed grant, Niels Holten-Andersen, assistant professor, and Pangkuan Chen, postdoctoral associate, both of materials science and engineering, have combined selected photo-luminescent lanthanide complexes with polymers to create novel gels and liquids with controllable light-emitting properties. The vials shown above contain a series of these light-emitting gels under ultraviolet light, demonstrating that the researchers can tune the gels to emit a desired color. The gels display color changes in response to various stimuli such as changes in temperature, pH, mechanical stress, and exposure to toxins such as cyanide.

In-situ and above-ground chemical oxidation strategies for treating hazardous flowback water generated from hydraulic fracturing

Benjamin Kocar
Civil and Environmental Engineering

Electrochemical methane upgrading at carbon-supported catalysts

Yogesh Surendranath
Chemistry

Robust nano-engineered composite ceramic surfaces for harsh environments with applications to corrosion and fouling mitigation

Kripa Varanasi
Mechanical Engineering

Hierarchical CNT electrodes for capacitive-based brackish water desalination

Evelyn Wang
Mechanical Engineering
Carl Thompson
Materials Science and Engineering

Brian Wardle
Aeronautics and Astronautics
Karen Gleason
Chemical Engineering and Office of the Provost

Data analytics for behavioral energy efficiency: Linking mobility and energy services through ICT-based behavioral feedback

P. Christopher Zegras
Urban Studies and Planning
Moshe Ben-Akiva
Civil and Environmental Engineering

MIT architects tackle India's slum problem

India is facing a housing crisis of epic proportions, with an estimated 700–900 million square meters of new residential space required annually to accommodate its burgeoning population. In many cities, housing needs are being met by slum dwellings, but MIT researchers are working to provide a better solution—one that is energy-efficient, environmentally sustainable, and ultimately safer for low-income residents.

Under the aegis of MIT's Tata Center for Technology and Design, three faculty members from the Department of Architecture have teamed up with an Indian nonprofit to work on a Rajiv Awas Yojana Slum-Free City Plan of Action for Bhuj, a city in Gujarat that suffered major housing losses during the earthquake of 2001.

Working to create not only a plan for the city but also a model for cities worldwide, the researchers—with the help of well over a dozen MIT graduate students and postdocs—are employing a three-pronged strategy for development that includes new designs for safer, more sustainable neighborhoods, buildings, and construction materials.

"To solve the problem of housing at the scale that India and the world needs, solutions don't live in one discipline," says Tata researcher John Ochsendorf, a professor of architecture and of civil and environmental engineering. "To really move the world forward, we need solutions that solve multiple problems simultaneously."

Flexible housing options

Assistant Professor of Architecture Miho Mazereeuw is leading the effort to examine Bhuj's needs at the neighborhood level. Partnering with the



Photo: Madeline Gradillas G

Located in one of the first three neighborhoods slated for redevelopment in Bhuj, India, this house shows the typical use of found materials for slum construction.

Hunnarshala Foundation, a nongovernmental organization with strong community ties, Mazereeuw's team interviewed residents from numerous slums and conducted 52 in-depth studies of existing housing. In the process, they discovered that slums actually have an advantage over other low-cost housing options in that they provide opportunities for street-level micro-entrepreneurship.

"People make shops. People rent out spaces. Their homes incrementally grow as they gain income, gain family members," Mazereeuw says. "They can keep adding on, so that investment keeps growing and their assets keep growing." Such benefits are not available in the high-rise housing typically built for low-income residents.

Mazereeuw and her team are therefore designing mixed-use, low-rise housing that will give residents the flexibility to expand their homes safely as needs arise. In collaboration with Hunnarshala, the researchers have been working on three neighborhoods that will begin construction this summer. Ultimately, Mazereeuw and her colleagues at the Tata Center hope to

provide a blueprint for methods that will enable residents to weigh in on the designs for all new neighborhoods being developed under a slum eradication effort sponsored by the Indian Ministry of Housing and Urban Poverty Alleviation.

"The work Miho is doing is helping us understand if you're building walls, where should the walls be," Ochsendorf says.

Ochsendorf and his team are conducting associated research focused on addressing the omnipresent risk of earthquake devastation in Bhuj while enabling slum residents to continue to build their own low-cost homes. Currently, researchers are working to adapt a construction technique known as confined masonry to the conditions in India and to popularize it.

Common in South America, confined masonry interconnects a building's brick walls with poured concrete corner columns in order to engage the full wall in transferring seismic loads to the ground. "Typically, a concrete frame will resist earthquake loads but the bricks in the walls aren't considered part of the

resistance strategy. If anything they're considered a hazard," Ochsendorf says. "In our mind [confined masonry is] about the best way to build an earthquake-proof house out of brick."

The researchers want to use brick because that's the material most familiar to residents. However, traditional Indian brick-making strips clay from the landscape, destroying arable land, and uses inefficient kiln-firing, which produces significant greenhouse gas emissions. "We've arrived at a scale where it's no longer possible to satisfy the country's demand for brick with the raw materials they have," Ochsendorf says. "It's kind of the perfect problem that combines energy, environment, and economics."

Ochsendorf's team of researchers is therefore developing a new, environmentally friendly kind of brick that substitutes waste boiler ash for some of the clay and dries at ambient temperatures, eliminating the need for a kiln. This work has already led to a startup business, eco-BLAC, which was a finalist this winter in MIT's \$100K business plan competition.

Designing for the long term

The third element of the Tata Center project focuses on passive techniques for making homes safer and more comfortable without adding significant energy demands. "Starting at the lowest level, the question is, can you

construct housing with structural systems using more renewable, less expendable resources while making them more environmentally acceptable from the point of view of air quality and particularly comfort?" says Tata researcher Leon R. Glicksman, a professor of building technology and mechanical engineering.

Glicksman, a member of the MIT Energy Initiative's Energy Council, is leading a team examining the thermal performance of existing housing stock and testing the effectiveness of low-cost local options for insulation, such as rice husks stuffed into burlap sacks. The team is also exploring various building designs to maximize natural ventilation. "If you design the openings of buildings properly you can use just buoyancy-driven natural ventilation. If you have one opening at a low level and another opening at a higher level, if there's a temperature difference between the inside and the outside, you get a chimney effect and that chimney effect will essentially drive air circulation through buildings," he says.

One long-term goal of this project is to reduce the need for air conditioning. While air conditioning is currently a pipe dream for India's poorest residents, the pattern in other countries such as China has shown that as economies improve, energy consumption rises precipitously. "The hope here is that as we develop housing and people move up in economic status, they'll find that the more passive solutions are very comfortable and they won't necessarily go to the solutions that use exorbitant amounts of energy," Glicksman says.

Glicksman's team has built five tiny one-room demonstration units in Bhuj, which members are using to test the performance of different kinds of

Photo: Ben Miller, MIT



Graduate student Michael Laracy (left) and postdoc Thomas Poinot hold up the environmentally friendly eco-BLAC bricks they developed at MIT to substitute for the kiln-fired clay bricks (seen stacked behind them at an Indian paper mill) that are ubiquitous across India.

Photo: Madeline Gradillas G



insulation, roof designs, and natural ventilation, as well as to demonstrate the advantages of the new systems to residents. Persuading the local population of the need to change their traditional building methods is a critical part of the Tata Center project and a key reason for partnering with Hunnarshala, the researchers say.

“This is a notion of development that isn’t the conventional one,” Ochsendorf says. “From what we’ve seen and learned, we think it’s far more effective to work with local partners that can help us work out the challenges ... [and] pilot innovation at a smaller scale before scaling up.”

Noting that the mission of the Tata Center is ultimately to develop solutions for resource-constrained communities around the world, Ochsendorf says the team has found India an ideal proving ground for research. “The problems in India are the problems in so many areas around the world, so if we can develop solutions that work there, we can develop solutions that work anywhere,” he says.

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By Kathryn M. O’Neill,
MITEI correspondent

This research was funded by the Tata Center for Technology and Design.



Photo: Nipun Prabhakar

MIT graduate student and architect Madeline Gradillas, left, installs thermal sensors in one of five test units built in Bhuj, India, to assess the performance of different insulation techniques, roof designs, and natural ventilation controls. She is accompanied by Pradip Rangani, a project manager at the Hunnarshala Foundation. The photo at top left shows one of the test units from the exterior.

Below:
Construction staff from the Hunnarshala Foundation, an Indian nongovernmental organization working with MIT on slum eradication, mock up a double-layer roof assembly. This roof design is intended to improve home insulation in Bhuj, India.



Photo: Madeline Gradillas G

Ruben Juanes: Exploring subsurface energy, from academics to industry

Ruben Juanes was in middle school in northwestern Spain when he first knew what he wanted to study in life. “I had a very, very inspiring teacher for two years in a row. I really think that that was what sparked my interest in the sciences.” He was enrolled in an experimental sciences course that “was designed as a first exposure to mostly the natural sciences,” he says. “We learned about things like photosynthesis and the greenhouse effect and the laws of mechanics and gravity.”

He had another life-changing “first exposure” around this time, too. “I still remember.... When I was maybe twelve or so, I learned about MIT and I thought, oh, I would like to go there one day.”

It was only a matter of time. Juanes, the ARCO Associate Professor of Energy Studies in MIT’s Department of Civil and Environmental Engineering (CEE), has been part of the Institute since 2006, when he was hired as an assistant professor.

As happens in life, though—and in the underground multiphase flows that Juanes now researches—there have been some unexpected twists and turns along the path. Juanes’s journey into academia began during his undergraduate years, when he worked with a professor who had done his PhD in the United States and was a groundwater hydrologist. “That was my first exposure to actual research,” he says. “At the time I didn’t think hydrology would turn out to be my lifetime academic path, but it did.”

During graduate school, Juanes performed his PhD research with a professor at the University of California at Berkeley who, before joining the faculty, had been a researcher for Shell. Working with this former industry

professional led Juanes to broaden the way he thought about subsurface flows: He expanded his focus to include not just water but also oil and gas. Now the topic of his research had become “three-phase flow”—the three phases here being water, oil, and gas.

Since then, Juanes has studied flows of all kinds but particularly the simultaneous flow of multiple fluids through porous media—a topic that requires an understanding of the intricate roadwork of cracks and fissures that fluids find their way into while traveling underground, as well as the interaction between the different fluid phases.

Much of his research is dedicated to flows related to energy and the environment. For example, recent work has focused on carbon capture and sequestration (CCS), a process of great interest to energy companies working with coal or gas and seeking to make their operations more environmentally friendly. The “sequestration” part of CCS involves taking carbon dioxide (CO₂) that has been captured at power plants and other sources and injecting it into geologic reservoirs, thereby preventing it from reaching the atmosphere.

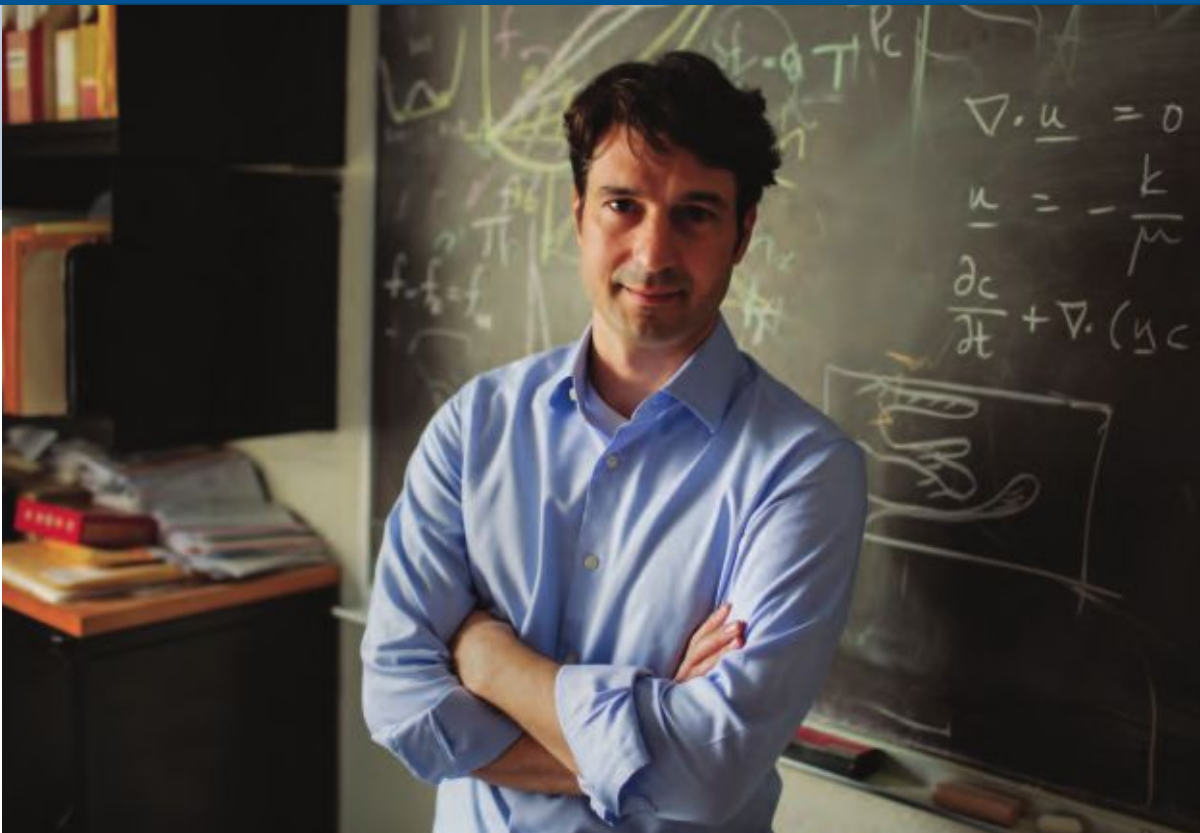
To determine the effectiveness of that process, Juanes and his team study how CO₂ behaves underground. Under the high temperatures and pressures of reservoir conditions—typically at 2 kilometers deep—CO₂ goes into a new form. It is neither a gas nor a liquid but rather a supercritical fluid. It is like a dense gas, so it has low viscosity, is mobile, and is less dense than water. “As a result, it is buoyant with respect to water and will tend to rise in the subsurface,” Juanes says. “But you don’t want CO₂ to rise all the way up to the surface...because that would

defeat the purpose of carbon capture.” Juanes is now investigating natural mechanisms that hinder that buoyant migration. His hope is that understanding those mechanisms could lead to the development of techniques for preventing the escape of CO₂ sequestered in geologic reservoirs.

Another situation where underground flows don’t behave as might be expected is when energy companies inject water into an oil reservoir—a standard method of increasing the yield of oil from a well. Often the water is injected in one location and extracted from another. “But some of the fluid you inject arrives very early, and some of it arrives very late,” Juanes says. “It takes forever, to our minds.” This is a signature of anomalous transport—meaning behavior not described by classical theories. (While “anomalous” may imply “unexpected,” in the world of subsurface flows, unanticipated behavior is not the exception but rather the rule, notes Juanes.) One possible explanation is that flow is fast through fractured networks and slow through the remainder of the reservoir. Juanes and his team are working to verify such mechanistic explanations for anomalous transport, with a goal of creating models that can—with very few parameters—simulate the subsurface flow of critical fluids.

In performing such work, Juanes and his team typically run laboratory experiments and computer simulations. A different project takes them out into the field—or to be more precise, out by the lakeside. This work focuses on the natural processes by which lakes release methane, a powerful greenhouse gas. At the bottom of every lake is a layer of fine-grained, organic-rich sediment that naturally produces methane. “This methane will eventually

Photo: M. Scott Brauer



Ruben Juanes, the ARCO Associate Professor of Energy Studies in MIT's Department of Civil and Environmental Engineering.

be released into the lake," Juanes says, "but in a very irregular, episodic, point-like fashion." How the releases occur will determine whether the methane traverses through the water column and reaches the atmosphere. To explore that process, Juanes and his team deploy a multi-beam sonar system on the lake floor that records with tenth-of-a-meter and single-second resolution the venting of methane bubbles from the sediment layer.

Juanes's research into underground flows of oil and natural gas brings him into direct contact with scientists who work in the energy industry. These partnerships, he says, have been some of the most fruitful collaborations he's been a part of. "The most successful projects scientifically—the ones where we've published the best work—were the ones where we had the closest collaboration with the sponsor," Juanes says. "In many ways [working with industry scientists] has sparked our creativity in ways we perhaps did not anticipate. They have very practical problems, and that forces us to step outside of our comfort zone."

While Juanes thrives on collaboration with other scientists, he is first and foremost a professor, and his students and their education are incredibly important to him. He and his peers in CEE are continually thinking of new and better ways to challenge and prepare the young engineers under their tutelage. For example, Juanes and some fellow CEE professors recently launched a plan to give the topic of energy a more prominent place in their department. "[We] feel strongly that we can have a positive presence, a positive offering, when it comes to energy education," says Juanes. They are working to incorporate more energy-related topics into their current class offerings, and they are looking into a broader revamping of CEE's overall curriculum. Juanes envisions these larger changes as "a kind of 'energy track' in the new flexible curriculum in our department."

Juanes feels strongly about both MIT and his students. "[MIT] is a very stimulating place," he says. "It really challenges you to rise up to the occasion, to go past what you are comfortable with and really develop into a

professor, a researcher, at the forefront of whatever it is that you do." But in his mind, what really makes MIT special is the students. He feels he has been "blessed with fabulous students over the years."

He cites one specific part of the teaching experience as most rewarding: "witness[ing] the evolution of a grad student." To him, there's nothing as fulfilling—from an academic perspective—as seeing students evolve and mature and become the world experts in their field. "To see the confidence they display, the knowledge they amass, and how they're able to, along the way, go from being students who are on the receiving end to really being mentors to the new batch of students coming in—that process, I must tell you, is magical."

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By Francesca McCaffrey, MITEI

Ruben Juanes has just been awarded an energy curriculum development grant. See page 34 for details.

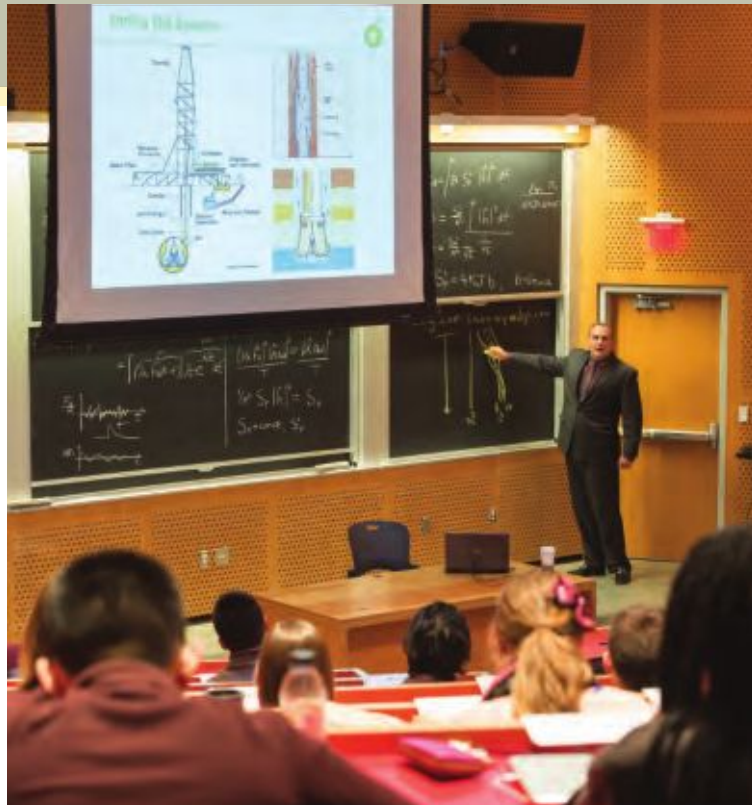
Sustainable Energy class cultivates critical thinking

Cross-listed among six engineering departments and a mainstay of MIT's energy minor curriculum, the class known as Introduction to Sustainable Energy (undergraduate level) or Sustainable Energy (graduate level) provides an essential survey of technologies for addressing the 21st century energy challenge. But it fulfills an even broader purpose, according to Michael Golay, lead instructor and professor of nuclear science and engineering: "I prefer to look at it as a course in critical thinking," he says.

The class "tries to teach students how to evaluate a new energy technology and identify the challenges it must overcome," says co-instructor William Green, the Hoyt C. Hottel Professor of Chemical Engineering. "We have students adopt the perspective of an investor, consultant, or an inventor trying to make a new product successful, and ask if the technology will make more energy than it consumes, if it can be produced at the right scale and for the right cost, and if regulatory issues might be showstoppers," says Green, who sits on the Energy Minor Oversight Committee.

With the participation of MIT faculty from a range of disciplines, the class ponders the plausibility of energy technology solutions using multiple lenses, including economics, public policy, and science. It is an approach students appreciate.

"There is no other class at MIT where such different viewpoints can be found in one place," says Anisha Gururaj '15, a senior in chemical engineering and a Rhodes Scholar. "I came out of the class realizing that the energy crisis is extremely complicated in part because the different technological solutions come with their own problems," she says.



Photos: Justin Knight

Guest speaker Eugene Sweeney, leader of the well control team at BP, discusses offshore drilling and production during the energy technology-focused portion of the Sustainable Energy class in fall 2014.

Mechanical engineering major Catherine Fox '15 says that learning from experts in different fields was the most valuable aspect of the class for her. "You hear a lot in the media about renewables and fossil fuels, and taking a deeper look at a range of technologies, at the calculations behind them, allowed us to debunk some of the myths."

Launched in 1996 by Golay along with a colleague from nuclear science and engineering and three faculty and staff members from chemical engineering, the initially graduate-only class has evolved into a school-wide elective. "There was a lot of interest at the undergraduate level for a broad energy course," says Golay. Acknowledging this demand, the MIT Energy Initiative (MITEI) stepped in to help develop an undergraduate section of the class, 22.081J, which became one of the key requirements for the Energy Studies

Minor when it was launched six years ago. MITEI also has provided teaching assistant support to the class.

As a result of its broadened audience, the class enjoys high enrollment and attracts students not only from engineering departments but also from the Department of Urban Studies and Planning and the MIT Sloan School of Management. Golay notes, though, that "this is a real engineering course, not energy for poets." Students who lack some of the engineering fundamentals "have to work harder, but they'll get a lot of help."

Undergraduates face engineering problem sets and exams, and graduate students taking the class must produce a case study of a new technology demonstrating analysis from a variety of perspectives. The primary text for the class is what Golay describes as an "encyclopedia on energy, a real

doorstop”—written by Golay and his colleagues. This serves as scaffolding for a sequence of sessions that begin with such basic energy topics as thermodynamics, and energy conversion and transfer (part of what Golay calls the “toolbox”); next examine energy in context; then interrogate specific energy technologies, from wind power and fusion energy to biomass, nuclear, and solar technologies; and finally look at energy end use globally, with a focus on economic and social tradeoffs.

While the class includes field trips to energy-related facilities, it most prominently features a host of expert lectures by MIT researchers, many of which prove memorable for participants.

Gururaj recalls Christopher Knittel, the William Barton Rogers Professor of Energy Economics at MIT Sloan, discussing “the ethics of driving a Hummer, addressing what it means to face the social cost of something.” Fox recounts Donald Sadoway, the John F. Elliot Professor of Materials Chemistry, “hammering home the point about physics limiting current battery storage.” Both students remember the way Anne White, associate professor of nuclear science and engineering, helped them scrutinize the headline-grabbing claims made by designers of a new fusion reactor.

Instructors make it interesting for themselves, too. “We have fun going through the periodic table identifying all the elements you can make fuel out of,” says Green. “Students learn it’s hard to get away from hydrocarbons, even when you’re making something artificially.”

There also are guest lectures by industry experts. BP, a Founding Member of MITEI, participated in several sections,



Sustainable Energy students review a flow chart of the cogeneration of electricity and steam heat at MIT’s Central Utility Plant with plant engineer Seth Kinderman.

sending its chief bioscientist to talk about biofuels and the head of global exploration to discuss deep sea drilling. “We try to bring business realities and context that faculty may not be as conversant with,” says Andrew Cockerill, the company’s director of university relations. “We talk about how to use energy technologies at scale, and students see that there are sometimes conflicting needs in having a reliable and clean source of energy.”

The class has not remained static in content: In recent years, it has focused increasingly on climate change both because the “evidence becomes more and more conclusive,” says Golay, and because students are deeply motivated by the issue. “We tell them climate change is one of the biggest things going on in their lives, and there’s not a lot of time to figure things out.”

The class does not sugarcoat the challenge, emphasizing that while there is an urgent need to move away from fossil fuels, “there is nothing at hand that gives us a realistic prospect of doing it in the short run,” says Golay. The class offers examples of promising biofuels hung up by patent litigation

and windfarms sunk by community opposition. Students come to realize, says Golay, that “the problem is not so much about technology but about organization—economic incentives, taxes, ways to amplify efforts of the private sector.” For most students, says Green, this is an entirely new way of thinking. “They come in focused on invention, but we want them to see the constraints, the rules the world operates under.”

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*By Leda Zimmerman,
MITEI correspondent*

Development of the original Sustainable Energy class was led by Golay and Jefferson Tester, then an MIT professor of chemical engineering and now professor of sustainable energy systems at Cornell University. Others who played an important role in founding the course and—with Tester and Golay—in producing two editions of the textbook were Professor Michael Driscoll of nuclear science and engineering and Drs. William Peters and Elisabeth Drake, both then affiliated with the MIT Energy Laboratory and the Department of Chemical Engineering.

Nine undergraduate energy curriculum development projects launch in summer 2015

To keep the undergraduate Energy Studies Minor current with the ever-changing landscape of energy science, policy, and technology, the S.D. Bechtel, Jr. Foundation has provided funding for developing new classes and adapting existing ones. Nine projects will launch with this support in summer 2015. Five of the projects will create new energy-focused classes, and four will adapt classes already in MIT's curriculum.

New classes

Energy Management for a Sustainable Future

Harvey Michaels,
Sloan School of Management

An elective focused on the demand side of energy in the built environment, including technology, services, analytics, and policy.

Fundamentals of Smart and Resilient Grids

Konstantin Turitsyn,
Mechanical Engineering

A technical elective emphasizing the integration of novel technologies (renewables, storage) into existing power systems.

Hey Atoms, What Have You Done for Me Lately?

Jeffrey Grossman,
Materials Science and Engineering

An elective introducing first-year students to the challenges of energy generation, storage, and distribution at an atomic scale.



Photo: Benzhong Zhao G

This microfluidic device will be used in the new Reservoir-on-a-Chip class to help students visualize and model the behavior of a stream of water injected into a porous medium filled with oil—a technique used to displace oil during the development of a petroleum reservoir. The viscosity difference between the injected water (here dyed fluorescent green) and the oil in the device produces a fingering pattern that propagates outward.

Political Economy of Global Energy Markets

Valerie Karplus,
Sloan School of Management, and
Christopher Warshaw,
Political Science

A multidisciplinary option for the Energy Studies Minor's Social Science Foundations of Energy requirement examining how political and economic motivations and constraints shape energy systems.

Reservoir-on-a-Chip

Ruben Juanes,
Civil and Environmental Engineering

An Energy Studies Minor elective and a core class for the energy resources track in Course 1's new flexible 1-ENG major, where students will be involved in emerging research on the physics and visualization of subsurface reservoir flows.

Adaptations of existing classes

22.081J, Introduction to Sustainable Energy

Michael Golay,
Nuclear Science and Engineering
Designing an online class.

10.28, Chemical-Biological Engineering Laboratory

Jean-Francois Hamel,
Chemical Engineering
Incorporating clean energy.

6.061, Introduction to Electric Power Systems

James Kirtley,
Electrical Engineering and Computer Science
Incorporating energy storage.

ESD.162J, Engineering, Economics, and Regulation of the Electric Power Sector

Ignacio Perez-Arriaga,
Engineering Systems Division
Adapting for undergraduates.

• • •

By Amanda C. Graham, MITEI

Energy minor alumni: Where are they now?

Photo: James Rudd



**Chris Carper SB '10,
Mechanical Engineering**

To energy minor alumnus Chris Carper, how our offices, classrooms, and labs use energy is one of many factors that make buildings fascinating to study—and to improve. As an energy engineer at Honeywell, Carper hopes to help people make smart energy choices by thinking with a long-term perspective.

How did you know you wanted to become an energy engineer?

I've always been interested in buildings. I focus on energy efficiency in commercial buildings, and buildings are surprisingly complex. They all use energy in different ways. Each one is unique—like its own little puzzle—and that's what I like about what I do.

What is the best experience you've had working in the energy sector?

The most fulfilling part is being able to help school districts save [money] on their energy bills. It's money that they can put toward paying teachers, buying

computers, or investing in other educational media. It's great for them, because they get the extra money and their buildings get updated. It's a win-win for everyone.

How has your time at MIT played into what you're doing now?

I still think about the classes I took [at MIT]. In particular, the classes in building technology and the economics of energy have played into what I do now. I was really glad that MIT offered [the Energy Studies Minor] because it fit what I was looking for really well.

(LMAES), Amadeo looks forward to making those plans a reality.

How did you first become interested in chemical engineering?

In high school I got really involved with a biodiesel project—working that project from the ground up, learning how to make my own biodiesel processor out of a 10 gallon water heater, getting involved with the chemical reactions that happen during that process, and then producing the biodiesel and actually getting it up to [standards] to run in diesel engines. From that project, I knew I wanted to pursue chemical engineering.

What's been the best part of working in the energy sector?

As an engineer, I love working on something tangible but also innovative. For example, my work at LMAES has taught me that the possibilities for designing and synthesizing molecules for improved battery electrolytes are seemingly endless. [It's] exciting seeing how your work can improve the technology to make it more efficient and lower in cost. Energy storage is going to play a huge part in the energy sector, so I feel very privileged to be playing a significant role in a technology that could be at the forefront of that market.

Photo courtesy of Desiree Amadeo '11



**Desiree Amadeo SB '11,
Chemical Engineering**

From creating a biodiesel processor in high school to developing artificial hydrogen-producing nanoparticles at a startup out of MIT, Desiree Amadeo has had her mind on alternative energy for some time now—and she has big plans for its future. As a research and development engineer at Lockheed Martin Advanced Energy Storage

What are you most looking forward to right now?

I'm looking forward to continued improvements and upcoming milestones that will enable our flow battery to get out into the market in just a couple short years. We are moving full steam ahead, and I feel ready for the challenge.

Photo: Bryan Tan Photography



Shaena Berlin SB '13, SM '14, Earth, Atmospheric, and Planetary Sciences

With her master's in atmospheric science from MIT, Shaena Berlin moved cross-country and became an air quality associate at ENVIRON in California. What she found was that energy plays a role in everything, from housing developments to the atmosphere.

How did you first become interested in energy?

[Energy] permeates all of the policy decisions, all of people's everyday lives, so it seemed like a logical thing to try to be involved in. I was interested in air and in atmospheres, but I wanted to do something more applied with that rather than basic research. It made sense to look into how energy could relate to air quality and atmospheric science.

What have you enjoyed about working at ENVIRON?

I've [learned that] California's regulations and goals toward climate change and energy efficiency are really impressive. We're helping with permitting for new developments, and we essentially have to meet these very strict standards—one of which is trying to become zero net energy for all new residences by 2020. I've gotten to spend some time looking into the most cost-effective and efficient ways that you can reduce energy consumption and greenhouse gases.

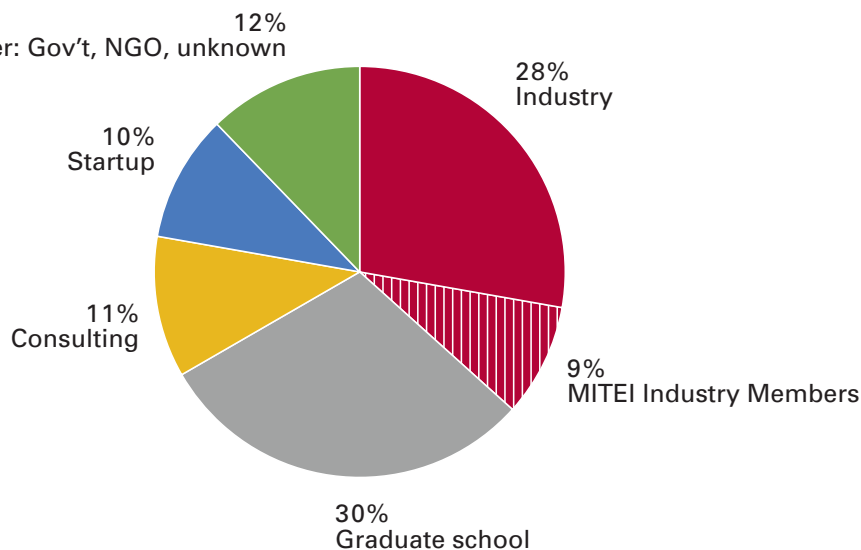
How has your energy minor played into the work you're doing now?

I think it was pretty vital for me getting this position, actually, because most of our work is engineering-focused. So just having a basic understanding of where the energy [in a new development] is coming from, where it's going, and how much is being used, has been really helpful in . . . understanding what's going on with these projects.

• • •

By Molly Tankersley, MITEI

Current status of Energy Studies Minor graduates, 2010–2014



Of the 89 Energy Studies Minor alumni to date, roughly one third are working in industry, and another third are pursuing graduate degrees. The remaining third are split among consulting firms, startup companies, government, and nongovernmental organizations (NGOs).

Five years of graduates: MIT's Energy Studies Minor comes of age

Since its launch in fall 2009, MIT's Energy Studies Minor has been engaging undergraduate students who want to broaden the expertise they obtain in their major with a deeper understanding of energy and associated environmental challenges from an interdisciplinary perspective that links natural science, social science, and technology. In 2014, the energy minor was the third largest of almost 50 minors offered at MIT. The class rosters below demonstrate the growth and breadth of the program since its founding. (Because MIT Commencement occurs after *Energy Futures* goes to press, the 2015 energy minor graduates will be listed in our next issue.)

See page 38 for a list of departments and abbreviations.

2010

Ethan Bates, NSE
Chris Carper, ME
Jeff Mekler, AeroAstro

2011

Desiree Amadeo, ChemE
Riley Brandt, ME
Tim Grejtak, ME
Yoshio Perez, ME
Nicholas Sisler, ME
Juliana Velez, ME
Erik Verlage, Physics
Rasmus Wallendahl, CEE and Mgmt
Teerawut Wannaphahoon, ME and Econ
Mitchell Westwood, ME
Ashley Wong, Mgmt
Kesavan Yogeswaran, EECS
Paul Youchak, NSE

2012

Jessica Artiles, ME
William Bender, ChemE and Econ
Matt Chapa, NSE
Brian Chmielowiec, ChemE
Zac Dearing, PoliSci and Econ
Brendan Ensor, NSE



Photos: Justin Knight

Christian Welch '13 (Mechanical and Ocean Engineering) answers questions during his team's final presentation in 15.031J, Energy Decisions, Markets, and Policies, in fall 2012. The class fulfilled Welch's Social Science Foundations of Energy requirement for the Energy Studies Minor.

Ying (Lucy) Fan, ChemE
Martha Gross, MSE
Latifah Hamzah, ME
Kirsten Hessler, MSE
Jeffrey Huang, ME
Russell Kooistra, PoliSci
Columbus Leonard, CEE
Jean Mario Martin, ME
Roberto Martinez, ChemE
Perry Nga, ChemE
Cat Thu Nguyen Huu, ME
Uuganbayar Otgonbaatar, NSE and Physics
Pedro Salas, Econ
Bensey Schnip, Math
Scott Sundvor, ME
Alex Vaskov, ME
Sean Vaskov, ME

2013

Shaena Berlin, EAPS
Sara Rose Comis, ME
Jackson Crane, ME
Vivian Dien, MSE
Christopher Hammond, ME
Timothy Jenks, ME
Nityan Nair, Physics



Since graduation, Ying (Lucy) Fan '12 (Chemical Engineering) has applied her training in the energy minor to professional work in energy market analysis and renewable energy investment management.

Prosper Munaishe Nyovanie, ME
 Brian Oldfield, ME
 Nathan Robert, ME and Physics
 Ron Rosenberg, MSE
 Melissa Showers, ME
 Casey Stein, DUSP
 Christian Livingston Welch, MOE
 Trevor Zinser, ME

2014

Ignacio Bachiller, ME
 Jacqueline Brew, ChemE
 Ronald Chan, ME
 Alix de Monts de Savasse, ME
 Daniel Eisenberg, ChemE
 Jad El Khoury, ME
 Taylor Farnham, ME
 Ryan Friedrich, ChemE
 Brian Gager, MSE
 Samantha Hagerman, ChemE
 Jacqueline Han, PoliSci
 Jenny Hu, Mgmt
 Jacob Jurewicz, NSE and Physics
 Marc Kaloustian, ChemE
 Claire Kearns-McCoy, ME
 Charlotte Kirk, ChemE
 Johnathan Kongoletos, ME
 Erica Lai, MSE
 Zainab Lasisi, ChemE
 Lisa Liu, EECS
 Phillip Marmolejo, ME
 Matthew Metlitz, ME
 Jordan Mizerak, ME
 Mateo Pena Doll, ME
 Sidhanth Rao, ME
 Jonathan Rea, ME
 Manuel Romero, ME
 Christiana Rosales, ME and Arch
 Anthony Saad, ChemE
 Dhanansai Saranadhi, ME
 Samuel Shames, MSE
 Katherine Spies, ME
 Maria Tou, ChemE
 Aleyda Trevino, Physics and Math
 Akshar Wunnava, ChemE

Photos: Justin Knight



Juliana Velez '11 (Mechanical Engineering) examines part of the low-cost device for cutting scrap solar cells she helped design and build in EC.711, D-Lab: Energy for use in Nicaragua.

Departments and abbreviations

Aeronautics and
 Astronautics (AeroAstro)
 Architecture (Arch)
 Biological Engineering (BE)
 Chemical Engineering (ChemE)
 Civil and Environmental
 Engineering (CEE)
 Earth, Atmospheric, and
 Planetary Sciences (EAPS)
 Economics (Econ)
 Electrical Engineering and
 Computer Science (EECS)
 Management (Mgmt)
 Materials Science and Engineering (MSE)
 Mathematics (Math)
 Mechanical Engineering (ME)
 Mechanical and Ocean
 Engineering (MOE)
 Nuclear Science and Engineering (NSE)
 Physics (Physics)
 Political Science (PoliSci)
 Urban Studies and Planning (DUSP)



Left to right: Zainab Lasisi '14 (Chemical Engineering), Samuel Shames '14 (Materials Science and Engineering), and Jenny Hu '14 (Management) graduated with 32 other students in the largest class of Energy Studies Minor students to date.

MITEI sponsors energy-related tours, events during IAP 2015

Every January, MIT students, faculty, and staff take part in the Institute's Independent Activities Period (IAP), when they are invited to step outside their comfort zones, dabble in unfamiliar areas, and encounter a richer view of the world. In 2015, members of the community could fill their days and nights with new experiences ranging from touring a nuclear fusion reactor, to using Fermat's rule to analyze election results, to trying a (very steady) hand at the art of the Japanese Tea Ceremony.

Each year, the MIT Energy Initiative (MITEI) sponsors a number of energy IAP events and helps publicize other energy-related activities organized by faculty and students across campus. This year, MITEI's offerings included tours of the Kendall Cogeneration Station, the Massachusetts Department of Transportation Highway Operations Center, the MBTA Operations Control Center, the Aramco Research Center, the LEED Platinum Artists for Humanity building, and the Massachusetts Clean Energy Center's Wind Technology Testing Center. MITEI also offered information sessions for undergraduate students interested in learning more about energy-related undergraduate research opportunities (UROPs) and MIT's Energy Studies Minor.

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By Francesca McCaffrey, MITEI

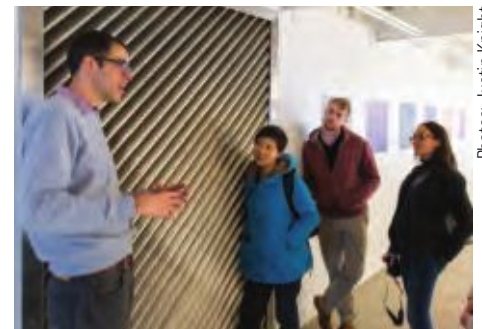


Photo: Dylan Ayers, MITEI

Those on the Energy Underground: MassDOT and MBTA Facilities and Tunnel Tour were given a first-hand look at what goes on in the MBTA Operations Control Center, shown above. Screens paneling the room monitor everything from weather to in-station security cameras and the status of trains traveling the tracks. Participants learned how America's oldest subway system operates on a daily basis, as well as how it handles weather emergencies—a particularly timely topic this winter.



During IAP, MITEI organized a group tour of Veolia Energy North America's Cogeneration Station in Kendall Square, Cambridge. The facility generates electricity to power the region's electrical grid and provides steam heat to Veolia's 220 customers throughout Boston and Cambridge. Within the plant, natural gas is burned in an electricity-generating combustion turbine. Heat remaining in the exhaust gas is used in a heat-recovery steam generator to produce high-pressure steam. Some of this steam is exported, while the rest runs a steam-driven electric power generator. A recent reconfiguration of the facility, including a 7,000-foot steam pipeline extension, is estimated to reduce greenhouse gas emissions by approximately 475,000 tons per year. Giving the tour at the far right of the photo is Veolia's Director of Network and Distribution George Hengerle.



Photos: Justin Knight

From left: During a tour, Andrew Motta, operations director for Artists for Humanity, describes highlights of the group's LEED Platinum-certified studios to MIT graduate student Yuqi Wang, Dylan Ayers of MITEI, and MIT postdoctoral fellow Ornella Iuorio. Behind Motta is a vent that provides cool air to the building. To save energy, Artists for Humanity's studios were built without air conditioning. Instead, fans situated on the building's roof blow air down a shaft and into this vent at night, when the outdoor air is coolest. As a result, the building starts each day cooled to a comfortable temperature, with no need for the constant energy expenditure of air conditioners.

Changing the game: Building MIT's capacity for a sustainable future

It was an event “choreographed in true MIT fashion,” stated Julie Newman, director of MIT’s Office of Sustainability. This meant that the Institute’s March 2 conference, SustainabilityConnect, was emphatically multidisciplinary and designed to promote systems thinking. From the wide range of campus presenters and panelists to the paper-free, real-time, online agenda, the daylong forum signaled its singular purpose: to make MIT a game-changing force for sustainability in the 21st century.

On the job for 18 months, Newman has been assessing the Institute’s standards, practices, and aspirations related to energy and the environment; synthesizing input from a multitude of sustainability stakeholders, including the MIT Energy Initiative, the MIT Environmental Solutions Initiative, and the Climate Change Conversation; and convening new campus working groups—in such arenas as design and construction; waste, stormwater, and land management; and green laboratories. Faced with the task of drafting recommendations, Newman proposed to bring together key players from across MIT in the belief, she said, that “innovation emerges from collisions.”

This gathering came at a critical moment for MIT, as Israel Ruiz, executive vice president and treasurer for the Institute, explained to attendees. “We are in one of the largest construction periods MIT has ever undertaken, and it is an opportune time to think what the campus should look like in 2025 and beyond,” he said. There are billions of dollars at stake, not just in new construction but in deferred maintenance for the old buildings. “The elephant in the room is the age of the campus,” noted Tony Sharon, MIT deputy executive vice president, who is in charge of this capital renewal. “There is a huge



Photos: Justin Knight

Israel Ruiz, MIT's executive vice president and treasurer, observed that the Institute is currently in one of the largest construction periods it has ever experienced, offering opportunities to ensure that new buildings and renovations respect—from the earliest design stages—principles of efficiency and sustainability in their energy, water, waste-handling, and other systems.

opportunity here, but we don't have the right metrics for sustainability.”

To that end, SustainabilityConnect invited approximately 125 staff, faculty, and administrators to share their expertise and to discuss the most effective ways of improving and reinventing the systems that make MIT run—such as the energy mix that powers buildings, the flow of materials through campus via procurement and waste management, and the ways in which people move to, from, and around campus. The conversations also covered the imperative to collect meaningful data and measure outcomes, set aggressive policies, assess risk and strengthen resilience, and work cooperatively with neighbors in Cambridge, Boston, and beyond. MIT could serve as a living laboratory for innovative, proven sustainable strategies, suggested Newman, ultimately scaling up its solutions to make a global impact.

Judging from the testimony of panelists, the Institute already has begun pushing the edge on key sustainability issues. For instance, construction is just beginning on MIT.nano, a research and fabrication facility that—like most laboratories—is particularly energy-intensive. The project's director, Vladimir Bulović, the Fariborz Maseeh Chair in Emerging Technology and associate dean for innovation, said he would like this center, which will host up to 2,000 researchers, to “show the best paradigm and practices.”

His team identified more than 100 different sustainability options, such as bigger air purifying filters that require fewer air exchanges per hour and less energy to operate, and a means of reutilizing heated air. Running the numbers, Bulović noted, demonstrates that it is possible to recover any additional costs for sustainable measures quickly and that there are “even extra energy savings after point of payback.”



Members of the panel “Framing Our Future: How Can MIT be a Game-changing Force for Campus Sustainability?” (from left): Frank O’Sullivan, director of research and analysis, MIT Energy Initiative (moderator); Henry Jacoby, William F. Pounds Professor of Management Emeritus, Joint Program on the Science and Policy of Global Change, and member, MIT Climate Change Conversation Committee; Jeremy Poindexter, graduate student in materials science and engineering; John Charles, vice president for Information Systems and Technology; Bina Venkataraman, director of global policy initiatives at the Broad Institute; and Vladimir Bulović, associate dean for innovation and professor of electrical engineering.

Look around campus, advised Bulović, and “you’ll recognize a tremendous number of opportunities” for energy savings.

Such opportunities might include new energy sources. Another speaker, Jeremy Poindexter, a second-year PhD student in materials science and engineering, described a class project that identified campus rooftops with “the potential for providing up to 4 megawatts of solar capacity...and these are buildings where we could install solar systems immediately without the need for any serious retrofit work.”

Speakers also addressed critical issues of risk and resilience. Nathalie Beauvais, a project manager with Kleinfelder Associates, is developing a comprehensive assessment of climate change vulnerability for the City of Cambridge. She projected an enhanced threat of flooding on the MIT campus due to increased precipitation between now and 2030. This risk, she said, along with the likelihood of more frequent extreme heat events, suggests that MIT should look now for ways to protect infrastructure, especially vital systems such as its power plant.

These kinds of vulnerabilities are shared with Kendall Square and other parts of Cambridge, noted Henry Jacoby, William F. Pounds Professor of Management Emeritus, Joint Program on the Science and Policy of Global Change. “This is a game we need to be in, not just for ourselves but to support our communities,” he said. “The campus is really the city, because we don’t survive, or sustain, unless the city we’re in sustains as well.”

James Wescoat, Aga Khan Professor in architecture, pointed out that disaster resilience could be more than just a



Photo: Justin Knight

Bina Venkataraman, former senior advisor on climate change innovation for the Obama administration and now at the Broad Institute, said that MIT could inspire and empower communities and companies by modeling new technologies and innovations at scale.

risk-management or building-design question but “rather a visionary principle for campus planning.” He suggested it might be useful to broaden the concept of resilience to include ecosystem and psychosocial well-being. In particular, he noted “enormous opportunity for the outdoor campus, the environment outside of buildings, to become a great laboratory.”

Since MIT stands at the intersection of research and practice, Bina Venkataraman, director of global policy initiatives at the Broad Institute, said that MIT could help originate a marketplace for climate change risk information and also model new technologies and innovations at scale. Such a venture might really inspire and empower communities and companies to make constructive decisions around policy and to prepare for a changing environment. “MIT can and should evolve the role of scientists and campus operations to develop a clinical practice for climate change,” she said.

In workshops, faculty, students, and administrators wrestled with ways to integrate sustainable principles and practices into the fabric of MIT. Many warmed to the idea of organizing a

hackathon and competitions to spur new approaches to campus energy innovation. Some groups wanted to set guidelines for new and renovated buildings to ensure their survival in 10-year storms. Others suggested using sensors and digital technology to create real-time data feeds on air quality, energy use, and water use—available to the entire MIT community—to track progress and to help people make decisions that address climate change.

Some groups targeted the creation of a sustainable campus by seeding an urban canopy, capturing stormwater for reuse as gray water, and launching a community farm with compost generated onsite. “One thousand flowers blooming is the nature of a living lab,” said Jason Jay, senior lecturer and director of the Sustainability Initiative at the MIT Sloan School of Management. It will be hard to know “all the cool stuff going on, so we should have a way of accumulating this learning and institutional memory.”

In the coming months, the Sustainability Office will begin channeling these ideas into a set of recommendations for the newly appointed Sustainability

Task Force, a group of faculty, students, staff, and representatives from key administrative areas who will together shape the vision and plan of action for campus sustainability at MIT. “We think of it as mapping components together, providing a systems response,” said Newman, “because making decisions through a sustainability lens means integrating questions of energy, transport, stormwater and land management, design, construction, procurement, and materials.”

These are questions she believes the Institute will revisit frequently over time. But, she says, “I feel reassured after this forum that we have the ability not only to embrace complexity but to think collectively and creatively—just the kind of capacity-building we need as we embark on the long-term commitment to sustainability.”

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*By Leda Zimmerman,
MITEI correspondent*

[For videos and other materials from the forum, please visit sustainability.mit.edu/sustainabilityconnect.](http://sustainability.mit.edu/sustainabilityconnect)

MIT Energy Conference: “There is no more important issue than energy”

At the conclusion of MIT’s 10th annual Energy Conference, panelist Cheryl Martin, director of the US Department of Energy’s ARPA-E research program, declared, “There is no more important issue than energy.”

Urging students to work to supply sufficient energy for a growing population while reducing emissions, Martin added, “It needs every discipline to be in the game.”

The student-run event, held this year on February 27–28, was founded by David Danielson PhD ’08, then an MIT graduate student and now the US assistant secretary of energy and director of the Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy. Danielson, who also founded MIT’s Energy Club—now the Institute’s largest student group—returned to campus both as a keynote speaker and as moderator of the final panel discussion at this year’s conference.

“The last 10 years have been a wild ride in energy,” Danielson said, reflecting on dramatic and unexpected changes including the shale-gas boom, the rise of extreme weather events, and a steep drop in the costs of solar and wind power.

Danielson observed that MIT’s long history of cross-disciplinary research has been especially relevant to energy and combating climate change. “This interdisciplinary culture is a critical element,” he said. “The divisions really blur.”

Danielson also reflected on how far the Institute has progressed in energy research and education. When he arrived on campus, in 2001, as a student interested in solar power, he was

Photo: Justin Knight



Professor Robert Armstrong, director of the MIT Energy Initiative, welcomed attendees to this year’s MIT Energy Conference and outlined his view of the world’s energy challenge and five key technologies that can help.

astonished to find only one course in that field, and no energy-related student organization. Now MIT has dozens of researchers working in the solar arena; and the Energy Club has more than 5,000 student, faculty, staff, and alumni members and organizes more than 100 events every year. Danielson also pointed out that five of the club’s past presidents are now working at DOE.

And MIT research is having a real impact, he added: Among the 17 initial advanced research projects that DOE funded when Danielson started working there, one was by Donald Sadoway, the John F. Elliott Professor of Materials Chemistry, to produce a low-cost liquid battery for utility-scale storage. While this “phenomenal idea” was first seen as risky and speculative, it has now led to the creation of a company that has raised \$50 million and will be installing its first grid-scale batteries this year.

Robert Armstrong, the Chevron Professor of Chemical Engineering and director of the MIT Energy Initiative,

kicked off the conference by summarizing a dual challenge: On the one hand, he said, the world is expected to need to double its energy supply by 2050, thanks to a combination of population growth and rising standards of living in developing nations. At the same time, there is a need for drastically reduced emissions from present energy-supply systems, which are still mostly based on fossil fuels. “How do you double the output and still reduce carbon emissions?” Armstrong asked.

He suggested five broad areas that could contribute: a major growth in cheap, reliable solar energy; better methods for storing energy; improvements in the adaptability and reliability of the electric grid; increased use of nuclear energy; and the development of affordable and dependable carbon capture and sequestration systems.

Other keynote speakers at the conference were Thomas Siebel, founder and CEO of C3 Energy; William Colton, vice president for strategic planning at ExxonMobil; Ahmad Chatila, president and CEO of SunEdison; Dirk Smit, vice president of exploration technology research and development at Shell Oil; and William von Hoene Jr., chief strategy officer of Exelon Corporation.

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

To read the full article, go to newsoffice.mit.edu/2015/mit-energy-conference-0303. For more information about the 2015 MIT Energy Conference, go to mitenergyconference.org.

MITEI Founding and Sustaining Members

MITEI's Founding and Sustaining Members support "flagship" energy research programs or individual research projects that help them meet their strategic energy objectives. They also provide seed funding for early-stage innovative research projects and support named Energy Fellows at MIT. To date, members have made possible 140 seed grant projects across the campus as well as fellowships for more than 300 graduate students and postdoctoral fellows in 20 MIT departments and divisions.

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MITEI Associate and Affiliate Members

MITEI's Associate and Affiliate Members support a range of MIT energy research, education, and campus activities that are of interest to them. Current members are now supporting various energy-related MIT centers, laboratories, and initiatives; fellowships for graduate students; research opportunities for undergraduates; campus energy management projects; and outreach activities, including seminars and colloquia.

Associate Members

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Jerome I. Elkind '51, ScD '56
Ernst & Young LLP
Dennis Fromholzer '75
Fundació Barcelona Tecnológica (b_TEC)

Gas Technology Institute
Natalie M. Givans '84
Gail Greenwald '75
Roy Greenwald '75
Thomas Guertin PhD '60
Harris Interactive
Lisa Doh Himawan '88
Andrew A. Kimura '84
Paul Mashikian '95, MNG '97
Massachusetts Clean Energy Center
New York State Energy Research and Development Authority
Osaka Gas Co., Ltd.
Philip Rettger '80
Doug Spreng '65
George R. Thompson, Jr. '53
David L. Tohir '79, SM '82
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MIT architects tackle India's slum problem

MIT researchers affiliated with the Tata Center for Technology and Design are teaming up with staff from the Hunnarshala Foundation, a leading Indian nongovernmental organization, to design, test, and demonstrate housing for low-income residents in India. Their goal: to provide options that are energy efficient, environmentally sustainable, and safe in earthquake-prone regions of the world. In one project, they are constructing tiny one-room structures—such as the one shown above being built by a Hunnarshala staff member—and are using them to assess the thermal performance of new kinds of low-cost insulations and roof assemblies as well as designs for natural ventilation. Other work focuses on developing safer, more sustainable neighborhoods and designing construction materials based on readily available materials. For more information, see page 27. Photo: Madeline Gradillas G