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300

200

359

65

25

671

39

76

81

41

10.7

12

STRENGTH IN NUMBERS

A LETTER FROM THE PRESIDENT

MIT'S ENERGY INITIATIVE

When I arrived at MIT more than seven years ago, I began by listening — and I heard, from every quarter, the clear, unambiguous message that it was time for the Institute to step up and do some truly serious work to help change the world's energy equation. By launching the MIT Energy Initiative (MITEI) in the fall of 2006, we committed the full force of MIT's irrepressible problem solving and bold creativity to the challenge of inventing a sustainable energy future.

Since then, MITEI has turned MIT into a hotbed of energy innovation, a central source of unbiased analysis for framing national policy, a model for campus energy management, and a leader in preparing and inspiring the next generation of energy pioneers. This issue of SPECTRVM celebrates MITEI's achievements on the frontiers of energy research, from bioengineering strategies for better biofuels, to construction technologies geared to deliver dramatic increases in energy efficiency, to nanoengineered surfaces designed to help alternative energy technologies become competitive with fossil fuels.

From engineering and science to economics, architecture, urban design and management, MIT offers unparalleled expertise in the key energy-related disciplines, together with a gift for finding answers at the intersections in between. Given these distinctive strengths, for MIT the challenge of making sustainable energy a mainstream solution represents both an opportunity and a responsibility of unprecedented scale. Thanks to the vision and generosity of many individual donors and of the dozens of corporations and government entities that have stepped forward as MITEI sponsors, MITEI faces this challenge armed with nearly $360 million in research and educational funding. For designing and driving this remarkable engine of new ideas, we owe enormous thanks to MITEI's Director, Professor Ernest J. Moniz, and Deputy Director, Professor Robert C. Armstrong, as well as to MITEI's distinguished External Advisory Board, under the leadership of former U.S. Secretary of State George P. Shultz PhD '49.

In the last five years, the broad terrain of energy has heaved and buckled beyond anyone's power to predict — including the global economic crisis and the collapse of carbon policy, the Fukushima disaster and the Macondo oil spill, and the rise of new shale technologies that have transformed the U.S. into the world's leading producer of natural gas. But through it all — with a signature MIT combination of optimism, curiosity, ingenuity, and eagerness to serve — MITEI's faculty, students, staff, and supporters have sustained a singular focus and remarkable momentum for change. I am proud of all they have accomplished and deeply grateful for their unswerving commitment to solving the urgent human need for sustainable energy.

Sincerely,

Susan Hockfield

SPRING 2012

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MITEI@5

300 FACULTY MEMBERS INVOLVED

200 GRADUATE FELLOWS IN ENERGY

$359 MILLION RAISED FOR RESEARCH/EDUCATION

INDUSTRY/INDIVIDUAL MEMBERS **65**

SUPPORT RESEARCH AND ANALYSIS **25**

671 FUNDED RESEARCH PROJECTS

39 STUDENTS ENROLLED IN ENERGY MINOR

76 FUNDED STUDENTS IN UNDERGRADUATE RESEARCH OPPORTUNITY PROGRAM

81 SEED FUND PROJECTS TOTALING **$10.7 MILLION**

41 SEMINARS SYMPOSIA COLLOQUIA

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MIT's Energy Initiative Reaches a Milestone

Energy for the Future

Since the creation of the MIT Energy Initiative (MITEI) five years ago the world's energy landscape has changed, from the lows of the Fukushima nuclear disaster to the highs of a game-changing source of natural gas. Over that period, MITEI has thrived. Ernest Moniz, the Cecil and Ida Green Professor of Physics and Engineering Systems and director of MITEI, says it has had an impact on research, education, and policy. "I'm encouraged by our approach," says Moniz. "The energy world has changed dramatically in five years, but I think MITEI's portfolio has proved to be quite up to the task."

Chief among the world's energy challenges, says Moniz, is climate change, triggered in large part by the carbon dioxide released during the use of traditional fuels. If we don't dramatically cut those emissions, "Mother Nature will give us sterner and sterner warnings. I believe she already is," says Moniz, who leads MITEI with Deputy Director Robert Armstrong, the Chevron Professor of Chemical Engineering. "We'll probably need to reduce carbon emissions by at least half over the next 50 years, and that's while serving many more people."

The Institute-wide initiative aimed at tackling the world's energy problems has more than 20 industry members sponsoring research and analysis and has helped launch nearly 700 research projects. Major concentrations range from solar energy to hydrocarbon production. Many projects have gone on to procure significant follow-on government and industry funding and to patent applications, in addition to publications and theses. More than 10 energy technology spinoff companies have emerged. "We are seeing the fruits of MITEI research projects along the whole innovation chain, from basic science to the marketplace," says Moniz.

MITEI also last year released three multidisciplinary studies on the Future of the Nuclear Fuel Cycle, of Natural Gas, and of the Electric Grid. The 287-page natural gas report by 30 MIT researchers was presented to the U.S. Senate in a hearing before its Committee on Energy and Natural Resources. MITEI has "helped influence the national — and to a certain extent international — debate" over the future of energy, says Moniz, who is one of 20 U.S. scientists and engineers on President Obama's Council of Advisors on Science and Technology and served as a past undersecretary of the U.S. Department of Energy.

MITEI has also had an impact on education at MIT, most notably through the creation of an energy minor for undergraduates. The minor, like MITEI's research portfolio,

Ernest Moniz and Meg Jacobs are shown before a world map depicting energy consumption from space.

Len Rubenstein / Richard Howard / World map courtesy NASA

is multidisciplinary, cutting across all five MIT schools. “Disciplines from engineering to social science are essential to solving the energy problem,” says Moniz. He notes the importance of new teaching materials that are growing from MITEI’s support of educational initiatives, such as a 1,000-page textbook being written for Cambridge University Press by two faculty who developed a new course on the physics of energy. Another important MITEI initiative: catalyzing collaboration of faculty and students with MIT’s physical plant to reduce campus energy use.

What’s next for MITEI? For one, the initiative will have some new research emphases, says Moniz. These include studies around the intersection of energy and water — how much energy it takes to create clean water, and how water is used to produce energy. Another major thrust involves large-scale infrastructure systems like the electric grid. For example, says Moniz, “how can we integrate renewable energy sources at a very large scale into a reliable, efficient energy delivery system?”

Assoc. Prof. Meg Jacobs is a historian on energy issues. “One of the important lessons from the nation’s first energy crisis in the ’70s is the need for ongoing, sustained research that’s independent of both politics and market positions,” says Jacobs, who teaches a new class, *The Energy Crisis: Past and Present*, and is writing a book about the ’70s crisis called *Panic at the Pump.* She explains that when that crisis ended in the ’80s because of changes in the market and politics, momentum for tackling energy challenges stalled.

MITEI matters, she says, because the initiative, and President Susan Hockfield’s commitment to it, “announces to the world that MIT is going to make a sustained effort and therefore a real contribution to solving today’s crisis.” Further, MIT not only conducts core research, “it has longstanding ties to government and industry that can translate technological breakthroughs into real-world applications.”

Moniz says: “Clean energy is obviously an area where a lot of MIT faculty and students want to make a difference. It’s that tremendous enthusiasm that makes us feel like going to work.” ~ ELIZABETH THOMSON

In this issue:

innovations

TRICKLE DOWN EFFECT

Geoscientist Ruben Juanes takes the notion of "trickle down" farther than most — thousands of meters farther.

Juanes, ARCO associate professor of energy studies, looks at how fluids interact in out-of-the-way places in the earth's crust where excess carbon dioxide (CO_2) might be stowed and untapped oil reserves lurk. Less viscous fluids, he has found, percolate through thicker ones in "viscous fingers" that look like tentacles or drips on the side of a paint can. Juanes explores how these fingers, with the help of gravity, migrate through porous solids. His work is primarily funded by the U.S. Department of Energy and Eni SpA.

When CO_2 dissolves in water, the density of water increases. This seemingly innocuous phenomenon has profound implications for geologic carbon sequestration, in which compressed CO_2 is injected in deep porous layers filled with brine. As a result, a configuration with heavy fluid on top leads to an instability that can increase storage capacity of underground reservoirs by a factor of five or more, providing "a huge advantage" in sequestering CO_2 to prevent it from contributing to global warming, he says. "Once CO_2 is in water, you've won the game."

Knowing how fast CO_2 will dissolve in water and how likely it is to leak through an underground fault or to reach an outcrop are key bits of information for engineers. Juanes' research team has already measured the CO_2 capacity for the most promising geological basins in the U.S. and is about to embark on an international project with far-reaching significance. In Abu Dhabi, Juanes will lead a multi-institution collaboration to sequester CO_2 on an ambitious scale. "This is a world-class project that could really influence the prospects of sequestration in the Middle East and worldwide," he says.

Ruben Juanes examines fluids in out-of-the-way places in the earth's crust. Len Rubenstein

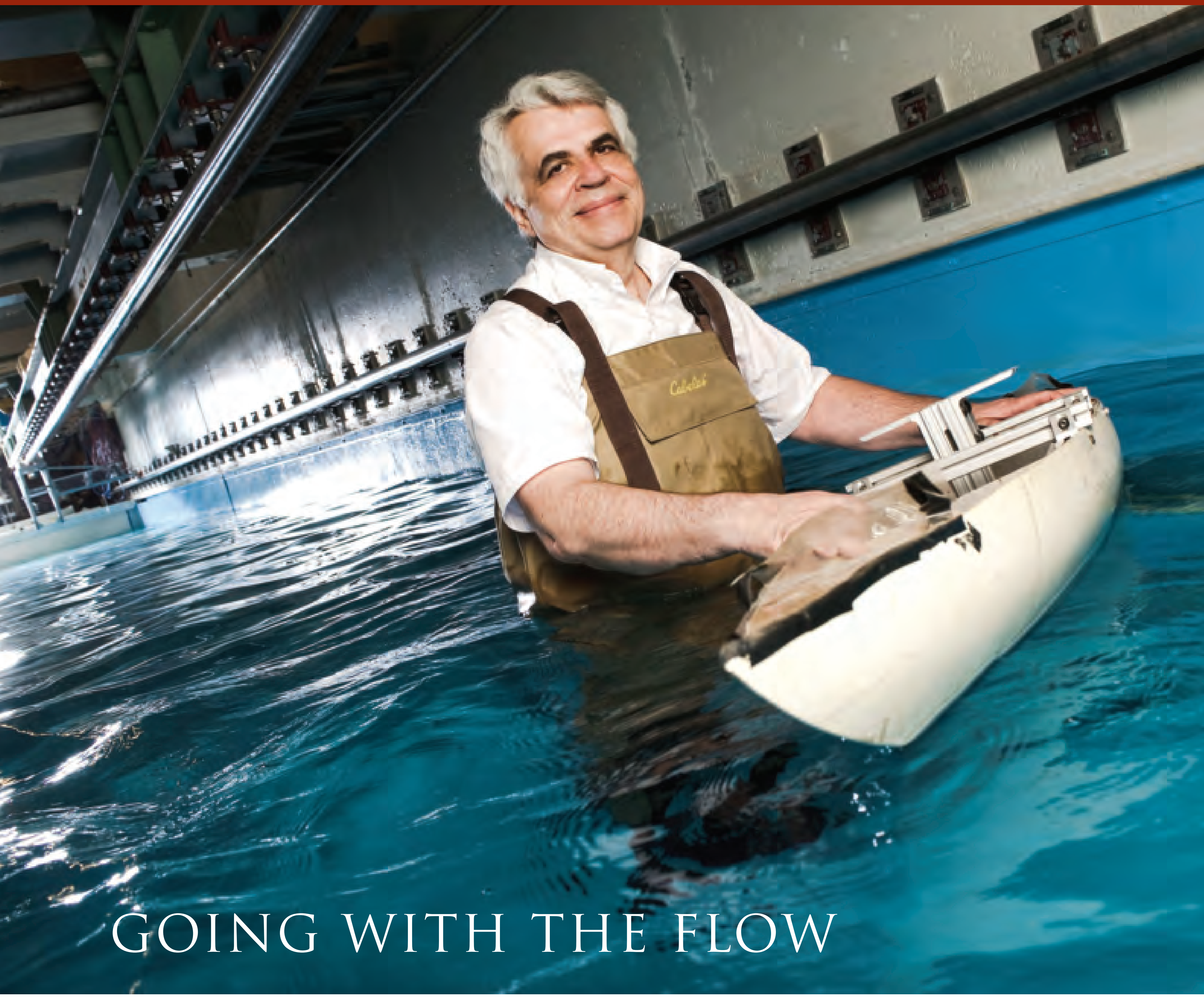
"In Abu Dhabi, Juanes will lead a multi-institution collaboration to sequester CO_2 on an ambitious scale."

Juanes' work also has implications for the oil industry. To extract viscous crude oil the consistency of honey from porous rock, engineers have typically injected steam into crevices to increase the oil's temperature and flow. This is energy-intensive, expensive and not always feasible. Juanes has studied the process of "viscous fingering," which takes place when fluids less viscous than oil are introduced. "With viscous fingering, the two fluids mix more rapidly," he says. This process allows the oil itself to become less viscous and easier to extract, potentially facilitating the recovery of a whole new energy source. So-called heavy oil "has the potential to shift the geopolitics of oil to areas such as Canada, the U.S., and South America, areas not typically perceived as the biggest oil producers," he says.

"Addressing these very large-scale problems with important societal ramifications, such as access to energy and striking a balance between energy and the environment, really relies on understanding the fluid dynamics that control these processes at a much smaller scale," he says.

~ DEBORAH HALBER

The world's global energy consumption rate today, in trillions of watts: 14



GOING WITH THE FLOW

Michael Triantafyllou is giving vessels fish-like perception. Len Rubenstein

Losing the flow is a drag — literally. When a submersible or ship turns, or the current shifts, water flowing along one side of its hull pulls away. The resulting flow that looks like a large rotating and turbulent cavity produces a large force that takes a lot of energy for the vessel to overcome. Michael S. Triantafyllou has a solution: give vessels fish-like perception.

Fish have lateral lines of pressure sensors along the sides of their bodies. The sensors let fish sense flow, which allows them to maneuver efficiently, said Triantafyllou, the William I. Koch Professor of Marine Technology and director of MIT's Center for Ocean Engineering.

As it turns out, he says, a well-developed technology is ideal for making artificial lateral lines: pressure sensor arrays made from microelectromechanical systems, or MEMS. Each sensor is about a millimeter in diameter.

"AUVs are poised to play an important role in the future of the world's energy supply."

Triantafyllou, whose work is funded by Chevron Energy Technology, is focusing his initial efforts on putting artificial lateral lines on autonomous underwater vehicles, or AUVs. Saving energy is critical for these battery-powered vessels. Despite ongoing advances in battery technology, AUVs are still limited to about six hours of operation.

As oil and gas companies increasingly operate in deep waters, AUVs are poised to play an important role in the future of the world's energy supply. The vehicles promise to be more maneuverable than today's tethered remotely operated vehicles when operating in dark, turbulent waters thousands of meters below the surface. Extending the vehicles' operating times by making them more energy efficient is a key requirement for using them in deepwater oil and gas operations.

The energy savings are significant. "We're estimating a 30 to 40 percent savings in energy by having these sensors," Triantafyllou said. Add flow control, and you save more energy, he added.

Triantafyllou's team is beginning to move beyond simply sensing flow to the ability to control it. Taking another lesson from fish, Triantafyllou is looking to give AUVs fins that can oscillate. "This oscillation causes the flow to change," he said. Instead of being separated, the flow reattaches.

Saving energy isn't the only advantage of artificial lateral lines. Fish also use their natural pressure sensors to sense nearby objects. Triantafyllou calls this ability touch at a distance. This sense is so finely developed that blind Mexican cave fish are able to dart among obstacles that are new to them. AUVs with this capability could maneuver in the equipment-cluttered environments typical of deepwater energy operations.

The technology is poised for rapid adoption. Triantafyllou noted that 15 years ago, a similar technology — a MEMS-based accelerometer — cost as much as $200. Today it costs 30 cents. This allows auto manufacturers to put 50 of them in a car, he said. Add MEMS-based pressure sensors to sea-going vessels and you get "a substantial immediate savings with very little investment," Triantafyllou said.

~ ERIC SMALLEY

outreach

THE ECONOMICS OF ENERGY

A major challenge in tackling the energy and climate crises is figuring out what policies are effective in the real world. MIT's Christopher Knittel tackles this by applying empirical science- and engineering-informed economic research. "I look to see how consumers and firms react to changes in energy prices and what that means for the costs and benefits of environmental policies," Knittel said.

Last year Knittel was named to the first energy chair at MIT: the William Barton Rogers Professor of Energy Economics at the MIT Sloan School of Management. The MIT Energy Initiative (MITEI) has launched a program to create several endowed faculty chairs in order to expand the Institute's already substantial commitment to energy research and education.

Knittel's recent attention-getting research includes a paper that examines technological progress in the automobile industry from 1980 to 2006. Knittel found that fuel economy increased by 12 percent, horsepower doubled, and weight increased by 30 percent. So nearly all of the technological progress in the industry has gone into weight and horsepower, said Knittel. "That's not surprising given that gasoline prices were so cheap from the late '80s on," he said.

Knittel's analysis allowed him to answer a key question: What would have happened had the industry's technological progress gone into fuel economy instead. The answer: it would have been 60 percent higher than 1980 levels rather than 12 percent higher. "So that tells us that had policies been in place that incentivized consumers and firms to care more about fuel economy, the [policies] would've had a big impact," said Knittel.

Cap and trade, the market-based approach to curbing greenhouse gas emissions, also was examined under Knittel's microscope. Knittel assessed the impact of cap-and-trade policies on local pollution and found that raising fuel prices drives many of the dirtiest cars off the road. The result is a co-benefit: reduced greenhouse gas emissions and reduced local pollution. "In some cases, even if you ignore the greenhouse gas benefits from this policy, the local pollution benefits are larger than the cost to consumers," Knittel said.

He also compared fuel-side policies — renewable fuel quotas and subsidies — to cap and trade to determine which approach is more cost effective in reducing greenhouse gas emissions. "These other policies are anywhere between three and five times more expensive than a cap-and-trade program," he said.

This raises the question of how these policies are enacted. The answer is that a few communities gain substantially, but the overall costs are spread across the population. "These other policies are bad on average but the typical consumer doesn't lose that much, so there's no real natural group that's going to oppose [them]," Knittel said. "In contrast, they produce a few huge winners, so there is a natural group of supporters."

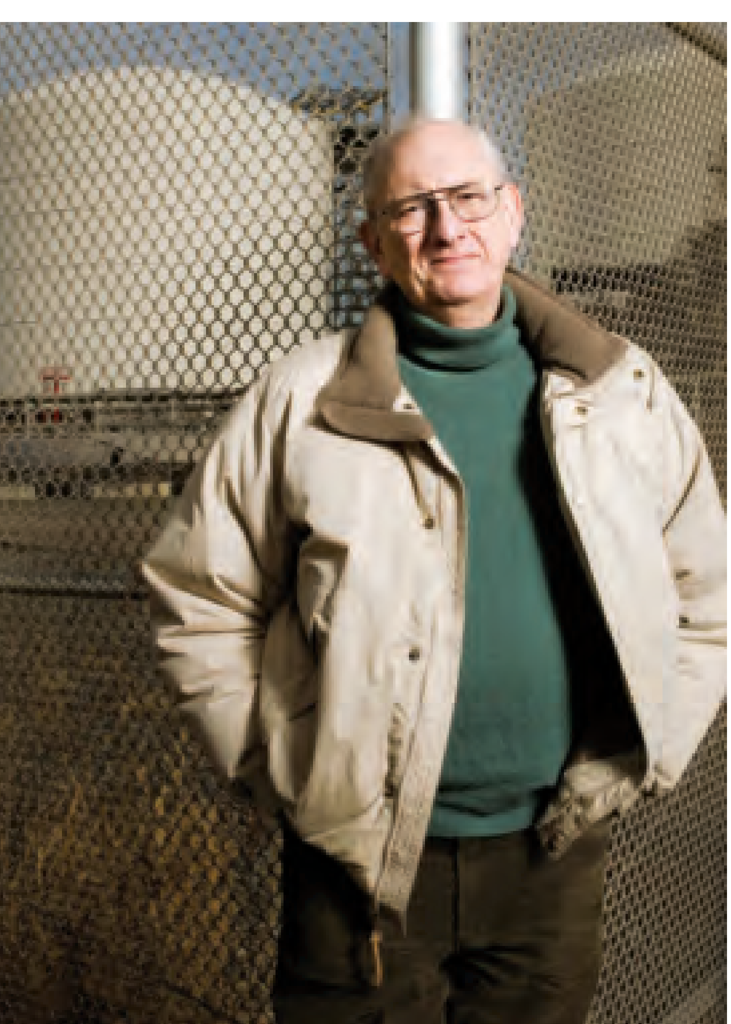
Economists studying energy policy have to have access to experts in science and engineering, Knittel said. "Interdisciplinary work is encouraged at MIT. It's fostered here. I can't think of a better place to be." ~ ERIC SMALLEY

Christopher Knittel focuses on transportation policy.

Len Rubenstein

THE FUTURE OF NATURAL GAS

Since its release last year, an MIT study on the future of natural gas has generated nearly 17,000 unique page hits on its website. Not bad for a 287-page technical report.



Henry Jacoby at the liquefied natural gas tanks in Chelsea, MA. Len Rubenstein

Among its conclusions: natural gas will play a major role in reducing greenhouse gas emissions over the next several decades, largely by replacing inefficient coal plants with gas plants that emit less carbon dioxide. Also it reveals, we must pay attention to environmental concerns related to the resource. "If we don't deal with these concerns seriously, we could lose access to the resource and its positive environmental and economic effects," says Henry Jacoby, who led the study with Ernest Moniz, director of the MIT Energy Initiative (MITEI), and Visiting Engineer Anthony Meggs. Another conclusion is that increasing supplies of the fuel could have important geopolitical implications, changing the dynamics of the international energy market.

Over the last few years, natural gas from an unconventional source — shale — has become the largest U.S. energy story in decades, says Moniz, past undersecretary of the U.S. Department of Energy. Thanks to new technologies that make it easier to access, "shale gas has gone from contributing to almost none of the natural gas produced in the U.S. to accounting for about 25 percent of U.S. gas production. I cannot remember anything scaling that fast in the energy business."

Of the MIT work, Jacoby says: "There have been other studies on natural gas, but none has had the same depth. We went at this in an MIT-ish kind of way, getting into the down-and-dirty details of understanding and managing the resource, and creating national and global economic analyses." Jacoby is co-director emeritus of the MIT Joint Program on the Science and Policy of Global Change, which conducted the economic analyses.

From the beginning, MITEI has sought not only to tackle the research challenges behind the world's energy crisis, but also to influence and inform public policy through in-depth multidisciplinary studies. It has coordinated and released five such reports, including that on natural gas, funded by the American Clean Skies Foundation, Hess Corporation, Agencia Naçional de Hidrocarburos, the Gas Technology Institute, Exelon, and an anonymous donor.

The MITEI studies, which include policy recommendations, have been released at public events and have been presented to senior administration officials and lawmakers. Moniz has testified multiple times before Congress.

"Our energy problems are very large scale. To deal with them in any depth you have to bring together people from a variety of disciplines," says Jacoby, the William F. Pounds Professor of Management, Emeritus. "Not many universities can pull this off," but at MIT "the barriers between departments are not very high." Further, he says, "it's part of our self-image. When there is a problem, we go after it."

"Natural gas is a big deal, with important potential for the control of greenhouse gases, but the environmental issues have to be managed," Jacoby concludes. "The MIT study attempts to capture that and more." ~ ELIZABETH THOMSON

new directions

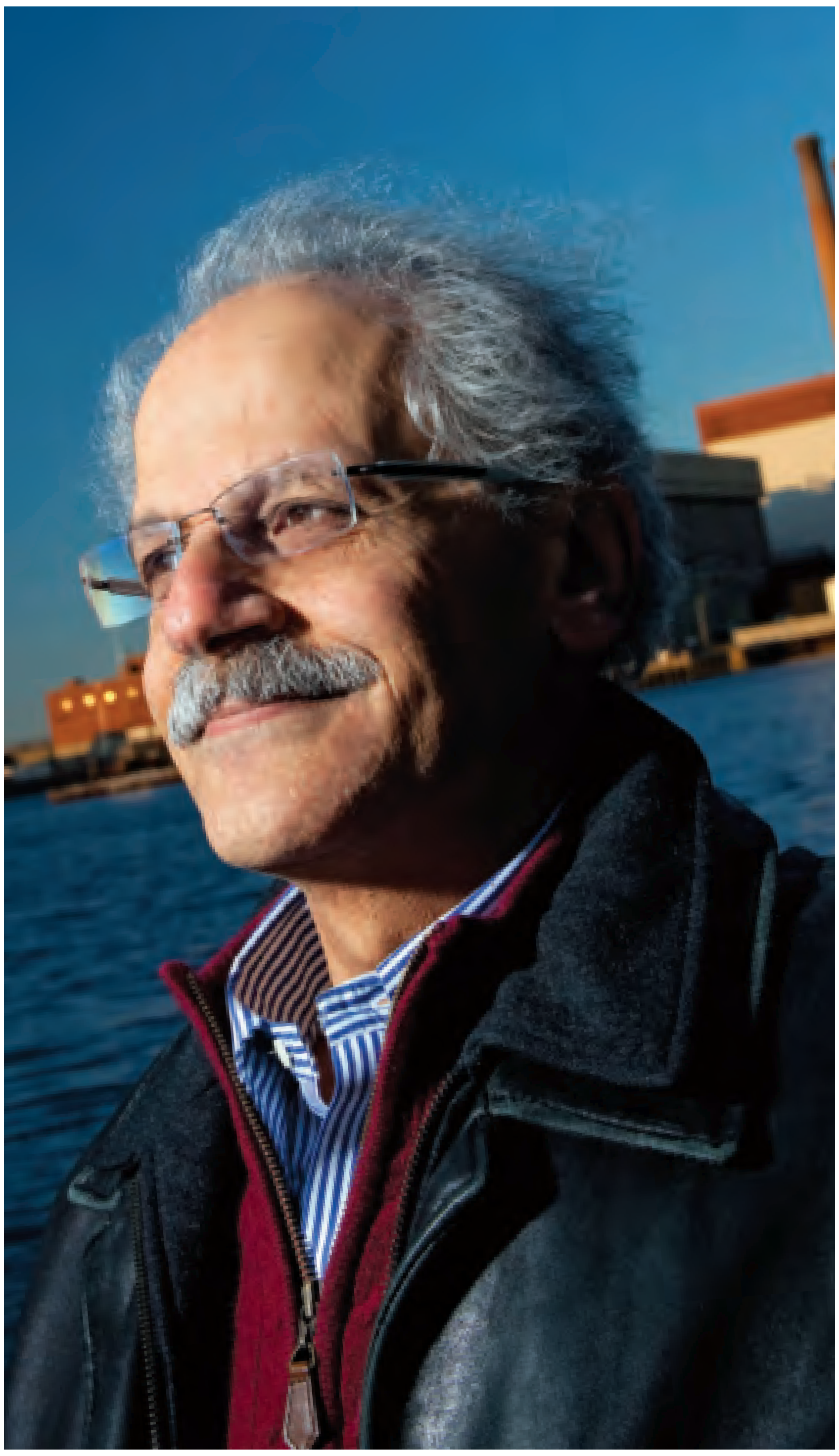
THE ENERGY-WATER NEXUS

Every day the United States withdraws more than 200 billion gallons of water to cool the power plants that give us electricity. That's more water than we use to irrigate the land. Meanwhile, about 13 percent of the electricity produced in the United States is used to bring us water for domestic purposes, including pumping it from the ground, transporting it to our homes, and heating it for our showers.

It takes a great deal of water to produce energy, and a great deal of energy to produce clean water. And these relationships will become more significant as the world's growing population demands more of each resource. Global warming further complicates the situation, changing the availability and therefore politics of water around the globe as some areas receive more rain and others become more arid.

A new research effort organized by the MIT Energy Initiative aims to help the world better understand the relationships between water and energy both now and in the future. The multidisciplinary, MIT-led study, which involves 16 researchers on 5 teams, is part of a broader, multi-institutional program on energy sustainability sponsored by BP.

Ahmed Ghoniem leads an MIT group examining how much water it takes to produce energy globally. John Lienhard and a colleague are examining how much energy it takes to provide clean water. For the past year, Lienhard and Ghoniem have been collecting data to establish the technical foundation for the study. Lienhard, the Samuel C. Collins Professor of Mechanical Engineering, is currently putting the "sheer morass of information we have" into a rigorous framework to make it accessible to others.



John Lienhard (top) examines the energy footprint of water, while Ahmed Ghoniem examines the water footprint of energy. Len Rubenstein

Ghoniem and Lienhard's data will now be used to inform a suite of other cross-disciplinary MIT projects involving additional faculty from several schools and departments.

Ghoniem's team, which is also compiling data, has developed a physics-based model to better understand the use of water in producing energy. "Our model can estimate the water use at a given power plant with a reasonable degree of accuracy from readily available data sources like weather conditions. We think it will help fill in gaps in the field data available," says Ghoniem, the Ronald C. Crane Professor of Mechanical Engineering.

Further, the model will help scientists and policymakers explore hypothetical situations like the effect on water withdrawal of adding a new technology for capturing carbon dioxide to a power plant. It could also help evaluate tradeoffs involved in not only producing power and conserving water, but minimizing environmental impacts. (Both Ghoniem and Lienhard note that withdrawing large amounts of water from, say, a river can affect the ecosystem of that river, and such environmental impacts are becoming ever more important.)

Ghoniem and Lienhard's data will now be used to inform a suite of other cross-disciplinary MIT projects involving additional faculty from several schools and departments. For example, Professor Dara Entekhabi of civil and environmental engineering is examining the risks surrounding various sources of water supply.

"The challenge of water supply is one that we can meet," says Lienhard, adding that the whole problem and its solutions are multidisciplinary. "It's not just about technology, but also about economics and governance, and it's going to take careful effort on the part of the leadership of countries." ~ ELIZABETH THOMSON

BIOFUEL IN THE PIPELINE

What's so great about ethanol? Chemical engineer Kristala Jones Prather thinks she can design a better biofuel — one that's closer to the octane of gasoline and doesn't absorb quite as much metal-corroding water.

The U.S. Department of Energy reports that the U.S. spends nearly $1 billion a day on imported oil. Fuels derived from biomass hold a great deal of promise as renewable energy sources and may significantly diversify the menu of transportation fuel options available to consumers. To produce a better biofuel, Prather, the Theodore T. Miller Career Development Associate Professor of Chemical Engineering, looks for molecules that have physical and chemical characteristics that — unlike ethanol — will make them compatible with today's cars, pipelines, and other aspects of the U.S. petroleum infrastructure.

"We live in a world where liquid transportation fuels dominate. So given that reality, we've got to come up with alternatives that will work within the existing infrastructure," she says. Butanol, or butyl alcohol, has been demonstrated to work in vehicles designed to run on gasoline and packs more of an octane punch than ethanol. Prather looks to this and other natural pathways for inspiration to design biosynthetic routes to new molecules.

The U.S. Department of Energy reports that the U.S. spends nearly $1 billion a day on imported oil.

Prather is enlisting the help of bacteria as micro biofuel factories. A bacterium called *Clostridium acetobutylicum* can ferment glucose to produce butanol, but it's not very efficient. Prather has genetically tweaked other bacteria such as *E. coli* to use sugars in plant material to churn out butanol. In the process, Prather has happened upon new ideas about how to produce even better biofuels. The secret is in the enzymes that drive the fermentation process, so Prather has teamed up with Bruce Tidor, MIT professor of biological engineering and computer science, to engineer new enzymes and to predict which ones would be most effective in which biological systems. "Microbes are promising as chemical factories because of the ease with which these enzymes can be introduced into them from a wide variety of natural sources," she says. Additionally, there is already a rich and growing body of industrial experience in using microbial systems to produce biofuels and biochemicals at very high volumes.

Prather, whose work is funded by Shell Global Solutions, sees biofuels as one of a diverse array of solutions to the energy crisis. "We can easily run into a situation where the rate at which we consume biomass is greater than the rate at which we can produce it," she warns. But how long it takes to implement a solution is key, and "in the short term, biofuels can be more rapidly brought on line than other alternative energy sources, especially for transportation." ~ DEBORAH HALBER

Kristala Jones Prather is working to develop a better biofuel. Len Rubenstein

transformations

Prof. Karen Gleason has come up with a low-cost, environmentally friendly way to make solar cells on ordinary tracing paper. Len Rubenstein

SOLAR CELLS ON PAPER

Chemical engineer Karen K. Gleason would like to paper the world with solar cells. Glued to laptops, tacked onto roof tiles, tucked into pockets, lining window shades, she envisions ultrathin, ultra-flexible solar cells going where no solar cells have gone before.

Silvery blue solar cells seem to magically generate electricity from sunlight the way Rumpelstiltskin spun straw into gold but in their present form, they're more akin to gold than straw. The cost of manufacturing crystalline and thin-film solar cells with silicon, glass, and rare earth materials like tellurium and indium is high.

Gleason, the Alexander and I. Michael Kasser Professor of Chemical Engineering, has collaborated with Vladimir Bulovic, professor of electrical engineering; former chemical engineering graduate student Miles C. Barr; and others to come up with a low-cost, environmentally friendly way to make practically indestructible solar cells on ordinary tracing paper. One day, a paper solar cell might help us charge a cell phone. "A paper substrate is a thousand times cheaper than silicon and glass. What's more, these solar cells can be scrunched up, folded a thousand times, and weatherproofed," she says.

Using abundant, inexpensive organic elements like carbon, oxygen, and copper — "nothing exotic," she says — in a vacuum chamber, layers are "printed" through a process called vapor deposition, similar to frost forming on a window. At less than 120 degrees Celsius, the method is gentler and cooler than that normally used to manufacture photovoltaic materials, allowing it to be used on delicate paper, cloth, or plastic. "We repeat that five times and you end up with a solar cell," she says; tweaking the composition of the five layers of materials determines the cells' energy output. The research is funded by MITEI founding member Eni SpA, Italy's biggest energy company, which is pursuing new advances in biofuels, solar, and other forms of alternative energy.

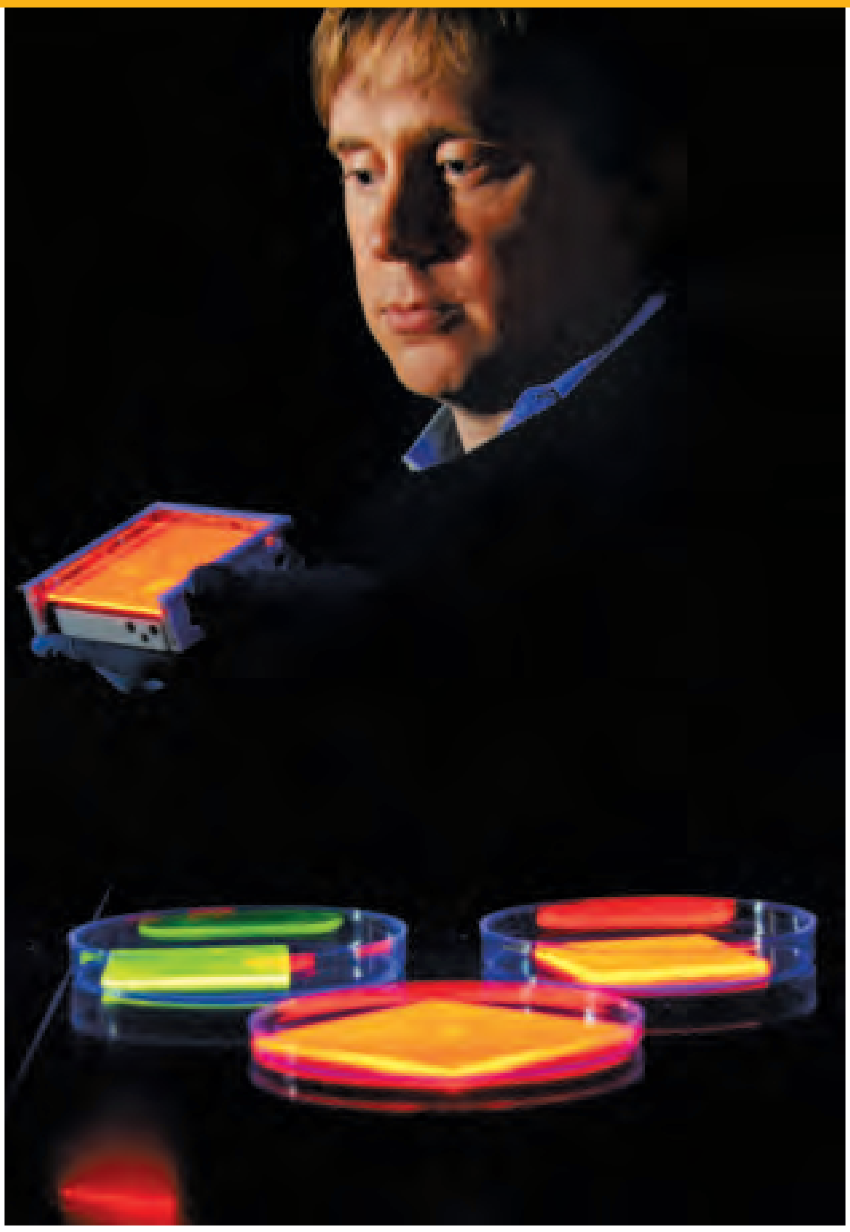
"The challenge of the project appealed to me," she says. "I also thought it would be fun." Her students display a prototype solar cell (a sheet of paper embossed with a pinstripe and chain-link design) folded into a paper airplane as a power source for an LCD clock. Gleason would like to see the first commercial solar paper devices hit the market in five years, but first the cells' efficiency has to be ramped up from nearly 4 percent to at least 10 percent. (Commercial solar cells have an efficiency of around 15 percent.) MIT engineers believe this is doable. Then, the sky's the limit — solar cells could power iPads, generate lighting inside tents, keep ski clothing toasty. "The paper cells' portability could have a big impact in developing countries, where the cost of transporting solar cells has been prohibitive.

"Rather than confining solar power to rooftops or solar farms, paper photovoltaics can be used virtually anywhere, making energy ubiquitous," Gleason says.

~ DEBORAH HALBER

Rank of the electric power sector as a carbon emissions source in the U.S. : **1**

funding



Marc Baldo is shown with solar concentrators developed by his group. Len Rubenstein

Jeff Grossman and colleagues are developing a "rechargeable heat battery." Richard Howard

POWER FROM NATURE

From a multi-million dollar center focused on a hot new field in solar energy to a project on a novel way to store the sun's energy, federal funding is helping MIT researchers not only explore the fundamental science behind promising energy systems, but also turn their work into products in the marketplace. Marc Baldo heads the Center for Excitonics at MIT, which focuses on the nanoscale packets of energy — excitons — key to photosynthesis. Although scientists have long known about excitons, "it's only recently that we've started to have the tools to understand them," says Baldo, an associate professor of electrical engineering.

Ultimately, he says, "we're interested in physically moving excitons around. If we can control where they go, then we can control energy on the nanoscale." And that could lead to new materials and devices for energy production and storage. "It's a very hot field," says Baldo, associate director of the Research Laboratory of Electronics.

Funded by a $19 million grant through the U.S. Department of Energy (DOE), the Center for Excitonics at MIT is one of 46 Energy Frontier Research Centers (EFRCs) established nationwide in 2009 to pursue advanced scientific research on energy. MIT is also home to a second EFRC, the Solid-State Solar-Thermal Energy Conversion Center, run by Prof. Gang Chen.

"I think without the EFRCs, we'd have a much more scattershot, less coordinated approach to solving major energy problems. And, frankly, a lot of innovation would probably take longer to occur," says Baldo, noting that the MIT Energy Initiative (MITEI) played a key role in the establishment of both MIT EFRCs. "They organized us, mentored us, and gave us critical feedback on our proposals."

Jeffrey Grossman also notes the importance of federal support for his research, and MITEI's role in landing that support. Two years ago Grossman, the Carl Richard Soderberg Career Development Associate Professor of Power Engineering, won a $150K seed grant from MITEI to develop a material that can absorb solar energy, then release it on demand, and repeat the process over again. Such "rechargeable heat batteries" have been studied since the '70s, but they could not be recharged many times. Grossman soon proved the potential of a new material involving nanotechnology "that can undergo this cycle of charging and discharging thousands of times without degradation."

Last September, Grossman and four MIT colleagues were awarded a $3 million grant over three years from the DOE's Advanced Research Projects Agency-Energy (ARPA-E). Four other MIT teams have also won ARPA-E grants.

Grossman explains that the ARPA-E award isn't just monetary. "What ARPA-E does so well is identify high-risk, high payoff opportunities, then help inventors think about how to commercialize them. So the ARPA-E funding allows us to bridge the gap between this exciting basic research and potential high-impact energy applications."

MITEI not only gave Grossman the opportunity to begin the work, but also gave him the connections to take it further, he says. "It's a classic seed-fund success story." ~ ELIZABETH THOMSON

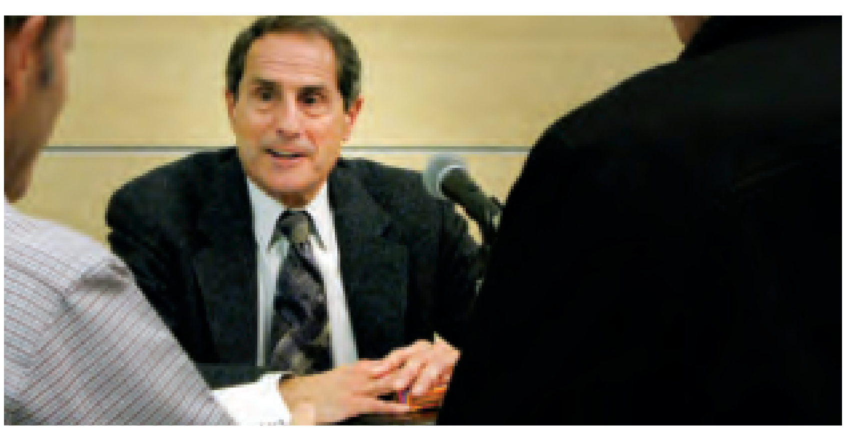
Factor by which MIT researchers increased the power from solar cells by using a solar concentrator: 10

WHY WE GIVE

Philanthropic Investments in Energy

DOUGLAS SPRENG

Doug Spreng believes that MIT is — and should be — the world's leader in research toward a more sustainable energy future. As a result, he has given generously to the Institute to help support that research, and actively works to convince others to do the same. "MIT is special," says Spreng (MIT SB '65), who recently was named a MITEI affiliate member. He conceived and runs the MITEI On the Road program, which brings MIT faculty involved in energy research to Northern California. "The Institute has tremendous strengths in the physical sciences, such as chemistry, physics, and materials engineering, that are key to solving energy problems. It also has a history of bringing these kinds of disciplines together — merging them — that can create very innovative solutions." Six years ago, Spreng retired from a successful career in the semiconductor industry. At the time, he said, "I was thinking, what am I going to do with the rest of my life? How do I make a contribution to something important?" Enter MIT President Susan Hockfield, who gave a talk Spreng attended about the then newly established MIT Energy Initiative. "And I thought, that's something I could get really excited about," Spreng remembers. Spreng has already seen what can happen when MIT researchers have the means to explore more speculative — but potentially breakthrough — research. For example, his support of Prof. Tonio Buonassisi's work toward more-efficient solar cells has led to several patents, and his support of Prof. Jacopo Buongiorno's work on a solar thermal power plant concept has been optioned by a potential licensee.



Doug Spreng Amy Marcott

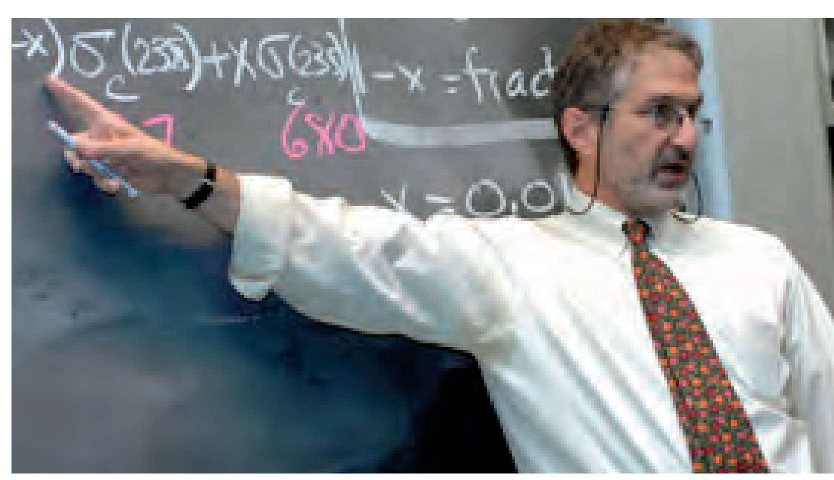
ARUNAS CHESONIS

In late 2007, Arunas Chesonis attended an MIT symposium that would lead to a lunch with MIT Prof. Daniel Nocera, a dream sketched on a placemat, and, ultimately, a gift from Chesonis to bring forth that dream. Nocera gave a lecture at the symposium explaining our global energy inventory. Says Chesonis (MIT SB '84), "His talk included information about how much energy we demand today and what we use to meet this demand, as well as his projections for 2050. What he said left me reeling and wondering what we could do to help ensure a safe future for our children and grandchildren. How could our family make any impact to address this vast, complex, and seemingly insurmountable scenario?" Chesonis invited Nocera to lunch, where he asked him to outline what he would do with $10 million to address our planet's energy challenges. Nocera's answer: the Solar Revolution Project at MIT. Its ultimate goal? The replacement of fossil fuels with solar energy as the world's primary carbon-free energy source. In 2008, the Solar Revolution Project began thanks to the Chesonis Family Foundation's gift. The experience, Chesonis notes, "has been extremely rewarding. Dan's original sketch has evolved into an ecosystem of interdisciplinary work and a family of over 100 collaborators. We continue to feel that our family is making a highly leveraged investment by taking a chance on early-stage research, and we cannot wait to watch the seeds we've planted bloom."

Arunas Chesonis Len Rubenstein

JEFFREY SILVERMAN, DAVID DESJARDINS

One hurdle universities face as they try to improve their own energy efficiency is figuring out how to pay for it. The long-term saving from these kinds of projects can be significant for a large institution — done right, such a plan could save MIT several million dollars on its energy bill each year. But these energy projects require substantial up-front investment, and that can be challenging for schools. MIT is well on its way to meet this challenge, thanks to a $1 million gift from Jeffrey Silverman (MIT SB '68). With this money, the Institute has established a fund to support campus energy and efficiency projects that have rapid "paybacks" — or savings that accrue and then can be reinvested into additional projects. Silverman first heard about the investment opportunity from Theresa Stone, MIT's former executive vice president and treasurer, who also co-chaired the Campus Energy Task Force. The Task Force was established by the MIT Energy Initiative to help MIT "walk the talk" on energy use. "The idea of providing the seed money that was going to create savings and then get reinvested into more savings interested me," Silverman says. He was also impressed that the fund was designed so that the savings would be rigorously measured, documented, and verified. So in April 2009 he formed the Silverman Evergreen Energy Fund. "Archimedes said: 'Give me a lever long enough and a place to stand and I will move the world,'" Silverman says. "We instantly saw the concept of how the Silverman Family Evergreen Energy Fund could leverage MIT's strength in science, engineering, and management into a truly earth-moving concept." David desJardins (MIT SB '83) has since donated an additional $500,000 to the effort.



Prof. Robert Jaffe Donna Coveney

DERRY AND CHARLENE KABCENELL
THE S.D. BECHTEL, JR. FOUNDATION

MIT is changing the face of energy education. In 2007, Derry and Charlene Kabcenell gave a gift for the creation of curricula in this area that led to a new MIT undergraduate minor. In 2010 gifts from the S.D. Bechtel, Jr. Foundation and an anonymous alumnus moved the minor out of the startup phase. Unlike most energy concentrations available at other universities, the Energy Studies Minor is inherently cross-disciplinary. Administered by the MIT Energy Initiative with oversight from faculty in all five schools, the minor is designed to complement any undergraduate major. Derry (MIT SB '75) and Charlene (MIT SB '79) Kabcenell have been awarding grants in environmental and energy education for years. "Energy issues are the defining issues of our times," says Derry. "MIT has a history of working on problems in the world that really matter and certainly has the capabilities to be a leader in solving this one." The five-year grant from the S.D. Bechtel, Jr. Foundation is being used to create eight new energy-related classes, identify and renovate teaching space, and share the new approaches of the energy minor with others, including students and teachers worldwide. "By applying a multidisciplinary approach and emphasizing project-based learning, the Energy Studies Minor at MIT provides students with the means to address complex problems and propose 21st century solutions," says Lauren Dachs, president of the S.D. Bechtel, Jr. Foundation. ~ ELIZABETH THOMSON

global systems

BUILDING WISE

John Ochsendorf examines tile vault construction at MIT which inspired him to create a dramatically low-carbon building in South Africa. Len Rubenstein

"Ancient buildings were greener than new buildings today," says John Ochsendorf, adding that buildings in the U.S. now consume 40% of all energy.

Old buildings were built to the natural environment. They took advantage of prevailing winds in summer or natural light in winter. Overhangs were built for shade in hot climates; in cold ones, buildings faced the sun.

"Over the past century, heating and air conditioning became widespread and energy has been relatively cheap, so now, rather than designing a low-energy building at the start, we just correct a poor design by pumping in energy."

A world expert on ancient buildings and a pioneer in alternative engineering, Ochsendorf is now working to design zero-energy buildings for the world. The winner of a MacArthur "genius" award, and an associate professor of architecture and civil and environmental engineering, he recently partnered with students and local architects to build an innovative, energy-smart museum in rural South Africa. The result was a lower-cost design and an environmental impact reduced by 80%.

Rather than conventional construction, the team used local materials (mostly soil) and hired local people. They used a 600-year-old vaulting technology, and a quarter of the energy normally used in materials and in the construction process. By supporting the local economy, Ochsendorf says, side benefits of his method can include reducing poverty in the area and empowering local people with new skills and experience. The building won several international awards, including World Building of the Year at the 2009 World Architecture Festival.

"A good solution solves multiple problems, and lowering energy use in buildings is a win-win. It reduces costs, it pays for itself almost immediately, it reduces environmental impact so it's better for the planet, and it can lead to healthier communities and healthier people."

With an 800-year-old Gothic cathedral in mind, Ochsendorf and his students also helped design an energy-efficient conference center in England near the White Cliffs of Dover. The building uses the medieval technology of masonry vaulting. Compared to a standard glass-box office building, the conference center took 80% less energy to build and now takes 70% less energy to operate.

"When you can develop home-grown technologies with locally available resources and locally available talent, you're closer to realizing a more sustainable future for that region," he says.

With funding from Kabcenell Foundation, Ochsendorf recently rounded up a team of students to build latrines at schools in Cambodia. They reduced the cost of construction and increased the use of local materials, this time by using agricultural waste — the ash from rice husk — to create concrete.

"Our fundamental challenge is to rethink how we use and consume our resources, how we meet our needs and live the affluent lifestyles we're used to while dealing with climate change."

A housemaster at an MIT graduate dorm, where he lives with his wife and two children, Ochsendorf is installing light sensors, using low-energy light bulbs, and posting signs on elevators marked: "Take the stairs." "By making occupants aware, we're moving towards smarter buildings," he says.

"Thirty years ago, nobody was asking for zero-energy houses. It just wasn't on the radar. Today, people want to live in homes that use dramatically less energy for economic, security, and environmental reasons.

"In 50 years, I'd love to see us living in more intelligent buildings, buildings that can adapt to outside climate, healthier buildings that bring in fresh air and more light. I'd like to see us create a new generation of creative engineers and architects, who are thinking in highly creative ways backed up by rigorous analysis, and showing that zero-energy buildings are possible — because that's where we're headed."

~ LIZ KARAGIANIS

COOKSTOVES AND BIOMASS

Some of MIT's most important energy-related research involves the most mundane of objects: the cookstove. In January 2008, the MIT Energy Initiative (MITEI) launched the Energy Research Seed Fund Program. Among those first grant recipients were Esther Duflo, the Abdul Latif Jameel Professor of Poverty Alleviation and Development Economics; Michael Greenstone, the 3M Professor of Environmental Economics; and Amy Smith, a senior lecturer in mechanical engineering and founder of MIT's D-Lab. This research supergroup proposed studying the health consequences of energy consumption in India.

Half the world's population burns biomass for cooking and heating, and many people in developing countries use these fuels in traditional cookstoves inside their homes. Because there's usually little ventilation, these homes have dangerously high levels of indoor air pollution. This issue affects the health of billions of people.

To tackle the problem, governments and nongovernmental organizations have been installing clay stoves with chimneys in rural homes. The MITEI-funded project was an opportunity to do a randomized control trial evaluation of this popular stove. "Improved stoves are regarded as the solution to this problem, but there was no systematic evidence on whether, used in the normal conditions of the households, they can really make a difference," said Duflo. "Our study was the first one to attempt to do that."

Some households in the state of Orissa were offered the stove and others were not. The researchers tracked the study participants for four years and will publish their results this year. "We uncovered the potential for the stoves, but also the very big difficulties that exist in implementing them in practice," said Duflo. "It is essential to spend more time figuring out practical solutions to this problem that will be adopted in a sustained way by the households."

The study also opened doors to opportunities for other energy environmental projects in India. One of these involves the effectiveness of the pollution control board in the state of Gujarat. Factory pollution in the state was monitored by a third-party audit market. For the most part, the auditors were simply collecting their fees and issuing positive reports, said Greenstone. "The problem is that these reports systematically understate the factories' true emissions."

The researchers conducted a trial involving the random assignment of auditors to factories and the payment to auditors from a central pool, rather than from the factory owners. "After fixing the economic incentives so that the auditors were no longer beholden to the manufacturers, the auditors reported the truth," said Greenstone. "And that allowed for more effective regulatory oversight." The success of this study has generated a lot of interest and it may be expanded to other parts of the country.

It also caught the attention of the Indian Minister of Environment and Forests. The researchers talked with him about a cap-and-trade program for soot and other forms of particulate air pollution. They are now assisting the government in creating and evaluating the program, which would be the first cap-and-trade program ever in a developing country, Greenstone said.

"It has been a long and winding road from clay stoves in Orissa to a cap-and-trade program, but it has included several exciting steps at the intersection of research and policy," said Greenstone. "And we got started on that road with an initial seed grant from the MIT Energy Initiative." ~ ERIC SMALLEY

"It has been a long and winding road from clay stoves in Orissa to a cap-and-trade program," Michael Greenstone says. Len Rubenstein

education

AN ENERGY EDUCATION

Kwabena Bediako was first drawn to energy studies by the power of the African sun. Growing up in Ghana, he said he was struck by "a simple thought: Why aren't we doing more with solar energy?"

Today, in collaboration with the MIT Energy Initiative (MITEI), Bediako is a Saudi Aramco-MIT Energy Fellow working on an "artificial leaf" — a device invented in the lab of Professor of Chemistry Daniel Nocera that uses energy from the sun to make chemical fuel.

"MIT has made energy a priority," Bediako said. "MIT brings together many different fields of research — from architecture to chemistry," he said, to consider the broader problem of energy and to work toward progress from a range of disciplinary angles.

Bediako helped Nocera improve the catalysts needed to channel the sun's energy to split water into hydrogen and oxygen. "Hydrogen is the fuel," Bediako explained. "When you burn hydrogen you get water, so you close the cycle. It's a zero carbon process."

A third-year doctoral candidate, Bediako is just one of nearly 200 graduate and postdoctoral fellows who has benefited since MITEI was founded five years ago. The Society of Energy Fellows currently includes researchers in 20 different departments — spanning all five schools — supported by 22 companies.

MITEI introduces incoming freshmen to campus energy activities through its Freshman Pre-Orientation Program and supports such student activities as the Energy Club, the Electric Vehicle Team, and Biodiesel @MIT, a group working to produce fuel from used vegetable oils.

A MAJOR MINOR

But a significant educational accomplishment of MITEI is the 2009 launch of the Energy Studies Minor, made possible by gifts from Derry and Charlene Kabcenell, the S. D. Bechtel, Jr. Foundation, and an anonymous donor. The minor offers undergraduates an integrated, multidisciplinary view of energy and its implications. "It's an innovative program," Armstrong said. "It's the first really interdepartmental, interschool academic program we have on campus."

The curriculum — including more than 40 classes across all five schools — last year enrolled nearly nine percent of undergraduates. Nearly 40 students have minored in energy to date. "The minor allows any student to put a coherent overlay of energy subjects on any major," Armstrong said. "There's not a better place in the world to be an undergraduate if you're interested in energy."

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"When MITEI started, one of the big problems we noticed was that there weren't a lot of faculty members on campus whose research programs were focused specifically on energy," said Robert C. Armstrong, MITEI deputy director who is also the Chevron Professor of Chemical Engineering. Today, he said, nearly 30 percent of the faculty is involved in energy — more than 270 faculty members. "In the first five years, we've done, or are doing, some 700 projects with $360 million in funding." As a result, he noted, "The graduate pipeline at MIT is pretty full."

Undergraduates are also benefiting from the uptick in energy research on campus — gaining hands-on experience through the Undergraduate Research Opportunities Program (UROP). "These kids are doing extraordinary things, from exploring the theory of light and luminescence to the microbial understanding of critters able to digest material and produce energy from it," said Amy Glasmeier, co-chair of the MITEI Energy Education Task Force, professor of geography and regional planning, and head of the Department of Urban Studies and Planning.

"As soon as I heard about the energy minor, I knew I wanted to do it," said Lucy Fan '12, a chemical engineering major. Initially focused on sustainability and renewable energy, Fan said that when she took a class called Energy Decisions, Markets, and Policies — a requirement for the minor — it opened her eyes to the need to consider not just technical solutions but also the economic feasibility and policy implications of technology. Regarding complex energy challenges, she says, "there's no one solution; you need to have a portfolio."

Fan's energy studies led her to intern last summer with Exelon Corporation, where she worked on load forecasting and gas-storage models for the quantitative and business analytics department. "Before the energy minor, I had been focused on technology," Fan said. Now she plans to work as a consultant in the electric power industry, helping to guide the evolution of the electrical grid.

"Our education program gives [students] this breadth of understanding that makes them capable of leaving the Institute and conveying the value of perspective in assessing energy issues in the modern world," Glasmeier said.

~ KATHRYN M. O'NEILL

Kwabena Bediako is working on an "artificial leaf" to make chemical fuel.

Lucy Fan is helping to guide the evolution of the electrical grid. Richard Howard

CAMPUS ENERGY EFFORT SAVES MILLIONS

At the Koch Institute for Integrative Cancer Research, numerous energy efficiency strategies save MIT more than $1.3M a year. Richard Howard

A new era of energy efficiency and sustainability was ushered in five years ago, when the MIT Energy Initiative's Campus Energy Task Force facilitated the development of a campus program to reduce energy use, enhance energy education, and provide a model of intelligent energy practices for the U.S. and the world. Now, that effort — which has transformed MIT's campus into a living laboratory — already has paid off. Last year, MIT saved $3.5 million and reduced its energy use by 5%.

"The Task Force relies on participation from the entire MIT community — faculty, students, and staff. This was one of the first cases where people across campus pitched in and made significant contributions," says Leon Glicksman, professor of building technology and mechanical engineering, co-chair of the Task Force along with Israel Ruiz, MIT's executive vice president and treasurer. That collaborative effort is among the Task Force's major achievements, Glicksman says, adding that key to the group's success has been engagement of many MIT administrative departments including Facilities; Environment, Health and Safety; Information Services and Technology; and Student Life.

What began as a small group of pilot projects has led to an Institute-wide phenomenon. Now, students have access to a richer learning experience because of an expanded energy curriculum and introduction of dozens of new Undergraduate Research Opportunities Programs (UROP) and internships. Additionally, MIT has been recognized for achievements in sustainability locally and nationally.

MIT's multiple energy-saving projects include renewal of steam traps in older buildings. A study of steam trap units across campus, for example, revealed that many units were failing, resulting in huge energy waste. The updates now save MIT $800,000 per year in energy costs, and the initial project costs were recouped within one year.

Another project involved reducing the air volume used in chemical fume hoods. Controlled experiments showed that reducing the airflow by 20% through the open sash could still guarantee a safe working environment. As a result, the Koch Institute for Integrative Cancer Research recently installed new low-flow hoods operating at the lower air volume requirement. The Koch Institute — MIT's first LEED gold certified laboratory building — uses 35% less energy than a standard laboratory building saving more than $1.3 million a year.

As a result of these and other successes, in 2010 MIT partnered with its utility NSTAR to create the region's largest energy efficiency program. This partnership, *Efficiency Forward*, aims to create a new model for enhanced utility efficiency programs. MIT has committed to reduce its energy use by 34 million kilowatt hours (kWh) — equivalent to 15% of its electrical use — over the course of three years through lighting updates, HVAC upgrades, and sustainable design. In 2011, MIT surpassed its first-year energy reduction goal by a third, saving 13 million kWh. In the second year, MIT saved an additional 10 million kWh, surpassing its two-year goal.

One of many benefits of the MIT-NSTAR partnership is MIT's access to NSTAR's preferred rates for equipment and service. Recently, NSTAR facilitated the replacement of more than 700 refrigerators in dorms across campus to more energy-efficient models. The new ones use a mere 40 watts of energy and are expected to reduce overall energy use by more than 30%.

A LIVING LAB

"Students are now able to use the campus as a test bed for their ideas, and the results benefit both the students and the Institute," says Steve Lanou, deputy director of environmental sustainability, adding that opportunities for students to engage in energy research have increased during the past five years.

Thirty UROPs and internships focused on energy have been supported by the Task Force, and more than 45 student projects have been supported through the MITEI Student Campus Energy Project Fund. Recently supported projects include a compact fluorescent bulb exchange program, dorm electricity competitions, and graduate dorm metering and monitoring systems.

With many near-term goals now met, Glicksman and Ruiz aim to amplify the impact of efficiency programs, engage more people on campus, and communicate on a global scale. A specific goal, Glicksman says, is to complete a long-range campus energy study, to help chart MIT's energy roadmap for the next 20 years. Working with the Education Task Force, the pair hopes to increase energy-related class projects, and obtain funding for energy-related graduate research and UROPs. ~ STEPHANIE EICH

Last year, MIT saved $3.5 million and reduced campus energy use by: 5%

tools

CARBON-CAPTURING ENZYMES

The students in Catherine Drennan's chemistry classes are silent with attention when she says the word "energy." They listen more intensely when she couples energy with the environment and pollution. For example, she tells them, it might be possible to use obscure chemical processes of microorganisms to simultaneously scrub carbon dioxide from coal smokestacks and produce fuel from the CO_2 waste product of energy production.

"When I began working on environmentally relevant enzymes about 12 years ago, it was a bizarre little thing," says Drennan, a professor of chemistry at MIT who is, uniquely, both a Howard Hughes Medical Institute Investigator and a Howard Hughes Medical Institute Professor recognized for outstanding undergraduate education. She was attracted to this combination of chemistry and biology because of the intriguing chemistry that some microbial enzymes carry out, including those that contribute to the global carbon cycle.

Many organisms produce enzymes with metal atoms stashed away in their centers — metallocenters. But some microorganisms produce unusual enzymes with nickel centers and uncommon enzymes containing vitamin B_{12} (which has a cobalt metallocenter). Such enzymes can use the nickel or the cobalt of B_{12} to form bonds with carbon, which effectively sequesters carbon dioxide out of the environment and converts it into fuel for growth.

Drennan has long asked herself if such microbes could help mitigate CO_2 emissions from energy production and consumption. Could we grow organisms that do more of their natural catalytic activity? This interest made her a natural fit for the MIT Energy Initiative (MITEI). Partly because of MITEI, Drennan's work is morphing from extremely basic to more applied research.

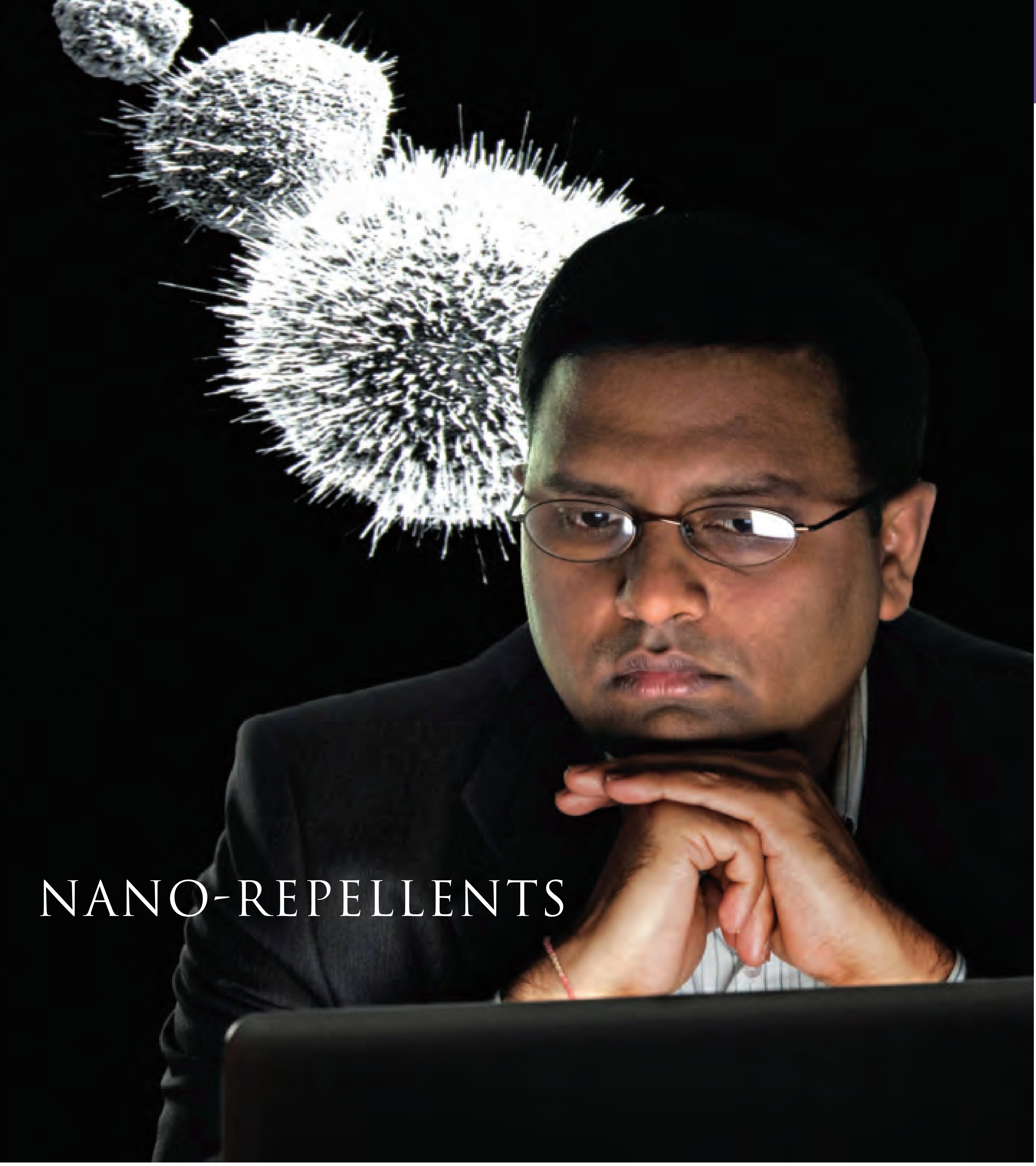
Now, she envisions a two-microbe system that removes carbon dioxide from the environment and converts it into energy. One nickel-centered bacterium, *Moorella thermoacetica*, would "eat" CO_2 and make acetate, a common carbon energy source for cells. A second bacterium eats acetate and makes electrons. "We could grow the acetate-eating microbes on electrodes to produce electricity from CO_2," she says.

Drennan, whose work is supported by MITEI's Energy Research Seed Fund Program via funds from the Singapore-MIT Alliance, is working with other MITEI researchers interested in applying these and similar ideas to energy problems. What do her colleagues need to know about these enzymes to go forward? Do smokestack emissions contain components that inhibit these enzymes? Can we increase the types of molecules these enzymes will accept? "There are so many smart people working on different aspects of these problems that the field is progressing faster than I anticipated."

Drennan uses structural techniques like x-ray crystallography to also study other environmentally relevant enzymes. For example, the process of making many pharmaceuticals involves halogenation, which adds chloride or bromide to a natural product and produces toxic byproducts. Likewise, an enzyme used in the 13-step organic synthesis of the vitamin biotin produces harmful waste products. "We want to use enzymes to replace the unfriendly organic chemistry and produce less waste."

In addition to research, Drennan loves training the next generation of scientists who want to use chemistry to solve energy and environmental problems. "They will have new technologies and will be able to answer questions we can't today" especially, she adds, if MIT alumni lend their expertise in science, engineering, economics, and business to the field. ~ CATHRYN DELUDE

Catherine Drennan says it might one day be possible for enzymes to convert some of energy's waste products into energy. Len Rubenstein



NANO-REPELLENTS

Kripa Varanasi's tough new nanoengineered surfaces and coatings could make energy systems more efficient. Len Rubenstein

When a device like an enormous inverted funnel failed to capture the oil gushing into the Gulf of Mexico in 2010, mechanical engineer Kripa K. Varanasi saw it as an interface problem: crystals of natural gas forming on the sides of the funnel caused the oil, instead of whooshing up, to slide off.

To Varanasi, the Doherty Associate Professor of Mechanical Engineering, many engineering problems come down to interface problems: ice forming on airplane wings and wind turbine blades, the crystalline hydrates that inhibit deep sea oil recovery, water boiling or condensing in steam power plants or desalination plants or electronics cooling systems. "The interface between two forms of matter is most often what becomes a bottleneck. Altering those interactions in a positive way can have a huge impact on efficiency," says Varanasi, whose work is supported by MITEI's Energy Research Seed Fund Program, Shell International, and Masdar Institute of Science and Technology.

For instance, water droplets striking the surface of steam turbine blades flatten into mega-droplets and then into sheets that fly from one blade to the next, wearing them down and forcing the turbine to work harder. This can cause up to 40 percent of the efficiency losses in a steam power plant. To counter this, Varanasi's tough new nanoengineered surfaces and coatings repel water the way duck feathers and lotus leaves shed water and debris.

Other materials repel ice or help transfer heat. A bonus is the new materials reveal thermal-fluid phenomena at the microscale. "Nucleation, such as carbon dioxide bubbles forming on the sides of a soda bottle, is a ubiquitous everyday experience, but spatial control of this phenomenon is extremely difficult," Varanasi says. He and his colleagues accomplished this for the first time by creating a surface patterned with orderly rows of hydrophobic, or water-repelling, and hydrophilic, or water-attracting, regions. These rows control where droplets form so they can be shed more easily.

In the deep sea, hydrates — methane gas molecules trapped in an icy cage of water — form at very high pressures, plugging oil pipelines, causing flow disruptions, and forming on equipment such as the funnel employed in the Gulf spill. According to the U.S. Geological Survey, up to 300 million trillion cubic feet of methane exists globally in hydrate form — most of it in the ocean floor. Varanasi hopes to use nanoparticles to control where and how hydrates form, much like cloud seeding. This would prevent hydrates from plaguing pipelines and make it safer for engineers to safely extract their methane, potentially opening up access to 10 times more natural gas reserves than now available.

"We're trying to come up with new materials, alter their structure at a molecular scale, and then scale them up to large-scale manufacturing with durable materials," Varanasi says. "Applying those materials to technology on both the macroscale and the nanoscale is able to give us things we haven't seen before." ~ DEBORAH HALBER

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THE POWER GENERATION

For students like Caleb Waugh, energy has become more like a movement. Richard Howard

David Danielson founded the MIT Energy Club in 2004 with one friend over a pizza. "I never expected it to grow like this. It never crossed my mind," he says of the 3,500-member club — the largest, fastest-growing extracurricular group on campus.

"Energy at MIT has become more like a movement. And we need a movement all over the country, all over the world," says Club Co-President Caleb Waugh, adding that energy is the defining challenge of this generation. "We need *more* people. The more novel ideas and solutions, the higher our likelihood of success."

"Energy is an incredibly complicated, massively intricate industry," says Co-President Michael Bishop. "It's a hugely complicated problem. MIT students love that. We recognize that it's a three, four, five decade endeavor to massively overhaul the infrastructure of one of the most important industries on the planet. And students are saying, 'Hey, let's get *behind* this.'"

Members spend a day with the U.S. Energy Secretary, tour a wind blade facility, or discuss the science of climate change or national biofuel policy over dinner, while the 20-member executive committee often invites industry experts to campus to lead discussions on electric vehicles, green buildings, or renewable energy. Entirely student run, the club hosts 100 events per year. The annual MIT Energy Conference — the most prestigious student energy conference in the world — is the club's flagship event, where CEOs and other industry experts discuss technology, policy, industry, and finance with a crowd of 1,500.

"The strength of the club is that it's multidisciplinary. We have business, technology, and policy students, engineers, scientists, grads, undergrads — and it's fantastic because it's such a multifaceted problem," says Bishop, adding that the MIT club was also a first member of the Collegiate Energy Association, a global network of 83 university energy clubs with more than 10,000 students.

"I do think this force of people will help solve the world problem," says Danielson, who earned a PhD in 2008 and recently was nominated as assistant secretary for energy efficiency and renewable energy at the U.S. Department of Energy. "The MIT Energy Club and the MIT Energy Initiative is an amazingly powerful network. It's a wave that's just starting to break onto the shore." ~ LIZ KARAGIANIS