Energy Futures

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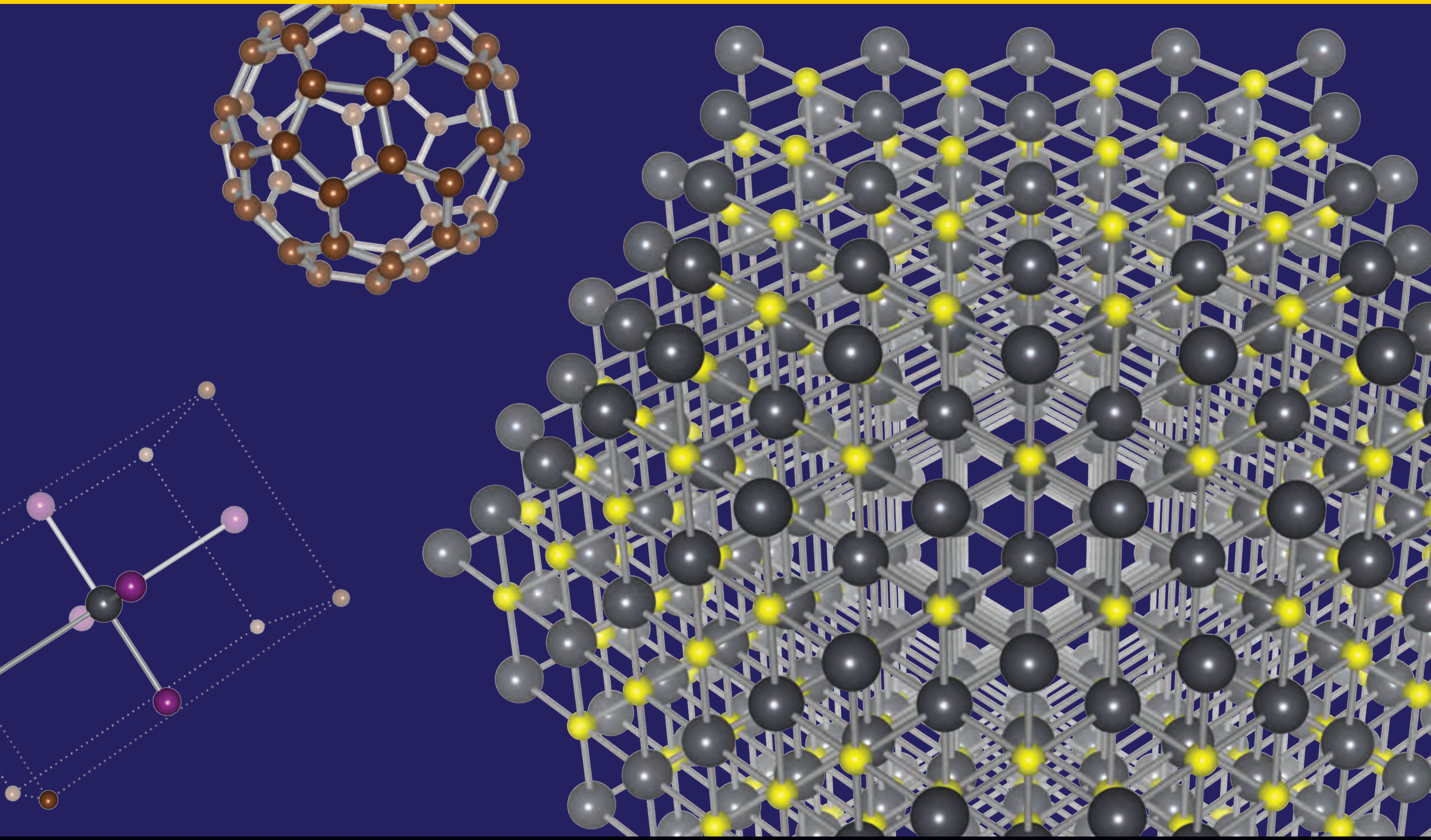

Solar photovoltaic technologies: Silicon and beyond

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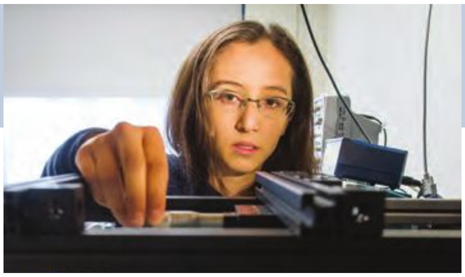

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Energy Futures

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MITEI MEMBERS

A letter from the director


Photo: Webb Chappell

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

Dear Friends,

On October 21, 2015, MIT launched *A Plan for Action on Climate Change* (climateaction.mit.edu), the Institute's multifaceted response to the urgent global challenges of significantly reducing carbon emissions while meeting growing energy needs.

A central element of the plan is a commitment to partner with industry to foster low-carbon energy research—a strategy the MIT Energy Initiative (MITEI) has embodied since its founding in 2006, guided by then-Institute President Susan Hockfield and led by my former colleague Professor Ernest Moniz, now US Secretary of Energy. As described in the plan, MITEI is developing interdisciplinary Low-Carbon Energy Centers to advance technology in key areas. The first five centers will focus on solar power; energy storage; carbon capture, use, and sequestration; advanced materials; and nuclear fission. These centers will be supported by industry and government consortia, with members ranging in size from startups to multinationals. Our shared objective is to put the global energy system on a path to rapid decarbonization within a generation.

In the coming months, we will provide more information as the centers take shape and begin their work. We have heard from existing industry MITEI Members and from smaller companies excited about the prospect of partnering with MIT researchers on projects in specific low-carbon technology areas. MITEI looks forward to convening members within each center to facilitate dialogue on common opportunities for technology development as well as lessons learned. We also anticipate helping to connect startups with established companies in each of the technology areas.

At MITEI, we value our role as a convener of industry, government, and academia around low-carbon energy research, education, and outreach. This year, we have had ample opportunity to play this role, particularly for solar energy, which is the focus of this issue of *Energy Futures*.

In September, MITEI had the pleasure of hosting researchers from across the Institute and beyond for MIT Solar Day, a full-day event dedicated to sharing solar technology and policy research with the MIT community (see page 46). Solar Day brought to life many of the research themes raised in *The Future of Solar Energy*, a comprehensive report written by MIT researchers to address vital questions of how to realize the potential of solar energy to meet a major portion of global electricity demand and dramatically reduce greenhouse gas emissions. At the report release on May 5 in Washington, DC, members of the solar study team briefed congressional and White House officials on the importance of the findings and distributed the executive summary for policymakers reprinted on page 4 of this issue.

The Future of Solar Energy was the most recent of MITEI's *Future of…* series of reports that shed light on possible roles for a number of technologies—including nuclear energy, coal, geothermal, natural gas, and the electric grid—in meeting growing energy needs in a carbon-constrained world. Each of the reports stems from a study that brought together experts from different disciplines to provide insights into key technology and policy questions along with detailed recommendations to shape future policy debates and decisions, technology choices, and research.

In this issue, you will find research reports related to topics discussed in *The Future of Solar Energy*. For solar energy to achieve its potential to transform our energy systems, new solar technologies will be needed. In this issue, we describe a rigorous assessment of the strengths and weaknesses of today's many solar photovoltaic technologies—both commercial and emerging (page 6)—as well as a research project demonstrating a novel way to provide critical materials for perovskite solar cells, a promising technology now being pursued worldwide (page 11). Other work focuses on challenges involved with deploying intermittent renewables such as solar and wind on the electric power grid. An analysis by MIT and IIT-Comillas University in Madrid, Spain, identifies steps to help prepare today's power grid to handle the large-scale deployment of solar power (page 15), and another MIT project has produced a novel, high-capacity, low-cost battery that could play a critical role on a solar-dominated power grid (page 20). Finally, projects focusing on reliable energy access in the developing world demonstrate the important role to be played by solar power in the expanding use of microgrids (page 25) and in the desalination of groundwater in India (page 29).

In early October, the Institute hosted the inaugural MIT Solve conference, and solar energy and other low-carbon energy technologies featured prominently in the “Fuel” pillar, which I co-moderated with Angela Belcher, the James Mason Crafts Professor in materials science and engineering and biological engineering. As detailed in “Fueling Solutions” (page 43), panels of scientists and policy experts discussed how to meet rapidly increasing global energy demands while providing food and clean water for the world’s growing population. At a final public session, Ratan Tata, chairman of the Tata Trusts, and Robert Stoner, director of the Tata Center for Technology and Design and deputy director for science and technology at MITEI, discussed the challenges involved in sustainably meeting the development needs of India and other developing countries.

Three other notable events rounded out our busy fall. On September 29, the first Tata Center Symposium gathered leaders from India’s business, government, and nonprofit sectors to consider the challenges and opportunities for applying MIT research in India and the developing world. On October 19–20, we held the MITEI Annual Research Conference, where MITEI Members gathered to hear about MIT researchers’ work and to participate in discussions on how to overcome hurdles to technology research and commercialization. And on November 4–5, the fourth annual C3E Women in Clean Energy Symposium convened leaders from all sectors to discuss pathways toward a low-carbon energy future (see the column at right).

MIT students have been engaged in many activities with MITEI this autumn. Among those highlighted in this issue of *Energy Futures* are undergraduate participation in summer research projects (page 34) and in MITEI’s pre-orientation program (page 40), development of an on-campus Undergraduate Energy Commons that will provide space for students to gather and work (page 41), and the induction of 32 graduate students into MIT’s Society of Energy Fellows (page 39). I would particularly like to congratulate the 2015 Energy Studies Minor graduates—listed on page 41—who are now embarking on careers in energy fields or continuing to earn higher degrees.

The launch of the MIT Climate Action Plan and the development of the new Low-Carbon Energy Centers make this an especially exciting time to be on campus. I look forward to engaging with new and returning students, faculty, and researchers to help advance the objectives of the climate plan, and I encourage alumni and the broader MIT community to contact MITEI with ideas and questions. Working together, we can ensure MIT’s enabling contributions as the world transitions to a low-carbon energy future while making affordable energy available to billions of people in the developing world.

Robert C Armstrong

Professor Robert C. Armstrong
MITEI Director

November 2015

Women leaders in clean energy gather at MIT

On November 4–5, 2015, MITEI and the US Department of Energy co-hosted the fourth annual Clean Energy Education & Empowerment (C3E) Women in Clean Energy Symposium. Highlights included panels addressing complex challenges such as the energy/water nexus and the transition to a low-carbon future; discussions of career advancement; and the presentation of awards to eight midcareer women for outstanding achievements in clean energy. C3E has issued a call for nominations for the next awards, to be presented in May 2016. Learn more at c3eawards.org.

Photos: Justin Knight

During a panel titled Clean Energy Technology Frontiers, moderator Karina Edmonds, executive director for corporate partnerships, California Institute of Technology (far right), is joined by (from left to right) Nancy Haegel, center director, Materials Science, National Renewable Energy Laboratory; Angela Belcher, the James Mason Crafts Professor at MIT; and Leslie Dewan (MIT ’07, PhD ’13), co-founder and CEO, Transatomic Power.

Left to right: Graduate student Rose Sobel of the University of Houston— first-place winner of this year’s C3E poster session—describes her research to Linda Silverman, US Department of Energy, and C3E awardee DaNel Hogan, director of The STEMAZing Project, Office of the Pima County School Superintendent.

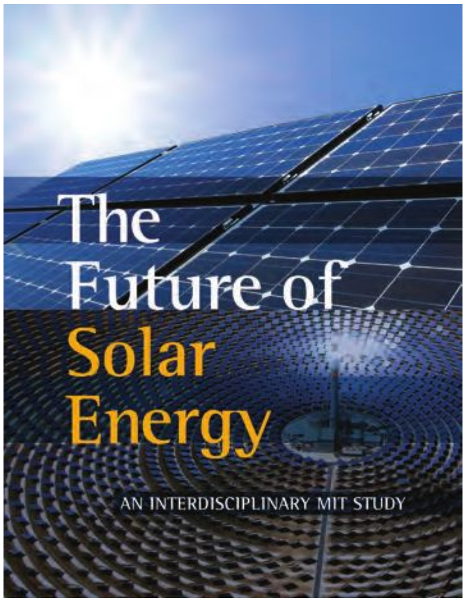
The Future of Solar Energy: A summary and recommendations for policymakers

On May 5, 2015, at the National Press Club in Washington, DC, an MIT team released The Future of Solar Energy, *the latest of seven multidisciplinary MIT reports that examine the role that various energy sources could play in meeting energy demand in a carbon-constrained future.*

Solar electricity generation is one of the few low-carbon energy technologies with the potential to grow to very large scale. Recent years have seen rapid growth in installed solar generating capacity; great improvements in technology, price, and performance; and the development of creative business models that have spurred investment in residential solar systems. Nonetheless, further advances are needed to enable a dramatic increase in solar penetration at socially acceptable costs.

In the Future of Solar Energy study—which led to the report—a team of more than 30 experts investigated the potential for expanding solar generating capacity to the multi-terawatt scale by midcentury. The experts examined the current state of US solar electricity generation, the several technological approaches that have been and could be followed to convert sunlight to electricity, and the market and policy environments the solar industry has faced. Their objective was to assess solar energy's current and potential competitive position and to identify changes in US government policies that could more efficiently and effectively support the industry's robust, long-term growth.

Their findings are presented in the 350-page The Future of Solar Energy *report and five related publications (available at mitei.mit.edu/futureofsolar). The following article presents a summary and recommendations for policymakers and is reprinted from the report.*



Summary for policymakers

Massive expansion of solar generation worldwide by midcentury is likely a necessary component of any serious strategy to mitigate climate change. Fortunately, the solar resource dwarfs current and projected future electricity demand. In recent years, solar costs have fallen substantially, and installed capacity has grown very rapidly. Even so, solar energy today accounts for only about 1% of US and global electricity generation. Particularly if a substantial price is not put on carbon dioxide emissions, expanding solar output to the level appropriate to the climate challenge likely will not be possible at tolerable cost without significant changes in government policies.

The main goal of US solar policy should be to build the foundation for a massive scale-up of solar generation over the next few decades.

Our study focuses on three challenges for achieving this goal: developing new solar technologies, integrating solar generation at large scale into existing electric systems, and designing efficient policies to support solar technology deployment.

Take a long-term approach to technology development

Photovoltaic (PV) facilities account for most solar electric generation in the US and globally. The dominant PV technology, used in about 90% of installed PV capacity, is wafer-based crystalline silicon. This technology is mature and is supported by a fast-growing, global industry with the capability and incentive to seek further improvements in cost and performance. In the United States, non-module or balance-of-system (BOS) costs account for some 65% of the price of utility-scale PV installations and about 85% of the price of the average residential rooftop unit. Therefore, federal R&D support should focus on fundamental research into novel technologies that hold promise for reducing both module and BOS costs.

The federal PV R&D program should focus on new technologies, not—as has been the trend in recent years—on near-term reductions in the cost of crystalline silicon.

Today's commercial thin-film technologies, which account for about 10% of the PV market, face severe scale-up constraints because they rely on scarce elements. Some emerging thin-film technologies use Earth-abundant materials and promise low weight and flexibility. Research to overcome their current limitations in terms of efficiency, stability, and manufacturability could yield lower BOS costs, as well as lower module costs.

Federal PV R&D should focus on efficient, environmentally benign thin-film technologies that use Earth-abundant materials.

The other major solar generation technology is concentrated solar power (CSP) or solar thermal generation. Loan guarantees for commercial-scale CSP projects have been an important form of federal support for this technology, even though CSP is less mature than PV. Because of the large risks involved in commercial-scale projects, this approach does not adequately encourage experimentation with new materials and designs.

Federal CSP R&D efforts should focus on new materials and system designs and should establish a program to test these in pilot-scale facilities, akin to those common in the chemical industry.

Prepare for much greater penetration of PV generation

CSP facilities can store thermal energy for hours, so they can produce dispatchable power. But CSP is only suitable for regions without frequent clouds or haze, and CSP is currently more costly than PV. PV will therefore continue for some time to be the main source of solar generation in the United States. In competitive wholesale electricity markets, the market value of PV output falls as PV penetration increases. This means PV costs have to keep declining for new PV investments to be economic. PV output also varies over time, and some of that variation is imperfectly predictable. Flexible fossil generators, demand management, CSP, hydroelectric facilities, and pumped storage can help cope with these characteristics of solar output. But they are unlikely to prove sufficient when PV accounts for a large share of total generation.

R&D aimed at developing low-cost, scalable energy storage technologies is a crucial part of a strategy to achieve economic PV deployment at large scale.

Because distribution network costs are typically recovered through per-kilowatt-hour (kWh) charges on electricity consumed, owners of distributed PV generation shift some network costs, including the added costs to accommodate significant PV penetration, to other network users. These cost shifts subsidize distributed PV but raise issues of fairness and could engender resistance to PV expansion.

Pricing systems need to be developed and deployed that allocate distribution network costs to those that cause them and that are widely viewed as fair.

Establish efficient subsidies for solar deployment

Support for current solar technology helps create the foundation for major scale-up by building experience with manufacturing and deployment and by overcoming institutional barriers. But federal subsidies are slated to fall sharply after 2016.

Drastic cuts in federal support for solar technology deployment would be unwise.

On the other hand, while continuing support is warranted, the current array of federal, state, and local solar subsidies is wasteful. Much of the investment tax credit, the main federal subsidy, is consumed by transaction costs. Moreover, the subsidy per installed watt is higher where solar costs are higher (e.g., in the residential sector), and the subsidy per kWh of generation is higher where the solar resource is less abundant.

Policies to support solar deployment should reward generation, not investment; should not provide greater subsidies to residential generators than to utility-scale generators; and should avoid the use of tax credits.

State renewable portfolio standard (RPS) programs provide important support for solar generation. However, state-to-state differences and siting restrictions lead to less generation per dollar of subsidy than a uniform national program would produce.

State RPS programs should be replaced by a uniform national program. If this is not possible, states should remove restrictions on out-of-state siting of eligible solar generation.

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This summary appears in *The Future of Solar Energy: An Interdisciplinary MIT Study*, by the Massachusetts Institute of Technology, 2015. The study was supported by the Alfred P. Sloan Foundation; the Arunas A. and Pamela A. Chesonis Family Foundation; Duke Energy; Edison International; the Alliance for Sustainable Energy, LLC; and Booz Allen Hamilton. Please go to mitei.mit.edu/futureofsolar to download a copy of the complete report and related publications and to watch a video of the release of the study on May 5, 2015. To receive a printed copy of the report, email rhowarth@mit.edu.

Other *Future of…* reports are available at mitei.mit.edu/publications/reports-studies.

Solar photovoltaic technologies

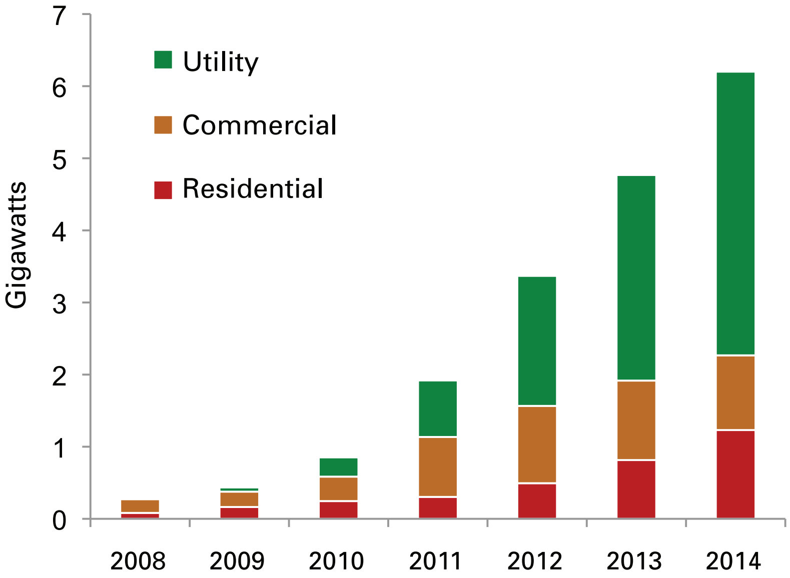
Silicon and beyond

Left to right: Joel Jean of electrical engineering and computer science (EECS), Vladimir Bulović of EECS, and Patrick Brown of physics and their collaborators have performed a rigorous assessment of today's many commercial and emerging solar photovoltaic technologies and conclude that none should be ruled out, given the urgent need to move to a low-carbon energy future.

This research was supported by the MIT Future of Solar Energy study (mitei.mit.edu/futureofsolar). See page 10 for publications resulting from this work.

Photo: Stuart Darsch

An MIT assessment of solar energy technologies concludes that today's widely used crystalline silicon technology is efficient and reliable and could feasibly be deployed at the large scale needed to mitigate climate change by midcentury. But novel photovoltaic (PV) technologies now being developed using specially designed nanomaterials may one day provide significant advantages. They could be easier and cheaper to manufacture; they could be made into ultra-thin, lightweight, flexible solar cells that would be easy to transport and install; and they could offer unique attributes such as transparency, opening up novel applications such as integration into windows or textiles. Since no single technology—established or emerging—offers benefits on all fronts, the researchers recommend rapidly scaling up current silicon-based systems while continuing to work on other technologies to increase efficiency, decrease materials use, and reduce manufacturing complexity and cost.



Annual PV capacity additions in the United States by system type

The world's installed PV capacity exceeds 200 gigawatts (GW), accounting for more than 1% of global electricity generation. The chart above shows annual additions to PV capacity in the United States from 2008 to 2014. Additions to utility, commercial, and residential capacity grew substantially each year, with the greatest increase occurring in the utility arena. Between 2008 and 2014, total US grid-connected PV capacity grew from about 0.8 GW to 18.3 GW. To put those numbers into context, the solar generating capacity added in 2014 is equivalent to the total capacity of several large power plants.

One of the few renewable, low-carbon energy resources that could scale up to meet worldwide electricity demand is solar. Silicon solar cells do a good job transforming the sun's energy into electricity today, but will they be up to the task in the future, when vast solar deployment will be needed to mitigate climate change? And what role might be played by the many other PV technologies now being developed in research labs the world over?

Addressing such questions was the goal of a recent wide-ranging assessment by Vladimir Bulović, the Fariborz Maseeh (1990) Professor of Emerging Technology and MIT's associate dean for innovation; Tonio Buonassisi, associate professor of mechanical engineering; Robert Jaffe, the Jane and Otto Morningstar Professor of Physics; and graduate students Joel Jean of electrical engineering and computer science and Patrick Brown of physics.

The solar resource

The researchers' first task was to examine their energy resource—sunlight. To no one's surprise, the assessment confirmed that solar energy is abundantly available and quite evenly distributed across the globe. It varies by only about a factor of three across densely populated areas, and it isn't highly correlated with economic wealth. In contrast, fossil fuels, uranium, and suitable sites for hydropower are heavily concentrated, creating potential tensions between the haves and have-nots. "Solar is a much more democratic resource," notes Jean.

And the world is beginning to take advantage of it. More than 1% of total global electricity is now provided by solar. Within the United States, solar deployment is growing at rates significantly exceeding projections made by experts just five years ago. In 2014, solar accounted for fully a third of all new US generation capacity; and as shown in the figure on this page, residential, commercial, and (especially) utility-scale PV installations have all flourished in recent years.

About 90% of current solar PV deployment is based on crystalline silicon solar cells—a technology that has been commercial for decades and is still improving. This efficient, reliable technology could achieve the needed large-scale deployment without major technological advances, says Bulović.

But it's tough to make it cheaper. In the solar PV business, costs are divided into two categories: the cost of the solar module—the panel consisting of multiple solar cells, wiring, glass, encapsulation materials, and frame—and the "balance of system" (BOS), which includes hardware such as inverters and wiring plus installation labor, permitting, grid interconnection, inspections, financing, and the like. Since 2008, the cost of the module has dropped by 85%, but the BOS cost hasn't changed much at all. Today, the solar module is responsible for just one-fifth of the total cost of a residential installation and one-third of the cost of a utility-scale installation in the United States. The rest is the cost of the BOS.

Reducing BOS costs isn't easy with silicon. Silicon isn't very good at absorbing sunlight, so a thick, brittle layer is needed to do the job; and keeping it from cracking requires mounting it on a heavy piece of glass. A silicon PV module is therefore rigid and heavy—features that raise the BOS cost. "What we need is a cell that performs just as well but is thinner, flexible, lightweight, and easier to transport and install," says Bulović.

Research teams worldwide are now on the track of making such a PV cell. They're starting not with silicon—a structurally simple material—but rather with a variety of more complicated nanomaterials that can be specially designed to capture solar energy and convert it into electricity.

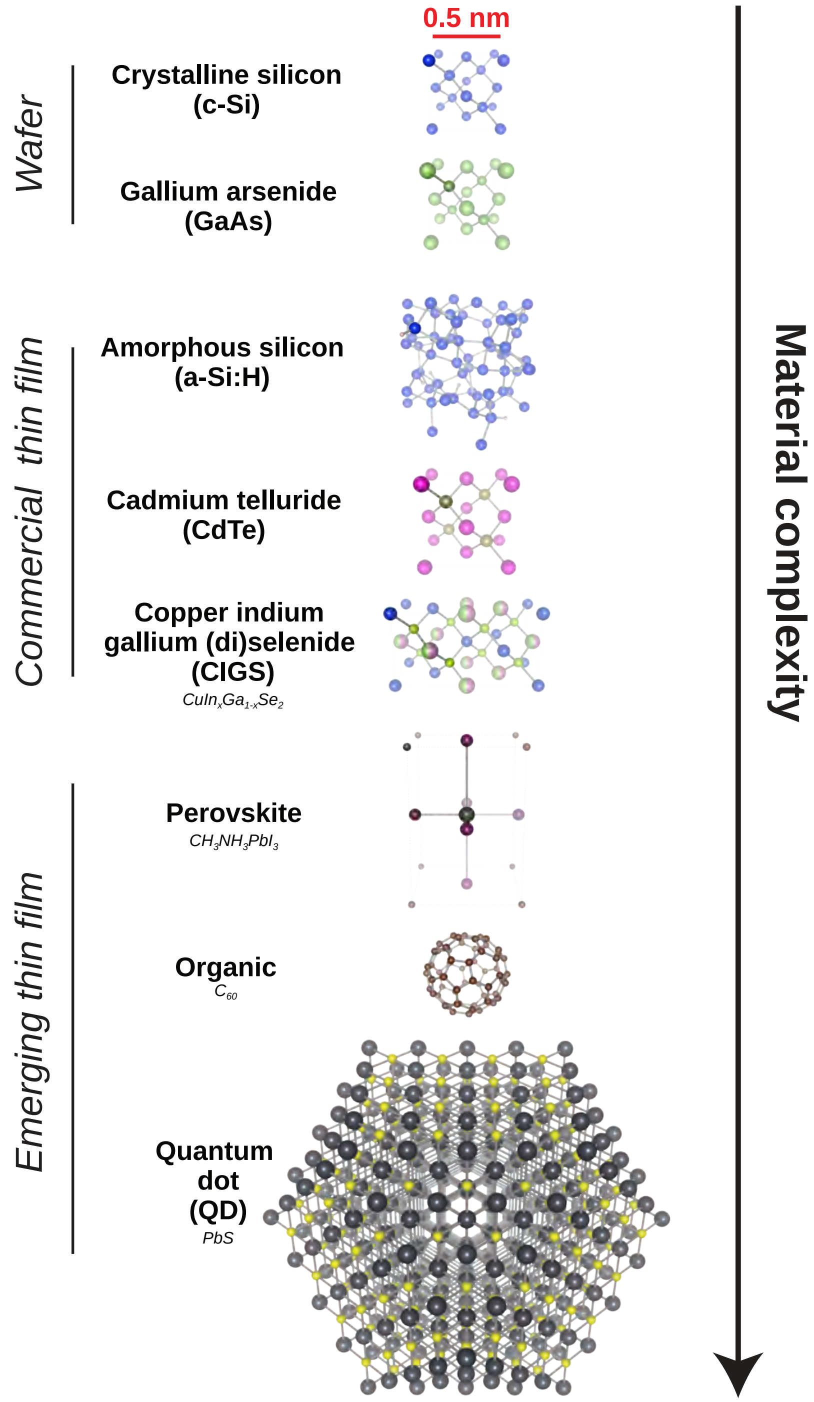
Comparing and contrasting the technologies

Evaluating the many PV technologies now in use and under development is difficult because they're all so different. At the most basic level, they employ different active materials to absorb light and collect electric charge. In general, they fall into three broad categories. Wafer-based cells include traditional crystalline silicon and alternatives such as gallium arsenide; commercial thin-film cells include amorphous (non-crystalline) silicon, cadmium telluride, and copper indium gallium (di)selenide (CIGS); and emerging thin-film technologies include perovskite, organic, and quantum dot (QD) solar cells.

Comparing the strengths and weaknesses of those and other options requires a way to organize them. The conventional classification system—established in 2001—groups solar technologies into three "generations" based on efficiency and cost. But that scheme "may not adequately describe the modern PV technology landscape," says Bulović, because many of the technologies—both old and new—don't fit well into their assigned categories. In addition, such a chronological scheme treats older technologies pejoratively. "Third generation" will always sound better than "first generation." But silicon—a first-generation technology—still offers many advantages and commands the vast majority of the solar cell market.

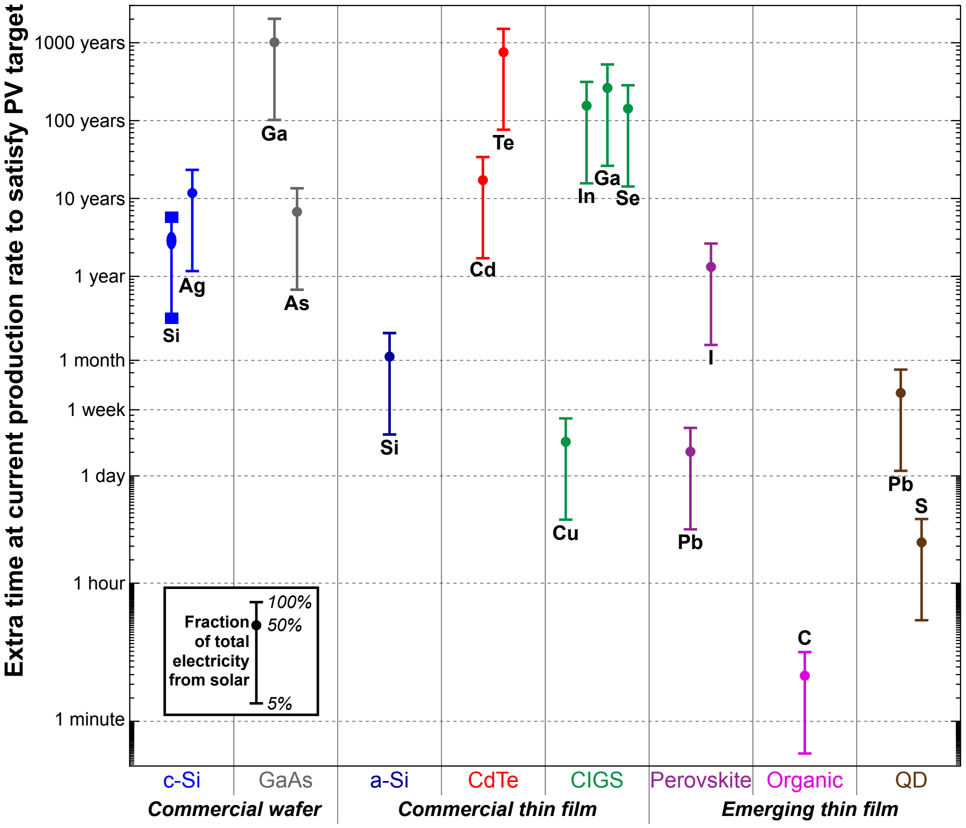
To help guide today's thinking, the MIT team came up with a new framework.

PV technology classification based on material complexity



This figure shows the researchers' proposed scheme for classifying PV technologies based on material complexity, defined roughly as the number of atoms in a molecule or repeating crystal unit. These "building blocks" are highlighted above to show their relative complexity. The wafer-based technologies near the top consist of single- or few-atom building blocks. The thin-film technologies are then arranged in order of increasing complexity, ranging from amorphous elemental materials such as amorphous silicon, through polycrystalline thin films such as cadmium telluride, to complex nanomaterials such as quantum dots, which contain thousands of lead and sulfur atoms.

Materials requirements for PV technologies



The availability of critical materials could constrain a major scale-up of solar capacity using certain PV technologies. This figure shows how much additional time would be needed at current production rates to supply key materials to meet three levels of 2050 electricity demand—5%, 50%, and 100%—using selected PV technologies. Materials availability doesn't limit the expanded use of today's silicon-based cells or emerging PV technologies. In contrast, using commercial thin-film technologies such as cadmium telluride to supply the bulk of projected electricity demand would require hundreds of years of producing key materials at current rates. The needed growth in annual production of those materials between now and 2050 would be well beyond the realm of historical precedent.

It's based on the complexity of the light-absorbing material—a concept defined roughly as the number of atoms in the molecule or crystal unit that forms the building block for the material. The building blocks in modern PV technologies range in complexity from single silicon atoms to increasingly complicated compounds and nanomaterials—from cadmium telluride through perovskites and organics and finally to QDs (see the diagram on page 8). In the new classification system, all of the technologies appear on a single scale; they don't move around over time; and one location isn't better than another. In addition, says Jean, "we find that there's some correlation between complexity and the performance measures that we're interested in."

One such measure is manufacturing complexity and cost. While silicon is structurally simple, turning it into wafers and solar cells is complicated and expensive, in part because of the need for stringent purity (>99.9999%) and high temperatures (>1400°C). Processing more complicated-looking nanomaterials is generally easier, cheaper, and less energy-intensive. For example, preliminary chemical reactions at moderate temperatures can be used to transform starting materials into organic molecules or QDs. Those complicated building blocks can then be deposited at low temperatures through vapor or solution processing, which could make them compatible with a variety of substrates as well as with high-speed production processes such as roll-to-roll printing.

Another critical measure of PV technology is power conversion efficiency, defined as the fraction of the incoming solar energy that comes out as electrical energy. Crystalline silicon is still the technology to beat, with record cell efficiencies of up to 26%. Emerging nanomaterial-based technologies are currently in the 10%–20% range. However, because complex nanomaterials can be engineered for maximum light absorption, they can absorb the same amount of light as silicon with orders of magnitude less material. "So while the typical silicon solar cell is more than 100 microns thick, the typical nanostructured solar cell—one that uses QDs or perovskites—can be less than 1 micron thick," says Bulović. And that active layer can be deposited on flexible substrates such as plastic and paper with no need for mechanical support from a heavy piece of glass.

Thus far, the high efficiencies promised by such novel thin-film PV technologies have been achieved only in laboratory samples smaller than a fingernail, and long-term stability remains an issue. But with additional work, technologies based on complex materials could offer a range of valuable attributes. Such technologies could be made into lightweight, flexible, robust solar modules, which could bring down BOS costs in systems connected to the power grid. They could be used to power portable electronic devices ranging from mobile phones to small water purification systems; they could be transported and installed in remote areas; and they could be well-suited to the low-power lighting and communication requirements of the developing world. Finally, they could have unusual properties that permit novel applications. For example, some nanomaterials can be engineered to absorb ultraviolet and infrared light while letting through visible light, so they could be integrated into, say, windows, skylights, and building facades.

Materials availability

The prospect of scaling up today's solar generation—perhaps by a factor of 100—raises another issue: materials availability. Will the large-scale deployment of solar power be limited by the availability of critical materials needed to manufacture solar cells? How do the different technologies perform on this measure?

To find out, the researchers determined the materials requirements for each PV technology. They then calculated how much of those materials would be needed if that technology were used to satisfy 5%, 50%, or 100% of global electricity demand in 2050. (Using the International Energy Agency's estimates of demand in 2050, those fractions translate to installed PV capacities of 1,250, 12,500, and 25,000 gigawatts [GW] of power—all of which dwarf today's installed PV capacity of roughly 200 GW.) Finally, they checked current global production of each material and determined how many additional hours, days, or years of production at current levels would be needed to meet the selected deployment targets with the various technologies.

The figure on page 9 summarizes their findings. Meeting 100% of 2050 global electricity demand with crystalline silicon solar cells would require the equivalent of just six years of current silicon production. Such a scale-up of production by 2050 is certainly feasible, so materials constraints are not a major issue for silicon.

The same can't be said of today's commercial thin-film technologies. Consider cadmium telluride. Tellurium is about a quarter as abundant as gold and is produced primarily as a byproduct of copper refining. Providing the tellurium for cadmium telluride cells to meet all of 2050 demand would require the equivalent of 1,400 years at the current rate of mining. Indium, gallium, and selenium are also produced as byproducts of major metals, and using CIGS solar cells to fulfill all electricity needs in 2050 would require well over 100 years of current production for all three. "That isn't to say these technologies don't have a future—they could still generate hundreds of gigawatts of power," says Brown. "But materials constraints make it seem unlikely that they will be the dominant solar technology."

In contrast, the emerging thin-film technologies use abundant primary metals that are produced in high volume. For example, meeting 100% of demand with QD-based solar cells would require the equivalent of only 22 days of global lead production and six hours of global sulfur production. Perovskites would require at most three years of current production of their constituent elements.

The bottom line

The researchers conclude that work should continue on all the technologies, with efforts focused on increasing conversion efficiency, decreasing materials use, and reducing manufacturing complexity and cost. Right now, no single technology promises to be best on all three measures, and predicting how each will evolve over time is difficult. For example, if emerging technologies start being used in mobile phone displays or windows or curtains, meeting that demand could help manufacturers work through production issues, perhaps enabling lower-cost, larger-scale production in the future.

The researchers also stress the time required to get a new technology developed and to market. "Today's emerging technologies are improving far faster than currently deployed technologies improved in their early years," says Bulović. "But the road to market and large-scale deployment is invariably long." In addition, PV deployment may be limited or influenced by unforeseeable technical, economic, and political factors. Given the urgency of the climate change problem, says Brown, "We need to be deploying and improving today's technology and at the same time setting the groundwork for emerging technologies that we might discover in the lab. It's critical that we push forward on both fronts."

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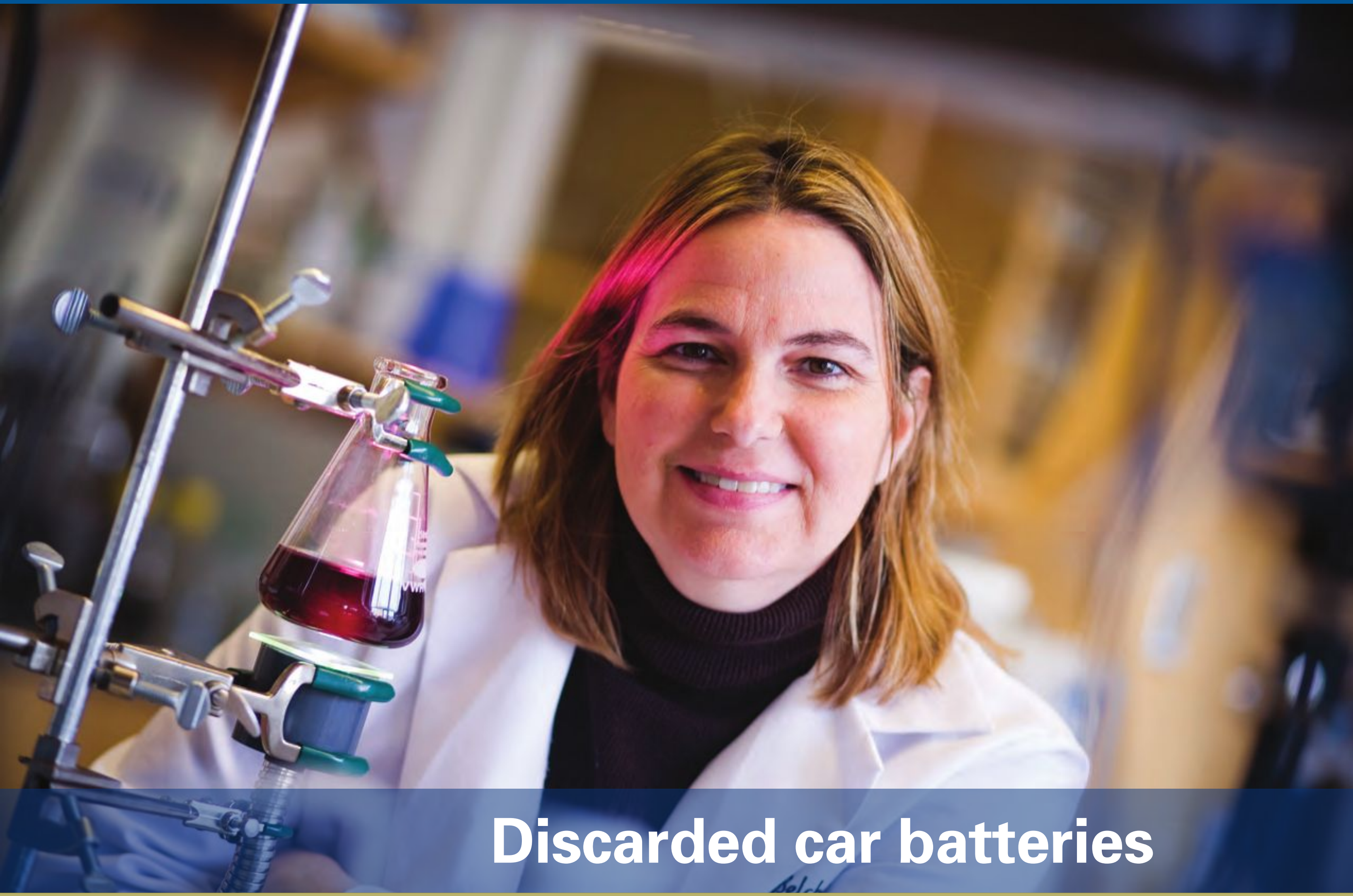
By Nancy W. Stauffer, MITEI

This research was supported by the MIT Future of Solar Energy study (see mitei.mit.edu/futureofsolar). Further information can be found in:

J. Jean, P.R. Brown, R.L. Jaffe, T. Buonassisi, and V. Bulović. "Pathways for solar photovoltaics." *Energy & Environmental Science*, vol. 8, pp. 1200–1219, 2015.

MIT Energy Initiative. *The Future of Solar Energy: An Interdisciplinary MIT Study.* Chapter 2: "Photovoltaic Technology," pp. 21–45, 2015.



Discarded car batteries

Recovering material for novel solar cells

Angela Belcher of biological engineering and materials science and engineering (above), Paula Hammond of chemical engineering (see page 12), Po-Yen Chen PhD '15 (now at Brown University), and others have shown that a novel, high-efficiency, low-cost solar cell can be made using lead recovered from an abundant, old-technology source: lead-acid car batteries.

This research was supported by the Italian energy company Eni S.p.A., a Founding Member of the MIT Energy Initiative. See page 14 for publications resulting from this work.

Photo: Dominick Reuter

MIT researchers have developed a simple procedure for making a promising type of solar cell using lead recovered from discarded lead-acid car batteries—a practice that could benefit both the environment and human health. As new lead-free car batteries come into use, old batteries would be sent to the solar industry rather than to landfills. And if production of this new, high-efficiency, low-cost solar cell takes off—as many experts think it will—manufacturers' increased demand for lead could be met without additional lead mining and smelting. Laboratory experiments confirm that solar cells made with recycled lead work just as well as those made with high-purity, commercially available starting materials. Battery recycling could thus support production of these novel solar cells while researchers work to replace the lead with a more benign but equally effective material.

Much attention in the solar community is now focused on an emerging class of crystalline photovoltaic materials called perovskites. The reasons are clear. The starting ingredients are abundant and easily processed at low temperatures, and the fabricated solar cells can be thin, lightweight, and flexible—ideal for applying to windows, building facades, and more. And they promise to be highly efficient.

Unlike most advanced solar technologies, perovskites are rapidly fulfilling that promise. "When perovskite-based solar cells first came out, they were a few percent efficient," says Angela Belcher, the James Mason Crafts Professor in biological engineering and materials science and engineering at MIT. "Then they were 6% efficient, then 15%, and then 20%. It was really fun to watch the efficiencies skyrocket over the course of a couple years." Perovskite solar cells demonstrated in research labs may soon be as efficient as today's commercial silicon-based solar cells, which have achieved current efficiencies only after many decades of intensive research and development.

Research groups are now working to scale up their laboratory prototypes and to make them less susceptible to degradation when exposed to moisture. But one concern persists: The most efficient perovskite solar cells all contain lead.

That concern caught the attention of Belcher and her colleague Paula Hammond, the David H. Koch (1962) Professor in Engineering and head of the Department of Chemical Engineering at MIT. Belcher and Hammond have spent decades developing environmentally friendly synthesis procedures to generate materials for energy applications such as batteries and solar cells. Although lead is toxic, in consumer devices it can be encapsulated in other materials so it can't escape and contaminate the environment, and it can be recovered from retired devices and used to make new ones. But lead mining and refining raise serious health and environmental issues ranging from the release of toxic vapors and dust to high energy consumption and greenhouse gas emissions. Therefore, research teams worldwide—including Belcher and Hammond—have been actively seeking a replacement for the lead in perovskite solar cells. But so far, nothing has proved nearly as effective.

Recognizing the promise of this technology and the difficulty of replacing the lead in it, in 2013 the MIT researchers proposed an alternative. "We thought, what if we got our lead from another source?" recalls Belcher. One possibility would be discarded lead-acid car batteries. Today, old car batteries are recycled, with most of the lead used to produce new batteries. But battery technology is changing rapidly, and the future will likely bring new, more efficient options. At that point, the 250 million lead-acid batteries in US cars today will become waste—and that could cause environmental problems.

"If we could recover the lead in those batteries and use it to make perovskite solar cells, it'd be a win-win situation," says Belcher.

Recovering and processing materials

According to Belcher, recovering lead from a lead-acid battery and turning it into a perovskite solar cell involves "a very, very simple procedure"—so simple that she and her colleagues posted a video of exactly how to do it. The sequence of steps is illustrated in the diagram on page 13. The first step—getting the lead out of the car battery—might seem a simple proposition. Just remove the battery from the car, cut it open with a saw, and scrape the lead off the two electrodes. But opening a battery is extremely dangerous due to the sulfuric acid and toxic lead inside it. (In fact, when Belcher learned that high school students were recreating the procedure for science fair projects, she had her team delete that section of the instructional video.) In the end, Po-Yen Chen PhD '15, then a chemical engineering graduate student and an Eni-MIT Energy Fellow and now a postdoc at Brown University, arranged to have a battery-recycling center near his home in Taiwan perform the disassembly process.


Photo: Webb Chappell

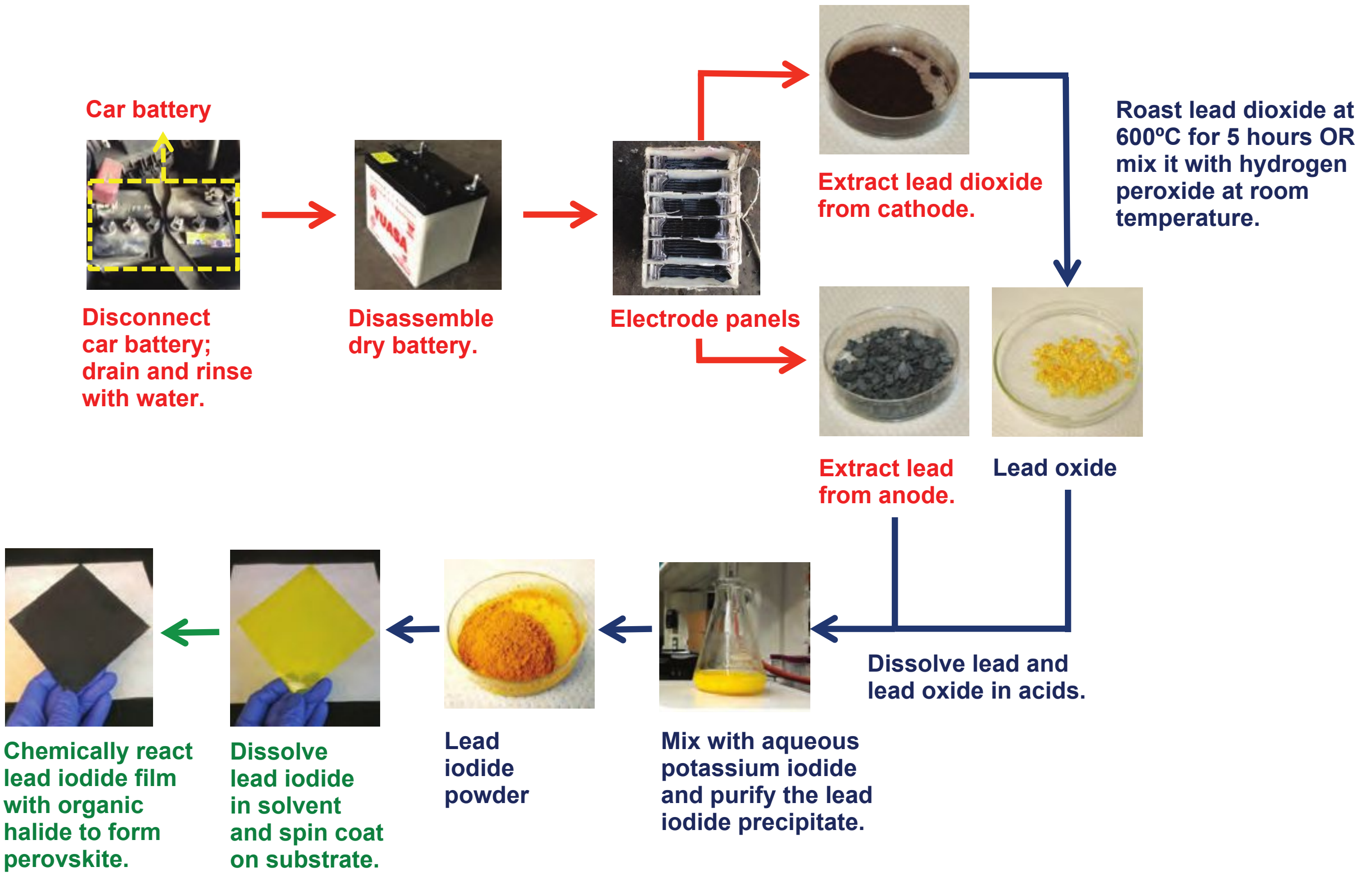
Paula Hammond, the David H. Koch (1962) Professor in Engineering.

Back at MIT, clad in protective clothing and working inside a chemical hood, the researchers carefully scraped material off the electrodes and then followed the steps in the illustration to synthesize the lead iodide powder they needed. They then dissolved the powder in a solvent and dropped it onto a spinning disk made of a transparent conducting material, where it spread out to form a thin film of perovskite. After performing a few more processing steps, they integrated the perovskite film into a functional solar cell that successfully converted sunlight into electricity.

Penalty for using recycled lead?

The simple procedure for recovering and processing the lead and making a solar cell could easily be scaled up and commercialized. But Belcher and

Using recycled car batteries to synthesize perovskite for solar cells



This figure shows how to synthesize lead iodide perovskite from a lead-acid battery. The simple process calls for three main steps: harvesting material from the anodes and cathodes of the car battery (shown in red); synthesizing lead iodide from the collected materials (blue); and depositing the perovskite film (green).

Hammond knew that solar cell manufacturers would have a question: Is there any penalty for using recycled materials instead of high-quality lead iodide purchased from a chemical company?

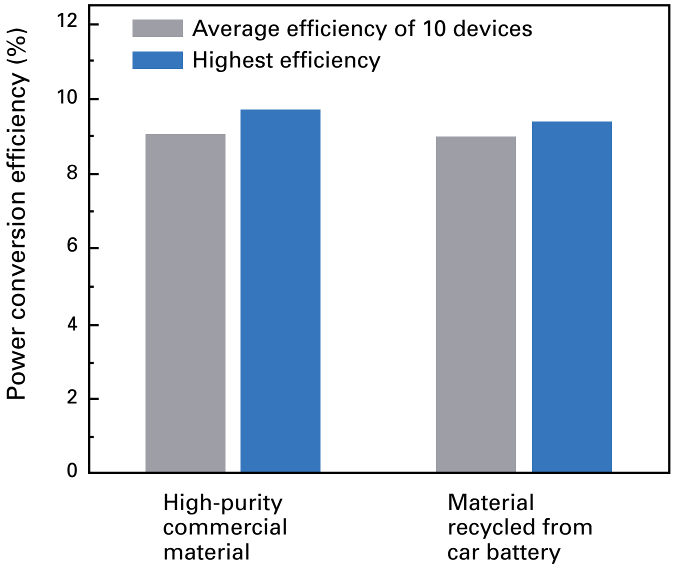
To answer that question, the researchers decided to make some solar cells using recycled materials and some using commercially available materials and then compare the performance of the two versions. They don't claim to be experts at making perovskite solar cells optimized for maximum efficiency. But if the cells they made using the two starting materials performed equally well, then "people who are skilled in fine-tuning these solar cells to get 20% efficiencies would be able to use our material and get the same efficiencies," reasoned Belcher.

The researchers began by evaluating the light-harvesting capability of the perovskite thin films made from car batteries and from high-purity commercial lead iodide. In a variety of tests, the films displayed the same nanocrystalline structure and identical light-absorption capability. Indeed, the films' ability to absorb light at different wavelengths was the same.

They then tested solar cells they had fabricated from the two types of perovskite and found that their photovoltaic performance was similar. One measure of interest is power conversion efficiency (PCE), which is the fraction of the incoming solar power that comes out as electrical power. The figure on page 14 shows PCE measurements in 10 of the solar cells fabricated from high-purity lead iodide and 10 fabricated from car batteries. Because efficiency measurements in these types of devices can vary widely, the figure presents not only the highest PCE achieved but also the average over the entire batch of devices. The performance of the two types of solar cells is almost identical. "So device quality doesn't suffer from the use of materials recovered from spent car batteries," says Belcher.

Taken together, these results were extremely promising—but they were based on solar cells made from a single discarded car battery. Might the outcome be different using a different battery? For example, they were able to recover more than 95% of the usable lead in their battery. Would that fraction

Power conversion efficiency of fabricated solar cells



This figure shows power conversion efficiency—the fraction of incoming solar power converted to electricity—in solar cells that the researchers fabricated using starting materials purchased from a vendor (left) and recovered from a spent lead-acid car battery. In each case, the gray bar shows the average efficiency of 10 devices, while the blue bar shows the highest efficiency achieved in a single device. Performance in the two groups of devices is essentially the same, confirming that using recycled material does not compromise device quality.

be lower in an older battery? And might the quality or purity of the recovered lead differ?

To find out, the researchers returned to the Taiwanese recycling center and bought three more batteries. The first had been operating for six months, the second for two years, and the third for four years. They then followed the same procedures to recover and synthesize the lead iodide and fabricate and test solar cells made with it. The outcome was the same—with one exception. In the older batteries, some of the lead occurs in the form of lead sulfate—a result of reactions with the sulfuric acid electrolyte. But they found that their original procedures were effective in recovering the lead from the lead sulfate as well as from the other compounds inside the batteries.

Based on their results, Belcher and Hammond concluded that recycled lead could be integrated into any type of process that researchers are using to fabricate perovskite-based solar cells—and indeed to make other types of lead-containing solar cells, light-emitting diodes, piezoelectric devices, and more.

Potential economic impact

A simple economic analysis shows that the proposed battery-to-solar-cell procedure could have a substantial impact. Assuming that the perovskite thin film is just half a micrometer thick, the researchers calculate that a single lead-acid car battery could supply enough lead for the fabrication of more than 700 square meters of perovskite solar cells. If the cells achieve 15% efficiency (a conservative assumption today), those solar cells would together provide enough electricity to power about 14 households in Cambridge, Massachusetts, or about 30 households in sunny Las Vegas, Nevada. Powering the whole United States would take about 12.2 million recycled car batteries, fabricated into 8,634 square kilometers of perovskite solar panels operating under conditions similar to those in Nevada.

In the long term, of course, the best approach would be to find an effective, nontoxic replacement for the lead. Belcher and Hammond continue to search for a suitable substitute, performing theoretical and experimental studies with various types of atoms. At the same time, they have begun testing the impact of another approach: replacing a portion of the lead with another material that may not perform as well but is more environmentally friendly. Already they've had promising results, achieving some "pretty decent efficiencies," says Belcher. The combination of their two approaches—using recycled lead and reducing the amount required—could ease near-term environmental and health concerns while Belcher, Hammond, and others develop the best possible chemistry for this novel solar technology.

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By Nancy W. Stauffer, MITEI

This research was supported by the Italian energy company Eni S.p.A., a Founding Member of the MIT Energy Initiative. Further information can be found in:

P.-Y. Chen, J. Qi, M.T. Klug, X. Dang, P.T. Hammond, and A.M. Belcher. "Environmentally responsible fabrication of efficient perovskite solar cells from recycled car batteries." *Energy & Environmental Science*, vol. 7, pp. 3659–3665, 2014.

P.-Y. Chen, J. Qi, M.T. Klug, X. Dang, P.T. Hammond, and A.M. Belcher. "Response to the comments on 'Environmentally responsible fabrication of efficient perovskite solar cells from recycled car batteries' by Po-Yen Chen, Jifa Qi, Matthew T. Klug, Xiangnan Dang, Paula T. Hammond, and Angela M. Belcher published in Energy Environ. Sci. in 2014." *Energy & Environmental Science*, vol. 8, pp. 1618–1625, 2015.

Preparing for large-scale solar deployment

Measures to ensure a reliable future power system

Deploying solar power at the scale needed to alleviate climate change will pose serious challenges for today’s electric power system, finds a study performed by MIT and IIT-Comillas University. For example, local power networks will need to handle both incoming and outgoing flows of electricity. Rapid changes in photovoltaic (PV) output as the sun comes and goes will require running expensive power plants that can respond quickly to changes in demand. Costs will rise, yet market prices paid to owners of PV systems will decline as more PV systems come online, rendering more PV investment unprofitable at market prices. The study concludes that ensuring an economic, reliable, and climate-friendly power system in the future will require strengthening existing equipment, modifying regulations and pricing, and developing critical technologies, including low-cost, large-scale energy storage devices that can smooth out delivery of PV-generated electricity.

This research was supported by the MIT Future of Solar Energy study (mitei.mit.edu/futureofsolar) and by the MIT Utility of the Future consortium (mitei.mit.edu/research/utility-future-study). See page 19 for a list of publications

Photo: Carlos Rosillo

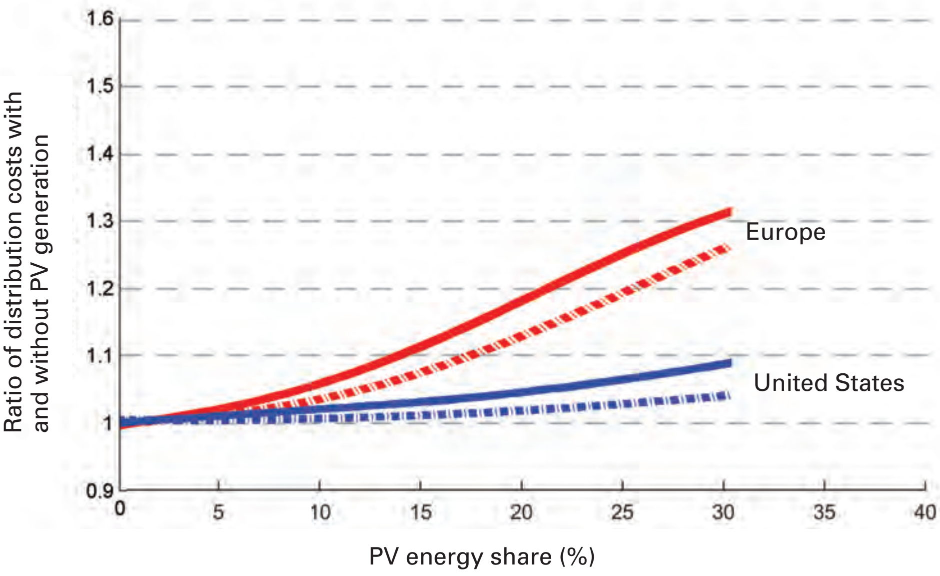
Ignacio Pérez-Arriaga of the MIT Sloan School of Management and IIT-Comillas University in Madrid, Spain (above), and a team of Comillas and MIT researchers are examining how the large-scale adoption of solar power may affect operations, costs, and other aspects of today’s electric power systems going forward.

Most experts agree that solar power must be a critical component of any long-term plan to address climate change. By 2050, a major fraction of the world's power should come from solar sources. However, analyses performed as part of the MIT Future of Solar Energy study found that getting there won't be straightforward. "One of the big messages of the solar study is that the power system has to get ready for very high levels of solar PV generation," says Ignacio Pérez-Arriaga, a visiting professor at the MIT Sloan School of Management from IIT-Comillas University in Madrid, Spain.

Without the ability to store energy, all solar (and wind) power devices are intermittent sources of electricity. When the sun is shining, electricity produced by PVs flows into the power system, and other power plants can be turned down or off because their generation isn't needed. When the sunshine goes away, those other plants must come back online to meet demand. That scenario poses two problems. First, PVs send electricity into a system that was designed to deliver it, not receive it. And second, their behavior requires other power plants to operate in ways that may be difficult or even impossible.

The result is that solar PVs can have profound, sometimes unexpected impacts on operations, future investments, costs, and prices on both distribution systems—the local networks that deliver electricity to consumers—and bulk power systems—the large interconnected systems made up of generation and transmission facilities. And those impacts grow as the solar presence increases.

Changes in network costs with growing PV penetration



These curves show the impact of solar generation on distribution network costs in the United States (blue) and in Europe (red). (Results differ in part due to differing network configurations and voltages.) Costs are measured relative to the cost of a corresponding no-PV scenario. Energy storage is assumed to be unavailable. Solid lines indicate 80% residential, 15% commercial, and 5% industrial demand. Dashed lines indicate 15% residential, 80% commercial, and 5% industrial demand. In all cases, costs increase as PV energy share increases, with the greater impact seen when residential customers dominate demand.

Supporting local distribution

To examine impacts on distribution networks, the researchers used the Reference Network Model (RNM), which was developed at IIT-Comillas and simulates the design and operation of distribution networks that transfer electricity from high-voltage transmission systems to all final consumers. Using the RNM, the researchers built—via simulation—several prototype networks and then ran multiple simulations based on different assumptions, including varying amounts of PV generation.

In some situations, the addition of dispersed PV systems reduces the distance electricity must travel along power lines, so less is lost in transit and costs go down. But as the PV energy share grows, that benefit is eclipsed by the need to invest in reinforcing or modifying the existing network to handle two-way power flows. Changes could include installing larger transformers, thicker wires, and new voltage regulators or even reconfiguring the network, but the net result is added cost to protect both equipment and quality of service.

The figure above presents sample results showing the impact of solar generation on network costs in the United States and in Europe. The outcomes differ, reflecting differences in the countries' voltages, network configurations, and so on. But in both cases, costs increase as the PV energy share increases from 0 to 30%, and the impact is greater when demand is dominated by residential rather than commercial or industrial customers.

The impact is also greater in less sunny regions. Indeed, in areas with low insolation, distribution costs may nearly double when the PV contribution exceeds one-third of annual load. The reason: When insolation is low, many more solar generating devices must be installed to meet a given level of demand, and the network needs to be ready to handle all the electricity flowing from those devices on the occasional sunny day.

One way to reduce the burden on distribution networks is to add local energy storage capability. Depending on the scenario and the storage capacity, at 30% PV penetration, storage can reduce added costs by a third in Europe and cut them in half in the United States. "That doesn't mean that deployment of storage is economically viable now," says Pérez-Arriaga. "Current storage technology is expensive, but one of the services with economic value that it can provide is to bring down the cost of deploying solar PV."

Another concern stems from methods used to calculate consumer bills—methods that some distribution companies and customers deem unfair. Most US states employ a practice called net metering. Each PV owner is equipped with an electric meter that turns one way when the household is pulling electricity in from the network and the other when it's sending excess electricity out. Reading the meter each month therefore gives net consumption or (possibly) net production, and the owner is billed or paid accordingly.

Most electricity bills consist of a small fixed component and a variable component that is proportional to the energy consumed during the time period considered. Net metering can have the effect of reducing, canceling, or even turning the variable component into a negative value. As a result, users with PV panels avoid paying most of the network costs—even though they are using the network and (as explained above) may actually be pushing up network costs. "The cost of the network has to be recovered, so people who don't own solar PV panels on their rooftops have to pay what the PV owners don't pay," explains Pérez-Arriaga. In effect, the PV owners are receiving a subsidy that's paid by the non-PV owners.

Unless the design of network charges is modified, the current controversy over electricity bills will intensify as residential solar penetration increases. Therefore, Pérez-Arriaga and his colleagues are developing proposals for "completely overhauling the way in which the network tariffs are designed so that network costs are allocated to the entities that cause them," he says.

Impacts on bulk power systems

In other work, the researchers focused on the impact of PV penetration on larger-scale electric systems. Using the Low Emissions Electricity Market Analysis model—another tool developed at IIT-Comillas—they examined how operations on bulk power systems, the future generation mix, and prices on wholesale electricity markets might evolve as the PV energy share grows.

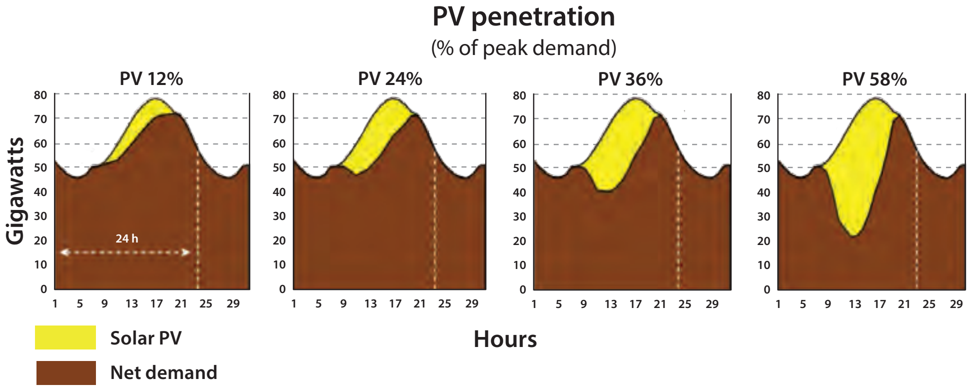
Unlike deploying a conventional power plant, installing a solar PV system requires no time-consuming approval and construction processes. "If the regulator gives some attractive incentive to solar, you can just remove the potatoes in your potato field and put in solar panels," says Pérez-Arriaga. As a result, significant solar generation can appear on a bulk power system within a few months. With no time to adjust, system operators must carry on using existing equipment and methods of deploying it to meet the needs of customers.

A typical bulk power system includes a variety of power plants with differing costs and characteristics. Conventional coal and nuclear plants are inexpensive to run (though expensive to build), but they don't switch on and off easily or turn up and down quickly. Plants fired by natural gas are more expensive to run (and less expensive to build), but they're also more flexible. In general, demand is met by dispatching the least expensive plants first and then turning to more expensive and flexible plants as needed.

For one series of simulations, the researchers focused on a power system similar to the one that services much of Texas. Results presented on page 18 (top) show how PV generation affects demand on that system over the course of a summer day. In each diagram, yellow areas are demand met by PV generation, and brown areas are "net demand," that is, remaining demand that must be met by other power plants. Left to right, the diagrams show increasing PV penetration. Initially, PV generation simply reduces net demand during the middle of the day. But when the PV energy share reaches 58%, the solar generation pushes down net demand dramatically, such that when the sun goes down, other generators must go from low to high production in a short period of time. Since low-cost coal and nuclear plants can't ramp up quickly, more expensive gas-fired plants must cut in to do the job.

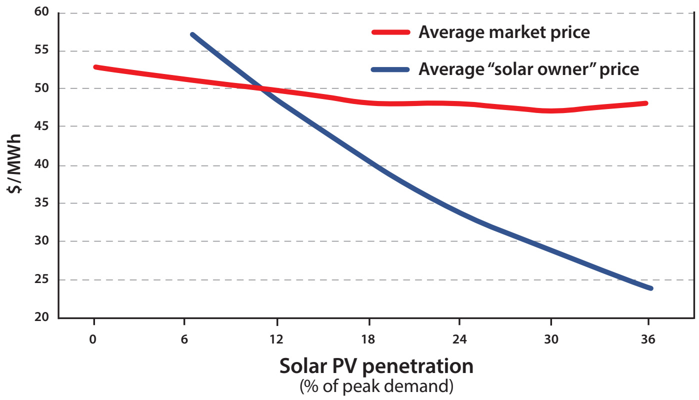
That change has a major impact on prices on the wholesale electricity market. Each owner who sends a unit of electricity into the bulk power system at a given time gets paid the same amount: the cost of producing a unit of electricity at the last plant that was turned on, thus the most expensive one. So when PVs come online, expensive gas-fired plants

Changes in demand as PV penetration increases



These diagrams show how PV generation affects the demand that must be met by other generating units on a summer day on a Texas-like power system. Yellow areas are demand met by PV generation; brown areas are "net demand" that must be met by other power plants. When PV penetration is low, net demand is simply reduced during the middle of the day. But as the PV energy share grows, net demand is far lower during the sunny part of the day and then must ramp up quickly when the sun goes down—a rapid change that can be handled only by expensive gas-fired power plants. Interestingly, as PV penetration grows, the peak in net demand shifts in time but never decreases appreciably. As a result, meeting the net-demand peak will require the same installed non-PV generating capacity in each case, but that capacity will be used less as PV generation increases.

Impact of solar PV penetration on prices paid to generators



These curves show average daily prices on the wholesale markets as the fraction of PV energy grows to 36% of all peak demand. The red curve shows average market price—the price perceived by a generator functioning at constant output all the time—while the blue curve shows the price seen by PV owners. Average market price doesn't change significantly with increasing PV penetration because the PV systems reduce prices when they're running and increase prices when they're not. But the price paid to PV owners drops dramatically. At some level of PV penetration, further investment in PV systems will no longer be profitable.

shut off, and the price paid to everyone drops. Then when the sun goes away and PV production abruptly disappears, gas-fired plants are turned back on and the price goes way up.

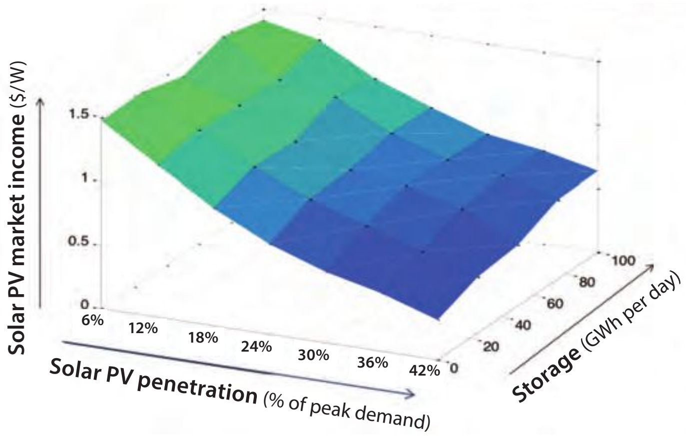
As a result, when PV systems are operating and PV penetrations are high, prices are low, and when they shut down, prices are high. Owners of PV systems thus receive the low prices and never the high. Moreover, their reimbursement declines as more solar power comes online, as shown by the downward sloping blue curve in the bottom figure on this page.

Under current conditions, as more PV systems come online, reimbursements to solar owners will shrink to the point that investing in solar is no longer profitable at market prices. "So people may think that if solar power becomes very inexpensive, then everything will become solar," says Pérez-Arriaga. "But we find that that won't happen. There's a natural limit to solar penetration after which investment in more solar will not be economically viable."

However, if goals and incentives are set for certain levels of solar penetration decades ahead, then PV investment will continue, and the bulk power system will have time to adjust. In the absence of energy storage, the power plants accompanying solar will for the most part be gas-fired units that can follow rapid changes in demand. Conventional coal and nuclear plants will play a diminishing role—unless new, more flexible versions of those technologies are designed and deployed (along with carbon capture and storage for the coal plants). If high subsidies are paid to PV generators or if PV cost diminishes substantially, conventional coal and nuclear plants will be pushed out even more, and more flexible gas plants will be needed to cover the gap, leading to a different generation mix that is well-adapted for coexisting with solar.

A powerful means of alleviating cost and operating issues associated with PVs on bulk power systems—as on distribution networks—is to add energy storage. Technologies that provide many hours of storage—such as grid-scale batteries and hydroelectric plants with large reservoirs—will increase the value of PV. "Storage helps solar PVs have more value because it is able to bring solar-generated electricity to times when sunshine is not there, so to times when prices are high," says Pérez-Arriaga.

Trading off solar PV penetration, PV incomes, and storage capacity



This diagram shows results from simulating the operation of a Texas-like power system while changing three factors: the penetration of PV as a fraction of peak demand, the income per installed watt seen by owners of PV systems, and energy storage capacity on the system. In the absence of storage, as PV penetration increases, PV system owners' income decreases. But at each level of solar PV penetration, the addition of storage increases that income, and in general, the more storage added, the greater the upward shift.

As the figure above demonstrates, adding storage makes investments in PV generation more profitable at any level of solar penetration, and in general the greater the storage capacity, the greater the upward pressure on revenues paid to owners.

Energy storage thus can play a critical role in ensuring financial rewards to prospective buyers of PV systems so that the share of generation provided by PVs can continue to grow—without serious penalties in terms of operations and economics. Again, the research results demonstrate that developing low-cost energy storage technology is a key enabler for the successful deployment of solar PV power at a scale needed to address climate change in the coming decades.

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By Nancy W. Stauffer, MITEI

This research was supported by the MIT Future of Solar Energy study (see mitei.mit.edu/futureofsolar) and by the MIT Utility of the Future consortium (see the sidebar to the right). Further information can be found in:

J.D. Jenkins and I. Pérez-Arriaga. *The Remuneration Challenge: New Solutions for the Regulation of Electricity Distribution Utilities Under High Penetration of Distributed Energy Resources and Smart Grid Technologies.* MIT Center for Energy and Environmental Policy Working Paper no. WP 2014-005, September 2014.

MIT Energy Initiative. *The Future of Solar Energy: An Interdisciplinary MIT Study.* Chapter 7: "Integration of Distributed Photovoltaic Generators," and Chapter 8: "Integration of Solar Generation in Wholesale Electricity Markets." 2015.

I. Pérez-Arriaga and A. Bharatkuman. *A Framework for Redesigning Distribution Network Use-of-System Charges Under High Penetration of Distributed Energy Resources: New Principles for New Problems.* MIT Center for Energy and Environmental Policy Working Paper no. WP 2014-006, October 2014.

MIT Utility of the Future study and consortium

The MIT Utility of the Future study is investigating the technical, economic, and regulatory transformations unfolding in the electric power sector as it transitions from a centralized system to a more distributed one due to the integration of multiple distributed resources, including renewable generation. The study utilizes quantitative analytical models being developed in the project to explore alternative business models and transformative technologies under diverse regulatory and market contexts within the global framework of an increasingly decarbonized power sector. The project is led by principal investigators Ignacio Pérez-Arriaga, visiting professor in the MIT Sloan School of Management, and Christopher Knittel, the William Barton Rogers Professor of Energy Economics, and is supported by Dr. Raanan Miller and Dr. Richard Tabors, directors, and by graduate students, postdocs, and researchers from MIT and IIT-Comillas in Madrid. The project is advised by a faculty committee that includes MIT Professors John Deutch, Richard Schmalensee, Richard Lester, and Robert Armstrong, and a distinguished external advisory board.

Launched in 2014, the study is supported by a consortium of 20 international companies and organizations. Current consortium members include leading electric utilities, oil and gas companies, an independent system operator, and equipment and solution providers to the power industry.

For more information about the study and ways to join the consortium, please go to mitei.mit.edu/research/utility-future-study.

A battery of molten metals

Low-cost, long-lasting storage for the grid

Donald Sadoway of materials science and engineering (right), David Bradwell MEng '06, PhD '11 (left), and their collaborators have developed a novel molten-metal battery that is low-cost, high-capacity, efficient, long-lasting, and easy to manufacture—characteristics that make it ideal for storing electricity on power grids today and in the future.

This research was supported in part by the US Department of Energy's Advanced Research Projects Agency–Energy and the French energy company Total, a Sustaining Member of the MIT Energy Initiative. See page 24 for other sponsors and a list of publications resulting from this research.

Photo: David Sella, courtesy of MIT Industrial Liaison Program

A novel rechargeable battery developed at MIT could one day play a critical role in the massive expansion of solar generation needed to mitigate climate change by midcentury. Designed to store energy on the electric grid, the high-capacity battery consists of molten metals that naturally separate to form two electrodes in layers on either side of the molten salt electrolyte between them. Tests with cells made of low-cost, earth-abundant materials confirm that the liquid battery operates efficiently without losing significant capacity or mechanically degrading—common problems in today's batteries with solid electrodes. The MIT researchers have already demonstrated a simple, low-cost process for manufacturing prototypes of their battery, and future plans call for field tests on small-scale power grids that include intermittent generating sources such as solar and wind.

The ability to store large amounts of electricity and deliver it later when it's needed will be critical if intermittent renewable energy sources such as solar and wind are to be deployed at scales that help curtail climate change in the coming decades. Such large-scale storage would also make today's power grid more resilient and efficient, allowing operators to deliver quick supplies during outages and to meet temporary demand peaks without maintaining extra generating capacity that's expensive and rarely used.

A decade ago, the committee planning the new MIT Energy Initiative approached Donald Sadoway, MIT's John F. Elliott Professor of Materials Chemistry, to take on the challenge of grid-scale energy storage. At the time, MIT research focused on the lithium-ion battery—then a relatively new technology. The lithium-ion batteries being developed were small, lightweight, and short-lived—not a problem for mobile devices, which are typically upgraded every few years, but an issue for grid use.

A battery for the power grid had to be able to operate reliably for years. It could be large and stationary, but—most important—it had to be inexpensive. "The classic academic approach of inventing the coolest chemistry and then trying to reduce costs in the manufacturing stage wouldn't work," says Sadoway. "In the energy sector, you're competing against hydrocarbons, and they're deeply entrenched and heavily subsidized and tenacious." Making a dramatic shift in power production would require a different way of thinking about storage.

Sadoway therefore turned to a process he knew well: aluminum smelting. Aluminum smelting is a huge-scale, inexpensive process conducted inside electrochemical cells that operate reliably over long periods and produce metal at very low cost while consuming large amounts of electrical energy. Sadoway thought: "Could we run the smelter in reverse so it gives back its electricity?"

Subsequent investigation led to the liquid metal battery. Like a conventional battery, this one has top and bottom electrodes with an electrolyte between them (see the diagram on page 22). During discharging and recharging, positively charged metallic ions travel from one electrode to the other through the electrolyte, and electrons make the same trip through an external circuit. In most batteries, the electrodes—and sometimes the electrolyte—are solid. But in Sadoway's battery, all three are liquid. The negative electrode—the top layer in the battery—is a low-density liquid metal that readily donates electrons. The positive electrode—the bottom layer—is a high-density liquid metal that's happy to accept those electrons. And the electrolyte—the middle layer—is a molten salt that transfers charged particles but won't mix with the materials above or below. Because of the differences in density and the immiscibility of the three materials, they naturally settle into three distinct layers and remain separate as the battery operates.

Benefits of going liquid

This novel approach provides a number of benefits. Because the components are liquid, the transfer of electrical charges and chemical constituents within each component and from one to another is ultrafast, permitting the rapid flow of large currents into and out of the battery. When the battery discharges, the top layer of molten metal gets thinner and the bottom one gets thicker. When it charges, the thicknesses reverse. There are no stresses involved, notes Sadoway. "The entire system is very pliable and just takes the shape of the container." While solid electrodes are prone to cracking and other forms of mechanical failure over time, liquid electrodes do not degrade with use.

Indeed, every time the battery is charged, ions from the top metal that have been deposited into the bottom layer are returned to the top layer, purifying the electrolyte in the process. All three components are reconstituted. In addition, because the components naturally self-segregate, there's no need for membranes or separators, which are subject to wear. The liquid battery should perform many charges and discharges without losing capacity or requiring maintenance or service. And the self-segregating nature of the liquid components could facilitate simpler, less-expensive manufacturing compared to conventional batteries.

Choice of materials

For Sadoway and then-graduate student David Bradwell MEng '06, PhD '11, the challenge was to choose the best materials for the new battery, particularly for its electrodes. Methods exist for predicting how solid metals will behave under defined conditions. But those methods "were of no value to us because we wanted to model the liquid state," says Sadoway—and nobody else was working in this area. So he had to draw on what he calls "informed intuition," based on his experience working in electrometallurgy and teaching a large freshman chemistry class.

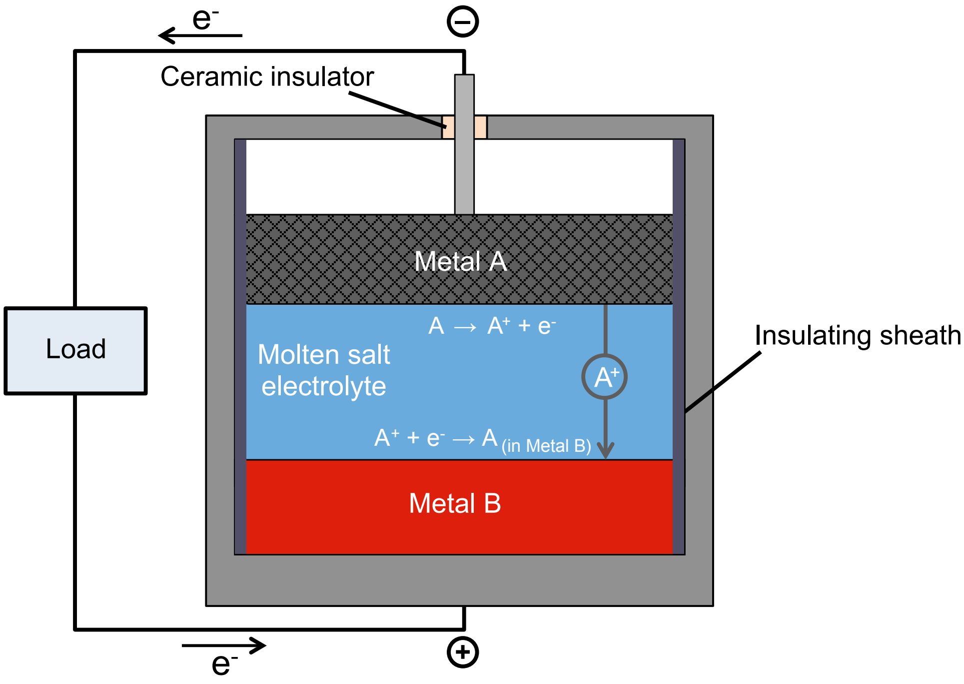
To keep costs down, Sadoway and Bradwell needed to use electrode materials that were earth-abundant, inexpensive, and long-lived. To achieve high voltage, they had to pair a strong electron donor with a strong electron acceptor. The top electrode (the electron donor) had to be low density, and the bottom electrode (the electron acceptor) high density. “Mercifully,” says Sadoway, “the way the periodic table is laid out, the strong electropositive [donor] metals are low density, and the strong electronegative [acceptor] metals are high density” (see the diagram on page 23). And finally, all the materials had to be liquid at practical temperatures.

As their first combination, Sadoway and Bradwell chose magnesium for the top electrode, antimony for the bottom electrode, and a salt mixture containing magnesium chloride for the electrolyte. They then built prototypes of their cell—and they worked. The three liquid components self-segregated, and the battery performed as they had predicted. Spurred by their success, in 2010 they, along with Luis Ortiz SB ’96, PhD ’00, also a former member of Sadoway’s research group, founded a company—called initially the Liquid Metal Battery Corporation and later Ambri—to continue developing and scaling up the novel technology.

Not there yet

But there was a problem. To keep the components melted, the battery had to operate at 700°C (1,292°F). Running that hot consumed some of the electrical output of the battery and increased the rate at which secondary components, such as the cell wall, would corrode and degrade. So Sadoway, Bradwell, and their colleagues at MIT continued the search for active materials.

Schematic diagram of the liquid metal battery



In this liquid metal battery, the negative electrode (top) is a low-density metal called here Metal A; the positive electrode (bottom) is a higher-density metal called Metal B; and the electrolyte between them is a molten salt. Because the three active components—all liquids—have differing densities, they do not mix but instead naturally separate into layers. During discharge (shown here), Metal A loses electrons (e^-), becoming ions (A^+) that travel through the electrolyte to the bottom electrode. The electrons pass through an external circuit, powering an electric load on the way. At the bottom electrode, the Metal A ions and electrons rejoin and then alloy with the Metal B electrode. During recharging, those processes happen in reverse.

Early results from the magnesium and antimony cell chemistry had clearly demonstrated the viability of the liquid metal battery concept; as a result, the on-campus research effort received more than $11 million from funders including Total and the US Department of Energy’s ARPA–E program. The influx of research dollars enabled Sadoway to grow the research team at MIT to nearly 20 graduate and undergraduate students and postdoctoral associates who were ready to take on the challenge.

Within months, the team began to churn out new chemistry options based on various materials with lower melting points. For example, in place of the antimony, they used lead, tin, bismuth, and alloys of similar metals; and in place of the magnesium, they used sodium, lithium, and alloys of magnesium with such metals as calcium. The researchers soon realized that they were not just searching for a new battery chemistry. Instead, they had discovered a new battery “platform” from which a multitude of potentially commercially viable cell technologies with a range of attributes could spawn.

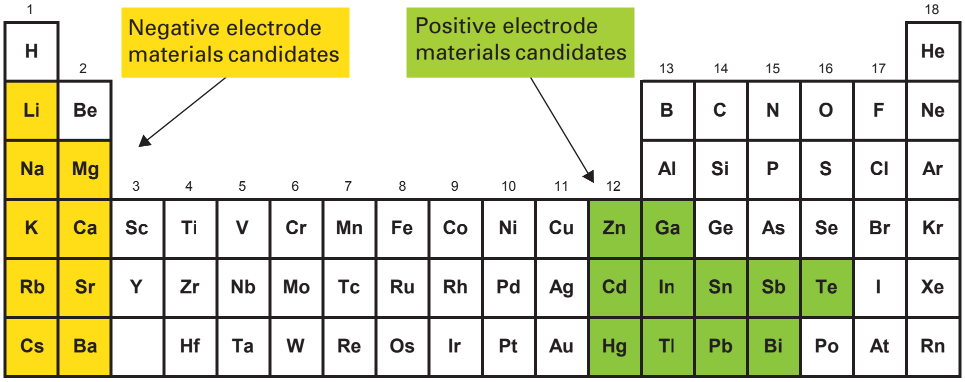
New cell chemistries began to show significant reductions in operating temperature. Cells of sodium and bismuth operated at 560°C. Lithium and bismuth cells operated at 550°C. And a battery with a negative electrode of lithium and a positive electrode of an antimony-lead alloy operated at 450°C.

While working with the last combination, the researchers stumbled on an unexpected electrochemical phenomenon: They found that they could maintain the high cell voltage of their original pure antimony electrode with the new antimony-lead version—even when they made the composition as much as 80% lead in order to lower the melting temperature by hundreds of degrees.

“To our pleasant surprise, adding more lead to the antimony didn’t decrease the voltage, and now we understand why,” Sadoway says. “When lithium enters into an alloy of antimony and lead, the lithium preferentially reacts with the antimony because it’s a tighter bond. So when the lithium [from the top electrode] enters the bottom electrode, it ignores the lead and bonds with the antimony.”

That unexpected finding reminded them how little was known in this new field of research—and also suggested new cell chemistries to explore. For example, they recently assembled a proof-of-concept cell using a positive electrode of a lead-bismuth alloy, a negative electrode of sodium metal, and a novel electrolyte of a mixed hydroxide-halide. The cell operated at just 270°C—more than 400°C lower than the initial magnesium-antimony battery while maintaining the same novel cell design of three naturally separating liquid layers.

Materials candidates for the liquid metal battery



The highlighted regions above show elements that are good candidates for use in the liquid metal battery. Those highlighted in yellow (for example, sodium, lithium, magnesium, and calcium) have a strong tendency to release electrons so are candidates for the negative electrode. Those in green (such as lead, antimony, tin, and bismuth) have a strong tendency to attract electrons so are candidates for the positive electrode. The green elements are also higher density than the yellow ones, so when they’re mixed together, the green ones will naturally form a separate layer on the bottom. By choosing among the options, designers of liquid metal batteries can optimize cost, material availability, operating temperature, cell voltage, or other characteristics to suit a particular application.

The role of the new technology

The liquid metal battery platform offers an unusual combination of features. In general, batteries are characterized by how much energy and how much power they can provide. (Energy is the total amount of work that can be done; power is how quickly work gets done.) In general, technologies do better on one measure than the other. For example, with capacitors, fast delivery is cheap, but abundant storage is expensive. With pumped hydropower, the opposite is true.

But for grid-scale storage, both capabilities are important—and the liquid metal battery can potentially do both. It can store a lot of energy (say, enough to last through a blackout) and deliver that energy quickly (for example, to meet demand instantly when a cloud passes in front of the sun). Unlike the lithium-ion battery, it should have a long lifetime; and unlike the lead-acid battery, it will not be degraded when being completely discharged. And while it now appears more expensive than pumped hydropower, the battery has no limitation on where it can be used. With pumped hydro, water is pumped uphill to a reservoir and then released through a turbine to generate power when it’s needed. Installations therefore require both a hillside and a source of water. The liquid metal battery can be installed essentially anywhere. No need for a hill or water.

Bringing it to market

Ambri has now designed and built a manufacturing plant for the liquid metal battery in Marlborough, Massachusetts. As expected, manufacturing is straightforward: Just add the electrode metals plus the electrolyte salt to a steel container and heat the can to the specified operating temperature. The materials melt into neat liquid layers to form the electrodes and electrolyte. The cell manufacturing process has been developed and implemented and will undergo continuous improvement. The next step will involve automating the processes to aggregate many cells into a large-format battery including the power electronics.

Ambri has not been public about which liquid metal battery chemistry it is commercializing, but it does say that it has been working on the same chemistry for the past four years. According to Bradwell, Ambri scientists and engineers have built more than 2,500 liquid metal battery cells and have achieved thousands of charge-discharge cycles with negligible reduction in the amount of energy stored. Those demonstrations confirm Sadoway and Bradwell's initial thesis that an all-liquid battery would be poised to achieve better performance than solid-state alternatives and would be able to operate for decades.

Ambri researchers are now tackling one final engineering challenge: developing a low-cost, practical seal that will stop air from leaking into each individual cell, thus enabling years of high-temperature operation. Once the needed seals are developed and tested, battery production will begin. The researchers plan to deliver prototypes for field testing in several locations, including Hawaii, where sunshine is abundant but power generation still relies on burning expensive diesel fuel. One site is the Pearl Harbor naval base on Oahu. "It's unsettling that our military bases rely on the civilian power grid," says Sadoway. "If that grid goes down, the base must power up diesel generators to fill the gap. So the base can be without power for about 15 minutes, which is probably enough time for some major damage to be done." The new battery could play a key role in preventing such an outcome.

Meanwhile, back at the lab, the MIT researchers are continuing to explore other chemistries for the core of the liquid battery. Indeed, Sadoway says that his team has already developed an alternative design that offers even lower operating temperatures, more stored energy, lower cost, and a longer lifetime. Given the general lack of knowledge about the properties and potential uses of liquid metals, Sadoway believes there could still be major discoveries in the field. The results of their experiments "kicked open the doors to a whole bunch of other choices that we've made," says Sadoway. "It was really cool."

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By Nancy W. Stauffer, MITEI

This research was supported by the US Department of Energy's Advanced Research Projects Agency–Energy (ARPA–E) and by the French energy company Total, a Sustaining Member of the MIT Energy Initiative. Early supporters were the Deshpande Center, the Chesonis Family Foundation, Total, and ARPA-E. Further information can be found in:

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Going off grid: Tata researchers tackle rural electrification

More than 300 million people in India have no access to grid electricity, and the problem is especially acute in rural communities, which can be difficult and expensive to reach with grid power.

At MIT's Tata Center for Technology and Design, researchers are exploring ways to extend electricity access to such communities using microgrids—independent electricity generation and distribution systems that service one village or even just a few houses. In addition to being flexible in size, microgrids can run on whatever power sources are available, including wind, hydropower, and the source accessible at all sites: solar power.

"A large number of people, particularly in rural India, won't be electrified for decades, and the situation is similar in other parts of southern Asia and [in] sub-Saharan Africa. The statistics say that 1.5 billion people worldwide lack access to electricity, but many more don't have reliable access," says Robert Stoner, deputy director for science and technology at the MIT Energy Initiative (MITEI) and director of the Tata Center. "We're looking for ways to make electricity available to everyone without necessarily having to go through the costly and time-consuming process of extending the [national] electric grid. With policy support in the form of regulation and financing…it's conceivable that microgrids could proliferate very quickly. They might not supply a level of access equivalent to that offered by a well-managed grid but would provide an affordable and significant step forward in quality of life."

Microgrids can be powered by diesel generators or by renewable technologies, among them solar power, which is becoming more attractive as the cost of solar technology falls. "If you use solar, [the fuel is] essentially free," says Rajeev Ram, MIT professor of electrical engineering and a Tata Center researcher. In addition, he says, "microgrids are attractive because they let you pool resources."

Nevertheless, the widespread adoption of microgrids has been stymied by several challenges, including the high cost of setting up private generation and distribution systems and the business risk of investing in a system that's susceptible to being undercut by an extension of the electric grid.

At the Tata Center, researchers are addressing such concerns from multiple angles—from mapping out national electrification networks, to providing planning assistance to rural entrepreneurs, to developing technology that can make it easier to build microgrids organically, from the grassroots up. Indeed, the researchers say that properly designed microgrids can be grid-compatible, reducing the risk to investors and providing an intermediate stage to grid connection where this is technically and economically viable.

"Everyone agrees we have to scale microgrids" to address the rural electrification gap, says Brian Spatocco, a Tata Fellow who worked on microgrids as a PhD candidate in materials science and engineering at MIT. The problem, he says, is that "not one size fits all."

Reference Electrification Model

To address the microgrid challenge at the macro level, Tata researchers led by Stoner and Ignacio Pérez-Arriaga, a visiting professor at the MIT Sloan School of Management from IIT-Comillas University in Madrid, Spain, have been developing and implementing a sophisticated computer program that can help government planners determine the best way to provide electricity to all potential consumers.

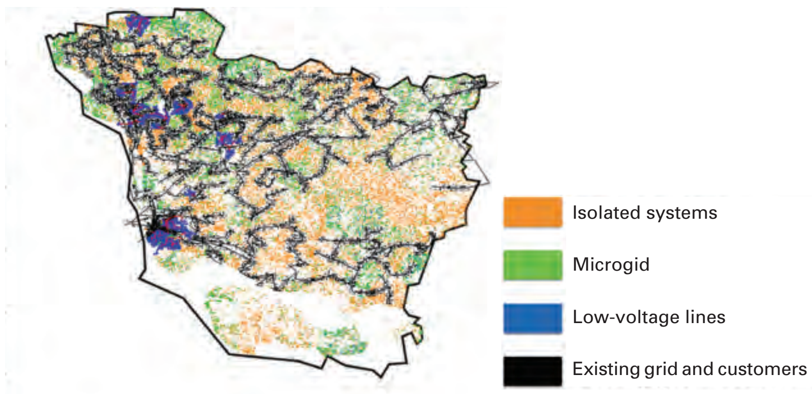
The Reference Electrification Model (REM) pulls information from a range of data sets—which in India include satellite imagery, the Census of India, and India's National Sample Survey, which gathers statistics for planning purposes. REM then uses the data to determine where extending the grid will be most cost-effective and where other solutions, such as a microgrid or even an isolated home solar system, would be more practical.

"We are approaching the problem of rural electrification from the perspective of planners and regulators," Stoner says.

Satellite imagery is used to map the buildings in a given location, and demand is estimated based on the types and profiles of the buildings. REM then uses pricing and technical data on such equipment as solar panels, batteries, and wiring to estimate the costs of electrification on or off the grid and to make preliminary engineering designs for the recommended systems. The model essentially produces a snapshot of a lowest-cost electrification plan as if one could be built up overnight.

"This is a technology tool that [officials] can use to inform policy decisions," says Claudio Vergara, a MITEI postdoctoral associate working on the REM project. "We're not trying to tell them what the plan should be, but we're helping them compare different options. After a decision has been made and detailed information about the sites is gathered, REM can be used to produce

REM case study: Vaishali district, Bihar, India



This map shows the results of using the Reference Electrification Model (REM)—a computer program designed at MIT with collaboration from IIT-Comillas University—to determine a minimum-cost electrification solution for each one of the approximately 400,000 buildings estimated to be non-electrified in the Vaishali district of Bihar, India. The program assigns each building to either a stand-alone system, a microgrid, or a grid extension (indicated by the low-voltage lines).

more detailed designs to support the implementation of each of the three electrification modes."

Currently, Tata researchers are using REM to model an electrification plan for Vaishali, a district of 3.5 million people in the state of Bihar in India. "We're designing the system down to every house," Stoner says.

In the project, results from REM were used to identify the best locations in Vaishali for microgrids (see diagram above). In July 2015, the team visited two candidate sites, each with between 70 and 250 houses, and REM will now be used to produce a detailed technical design showing all the equipment and wiring needed to electrify them. Then, Vergara says, a local Tata partner will put REM to the test by actually building the microgrids. "The pilot will help us improve the model," Vergara says. "We're making many modeling assumptions now, so we need real-world validation."

Once the software has been perfected, Stoner says, the researchers plan to make it openly available.

GridForm

Another project under way at the Tata Center addresses the barriers to entry for potential microgrid entrepreneurs. Such businesses face several hurdles, including the high cost of determining the most cost-effective sites for their projects. India's government and public utilities often provide no information about where the electric grid is likely to be extended next, and calculating the likely demand for electricity in a village typically requires costly, on-the-ground research—all of which makes it tough for any potential microgrid entrepreneur to make the case for profitability and to secure financing.

Three MIT graduate students and a postdoc are working to develop GridForm, a planning framework that rapidly identifies, digitizes, and models rural development sites, with the goal of automating some of the work required to design a microgrid for a small village.

"Doing a custom system for every village creates so much work for companies—in time and in the human resources burden—that it can't scale," Spatocco says. "We're trying to expedite the planning piece so [entrepreneurs] can serve more people and reduce costs."

Like REM, GridForm begins with satellite data, but GridForm goes on to use advanced machine learning to model individual villages with a high level of detail. "We'll say this is a house and this is a house, hit run, and the machine learns the properties of a house, such as size and shape," Spatocco says. The goal is to produce a hardware and cost model of a target village that is 90% accurate before anyone even visits the site.

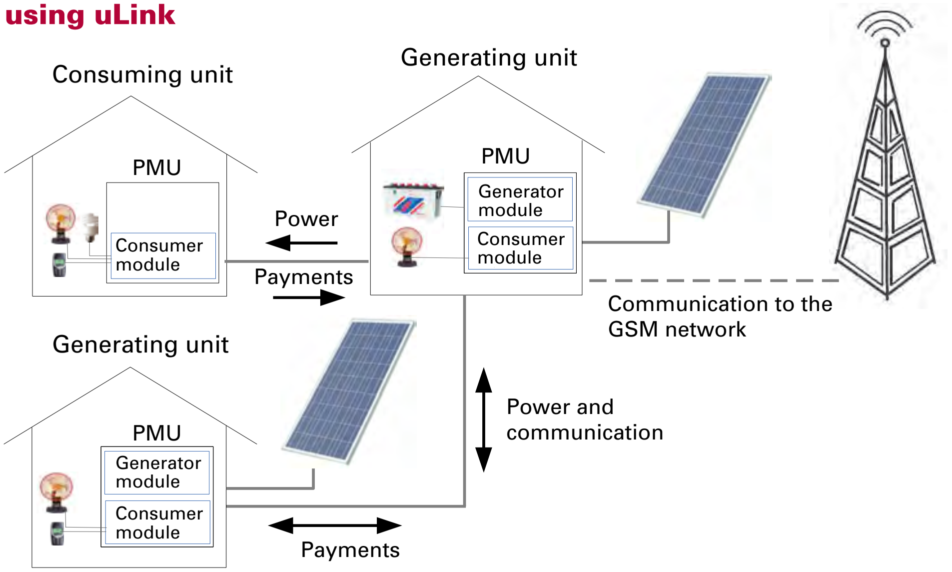
GridForm also develops load estimates, based on factors such as demographics and the proximity of buildings, and provides entrepreneurs with potential microgrid designs and even lists of necessary equipment. The program incorporates data sets on solar radiance and uses an algorithm to determine the best configuration of solar panels, battery packs, and distribution wires to power the greatest number of houses at the lowest cost.

"We're providing everything from siting to planning to implementation—the whole process," says Kendall Nowocin, a PhD student in electrical engineering and computer science working on GridForm. The other two researchers working on the project are George Chen PhD '15, an MITx postdoctoral teaching fellow, and Ling Xu, a PhD student in health sciences and technology.

Optimized microgrid layout and cost estimation for a village

This GridForm model of a village in Bihar, India, shows the optimal layout of hardware for the load profiles of the community. Each building, color-coded by the cost (in Indian rupees) of supplying electricity to that structure, is wired to a central generation/storage node (solid lines), and the nodes are connected to each other (dotted lines).

Sample microgrid with peer-to-peer electricity sharing using uLink



uLink's power management units (PMUs) are shown connecting generating sources, batteries, and loads to form an ad hoc microgrid. Sophisticated computing power within the units enables power and information to be transferred automatically throughout the microgrid, which could one day employ the mobile phone system (aka the GSM network) for payments and system monitoring.

The main difference from REM, the researchers say, is that GridForm envisions electrification being built from the ground up rather than from the top down. "We think rural entrepreneurs will electrify themselves," Spatocco says. "We want to create insights that are immediately useful to practitioners on the ground—what to buy, what it will cost, where to put it."

Already GridForm has been used to develop detailed microgrid plans for four villages in the state of Bihar, and the team is working with Indian social enterprise SELCO Solar to do the installations, providing service to 2,000 to 3,000 people.

uLink

A third Tata Center project focuses on fostering the organic growth of microgrids by enabling residents to share extra power-generating capacity with their neighbors via an inexpensive piece of hardware, the uLink power management unit (PMU).

A "demand response" system that meters and controls the flow of electricity, uLink can adjust the demands it serves based on the supply of electricity that's available. The system reflects an innovative approach to electrification, Ram says—one that acknowledges that the standards for electrification common in the developed world are unrealistically high for poor, remote areas. Building in the system redundancies necessary to ensure 99.9% availability is simply too expensive—and particularly unrealistic in India, where even the areas served by the grid are plagued by power outages.

"Here we can guarantee a basic level of service, but we don't guarantee 99.9%," Ram says. “This is a very powerful way to manage the cost of electricity infrastructure. Demand response allows you to size the system for average demand, versus peak demand.”

What that means is that when the sun is shining and batteries are fully charged, microgrid customers can run all of their appliances, but when it’s been cloudy for a few days and the system is low on power, uLink can signal users to shut off loads; as a last resort, it can even shut off loads automatically. Automating this function eases the social difficulty of sharing electricity, the researchers say. Once users have pooled their resources, there’s no need to argue over who can use which appliances; uLink allots electricity based on which loads have been predetermined as “critical” and therefore not subject to shutoff when system demand peaks. Everything else can be shut off by uLink as needs arise.

Users themselves determine which few loads are “critical,” providing an element of choice not typically seen in home solar systems, which hardwire their loads. uLink features several outlets, enabling users to plug in a variety of appliances. At maximum capacity, the initial prototype low-voltage, DC system provides about 25 watts per household, enough to run a fan, a cellphone charger, and a couple of lights.

“The hardest part is making a box with all these functions at a cost people can afford,” Ram says, noting that the uLink consumer unit is designed to cost about as much as a cellphone, making it affordable for most Indian villagers.

uLink was field-tested in June 2015—five houses were wired together for two weeks—and the delivery, metering, and networking systems worked well. The next milestone for the developers is to test the algorithm designed to estimate how much electricity is available from the system’s batteries and solar panels and optimally shed loads. “This is definitely a work in progress,” Ram says.

Indeed, all three Tata Center projects are still being refined, but together they offer a rich portfolio of potential solutions to the problem of rural electrification, the effects of which many of the researchers have seen firsthand.

“Electricity is not just empowering. It’s an enabling force. Electricity goes right into livelihood activities,” Spatocco says, noting that just a few lights make it possible for residents to work in the evenings, for example, or to improve their efficiency with simple machinery, such as sewing machines. “People can double or triple their economic output.”

There are also benefits few in the West might imagine, as Ram discovered by interviewing residents of one non-electrified Indian village: “They conveyed how frightening it can be to have a snake in the village if no one has a light.”

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By Kathryn M. O’Neill, MITEI correspondent

This research was supported by the MIT Tata Center for Technology and Design. Work on GridForm also received support from the MIT IDEAS Global Challenge. Publications to date include the following:

W. Inam, D. Strawser, K.K. Afridi, R.J. Ram, and D.J. Perreault. *Architecture and System Analysis of Microgrids with Peer-to-Peer Electricity Sharing to Create a Marketplace which Enables Energy Access*. 9th International Conference on Power Electronics (ICPE 2015–ECCE Asia), June 2015.

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Cleaning water without the grid

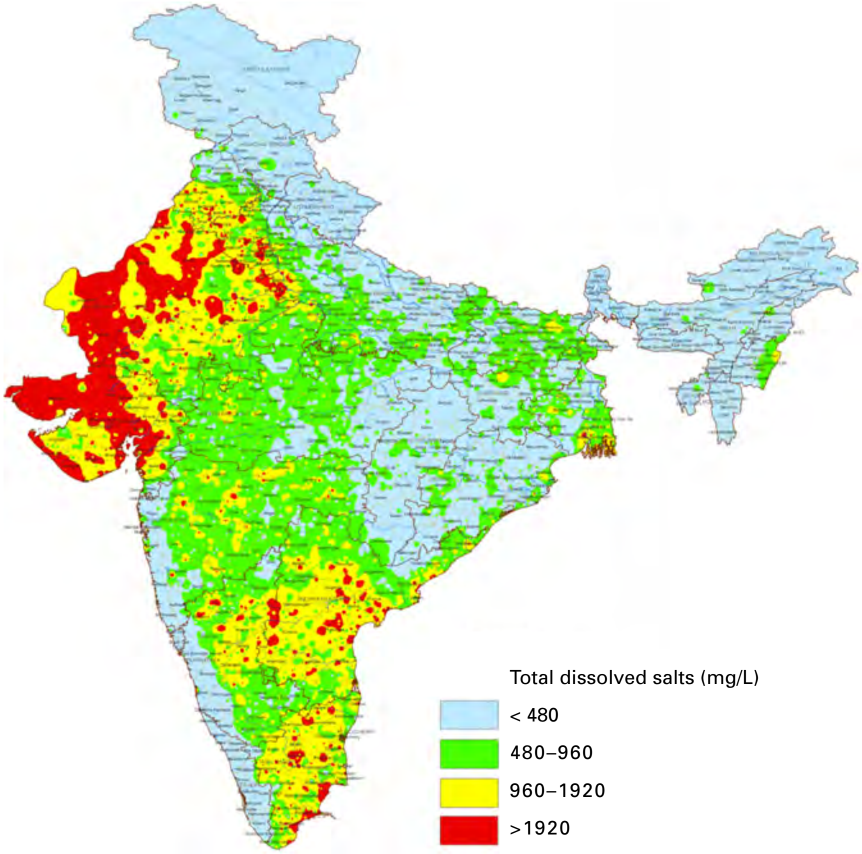
Amos Winter may be an assistant professor of mechanical engineering at MIT, but he describes one of the most important aspects of his job as "detective work." That's what he, MIT PhD candidate Natasha Wright, and their fellow researchers did for two years before coming up with a potential solution to issues of clean water access in India.

It paid off. Their research team, sponsored by the MIT Tata Center for Technology and Design and its partner, the Indian firm Jain Irrigation Systems, won the United States Agency for International Development (USAID)'s Desal Prize earlier this year with their design of a solar-powered electrodialysis desalination system.

The detective work began when Jain Irrigation pointed out that small-scale farmers in India who use Jain's irrigation systems often lack access to safe drinking water. Winter, Wright, and others on the Tata Center team spent two years meeting with farmers and village dwellers trying to understand the reason for drinking water shortages in rural Indian communities.

They expected the villagers' primary concern to be contamination of water by bacteria. But in their meetings, the team identified another, generally overlooked contaminant in India's water: salt. "What can happen frequently," Winter says, "is that people who only have access to a salty drinking source won't want to drink [the water] because it tastes bad. Instead, they'll go drink from a surface source like a pond or a river that can have biological contaminants in it." By removing salt from water sources, the team could more than double the groundwater available to villagers for drinking.

Groundwater salinity in India



This map shows salinity levels in Indian groundwater. Groundwater with a salinity level greater than 480 milligrams per liter (mg/L) underlies 60% of the land area in India. At this level, the aesthetic quality of the water is compromised. (Map: Central Ground Water Board, Government of India.)

The announcement of the USAID Desal Prize competition hit shortly after the team published a paper on the importance of desalination to clean drinking water. Background research already in hand, the team connected a trailer containing their prototype system to a Tata Center–supplied truck and drove it to the competition in New Mexico. And in a pool that had close to 70 applicants, they won. In fact, they were the only entry to meet all of USAID's specifications for flow rate and salinity.

The win was game-changing. According to Winter, the Desal Prize has seriously accelerated the typical development timeline for a project like this. Winning the prize has connected him and Wright with other major players in the clean water space, and international expertise provided by USAID has put more potential locations for the new desalination system on the team's radar. One of them is Gaza. "It's pretty exciting," Winter says, "because the needs and requirements for off-grid desalination [in the Middle East] are very similar to those in India."

First, though, the team has to work out a few kinks in the technology. Winter

The Tata researchers drove their entire system down to New Mexico in the trailer shown above. The day before the USAID Desal Prize competition began, they removed the solar panels from the trailer and set them up.

Professor Amos Winter of mechanical engineering (left) and graduate students Natasha Wright (top right) and Georgia Van de Zande (bottom right) assemble the system on the day before the competition.

Photos: Natasha Wright G

identifies two major “pain points”: the overall materials cost of the system and the energy needed to pump water through it. The only “real necessary power” for running the system is the power required by the electrodialysis technology to separate the ions of salt from the rest of the water, Winter says. Cutting down other energy consumption would both conserve power and bring down cost.

One way to cut cost could be to wean the system off battery usage. In fall 2015, the team began researching whether their system could run effectively on solar energy without using batteries as a buffer to store energy when the sun is down. The research involves conducting pilot tests in which farmers come to one of Jain Irrigation’s test farms in India and use the system in real time. Their experience will shed light on whether demand for water throughout the day aligns with the availability of solar energy.

Winter and Wright have also just signed a three-year contract with Tata Projects, an engineering subsidiary of the Tata Group currently focusing on village-scale water systems. Tata Projects already has a well-developed reverse-osmosis water-purifying operation, but it wants to expand to off-grid communities—places where solar-powered electrodialysis desalination would be a better option. Tata Projects is also looking into the possibility of using the technology in specific subsets of urban environments, such as apartment complexes. “There are a number of market opportunities for this technology beyond just small-scale villages,” Winter says.

The work, of course, is far from done. “The research that we’re doing now, and that the Tata Center in general does, involves tackling problems in emerging markets that require high-performance but relatively low-cost solutions,” Winter says. “We don’t just say, ‘OK, we’re going to make a technology [in our lab] and then see if we can commercialize it.’ We try to understand from the start the user-centered, real-life requirements for a technology so we can design to meet them.” Not elementary at all, but certainly the work of good detectives.

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By Francesca McCaffrey, MITEI

Graduate student Natasha Wright (front) and Abhishek Nirakhe of Jain Irrigation (back) take power readings to decide what adjustments need to be made for the remainder of the competition day. During each 24-hour competition, the teams were allowed to access their systems only during three time slots, each an hour long.

Georgia Perakis: On the road to better energy data

Georgia Perakis, MIT's William F. Pounds Professor of Management, started her academic career by researching traffic flows, but not because she loved highway infrastructure or urban planning. A fascination with analytics is what drew her to traffic. It's the overarching theme that links almost all of her work, including her current research in the green energy sector. She recently finished a study on subsidies for green technologies, and she works continually with industry players on energy analytics projects.

Perakis grew up on the island of Crete, off the coast of Greece. By her own admission, Crete is a traffic-filled place ("on a whole different level than Boston," she says). The traffic there may have had an impact on her later interest in road congestion, but her path to academia began much further back, even before her birth.

On the eve of the Second World War, the man who would become Georgia Perakis' father was in Switzerland on the way to completing his PhD. He hadn't yet finished when the war began. Called back to Greece to serve in the army, he was forced to put his academic aspirations on hold—a hiatus that would turn out to be permanent.

The inspiration from his years of study stayed with him, however, and for his children years later, the lure of academia was palpable. "He never told us what we had to do," Perakis says, "but I think from the way he talked, both my brother and I knew we wanted to become academics. He communicated his love for learning in a very implicit way."

Her father's experiences served as the first spark, but Perakis soon discovered that it was her own interests and strengths that would fuel her love of knowledge, especially in math and the sciences, for years to come.

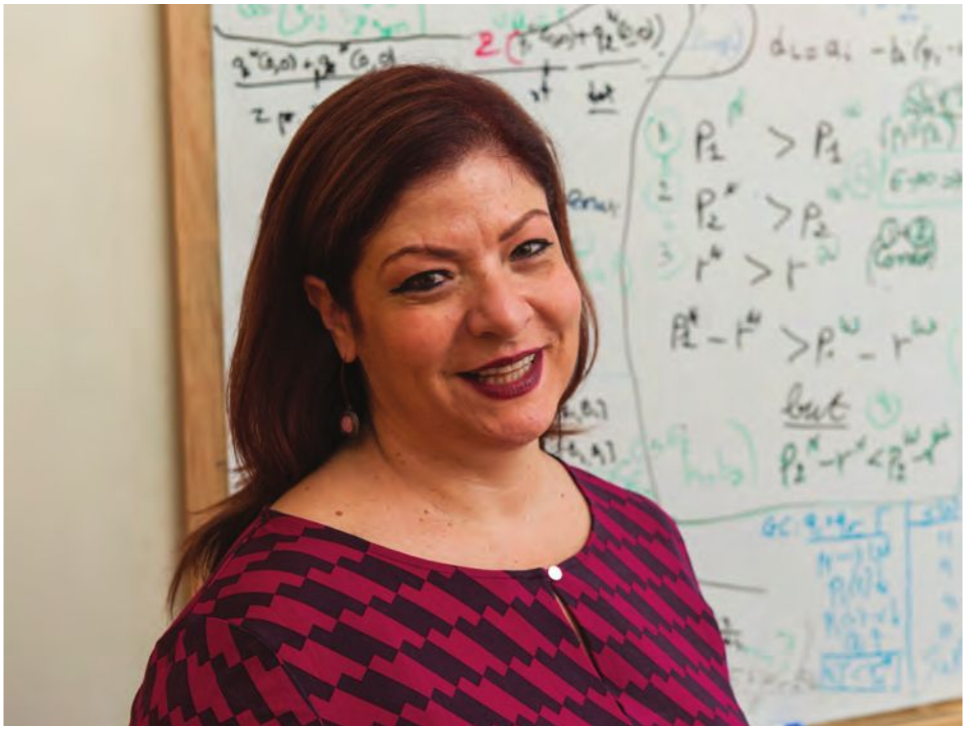
Photo: Justin Knight

Georgia Perakis, the William F. Pounds Professor of Management at MIT Sloan.

"Math to me felt like a game, like fun," she says. "As a young kid, I think part of it was I had the right teachers—they would give us lots of problems to solve. It felt like puzzles, and it was much more interesting than just reading."

Perakis never lost her love of math. Over the years, she honed in on the kind of math she found most captivating. "I didn't want to do pure math because it was too theoretical," she says. She preferred applied math, in which mathematical theories and modeling are applied to everyday situations. After completing her undergraduate studies in Athens, Greece, she came to the United States to begin a PhD in applied mathematics. This was where she took action on her interest in traffic. "Traffic drew me," she says, "because it was a very interesting phenomenon that you could model with math. When you visualize traffic, you find it moves very similarly to a fluid in a pipe, which allows you to use interesting mathematical models to study it."

From this starting point, her PhD thesis eventually came to focus on complex optimization models and methodological algorithms for solving them. As part of her thesis, she worked with operations research professor Thomas Magnanti at MIT, who would later become dean of the MIT School of Engineering and is now an Institute Professor. This was the beginning of a long and fruitful research partnership. Soon Perakis made the decision to come to MIT as a postdoc. Not long after, a faculty position in operations research opened up at the Sloan School of Management, and her career as an MIT educator began.

From there, Perakis' interests have broadened, though they remain connected by the common threads of operations research and optimization. Since her days studying traffic, she has branched out into subsidies for green energy technologies. Her original work on the topic (reported in *Energy Futures*, Autumn 2013) focused on incentives for green technology adoption—in her words, "what kind of subsidies the government should give to consumers." Her latest work deepens that research by focusing on two topics related to subsidies that she did not examine in her first pass.

"In the first [project], we ignored the fact that industry competes and [that] there are nowadays many electric vehicle companies in the market, which compete for the same customers," Perakis says. "This competition has changed the name of the game."

The other element Perakis and her fellow researchers have sought to quantify is a positive externality of the subsidies. When consumers adopt green technology, they reduce carbon emissions. "So, effectively, that reduction should be put into the model as well," Perakis says. She is referring to one of the nuances of economics: externalities, both positive and negative. Encouragement from the government to adopt green technology by using subsidies incentivizes consumers to come on board, which reduces emissions—a positive externality. Perakis is tackling this phenomenon with mathematics. The result is an insightful model that sheds more light on how government and industry should tackle tough policy questions related to green technology subsidies in the future.

Not all of Perakis' energy-related research falls into the public policy arena. A good deal of her time is spent working with companies in the energy industry. Often this involves tackling a specific operations challenge, such as predicting when and which pipes will corrode or forecasting where damage will occur from a superstorm and where emergency restoration crews should be placed before the storm in order to restore outages quickly. Apart from energy research, Perakis also does research in the retail industry, for example, using data to design models that can help retailers run promotions more efficiently. The common denominator in all her research is the availability and use of data to build models that will yield "better" decisions. Perakis cannot stress enough the importance of information gathering for leaders in the energy industry: "You need good data to be able to say something meaningful."

She says that the utilities she has worked with are quickly learning this truth. "I can see now that they're catching on to the fact that analytics is important," she says. "They see that they still need to streamline their data, and without good data, you cannot build good analytics models. But they now understand the importance of analytics. I can see it."

Perakis displays a warm camaraderie with her fellow researchers in both industry and academia. Only one set of relationships seems to rival it: those she cultivates with her students. She teaches graduate students—MBAs, master's, and PhDs—and she deems them "smart, extremely smart." She keeps in touch with many of them post-graduation, and she can rattle off the number of PhD students she has graduated to date without hesitation: 17.

"I am very close with my PhD students," Perakis says, and that closeness is evidenced by a collection of individual student photos, arranged in a frame shaped like a tree, that rests on the wall above her desk. She explains: "That was one of their birthday presents to me."

This recognition of her obvious popularity with her students is accompanied by a sizable dash of humility. When asked what the most challenging part of being a professor is, she laughs. "Everything."

She's also well aware of the challenges her students face. One topic in particular stands out: women in academia. "I think that people have at least tried to make an effort not to have any bias about men and women [in the workforce]. But there are still mental blocks that exist in people's subconscious."

However, she rarely discusses this issue with her female students. "If you just have a conversation it's not as effective," she says. "The way you act and the way you interact with them as a female in the field—that's how you inspire them."

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By Francesca McCaffrey, MITEI

Sallie "Penny" Chisholm appointed MIT Institute Professor

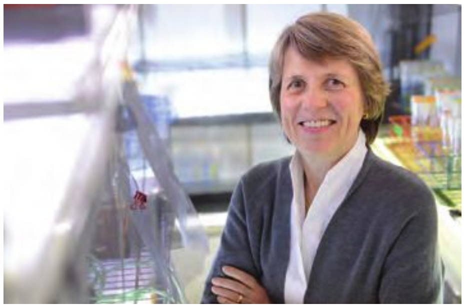


Photo: Richard Howard

In spring 2015, Sallie "Penny" Chisholm was awarded MIT's highest faculty honor: the position of Institute Professor. Chisholm, the Lee and Geraldine Martin Professor of Environmental Studies since 2002, joins an elite group of 13 current Institute Professors and 10 Institute Professors emeriti, all recognized for their scholarly and educational accomplishments and also for their outstanding leadership and service.

Chisholm joined MIT's Department of Civil and Environmental Engineering as a marine ecologist in 1976 and a decade later co-discovered *Prochlorococcus*, a tiny marine bacterium that is the most abundant photosynthetic cell on Earth. With the help of advancing genomic technology—and aided by MIT Energy Initiative (MITEI) seed grants in 2007 and 2012—Chisholm and her colleagues have gained insights into how crucial *Prochlorococcus* is to the ocean environment and to the planet as a whole.

In May 2015, Chisholm received MIT's prestigious Killian Award in recognition of her extraordinary research accomplishments, and in February 2013, she received the National Medal of Science, the nation's highest honor in science and engineering.

Chisholm is also author—with illustrator Molly Bang—of "The Sunlight Series," an award-winning set of children's books covering such topics as photosynthesis, ocean ecology, and climate change.

Paula Hammond named head of chemical engineering


Photo: Webb Chappell

In July 2015, Paula Hammond '84, PhD '93, the David H. Koch (1962) Professor in Engineering, became head of the MIT Department of Chemical Engineering. She is the first woman and first person of color appointed to the post. She is a core faculty member of the Koch Institute for Integrative Cancer Research, a faculty member of the MIT Energy Initiative, and a founding member of the MIT Institute for Soldier Nanotechnologies.

Hammond's research focuses on biomaterials and drug delivery. Key to the work is the self-assembly of polymeric nanomaterials, with an emphasis on the use of electrostatics and other complementary interactions to generate functional materials with highly controlled architectures, including the development of new biomaterials and electrochemical energy devices. Selected projects involve incorporating electroactive nanomaterials—including nanotubes, nanoparticles, polyelectrolytes, and genetically engineered viruses—within the electrode of electrochemical systems to create high power and energy storage batteries.

Hammond is a member of the American Academy of Arts and Sciences, a director of the board of the American Institute of Chemical Engineers, and a fellow of the American Physical Society and the American Institute of Biomedical and Biological Engineering, among other honors.

Ruben Juanes appointed director of MIT's Pierce Laboratory


Photo: M. Scott Brauer

Ruben Juanes, the ARCO Associate Professor in Energy Studies in the Department of Civil and Environmental Engineering, became director of the Pierce Laboratory on September 1, 2015. Located in Building 1, the Pierce Laboratory serves as a home for MIT's research and education activities relating to the design, manufacture, and operation of infrastructure. The focus is on using innovative science and engineering approaches to advance the design of infrastructure materials, transportation systems, cities, and energy resources.

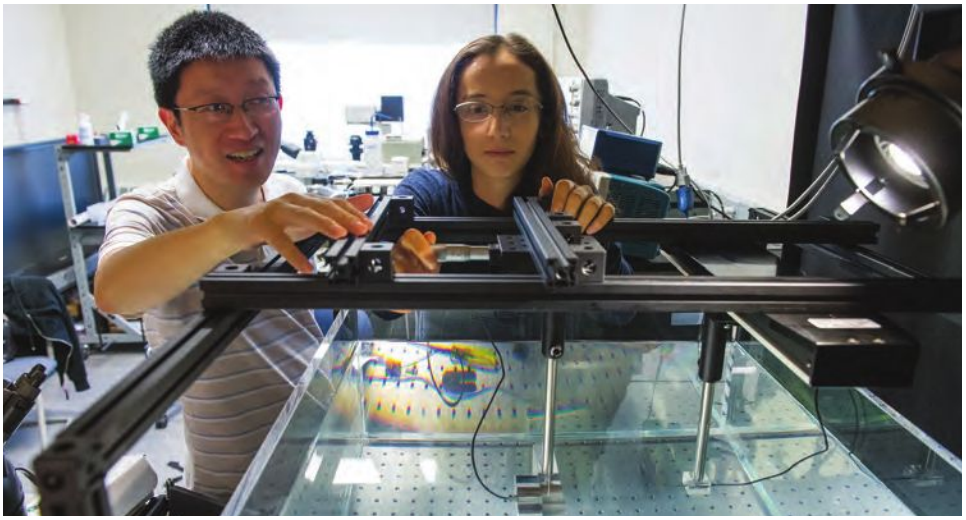
Juanes joined the MIT faculty in 2006. The Juanes research group focuses on energy-driven geophysical problems including carbon sequestration, methane hydrates, and energy recovery. He has been active in the MIT Carbon Sequestration Initiative, performing research on the geologic storage of carbon dioxide, and in 2013 he received a MITEI seed grant to investigate methods of quantifying leakage risks in geological carbon dioxide sequestration and shale-gas production.

Juanes teaches undergraduate and graduate classes focusing on structural and soil mechanics, groundwater hydrology, and other topics relevant to energy and the environment. With support from the S.D. Bechtel, Jr. Foundation, he is now developing a new Energy Studies Minor elective in which undergraduates will learn to visualize and model subsurface reservoir flows.

Undergraduate energy researchers bridge disciplines in summer projects

MIT students are increasingly bridging disciplinary boundaries as they pursue energy research opportunities, and the MIT Energy Initiative (MITEI) is finding new ways to accommodate and support their expanding interest.

During summer 2015, MITEI sponsored 42 projects through the Undergraduate Research Opportunities Program (UROP). Twenty-two of the projects involved students working with faculty outside of their home majors, and seven projects connected students and faculty from different MIT schools. Five years ago, merely a third of the 23 MITEI-sponsored UROPs engaged interdisciplinary student-faculty pairings, and only a handful were cross-school collaborations.



Photos: Justin Knight

With Nicholas Xuanlai Fang, associate professor of mechanical engineering (left), Cali Gallardo '17 (Mathematics) tested lightweight composite materials that could be used for soundproofing in the automotive industry. Here, they measure how small samples respond to different sources of acoustic noise.

"Watching interesting partnerships arise between engineering students and architecture faculty, for instance, or mathematics majors and materials scientists, is really exciting for us," says Amanda Graham, who was director of education for MITEI until autumn 2015. "It gets at the heart of our educational mission, which is building bridges and capabilities that bring disciplinary skills together."

Cali Gallardo '17 (Mathematics) found a project developing lighter-weight soundproofing material to improve fuel efficiency in cars and aircraft with Nicholas Xuanlai Fang, associate professor of mechanical engineering. "We liked Cali's theoretical training as a math major, especially for designing and modeling acoustic composites," says Fang. "But our lab also provides her with the opportunity to do hands-on work, so she's not just solving equations." Says Gallardo, "The UROP seemed like a good opportunity to explore a different field while doing a wide range of tasks, from building to computer-aided design."

UROPs have been a mainstay of academic life at MIT since 1969. The vast majority of undergraduates seek out at least one opportunity during their four years at MIT to engage in significant research with a faculty member, earning credit or pay for work that might last a semester or even a number of years.

At MITEI, which has offered energy UROPs since 2007, the emphasis is on summer, when "students can perform the research full time and get a heck of a lot more done," says Graham. Private donors, Founding and Sustaining MITEI Members, and MITEI Affiliates typically sponsor these projects, and MITEI cultivates contact between sponsors and students.

Akwasi Owusu-Akyaw '17 (Mechanical Engineering) found the prospect of discussing his work with sponsor Lockheed Martin both "intimidating and exciting." His summer research involved testing a design of a small, two-phase induction motor intended to be as powerful but more energy-efficient than comparable motors now on the market, which are used in products such as fans.

Owusu-Akyaw has been developing this device through sequential UROPs with James L. Kirtley Jr., professor of electrical engineering and computer science. It was Kirtley's freshman seminar on energy generation and motor design that initially sparked Owusu-Akyaw's interest: "I wondered about ways to increase power in motors, and I asked to get into his lab," says Owusu-Akyaw. "I wanted to get into product design eventually, and the things you can do as a mechanical engineer are limited if you don't know the electrical side."

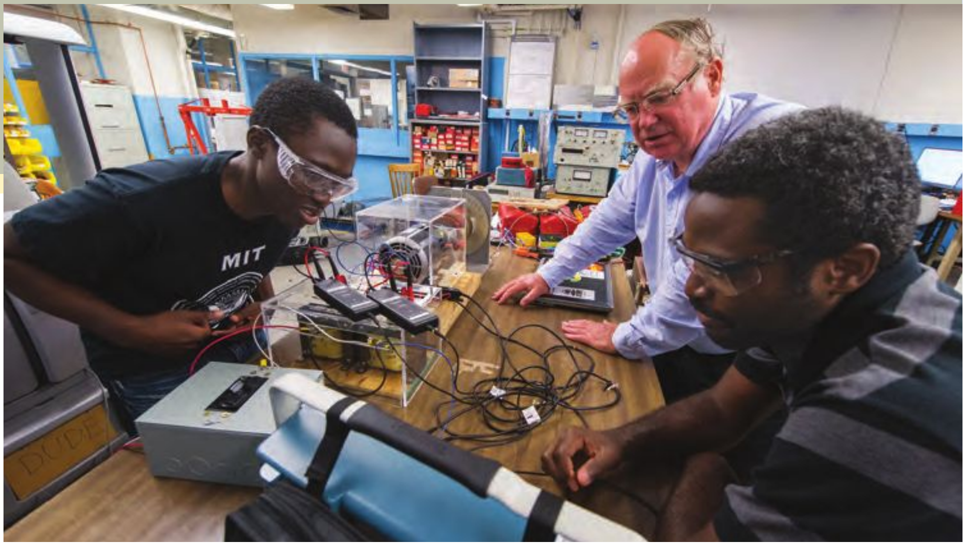
Given the demands of summer research work, MITEI offers one-on-one mentoring and other forms of assistance. Many of the students are just 18 or 19 years old and are holding their first jobs, and they may need "encouragement and a safety net," says Ann Greaney-Williams, MITEI's academic coordinator. And, adds Graham, while it may be ideal for undergraduates to work outside their home departments from a multidisciplinary education perspective, "it's quite a lot to ask these students to be bridge builders."

Supportive supervisors can help. Konrad J. Krakowiak, a research scientist in civil and environmental engineering, is managing undergraduates in aeronautics and astronautics and in biochemistry in a project on rocks involved in hydrofracking. "These kids are so great that I'm learning from them," he says. "If we get interesting results, they will co-author any articles."

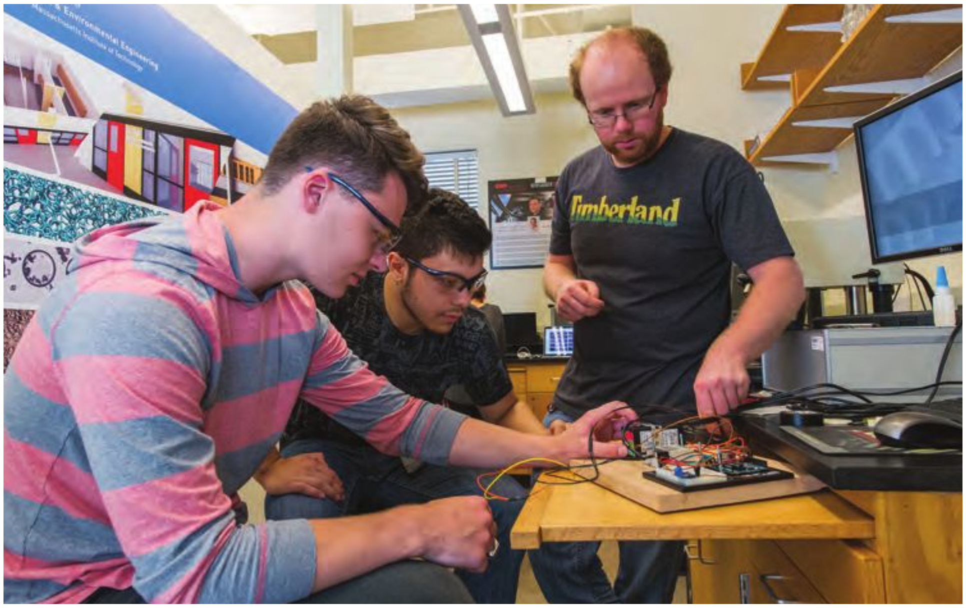
At summer's start, MITEI hosts an orientation session, bringing students together to meet each other and to learn about opportunities outside their UROPs. These include a series of workshops that Greaney-Williams introduced last summer and expanded this year "to offer career-based guidance related to energy, to give students skill sets, and to enhance their experience at school," she says.

"I learned the most from the networking workshop," says Reva Butensky '18 (Materials Science and Engineering). "We practiced 60-second elevator pitches about our interests, skills, and experiences, and it taught me how to be confident about what I've done and what I hope to achieve." This session, as well as workshops on resume writing and professional research presentations, provided "transferrable and valuable skills for internship searches and future career hunts," she says.

Butensky was too busy with her UROP to attend MITEI workshops on stress reduction and conflict resolution. Under the supervision of Kristala Jones Prather, the Theodore T. Miller Associate Professor of Chemical Engineering, she has been learning to synthesize biofuels. "I've been flying by the seat of my pants in a project that is intricately biology-based," says Butensky, who has not taken a formal course in biology since middle school. But through her UROP, she says, "I've become intimately familiar with the field, problem-solving my way through advanced research." After giving a wrap-up presentation at her lab, Butensky says, "I felt I had gained real insight into where future discoveries and technologies are going, and could be going, and it was extremely thrilling."



With Edwin Fonkwe Fongong, a graduate student in electrical engineering and computer science (right), Akwasi Owusu-Akyaw '17 (Mechanical Engineering, left) has been developing a two-phase AC electric motor devised by James L. Kirtley Jr., professor of electrical engineering and computer science (center). The goal of this multi-semester research project is to optimize reactive power to achieve greater efficiency than a single-phase capacitor starter motor of the same size.



Left to right: Sean Kropp '17 (AeroAstro), Riley Ledezma '16 (AeroAstro), and Konrad J. Krakowiak, a research scientist in civil and environmental engineering, probe the properties of hydrocarbon-bearing rock at different temperatures and pressures. This work may help improve estimates of the energy required in hydraulic fracturing projects. They conducted their research under the supervision of Franz-Josef Ulm, professor of civil and environmental engineering (absent from photo).

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By Leda Zimmerman,
MITEI correspondent

Energy alumni: Where are they now?


Photo: Justin Knight

Di Yang PhD ’14

Working for a major oil and gas company was never part of the plan for Di Yang. While pursuing his master’s at Nanjing University, Yang was an electronic engineering and biomedical student. But that all changed when he was admitted to MIT. With funding in his first year as an Eni-MIT Fellow, Yang was able to study whatever he desired. To fulfill his appetite for a challenge, he decided to tackle exploration geophysics and joined a research project being supported by MIT Energy Initiative (MITEI) seed funds. He also sat as the oil and gas subcommittee chair in MIT’s Energy Club, where he planned trips to oil companies to give members exposure to the industry. It was while presenting research he did for the Los Alamos National Laboratory that ExxonMobil saw potential in Yang’s work and decided to hire him. He’s now in his second year with ExxonMobil.

What made you switch from biomedicine to geophysics?

The two sound unrelated to each other, but actually a lot is shared between medical imaging and geophysics. While doing my master’s for sonic imaging, I realized that the medical world bases its imaging on a simple human body model—that everybody looks the same. In the geophysics world, because the subsurface of the earth is so complicated, you never assume any one place is similar to another. It’s a higher level of developmental technology. I soon realized the technology relevant to medical imaging that is applied in the energy sector is more advanced and complicated, and I gradually got interested in the broader picture of energy, too.

How did MIT prepare you for your work at ExxonMobil?

We work here as we worked at MIT. Other people might feel the pressure of cracking problems nobody has cracked before by the deadline. But any MIT graduate would feel comfortable working here because we’ve been working to solve problems by deadlines every day for over five years. It’s just normal to us.

I was also a member of the Energy Club starting in my first year. This experience definitely gave me a better understanding of how the energy business works and how engineers and geoscientists connect in the field. Even now the two are not fluidly connected in all their actions because their disciplines are so different, but they have to communicate to make the business run smoothly.

What would you tell MIT students about working in the energy industry?

For me and a lot of people, the first impression of the energy sector is that it’s an old-fashioned industry. It’s crude and brutal and makes lots of money with a few guys drilling some holes in the ground. But through understanding the industry—especially all the technology that has been developed and deployed—you realize you are solving business problems that make billions of dollars and are relevant to researchers in the industry. If you think you want to be a research scientist, especially coming out of MIT, this is a place you can burn your brain cells on some interesting problems and get well paid. And the personal growth space is huge.

Photo courtesy of USAID

Katherine Steel PhD ’08

After earning her undergraduate degree in mechanical engineering from Stanford University, Katherine Steel arrived at MIT to pursue a PhD in engineering systems. Following graduation, the first step in her international career was to work for the World Bank. There, Steel focused on energy projects in South Asia and Africa. After four years with the World Bank, she moved on to work with a team at Google that focused on providing Internet and energy access worldwide. In 2014 she made the switch back to the public sector, joining the United States Agency for International Development (USAID) as a senior advisor at Power Africa, where she now works to increase private sector investment in power projects in sub-Saharan Africa.

What skills did MIT help you develop that you find most useful in your work?

I think the biggest thing I learned from MIT, and from engineering systems in particular, was taking the systems-level approach—not really focusing in on specifically one project or one country but really thinking more from a macro level. Especially in my work with the World Bank and Power Africa, I’ve needed to be able to look across the power sector and think about how the system operates as a whole.

What made you want to work in developing nations?

I’ve always been interested in working in other countries but got specifically interested in energy and Africa after college. I was finishing up my undergraduate degree in mechanical engineering when I decided that I wanted to spend a year traveling and working overseas. So I moved to Kenya and worked as a teacher in Nairobi. I happened to be there at the time of an extended power crisis due to drought conditions limiting the electricity from hydropower dams. The power rationing we experienced got me very interested in issues of energy access and energy systems in the developing world.

What have you learned about country-specific solutions from your work abroad?

Everywhere is different. While some of the problems may be very similar, I think the resources the countries can tap into and the stage of development of the power sector mean that there is not one simple solution. “Well, this worked here; therefore it is going to work there” is rarely a true statement.

I’ve been working almost exclusively on energy in the developing world, and there are lots of problems: bureaucracy, corruption, trying to get investment in the market, in some cases low affordability if you are looking at trying to reach people who are in remote areas. I have really tried to figure out how you can take lessons learned from other places and apply them in new markets. I think any time you are trying to solve a really hard problem you’re going to run into some challenges. But I think all of that can be overcome—it’s just not easy.

Photo: Amanda Brewster

Joseph Shapiro PhD '13

Joseph Shapiro's skill with numbers brought him to the London School of Economics to pursue his master's in statistics. It wasn't until Shapiro arrived at MIT to obtain his PhD in economics, however, that he found connections between that skill and his interests in energy and the environment. At MITEI he interacted with energy-minded academics and professionals. Currently, Shapiro teaches graduate public finance and undergraduate international environmental economics as an assistant professor of economics at Yale University.

How did your time in graduate school further develop your interest in climate?

Time is a great luxury. Having time in graduate school to hit the ground running is invaluable, and MIT gave me time to look into research questions and start writing papers early. I also had support from many people in the economics department, Sloan, MITEI, and the Center for Energy and Environmental Policy Research. I had an office at the National Bureau of Economic Research during graduate school and [was involved in] one of their working groups on energy and the environment, where I interacted with many economists.

What are some of the economic challenges climate policy faces today?

Economists sometimes distinguish the "first best," or optimal policy in the absence of incentive or information constraints. For climate change, the standard policy prescription is when somebody who is generating costs for other people, or "externalities," has to pay those costs. Then there is "second-best" policy, which means that due to various economic constraints, some policy options are not on the table. But sometimes policymakers aren't working on first- or second-best policy; they're working on tenth- or eleventh-best policy. Some economics research is pushing toward more efficient climate policies, but in lots of cases the practical question isn't getting second or first best—it's whether there is any climate policy at all.

What is the focus of your National Science Foundation–funded research project?

I'm doing the project with Arthur van Benthem from the University of Pennsylvania's Wharton School, and it involves looking at used vehicles. In many states, there's a "smog check" regulation where you have to get your car inspected, and if you drive a really polluting car, you either spend money to clean it or you sell it. Then it can be sold to an outlying area that doesn't have this regulation. If you regulate an environmental problem in one area but not in neighboring areas, people worry that it's like whack-a-mole: it's going to move polluting activity away from the regulation and not decrease the total level of pollution. This is called "leakage." The idea of this project is to understand to what extent the smog-check regulation causes leakage and what its economic implications are.

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By Divesh Rupani, MITEI

Energy Fellows, 2015–2016

The Society of Energy Fellows at MIT welcomed 32 new members in fall 2015. The Energy Fellows network now totals more than 350 graduate students and postdoctoral fellows and spans 20 MIT departments and divisions and all five MIT schools. Fellows include incoming graduate students and graduate student researchers, teaching fellows, and postdoctoral associates. This year's fellowships are made possible through the generous support of nine MITEI Member companies.

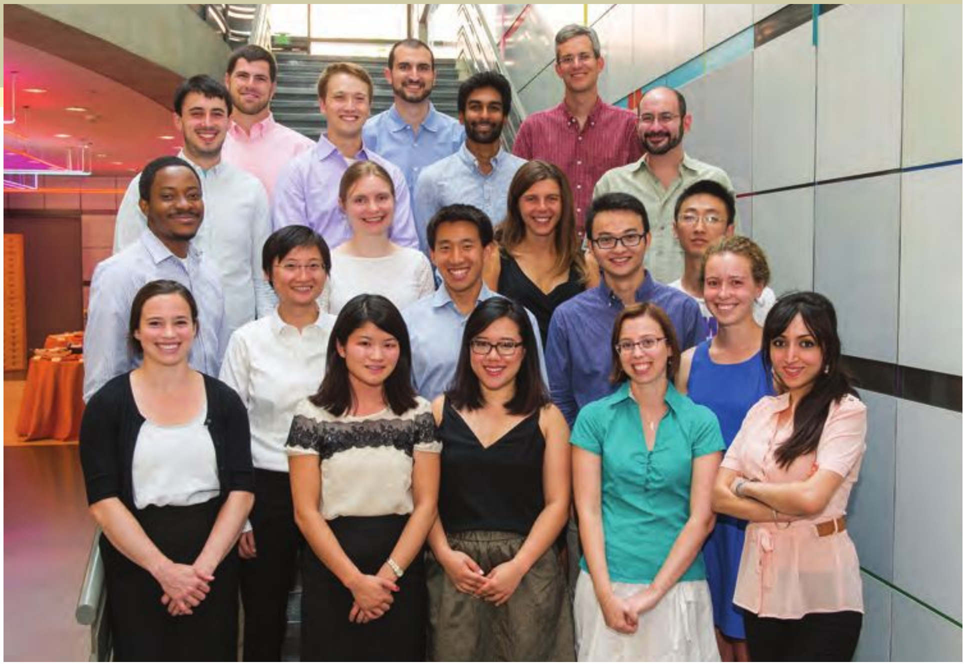

Photo: Justin Knight.

Bosch
Danhao Ma
Materials Science and Engineering

BP
Tochukwu Akobi
Engineering Systems
Alan Long
Chemical Engineering

Chevron
Jing Zhang
Biology

Eni
Marie-Julie Dalbe, PhD
Civil and Environmental Engineering
Francesca Freyria, PhD
Chemistry
Connie Gao
Chemical Engineering
Joel Jean
Electrical Engineering and Computer Science
Alexander Kohn
Chemistry
Byungjin Koo
Materials Science and Engineering
Jolene Mork
Chemistry

ExxonMobil
Dayong Chen, PhD
Chemical Engineering
Hongge Chen
Electrical Engineering and Computer Science
Henri-Louis Girard
Mechanical Engineering
Guillaume Giudicelli
Nuclear Science and Engineering
Brent Keller
Materials Science and Engineering
McLain Leonard
Chemical Engineering
Sina Moeini
Civil and Environmental Engineering
Samuel Shaner
Nuclear Science and Engineering
David Strubbe, PhD
Materials Science and Engineering
Brandon Talamini, PhD
Mechanical Engineering

Schlumberger
Elizabeth Strong
Mechanical Engineering

Shell
Jayadev Acharya, PhD
Computer Science and Artificial Intelligence Lab
Scott Burger
Engineering Systems
Danielle Gruen
Earth, Atmospheric, and Planetary Sciences
Chiao-Ting Li, PhD
Joint Program on the Science and Policy of Global Change
Ted Moallem, PhD
Office of Digital Learning
Kai Pan
Civil and Environmental Engineering
Nora Xu
Engineering Systems

Statoil
Michael Birk
Engineering Systems
Max Luke
Engineering Systems

Total
Rupak Chakraborty
Mechanical Engineering

Fellows as of November 15, 2015

New energy on campus: Arriving undergrads participate in pre-orientation activities at MITEI

During the week of August 26, 2015, 23 incoming MIT undergraduates participated in the MIT Energy Initiative's Freshman Pre-Orientation Program (FPOP)—Discover Energy: Learn, Think, Apply (DELTA). Elements of this year's program included visiting the MIT Nuclear Reactor Laboratory, participating in an energy transportation tour in cooperation with the Massachusetts Department of Transportation (MassDOT), and playing a round of World Energy, the energy science and policy simulation game.

Students had an opportunity to get to know the Institute's campus and surroundings, MITEI, and one another through an array of activities, presentations, and discussions. New undergraduates met members of the MIT Energy Club, participated in a photo scavenger hunt, visited the Museum of Science, and took a boat ride on the Charles River—activities designed to introduce them to the wealth of resources on the MIT campus and in the Boston area.

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By Ashley Cryan, MITEI

Photo: Ashley Cryan, MITEI

Climate Interactive's Ellie Johnston leads a round of the simulation game World Energy during FPOP week. Students were assigned roles as nations of differing development status and asked to negotiate a deal that would sustain energy production and management into the future, based on their respective nations' goals and interests.

Photo: Ashley Cryan, MITEI

During the World Energy game, students discuss the best strategies to implement in the energy arena to keep carbon emissions as low as possible and prevent global climate change from becoming too severe while also meeting global demands for energy.

Photo: Sara Gallegos, MITEI

Photo: Sara Gallegos, MITEI

Above photo, left to right: Veronica LaBelle, Benjamin Gray, and Wenyu Ma make their own solar cells during an FPOP activity led by Annie Wang, research scientist in the Research Laboratory of Electronics (not pictured).

Photo at left: During a tour of Boston's MassDOT tunnels, Kevin Arrigal, manager of station support for MassDOT (in white hard hat), accompanies FPOP students on an elevator ride down into a ventilation building beneath the city's highway system.

Energy Studies Minor graduates, 2015

Kaitlin Ahlers
Chemical Engineering
Cecilio Aponte
Materials Science and Engineering
David Bender
Chemical Engineering
Priyanka Chatterjee
Ocean Engineering
Staly Chin
Mechanical Engineering
Diego Giraldez
Chemical Engineering
Anisha Gururaj
Chemical-Biological Engineering
Karen Hao
Mechanical Engineering
Delphine Kaiser
Mechanical Engineering
Larissa Kunz
Chemical Engineering
Laith Maswadeh
Mechanical Engineering
Sarah Mayner
Chemical-Biological Engineering
Elizabeth Murphy
Materials Science and Engineering
Denise Neibloom
Biological Engineering
Dimitrios Pagonakis
Civil and Environmental Engineering
Dennis Prieto
Aeronautics and Astronautics
James Slonaker
Mechanical Engineering
Isaac Sosa
Mechanical Engineering
Sterling Watson
Mechanical Engineering

Photo: Justin Knight

Among the Energy Studies Minor graduates in 2015 were (left to right, front row) Sterling Watson, Sarah Mayner, Priyanka Chatterjee, and Delphine Kaiser; and (back row) Cecilio Aponte, James Slonaker, Dimitrios Pagonakis, and Diego Giraldez.

Introducing MIT's new Undergraduate Energy Commons

Photo: Christopher Harting

The MIT Energy Initiative is proud to announce plans for the creation of a brand-new community space devoted to energy students on campus. The Undergraduate Energy Commons is scheduled to open its doors to all in autumn 2016. Located directly under MIT's iconic dome in Room 10-063, the Energy Commons is a mixed configuration of educational and activity space.

As currently envisioned, the commons will feature study/breakout rooms with conference tables and audiovisual equipment; open space for group work, meetings, and presentations; a student lounge area; and room for energy-related demonstrations and/or displays. It will be a blended, collaborative hub where energy students from all majors can gather, hold events, build teams, and pursue shared projects to sustain and expand the undergraduate energy community.

The renovation and furnishing of this unique space is supported by a generous donation from the S.D. Bechtel, Jr. Foundation, which shares in MITEI's vision and goal to enhance opportunities for multidisciplinary, problem-focused energy education at MIT.

MITEI names co-chairs of Energy Education Task Force

Photo: Patrick Gillooly, MIT

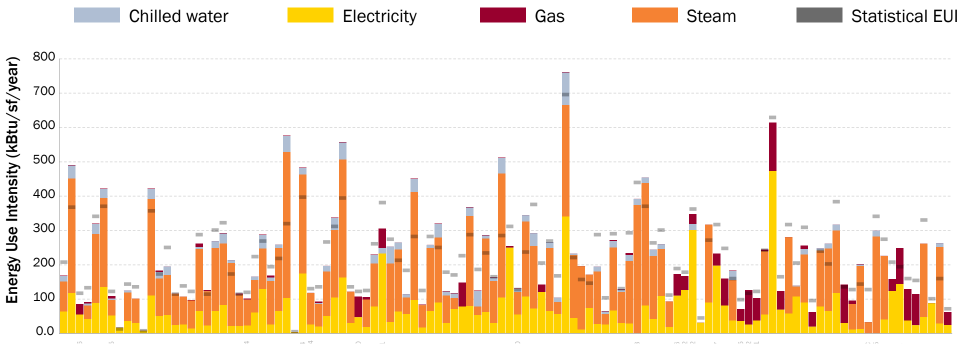
Photo: Caitlin Ram

Bradford Hager, the Cecil and Ida Green Professor of Earth Sciences and director of the Earth Resources Laboratory (above left), and Rajeev Ram, professor of electrical engineering and computer science, became co-chairs of MITEI's Energy Education Task Force and the Energy Minor Oversight Committee on October 5, 2015.

The task force is an Institute-wide committee of faculty and students that works with the MITEI Education Office to maintain and enhance the Energy Studies Minor, assess and support further development of MIT's energy curriculum, and communicate MIT's interdisciplinary energy education model. The oversight committee is a subset of faculty from the task force who provide institutional leadership for the development and support of the Energy Studies Minor curriculum. Committee members also serve as advisors to Energy Studies students.

Hager and Ram have long been strong proponents of MIT's energy education and the Energy Studies Minor, and their new leadership roles will enhance their ability to support MIT's education of students equipped to address the world's crucial energy challenges as well as the linked problems of reducing global poverty and preserving the environment.

New forecasting tool to aid MIT's energy planning



A tool recently developed by Atelier Ten enables MIT planners to visualize campus energy use at the building level and in aggregate. This graph shows energy use intensity (EUI) for numerous campus buildings, highlighting the distribution of energy among chilled water, electricity, gas, and steam. The tool uses a statistical estimate of energy use for each building (shown as a detached gray line) to evaluate the effect of various energy efficiency measures on campus emissions.

MIT took another step forward in the effort to reduce its carbon footprint in summer 2015 with the unveiling of an energy-forecasting tool that enables planners to assess current energy usage on campus and identify opportunities for improvement.

"We needed to understand how our buildings were currently performing in energy use and intensity, where energy was coming from, and what upgrades had taken place—a system of record," says Julie Newman, director of MIT's Office of Sustainability. "This tool is enabling us to see where we might get the most reductions in energy use and greenhouse gas emissions."

Commissioned in August 2014 by MIT's Net Zero Energy Working Group and developed by Atelier Ten, an environmental design consultancy, the tool for the first time brings together a wide variety of data about MIT's buildings—including age, square footage, program use, energy use, upgrade history, and whether the building is connected to MIT's central cogeneration plant.

The tool enables users to assess how upgrades in four key areas—lighting; building controls; heating, ventilation, and air conditioning; and building envelope (walls, roof, foundation)—are likely to affect the total greenhouse gas emissions produced by the campus.

"This makes goal setting more realistic or evidence-based," says Christoph F. Reinhart, associate professor of architecture, who served with Newman on the Net Zero Energy Working Group, an organization formed to shape MIT's response to a Cambridge, Massachusetts, initiative to reduce the city's carbon footprint. The term "net zero" refers to the goal of having buildings generate "net zero" greenhouse gas emissions—meaning that their energy consumption is perfectly offset by renewable energy production.

"The Atelier Ten tool was an attempt to, based on existing energy data, build a model to explain which buildings use energy for what. It's a very innovative thing," says Reinhart, who heads MIT's Sustainable Design Lab. "Once you have that, you can do an analysis and see what would happen if you introduced efficiency measures, better ventilation, etc. You can answer the question of how much impact specific changes would have on overall carbon emissions."

The task is challenging because building systems are interdependent. Electrical lighting generates heat, for example, so installing more energy-efficient lighting leaves rooms cooler, increasing the need for heating. How such a change impacts greenhouse gas emissions also depends on where the building is getting the energy for its utilities, says Nico Kienzl SM '99, Atelier Ten's New York director and an alumnus of MIT's building technology master's program. (Another MIT alum, Jessica Zofchak '08, SM '09, served as Atelier Ten's project manager for the forecasting tool.)

For example, much of MIT's energy comes from its central plant, which is significantly more efficient in generating and distributing power than the electric grid. Therefore, MIT's carbon emissions for every kilowatt-hour (kWh) generated on campus are lower than the same kWh purchased from the grid.

"This level of analysis is really useful for future resource planning," Kienzl says. "Now we can assess how a suite of improvements to existing buildings could allow us to reduce carbon emissions, and how that relates to costs."

Newman agrees. "We now have one data hub of information," she says, noting that the tool enables all of MIT's building stakeholders—including those focused on sustainability, utilities, capital projects, systems engineering, and planning—to work together to reduce the Institute's carbon emissions. "I'm not saying that the decisions [about allocating resources] will be easy to make, but we're moving toward being able to ask questions about what's possible."

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By Kathryn M. O'Neill,
MITEI correspondent

Fueling solutions: "Fuel" pillar at MIT Solve sets energy goals for a sustainable future

At a kickoff event for the inaugural MIT Solve conference, Jeffrey Sachs, director of the Earth Institute at Columbia University, commented on the growing need for the world to apply scientific thinking to the toughest global problems. In a discussion of how to achieve the United Nations' recently unveiled global sustainable development goals, Sachs said, "It's not a dream, it's an architecture. It's about how and why we act—and how to change [that]." At Solve, thought leaders from across the nation and the world gathered at MIT to draw up new blueprints for that architecture. They began by planning how they would tackle the world's greatest problems with a mix of critical thinking, imagination, and technology.

The issues at hand were organized under four pillars: "Cure" tackled the most pressing challenges in health care today; "Learn," those in the education system; and "Make," those related to infrastructure and the economy. The "Fuel" pillar's objective—"to double energy and food production, halve carbon output by 2050, and set a path to net-zero carbon emissions by 2100"—acknowledged the importance of improving quality of life in developing countries and protecting our environment while feeding a growing global population.

Note: All panels, with the exception of public sessions, were held under the Chatham House Rule in order to foster an environment of candid, respectful exchange. Under Chatham House Rule, participants are free to use the information received, but neither the identity nor the affiliation of the speaker(s), nor that of any other participant, may be revealed. Quotes from private sessions are attributed in this article only with the speaker's permission.

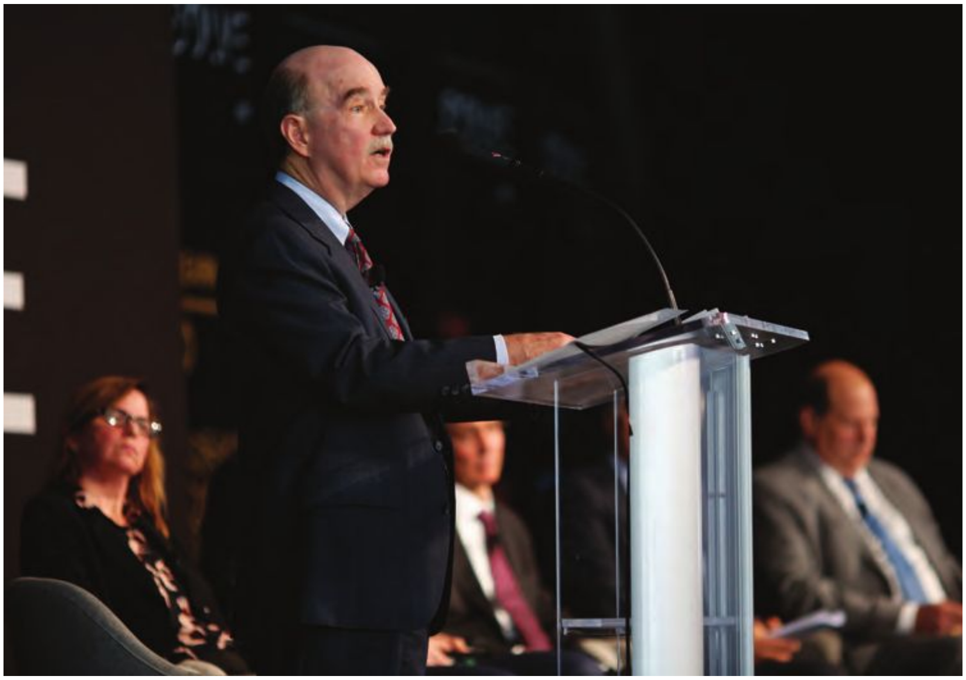

Photo: Dominick Reuter

Professor Robert Armstrong, director of the MIT Energy Initiative, discusses the elements of our current "energy revolution" during his introduction to the Fuel pillar of the MIT Solve conference, held on the MIT campus on October 5–8, 2015. Armstrong moderated the Fuel pillar with Angela Belcher, the James Mason Crafts Professor in biological engineering and materials science and engineering at MIT.

The Fuel pillar was moderated by MIT Energy Initiative (MITEI) Director Robert Armstrong and Angela Belcher, the James Mason Crafts Professor in biological engineering and materials science and engineering. In his introduction setting the framework for Fuel, Armstrong emphasized the strong connection he feels exists between MITEI and Solve's mission statement: "At MITEI, we feel that a collaborative approach is essential to making change. The key linkages that Solve seeks to create between like-minded individuals and institutions around the world will enable us to find inclusive solutions to global issues." He identified seven elements in particular that he considers important to what he called our current "energy revolution": solar; storage; carbon capture, use, and sequestration; nuclear; materials; the grid; and bioenergy.

At the kickoff roundtable panel for Fuel, leaders in the conventional energy industry focused on new horizons for energy and the need for sustainable and renewable energy solutions to meet growing energy demand in the developing world. Panelists also stressed the critical ties between energy issues and food and water issues. "Cheap renewable energy and clean water are critical to allowing the world to make, learn, and build," one speaker said.

After this opening session, Fuel participants broke off into four parallel sessions on renewable energy, nuclear, climate, and food.

The renewable energy panel focused on pathways to worldwide implementation of advanced renewable energy sources. Francis O'Sullivan, director of research and analysis at MITEI, echoed

Armstrong's heralding of an energy revolution, elaborating: "It's not just a revolution in respect to renewable energy or storage. The whole system is being turned upside down."

Solar energy and storage were major themes of the renewables discussion. On the topic of solar, one researcher said, "The big opportunity in the solar field today is in reimagining why it needs to cost so much to make a solar cell." He encouraged fellow researchers to "start reimagining the cells themselves, making them multilayered, making them stacked."

Another researcher commented on the promise and challenges of energy storage. "Today the biggest problem is not power with batteries—it's reaching a high enough energy density while also keeping costs down. Energy density translates to cost." One of his suggestions was to vertically integrate the production of new-era storage like lithium-ion batteries as a cost-cutting measure.

Cost was also a major factor in the nuclear panel. Several of the researchers and entrepreneurs representing nuclear startups made the case that reviving nuclear power is needed to help untangle the "Gordian knot" of simultaneously developing clean, low-cost, and secure energy supplies at a global scale. Discussions focused on how to make nuclear power more cost-effective in the face of rising costs—costs attributed to the lengthy licensing process and to development expenses.

A lead presenter put health concerns in perspective, citing "studies show[ing] that coal has historically caused many more deaths than nuclear." The promise of new nuclear technologies and safer reactor designs was a unifying theme among the startup companies represented. There was also much discussion about whether the length and cost of the Nuclear Regulatory Commission's licensing process is a bottleneck preventing timely implementation of such new technologies.

Photos: Dominick Reuter

MIT Professor Angela Belcher (left) moderates a panel discussion on climate change, which included Daniel Zarrilli, director of the New York City Mayor's Office of Recovery and Resiliency (center), and John Bolduc, an environmental planner for the City of Cambridge, Massachusetts.

Capitalizing on new technology was also at the forefront of the climate panel. Panelists discussed challenges associated with current carbon capture and sequestration methods, such as cost and reliability, but also identified opportunities related to novel membranes and absorption processes.

Researchers also highlighted the need for climate resiliency. "Hurricane Sandy, with lives lost and massive destruction, was a wake-up call for New York City on climate change," one researcher said. "Hurricane Joaquin luckily went out to sea this fall, but others will come." As cities plan for climate resiliency, the need to "empower citizens and institutions to prepare" was discussed as a high priority. Kerry Emanuel, the Cecil and Ida Green Professor of Atmospheric Science, who spoke as a panelist, reflected that "the panel brought together key elements at MIT that define the climate problem and address potential solutions to it, which is very much in the spirit of the Solve program."

The food panel was similarly enlivened by a sense of community and urgency. Panel attendee Markus Buehler, head of the Department of Civil and Environmental Engineering at MIT, noted the "great energy and intellectual vibrancy of discussions and commitment to the future"—including the future of agriculture in a world that will soon be faced with the challenge of feeding 10 billion people while still supporting the ecosystems that we rely on for clean water and air. "Enormous opportunities exist in the agriculture sector, where technologies could open the doors to solve grand challenge issues that include the carbon footprint and the emission of nitrogen," he said. "One day we may look back at this point in time and appreciate the paradigm shift that is occurring about how we produce food under changing environmental conditions, similar to the way the Industrial Revolution changed how we manufacture."

MIT Professors Yet-Ming Chiang of materials science and engineering (left) and Vladimir Bulović of electrical engineering and computer science participate in the panel on renewable energy sources.

A panel on energy in the developing world featured Ratan Tata, chairman of the Tata Trusts (left), and Robert Stoner, director of the MIT Tata Center for Technology and Design as well as deputy director for science and technology at MITEI.

MITEI Executive Director Martha Broad commented on the "dedication to positive change" evident as the researchers discussed their work and visions for the future, calling the Solve program "an important convening of experts and a fascinating meeting of the minds."

After the breakout panel discussions, Armstrong and Belcher reconvened the Fuel pillar participants for a public session with Ratan Tata, chairman of the Tata Trusts, and Robert Stoner, director of the MIT Tata Center for Technology and Design and deputy director for science and technology at MITEI. Before introducing Tata and Stoner, Belcher took a moment to express her "excitement about the engagement of the audience" in the panels. Armstrong added that in his panel session he heard several "interesting ideas about how government, academia, and industry can better work together."

Tata and Stoner discussed the origins of the MIT Tata Center and its eventful first three years supporting research designed to have an impact in the developing world. Speaking of the Tata Trusts' connection to the center's work, Tata said that the Tata Trusts did not define the projects that the MIT Tata Center would focus on. "We looked [to]…the innovation of MIT and faculty scholars to address the problems they saw [in the developing world]." Stoner echoed this sense of innovation and positive energy in discussing how seemingly intractable challenges can yield to sustained effort: "We keep pushing on these walls where we think we'll see resistance, but we're making progress. The walls are receding."

This kind of positive energy will be critical as participants harness the momentum from the inaugural Solve conference to become "local solvers," which MIT President L. Rafael Reif says are the necessary antidote to our global challenges.

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By Francesca McCaffrey, MITEI

A day in the sun: MIT Solar Day looks ahead to decades of innovation

Professor Vladimir Bulović of electrical engineering and computer science flips to the next slide, and an arresting image fills the screen above the stage. Bulović, the Fariborz Maseeh (1990) Professor of Emerging Technology and the School of Engineering's associate dean for innovation, describes the graphic: a cross-section of two thin-film solar photovoltaic technologies. The commercialized technology is approximately 7 microns in width. The emerging technology is, incredibly, even thinner. A cross-section of a human hair—a hefty 100 microns—is shown beside both of them for reference. It looks like a felled redwood next to two slips of paper shown edgewise.

Moments like this—with audience members from scientists to new students sharing a sense of wonder in the possibilities for the future—were plentiful at MIT Solar Day, which took place in the MIT Media Lab on September 10, 2015. Marc Baldo, professor of electrical engineering and computer science, could be seen describing ways to improve the efficiency of solar cells by generating and manipulating excitons in novel organic-inorganic layered structures. Tonio Buonassisi, associate professor of mechanical engineering, gave a presentation on the powerful potential of tandem solar cells, in which layers of two materials that usually appear in separate solar technologies are stacked in order to utilize more of the energy in the solar spectrum. Yang Shao-Horn, the W.M. Keck Professor of Energy, revealed the latest developments in using oxygen redox reactions to store energy from renewable sources in chemical form so it can be consumed at a later time.

More than the thrill of science

At MIT, there is always palpable excitement in the air when researchers get together. Many of the researchers present at MIT Solar Day inhabit specific niches in the energy field, and this conference was part of an effort to view the larger picture of solar research happening across schools, departments, and disciplines.

Photos: Justin Knight

Left to right: Robert Armstrong, director of the MIT Energy Initiative; Richard Schmalensee, dean emeritus of the MIT Sloan School of Management; and Maria Zuber, MIT's vice president for research, deliver opening remarks at MIT Solar Day and reflect on MIT's Future of Solar Energy study.

From the outset of the conference, it was also clear that solar energy research is about much more than the thrill of scientific exploration.

"The world will likely see a near doubling of demand" in the first half of this century, said MIT Vice President for Research Maria Zuber in her opening remarks. "At the same time, it is clear that in order to avert the worst impacts of global climate change, we need to rapidly reduce greenhouse gas emissions from the energy sector, notably CO_2 emissions. Solar energy provides a tremendous opportunity to realize this low-carbon energy future."

Bulović, in turn, added a global theme to his discussion of new solar technologies. While describing a photo of solar cells printed on paper, he took a moment to explain the significance of this particular breakthrough. "There are 1.5 billion people without grid electricity," Bulović said. "In remote areas, the last nine miles of delivery of solar panels are on average the…most expensive. If we could print solar cells on lighter material, like paper, that could help."

This observation reverberated through the rest of the day's panels. In a panel on solar energy in the developing world, Robert Stoner, deputy director for science and technology of the MIT Energy Initiative (MITEI) and director of the Tata Center for Technology and Design, elaborated by adding, "Twice as many people in developing countries probably feel like they lack electricity because their service is so unreliable."

Professor Rajeev Ram of electrical engineering and computer science added that researchers have a "moral imperative" to direct their work toward advances that will better others' lives.

During an end-of-day panel synthesizing the main ideas of the conference, MIT Institute Professor John Deutch translated Ram's convictions into sociological terms: "It can't be denied that access to electricity brings along with it better health, safety, and socio-economic status."

Time is short

Throughout the conference, there was a sense that time is of the essence and an appreciation for the importance of sharing great ideas with fellow MIT community members—inspiring minds and hands to continue innovating to meet current and future global challenges.

Even with many people working efficiently toward a goal, the research process can be long and arduous. Bulović aptly brought up the example of the zipper, a now-ubiquitous tool that took 12 years to reach mass usage after its first demonstrations. The conception-to-adoption pipeline for solar technologies is similarly lengthy.

That's why MIT researchers aren't indiscriminately focusing on new technologies—they're looking for the right technologies. Dr. Ellen Williams, director of the US Department of Energy's Advanced Research Projects Agency–Energy (ARPA–E) put it well: "With new technology, we're always thinking: If it works, will it matter?" Indeed, this is what ARPA–E as an organization was made for—its highly selective funding process is built around the goal of buoying the cutting-edge projects that, if brought to fruition in a timely way, will be most impactful.

Deutch agreed that this philosophy translates well for the Institute: "This is what MIT is supposed to be doing, what MIT is good at," he said. "We're all about advancing technical ideas that will really make a difference in the target space. None of this is certain, but there is so much potential there, if we could only lose some unnecessary weight."

Francis O'Sullivan, MITEI's director of research and analysis and the conference organizer, summed up the state of solar energy in this way: "Where we are today with respect to solar as a real option for addressing climate change would have been very hard to conceive even five years ago, and that's a great thing. … But right now, there is a gap between the types of technology we've rolled out and the types of technology that are happening in the lab. A scale-up challenge exists in between. That, for me, is one of the salient takeaways from today."

MITEI Director Armstrong added, "In addition to hearing about lots of different technology advances in today's sessions, what I saw today were the beginnings of more cross-disciplinary interactions. I'd hoped for this from Solar Day. I think that the answers and key issues we need to address in order to get solar deployed at large scale lie at the intersections of all of the different solar research niches."

Student showcase

This sense of innovation and promise carried over into the student poster session that capped off the day. More than 20 research groups gathered in the lobby of MIT's Bartos Theater to showcase their latest work. Posters covering research on everything from classic crystalline silicon solar cells to carbon nanotube photovoltaics were on display. Anna Osherov, a postdoc in the laboratory of Angela Belcher, the James Mason Crafts Professor at MIT, joined Bulović in discussing a novel way of producing organic-inorganic perovskite solar cells, a new technology with the potential for high efficiency and low cost. Rather than using conventional manufacturing pathways, the researchers are using inkjet printing, allowing for scalable and cost-sensitive deployment.

Dr. Ellen Williams, director of the US Department of Energy's Advanced Research Projects Agency–Energy, describes ARPA–E's programs and projects at MIT Solar Day.

Chitti Desai, an undergraduate researcher working with the MIT–SUTD International Design Center, presented her work as part of a team creating a dynamic online database for individuals planning to purchase small-scale solar lighting for their homes and businesses. The country-specific database will provide information on the best local suppliers of solar lighting, evaluated based on cost, quality, and a variety of other factors.

By bringing the MIT community together to learn about each other's research and to explore the potential of future technologies, MIT Solar Day has sparked a discussion about how the Institute can continue to be a leader in solar technology innovation for the climate, the economy, and the well-being of the global community. As ARPA–E Director Williams said, "Current energy and emissions projections are not what will happen and not what should happen. We can change them."

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By Francesca McCaffrey, MITEI

MITEI Founding and Sustaining Members

MITEI's Founding and Sustaining Members support "flagship" energy research programs and projects at MIT to advance energy technologies to benefit their businesses and society. They also provide seed funding for early-stage innovative research projects and support named Energy Fellows at MIT. To date, members have made possible more than 140 seed grant projects across the campus as well as fellowships for more than 350 graduate students and postdoctoral fellows in 20 MIT departments and divisions.

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

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

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Members as of November 15, 2015

MITEI members renew agreements

During October 2015, the MIT Energy Initiative (MITEI) signed multiyear renewal agreements with two of its members: Shell and Ferrovial.

"Shell is pleased to renew its Founding Membership in MITEI," said Dirk Smit, vice president exploration technology and chief scientist geophysics, Royal Dutch Shell. "MIT is a key academic partner, helping us drive critical R&D and innovation projects in the energy domain. Through our membership in MITEI, Shell gains access to new and emerging technologies and to nontraditional external collaboration partners."

"This renewal agreement signed with MITEI will build on a partnership that supports the development of innovative energy projects benefiting both our company and society," said Federico Flórez, chief information officer and innovation officer at Ferrovial.

Photos: Justin Knight

At the Shell signing: Robert C. Armstrong, director, MITEI (left), and Dirk Smit, vice president exploration technology and chief scientist geophysics, Royal Dutch Shell.

At the Ferrovial signing (left to right): Alberto Lopez-Oleaga, director of innovation, Ferrovial; Robert C. Armstrong, director, MITEI; and Federico Flórez, chief information officer and innovation officer, Ferrovial.

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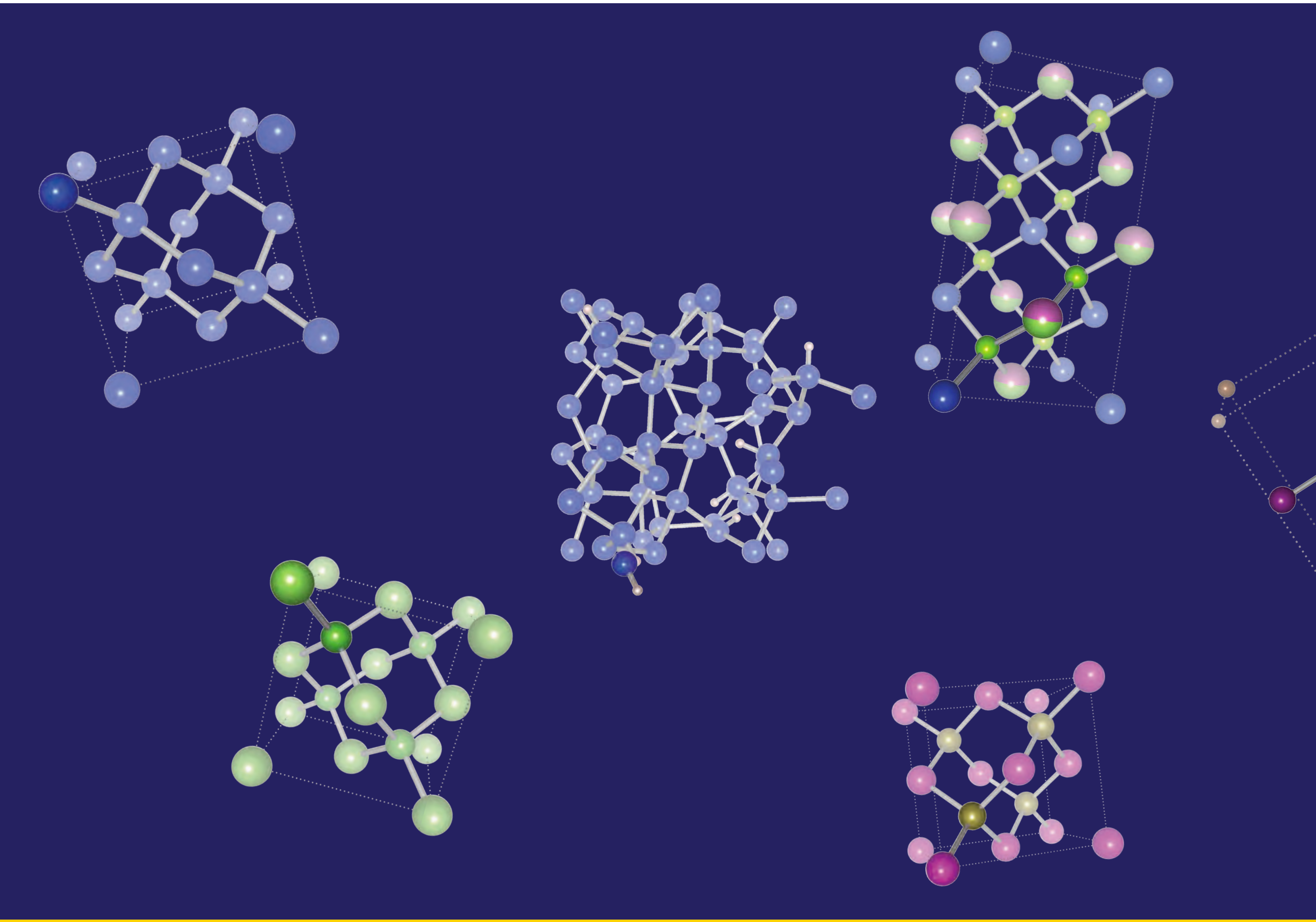

Solar photovoltaic technologies: Silicon and beyond

The cover of this issue shows the variety of molecules and crystal units now being used as “building blocks” in commercial and emerging solar photovoltaic technologies. They range in complexity from single silicon atoms to complicated compounds and nanomaterials, including the quantum dot featured on the front cover, which contains thousands of lead and sulfur atoms. An MIT assessment shows that today’s silicon technology is efficient, reliable, and scalable. However, novel solar cells now being developed could be easier and cheaper to manufacture as well as ultra-thin, lightweight, flexible, and transparent. The analysis concludes that all options should be pursued if we are to achieve the vast solar deployment needed to mitigate climate change. For more information, see page 6.