MIT Energy Initiative

The MIT Energy Initiative (MITEI) plays an important catalytic role in accelerating responses to the many challenges facing our global energy system. MITEI supports energy research teams across the Institute by bringing them together with government and industry to analyze challenges and develop solutions. MITEI also leads Institute energy education efforts and delivers comprehensive analyses for policy makers. Its accomplishments are enabled through the investment of member companies, government sponsors, and donors. From these funding sources, MITEI has raised more than $585 million to date to support MIT and MITEI research, education, and outreach programs.

MITEI is an Institute-wide initiative that, in its depth and breadth, is without peer at US academic institutions. MITEI-sponsored researchers are developing cutting-edge solutions and bringing new technologies to the marketplace. MITEI 2015 accomplishments include the acquisition of eight new members, the launch of two new consortia, and the release of the newest in the "*Future of…*" series of studies. This year, the Initiative has:

- Launched the study *The Utility of the Future,* an example of MITEI's consortium research
- Hosted the third annual Women in Clean Energy Symposium, titled Urban Strategies for a New Energy Future, where eight women received awards for their work in clean energy
- Facilitated the 2015 Associate Member Symposium, titled Storage, Renewables, and the Evolution of the Grid, which brought together experts to discuss changes in the power systems industry
- Published and announced the findings of The Future of Solar Energy study at the National Press Club, with additional meetings with lawmakers, senior government administrators, and MIT alumni
- Seen advancements in research regarding challenges faced by developing countries, resulting from work accomplished by Tata Center fellows and faculty members
- Started to create four Low-Carbon Energy Centers, each with a distinct focus: solar, materials, carbon capture and sequestration, and energy storage; MIT faculty experts will work with center members to expand the portfolio of existing MITEI-facilitated research in these areas and continue to create the path to a decarbonized energy future
- Provided a strong MIT presence for the second year at IHS Cambridge Energy Research Associates (IHS CERA) Week

Overall, MITEI members have sponsored more than 800 projects, many involving collaborations between MIT researchers and member researchers. Nearly 30% of the MIT faculty is engaged with MITEI's programs.

The MITEI Seed Fund Program supports innovative early-stage research projects that address energy and related environmental issues. Including 2015 grants, the MITEI Seed Fund Program has supported a total of 140 energy-focused research projects representing nearly $17.4 million in funding over the past eight years. The program encourages researchers from throughout MIT's five schools to collaborate in exploring new energy-related ideas, and attracts a mix of established energy faculty as well as many who are new to the field or to MIT.

More than two-thirds of MITEI's research portfolio reflects its core mission of enabling the low-carbon economy of the future through the adoption of renewable energy, energy efficiency, and carbon management technologies. The largest single area of funded research is solar energy technology and policy. Much of the remainder of the portfolio is concerned with meeting contemporary energy needs through the efficient use of conventional energy sources.

MITEI offers a "commons" approach that multiplies benefits to its member participants. Each member individually benefits from opportunities to pool resources that increase the overall understanding of research and analysis for their organization. Member shared value is created through consortia, seed fund research, and the sponsorship of fellows.

MITEI's educational offerings combine single-discipline depth with multidiscipline breadth, transforming the MIT campus into an energy learning laboratory. This year, MITEI funded nine undergraduate energy curriculum projects through a grant from the S. D. Bechtel, Jr. Foundation.

The Initiative has awarded nearly 350 graduate fellowships in energy and supported well over 200 Undergraduate Research Opportunities Program (UROP) students since 2008. One hundred and eight students have graduated with an Energy Studies minor since the minor began in 2009; 19 students graduated with this minor in 2015. Faculty associated with MITEI help shape energy education at both the undergraduate and graduate levels by teaching, advising, and developing new curricula.

MITEI's outreach program promotes and disseminates energy research findings to the MIT community, as well as to policy makers, industry leaders, and other stakeholders. Through colloquia, symposia, and seminars, MITEI introduces energy thought leaders from across the energy value chain to the local audience, which includes the MIT community, students and faculty at nearby colleges and universities, and Boston and Cambridge area politicians, energy industry personnel, and interested residents.

Through research, education, and outreach, MITEI's interdisciplinary approach covers all parts of the energy spectrum—from supply and demand to security and environmental impact.

Organization

Director Robert Armstrong's leadership team continues to build on MITEI's strong foundation and bold, interdisciplinary approach to deliver global energy solutions. In

addition, the team is broadening MITEI's membership base, increasing opportunities for faculty research, strengthening operations, and playing a lead role in energy education at MIT.

Armstrong, deputy director Robert James Stoner, and executive director Martha Broad are members of the Energy Council, which helps shape MITEI's research, education, and outreach directions. This past year, the council also included professors Angela Belcher (Materials Science and Engineering and Biological Engineering), Vladimir Bulović (co-director, MIT Innovation Initiative, Electrical Engineering and Computer Science), John Deutch (Institute Professor of Chemistry, emeritus), Leon Glicksman (Architecture and Mechanical Engineering), and Christopher Knittel (Sloan School of Management), who replaced Richard Schmalensee (Sloan School of Management) during this past year.

An External Advisory Board (EAB) composed of industry, academic, nonprofit, and public-sector leaders and chaired by George Shultz provides oversight to the Initiative. The views and guidance of the EAB greatly assist MITEI in maximizing its impact in helping to meet the world's energy needs, reduce the environmental impacts of energy production and consumption, and influence public discourse on energy and the environment. The EAB meets annually each fall; its ninth meeting was held in October 2015.

The Energy Education Task Force, composed of faculty members and students from all five of MIT's schools, oversees the Initiative's education program. Task Force members develop new directions and support activities in this realm of opportunity at MIT.

Members: Partnerships in Research and Education

Consistent with MIT's history of engaging with industry, MITEI reflects the understanding that robust research partnerships between academia and industry are highly effective vehicles for transforming the global energy marketplace. Achieving these outcomes through specific research programs involves multiple academic disciplines and personnel, supported by an infrastructure that maximizes opportunities for MITEI's industry partners.

MITEI aggregates MIT's research capability, innovation, expertise, and experience in successful industry collaborations to help meet its research partners' key strategic objectives. A multi-tiered membership structure enables private-sector partners to sponsor multidisciplinary, multiple faculty "flagship" research programs; contribute to energy-focused labs, programs, and centers at MIT; fund critical energy fellowships; support innovative energy concepts from proposals solicited across the campus; and participate in MITEI's seminars, lectures, and colloquia.

In the past year, ExxonMobil joined MITEI as a founding member; Shell is in the process of renewing its founding-level membership; Ferrovial and Chevron are in the process of renewing their sustaining-level memberships; China General Nuclear joined MITEI as an associate member; and six new affiliate members joined MITEI.

Members as of June 2015

Founding Members
BP
Eni S.p.A.
ExxonMobil
Saudi Aramco
Shell

Sustaining Members
Robert Bosch
Chevron U.S.A. Inc.
Ferrovial
Lockheed Martin
Schlumberger
Statoil
Total

Associate Members
Alliance for Sustainable Energy LLC
China General Nuclear Power Co., Ltd.
Cummins
EDF
Enel
Entergy
Hess
Iberdrola
ICF International
IHS Cambridge Energy Research Associates

Affiliate Members
8 Rivers Capital
Guillaume P. Amblard ’87, SM ’89
Asociación Nacional de Empresas Generadoras
Aspen Technology, Inc.
AWS Power LLC
Larry Birenbaum ’69
BlackRock, Inc.
John M. Bradley ’47, SM ’49
Bill Brown, Jr. ’77
William Chih Hsin Chao ’78
Constellation Energy
David L. DesJardins ’83
Cyril W. Draffin, Jr. ’72, SM ’73
Jerome I. Elkind ’51, ScD ’56
Ernst & Young LLP
Dennis Fromholzer ’75

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

Research and Analysis

MITEI is committed to working on key elements of the complex energy challenge through multidisciplinary research activities designed to address supply and demand, security, and environmental challenges. MITEI mobilizes the Institute’s research and educational capabilities to help meet the world’s most pressing energy challenges.

The facilitation of basic research is needed to bolster critical breakthroughs that can fundamentally alter energy systems at large scale several decades into the future and to accelerate the implied transformations. Such pre-competitive research has a time scale well suited to the university environment, both because its impact is often beyond the time horizon for funding by individual firms and because it educates the energy sector’s future leaders.

MITEI’s interdisciplinary research program and related education and campus-wide activities focus on:

- Innovative technologies and underlying policy analysis that will improve how we produce, distribute, and consume conventional energy
- Transformational technologies to develop alternative energy sources that can supplement and displace fossil fuels, including the economic, management, social science, and policy dimensions needed for this transformation
- Global systems to meet energy and environmental challenges through a multidisciplinary systems approach that integrates policy, design, and technology development
- Tools to enable innovation, transformation, and simulation of global energy systems through strategic basic research

Each of these concentrations includes several subgroups of disciplinary and interdisciplinary interest.

MIT Faculty Research Highlights

Over the past year, Francis O'Sullivan, MITEI's director of research and analysis, along with his students and postdoctoral associates, has engaged in a range of research activities studying topics relating to unconventional oil and natural gas resources, the energy-water nexus, energy storage and renewables integration, energy efficiency, and solar power. Significant contributions by O'Sullivan and his team during this period have included the development and publication of the MIT study *The Future of Solar Energy* and the report *Growing Concerns, Possible Solutions: The Interdependency of Natural Gas and Electricity Systems*, a study stemming from the MITEI Associate Member Symposium series.

In addition to this work, O'Sullivan has published a number of peer-reviewed articles during the past year. Notable contributions include "Methane Leakage from North American Natural Gas Systems," *Science,* 343, 733 (2014), and "The Environmental Costs and Benefits of Fracking," *Annual Review of Environment and Resources,* 39: 327–362 (2014). Both of these journals have been heavily cited as part of the emerging literature on the environmental impacts associated with unconventional oil and gas activities in the United States.

What follows are highlights from MIT faculty members focusing on energy research.

Climate Impacts of Energy Technologies

Assessing climate impacts of energy technologies: A new accounting of methane's role: Jessika E. Trancik and Morgan R. Edwards of Engineering Systems have formulated new methods of calculating the future climate impacts of energy technologies that more accurately account for the role played by methane—an approach that reduces the predicted long-term benefits of certain methane-emitting technologies.

Investigating carbon emissions in China: Can new policies curtail their growth? Valerie Karplus of the MIT Sloan School of Management and Xiliang Zhang of Tsinghua University are using a novel model to investigate the impacts of China's energy and climate policies on the country's future energy use, carbon dioxide emissions, and economic activity.

Energy in the Developing World

Tackling India's Slum Problem

MIT researchers are collaborating with staff from a leading Indian nongovernmental organization to design, test, and demonstrate housing for low-income residents in India. Their goal is to provide options that are energy efficient, environmentally sustainable, and safe in earthquake-prone regions of the world.

Facilitating Electrification Planning Activities

Visiting Professor Ignacio Pérez-Arriaga, jointly with Robert Stoner, is leading a group of five graduate students and one postdoctoral researcher in the development of computer software to support electrification planning activities in developing countries. Satellite imagery and specialized software are used to identify all of the individual households in a large region, which equates to hundreds of thousands or millions of houses. The team is employing distribution network planning models to design the best electrification model for each household—which could mean connection to the grid, off-grid microgrids, or individual standalone systems.

Bringing Microgrids to Rural Villages

MIT researchers have developed a system that will enable solar panel owners in rural villages to share power with their neighbors. This setup will allow the solar panel owners to generate income while providing their local communities with much-needed power via a power management unit—a power use, storage, and allocation director—that the team developed. This unit is smaller than a shoebox. The system operates entirely on DC current, which greatly simplifies setup, lowers costs, and is safer for users to operate. Test installations of this technology will take place in two villages in the Jamshedpur area of northeastern India.

Pushing the Limits of Pump Design for Small Farmers in India

A team of MIT graduate students—including two Tata Fellows—led by Assistant Professor Amos Winter is developing a solar-powered pump designed to meet the irrigation needs of small-acreage farmers in the Ganges River basin. The team sees promise in replacing relatively inefficient and expensive diesel-powered water pumps with solar-powered pumps, which would help increase yields and profits for these small-acreage farmers.

Fuels

Boosting Biofuel Production: Supplements Help Yeast Survive

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

Making clean, high-quality fuels from low-quality oil: William Green of Chemical Engineering and Ahmed Ghoniem and Ashwin Rhaghavan of Mechanical Engineering are developing new computer models that will help energy companies implement improved processes for converting low-quality crude oil into clean-burning, high-quality fuels.

Recovering natural gas at oil wells: Small-scale system converts it into liquids: Angela J. Acocella of the Technology and Policy Program, Daniel Cohn of MITEI, Leslie Bromberg of the Plasma Science and Fusion Center, and Emmanuel Lim of Mechanical Engineering

are working with others to explore the use of a specially adapted marine engine to convert natural gas into easily transportable liquid fuels—a small setup ideal for use in remote areas.

Nuclear Energy

Floating on the Deep Sea: A New Look for Nuclear Power

Michael Golay, Jacopo Buongiorno, and Neil Todreas of Nuclear Science and Engineering are designing a floating nuclear power plant that could provide enhanced safety, easier siting, and centralized construction—and could be deployed in time to play a critical role in a low-carbon energy future.

Solar Energy

Developing New Materials

Yafang Yang, Pablo Jarillo-Herrero, and Hugh Churchill of Physics and Britton Baugher PhD ’14 have developed a novel, inexpensive technique for making semiconductors and diodes, which they have used to build LEDs, solar cells, and light sensors that are just one molecule thick.

Using the Sun’s Heat to Make Electricity

Alexander Slocum of Mechanical Engineering is working with teams of collaborators from the MIT and Masdar Institute Cooperative Program to begin pilot-scale tests of a simple, inexpensive system in which a tankful of molten salt absorbs the heat of the sun, stores it, and delivers it for power generation at any time of the day or night.

Energy Economics and Policy

Creating a Cheaper and Greener Future

Christopher Knittel, the William Barton Rogers Professor of Energy Economics, continues his work with the E2e Project, which he established a few years ago with former MIT professor Michael Greenstone and Catherine Wolfram of the University of California, Berkeley.

E2e is a joint initiative of MIT, the University of California, Berkeley, and the University of Chicago: three recognized leaders in energy research. This group of economists, engineers, and behavioral scientists focuses on understanding the energy efficiency gap. They utilize randomized experiments and other state-of-the-art evaluation strategies to measure and enhance the impact of energy efficiency initiatives. The initiative strives to understand the difference between what is technically possible and what is practically achievable for energy efficiency in a wide variety of settings. Uniting the goal of creation of knowledge with a commitment to nonpartisan outreach, E2e aims to create a cheaper and greener future.

Estimating Reactions to Changes in Energy Prices and Regulations

Christopher Knittel's other research focuses on estimating how firms and consumers react to changes in energy prices and energy regulations. One of his recent working papers looks at the local economic impacts of hydraulic fracturing, or fracking. The paper finds that fracking leads to increases in employment, income, and most notably housing prices. The authors also find no evidence of an increase in criminal activity following fracking, and there is an offsetting increase in local government incomes and expenses.

Seed Fund Program

This year, MITEI awarded $1.65 million in grants to support innovative, early-stage energy projects across campus. For 2015, a total of 11 projects are receiving $150,000 each for research lasting up to two years. Funding for these grants comes from MITEI's founding and sustaining members, supplemented by funds from John M. Bradley '47, SM '49 (Bradley MITEI Innovation Seed Fund), an anonymous donor, and gifts from other MIT alumni. The program supports innovative early-stage research projects addressing energy and related environmental issues.

This year, MITEI received 60 proposals from across the Institute, setting a record for the largest number of applications. Applications came from 82 researchers from 29 different departments, labs, and centers across campus, and all five of MIT's schools. Twenty-five applications represented collaborations between two or more researchers, including 21 that spanned multiple departments, labs, and centers.

Projects are selected by the MITEI governing board and by the Energy Council faculty. Each of the selected projects has been chosen for its potential to advance energy research. Together, the projects respond to a variety of challenges in the energy field, on topics such as nano-engineered composite ceramic surfaces for harsh environments, water desalination, in situ and aboveground chemical oxidation strategies for treating hazardous flowback water generated from hydraulic fracturing, characterization and monitoring of geologic hazards, and scalable three-dimensional battery electrodes.

Past MITEI Seed Fund awards have helped launch a number of successful projects and startups. Professor Donald Sadoway's work as part of a Seed Fund grant led to Ambri, a company developing utility-scale energy storage for renewable energy. FastCAP Systems, under founder and CEO Riccardo Signorelli, is commercializing breakthrough ultracapacitor technology that received early support from a Seed Fund grant awarded to Professors Joel Schindall and John Kassakian with then-graduate student Signorelli. Professor Kripa Varanasi's past Seed Fund projects have led to more than one startup. One of his startups, LiquiGlide, has created a molecule-thin slippery coating for the insides of containers, which can be adapted to keep ice from building up on airplane wings and power lines.

Consortium Research

MITEI has a long history of identifying research topics that lend themselves to a consortium approach. Such topics benefit from aggregating a diverse set of perspectives on a set of critical issues facing the industry at large. The study *The Utility of the Future,* which takes this commons approach, is under way between MITEI and IIT-Comillas in Madrid, Spain.

The Utility of the Future 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 integration of renewables. The study utilizes quantitative analytical models being developed in the project to identify successful business models and transformative technologies and provide regulatory recommendations to shape in an economically efficient manner the increasingly decarbonized power sector. The project is being led by Ignacio Pérez-Arriaga and Christopher Knittel. It is staffed by an executive director, graduate students, postdocs, and researchers from IIT Comillas and is supported by a faculty committee and an advisory committee, including Professors Deutch, Schmalensee, and Armstrong, along with sponsor-level participating companies.

Launched in fall 2014, the study is supported by a consortium of 17 organizations from the United States, Europe, and Asia, including leading electric utilities (e.g., Duke Energy, Enel Green Power, Iberdrola, Public Service Enterprise Group), oil and gas companies (e.g., Saudi Aramco, Shell), an independent system operator (PJM), and equipment and solution providers to the power industry (NEC Corporation of America, Siemens).

Three *Utility of the Future* workshops have been held at MIT with the consortium members and the advisory committee since the project initiation, as well as numerous bilateral conversations between the companies, MITEI, and Comillas. Study participants have developed models to enable the analysis of key aspects of the power system, and preliminary results were presented for these at the most recent workshop event in May 2015.

An additional consortium, started this past year, focuses on supporting new towing tank experiments that will improve predictions of vortex-induced vibrations response and fatigue in ocean risers and other equipment critical to deep-sea oil operations. Two of MITEI's sustaining members—Lockheed Martin and Statoil—are jointly supporting this work, which uses a modeling tool, developed by Professor J. Kim Vandiver of Mechanical Engineering and his collaborators, that predicts vortex-induced vibrations, which can damage long cylinders deployed in ocean currents.

Reports and Studies

MIT faculty have conducted in-depth multidisciplinary energy studies over the last several years that have been designed to inform future energy options, research, technology choices, and policy development.

The Future of Solar Energy was released on May 5, 2015, at the National Press Club in Washington, DC, and was simultaneously webcast on MITEI's website. While in Washington, the study group presented its findings to lawmakers, senior administration officials, and a large gathering of MIT alumni. In addition, the study authors presented and discussed findings at a forum hosted by the Center for Security and International Studies.

The study focuses on solar energy's potential for meeting a significant fraction of humanity's future long-term energy needs while cutting greenhouse gas emissions. The study concludes that realizing this potential will require increased emphasis on developing lower-cost technologies and more effective deployment policy. The study assesses solar energy's current and potential competitive position and identifies changes in US government policies that could more efficiently and effectively support its massive deployment over the long term. The study shows that focus needs to shift toward new technologies and policies that make solar a compelling economic option.

The Future of Solar Energy study reflects on the technical, commercial, and policy dimensions of solar energy today and makes recommendations to policymakers regarding more effective federal and state support for research and development, technology demonstration, and solar deployment. Among its major themes is the need to prepare our electricity systems, both technically and from a regulatory standpoint, for very large scale deployment of solar generation—which can vary unpredictably throughout the day. To this end, the study emphasizes the need for federal research and development support to advance low-cost, large-scale electricity storage technologies.

The analysis finds that today's federal and state subsidy programs, which are designed to encourage investment in solar systems, should be reconsidered, with greater emphasis placed on rewarding the production of solar energy. The findings also recommend that state renewable portfolio standards, which are designed to increase generation of electricity from renewable resources, be brought under a unified national program that would reduce the cost of meeting set mandates by allowing interstate trading of credits. The study concludes by pointing to the urgent need for an ambitious and innovative approach to technology development, with federal research and development investment focused on new technologies and systems with the potential to deliver transformative system cost reductions.

A downloadable copy of *The Future of Solar Energy* is available online at http://mitei.mit.edu/futureofsolar.

MIT's "*Future of…*" studies are a series of multidisciplinary reports that examine the role various energy sources could play in meeting future energy demand under carbon dioxide emissions constraints. These comprehensive reports are written by multidisciplinary teams of MIT researchers. Findings are reviewed by an external advisory committee.

Grounded in science, supported by objective analysis, and comprehensive in scope and input, these studies underscore MITEI's role as an "honest broker" on energy issues.

Other MITEI activities, such as symposia that gather experts from academia, industry, and government, also generate reports on topics of interest to policy leaders. These energy studies and reports provide both Congress and the executive branch with detailed recommendations to shape and influence energy policy debates, responses, and outcomes.

International Initiatives

The large projected increases in global population and energy demand, led by those in developing and emerging economies, underscore the defining need for new energy technology and policy. These issues serve as a reminder that an international perspective is central to framing any energy research agenda. Issues such as the functioning of oil markets or climate change are inherently global in nature. However, certain technology opportunities can be pursued most easily to good purpose in the least-developed economies, where limited infrastructure may pose less complication for new energy architectures—if these solutions are advanced promptly. Developing country demographic trends, such as significant urbanization, also will call for creative approaches to energy delivery.

MITEI maintains ongoing international relationships and has established significant programs with Tsinghua University, Cambridge University, Shanghai Jiao Tong University, the Norwegian University of Science and Technology, and the Skolkovo Institute of Science and Technology (Skoltech). In addition, MITEI has established several initiatives with partners in China (including the Low-Carbon Energy University Alliance and the China Energy and Climate Project) and Portugal. Ongoing and new programs are under way in India (including the Solar Energy Research Institute for India in the United States), Spain, and France, and programs are under development with Chile and Brazil.

Tata Center for Technology and Design

The Tata Center for Technology and Design was launched at MIT in the summer of 2012, funded through a six-year, $65 million donation made by the Tata Trusts, which are chaired by Ratan Tata, former chairman of the Tata Group. Robert Stoner is now the director of the Center, following the appointment of former co-director Professor Charlie Fine (Sloan School of Management) as the founding dean and president of the Asian School of Business. The goal of the center is to create a graduate education program that teaches students how to apply deep technical knowledge to the challenges of the developing world guided by direct experience in India. The program is open to graduate students from all schools. The students, known as Tata Fellows, develop thesis projects that respond to large-scale opportunities to use technology to improve the lives of people in the lower strata of Indian society. The center provides funding for students to travel to India, generally during Independent Activities Period (IAP) and the summer, to work in Indian communities with local stakeholders and connect with prospective commercial development partners, nongovernmental organizations, and government officials. The center is currently supporting 59 Tata Fellows who are enrolled in master's and PhD programs across the Institute. Approximately 37 MIT faculty members from all five Schools have received support from the center. So far, five new classes have been established at MIT with center funding, with more planned for next year, and over 100 members of the MIT community spent time in India advancing their projects

during IAP. This year, the center held its first ceremony inducting 35 graduates into a permanent Society of Tata Fellows, and three of its members launched the center's first start-up company. Other Tata Fellows competed in and won numerous prestigious design and business competitions, including the $140,000 USAID Desalination Prize.

Skolkovo Institute of Science and Technology

Since October 2011, MITEI has engaged in Institute-wide efforts to build capacity in education, research, and innovation programs at Skoltech. Over the past year, MITEI supported the establishment and kickoff of the Electrochemical Storage Center for Research Education and Innovation (CREI), in which MIT plays the critical role of lead international institution partner. MITEI supported the identification and hiring of the Energy Systems CREI director and supported other activities related to shaping and forming the CREI.

In June 2015, Raanan Miller, executive director of MITEI's study *The Utility of the Future,* gave a talk at the First International Workshop on Advanced Mathematical Methods from Theory to Practice, held in Moscow. His talk focused on *The Utility of the Future* and some of its associated models.

Education

Catalyzing student knowledge and enthusiasm to solve technologically, socially, and politically challenging problems is a central component of MITEI's education program. Education is closely integrated with MIT's energy research as well as with campus energy management activities.

Energy Studies Minor

The Energy Studies minor was launched in September 2009 with a multidisciplinary curriculum that integrates energy science, social science, and technology/engineering. It is open to students from all majors. In June 2015, the total number of graduates from the minor surpassed 100, hailing from all five of MIT's Schools.

Energy UROP Students

During the summer of 2015, 42 students worked on energy projects in MITEI's Undergraduate Research Opportunities Program (UROP). Projects ranged from solar thermal fuels to electrocatalytic reduction of carbon dioxide to nanostructured surfaces for improved heat transfer. The education office conducted eight topical workshops designed to enhance skills and community among energy UROPs during the summer of 2015.

MITEI summer 2015 UROPs were supported by MITEI founding members BP and Shell, sustaining members Chevron and Lockheed Martin, and several MITEI affiliate members.

Society of Energy Fellows at MIT

The Society of Energy Fellows at MIT has grown to nearly 350 members representing more than 20 departments and all five schools. The fellowships are supported by a

group of MITEI's founding, sustaining, and associate members. The Society of Energy Fellows at MIT plays a key role in MITEI's intellectual and educational mission by cultivating a community of graduate students and postdoctoral researchers with a wide range of disciplinary perspectives and talents focused on a common set of energy challenges. Society-sponsored activities include dinner meetings with sponsors in conjunction with MITEI's Annual Research Conference and a range of informational gatherings.

Internships and Career Development

MITEI continues to expand efforts in the area of internships and career development. More than 400 students from across the Institute are engaged in energy internship opportunities. MITEI works closely with the MIT International Science and Technology Initiative, Global Education and Career Development, and other offices and programs that offer internships to encourage and support energy-related career opportunities.

Energy Education Task Force

MITEI's Energy Education Task Force guides the development of energy education at MIT. Professors Amy Glasmeier (Urban Studies and Planning) and Jeffrey Grossman (Materials Science and Engineering) serve as the task force's co-chairs. The task force meets regularly throughout the academic year and includes faculty from all five Schools at MIT as well as graduate and undergraduate student representatives. Professional staff members in MITEI's Education Office support the Energy Education Task Force by implementing energy education programs.

In 2015, MITEI provided support to nine undergraduate energy curriculum development projects through a grant from the S. D. Bechtel, Jr. Foundation. In addition, MITEI education director Amanda Graham represented MIT on the planning committee for the first National Energy Education Summit. Graham, MITEI academic coordinator Ann Greaney-Williams, and Energy Studies minor Priyanka Chatterjee '15 presented at the summit, which took place in Washington, DC, in January.

Outreach

MITEI's outreach program has two distinct components. First, MITEI shares the results of MIT and MITEI research and analysis programs with a broad external audience of energy, policy, environmental, and industry leaders through several publications. Second, MITEI brings experts to campus to enrich and broaden the MIT community's understanding of a range of energy issues and challenges. The outreach program includes a wide range of meetings and published materials that steadily increase in type and number each year. This past year, the program supported more than 100 separate meetings.

The outreach program produces or facilitates:

- Studies and reports, such as the "*Future of...*" series and the Associate Member Symposium series
- Publications, including the semiannual magazine Energy Futures

- Public and invitational events for a wide range of audiences
- Digital outreach in the form of the MITEI website, a monthly e-newsletter, and a social media presence
- Documents, video presentations, media relations, and publicity in support of MITEI-sponsored faculty members, studies, reports, and events

Studies and Reports

MITEI's outreach activities have included producing seven major "*Future of…*" studies in the past eight years. These multi-year and multi-disciplinary studies are designed to provide policy makers, researchers, environmentalists, and industry with technically grounded analyses to inform options for a clean energy future. As previously described, in May 2015, MITEI released the study *The Future of Solar Energy* in Washington, DC, and held a series of meetings with members of Congress and administration officials. The study received extensive press coverage, and MITEI outreach will continue with a daylong symposium on campus in the fall.

Another group of publications captures the proceedings of the MITEI Associate Member Symposium series. These topical meetings are designed to bring together groups of energy experts and stakeholders to discuss critical and timely energy issues. After each symposium, a report is prepared and published, providing a range of findings and recommendations. Graduate student research assistants involved in each project contribute supplemental information to the final presentations.

Meetings and Events

Attendance at public MITEI-sponsored events is enthusiastic, demonstrating a high level of demand for energy-related information, education, and networking throughout the MIT and local communities. This year, MITEI's meetings included the Fall Research Conference for MITEI members; the Associate Member Symposium, titled Storage, Renewables, and the Evolution of the Grid; the third annual Women in Clean Energy Symposium, titled Urban Strategies for a New Energy Future; a series of hands-on energy events during IAP; and MITEI researcher participation in IHS CERAWeek for the second year in a row.

Fall Research Conference

Since 2008, MITEI's invitation-only Fall Research Conference has provided a venue for its members to learn about advancement in research as well as developments at MITEI. This two-day conference features presentations on critical energy topics from MIT faculty and MITEI leadership; key results from Seed Fund and research projects; recruitment/networking dinners with fellows; and a forum in which members can interact and identify potential joint collaborations. This past year, at the request of the members, we expanded our invitation list campus-wide to all MIT principal investigators and featured a new panel, designed for the faculty audience, in which members discussed their research interests and seed fund priorities. The dinner following the panel included tables organized by topic to enhance networking and discussion between members and faculty. These innovations helped us double the

previous year's attendance, and the feedback we received was overwhelmingly positive from both the MITEI members and the faculty. MITEI will continue to build upon last year's success with a similar program this fall.

2015 Associate Member Symposium: Storage, Renewables, and the Evolution of the Grid

Today's power systems are changing. The penetration of intermittent renewable generation is growing rapidly. This trend is being aided by significant cost reductions in technologies like solar and, in the case of distributed generation, by novel business models. Moreover, the increasing electrification of energy in general, led by growth in electric vehicle usage, is altering the manner in which people consume energy services. These dynamics bring with them new challenges for utilities and grid operators, who must maintain service quality and reliability.

Increasingly, energy storage technologies are being viewed as providing solutions to the needs of the evolving grid; they also aspire to change the way electrical grids are built and operated. These technologies include everything from advanced batteries to flywheels, compressed air storage, and "virtual storage" in the form of demand management. In spite of this increasing popularity, however, there is significant uncertainty and debate over the need and ideal-use case for storage, particularly given the existence of alternative solutions and the uncertainty over future generation mix scenarios.

The 2015 MITEI Associate Member Symposium: Storage, Renewables, and the Evolution of the Grid—sponsored by Cummins, EDF, Entergy, and Hess—brought together a group of key thought leaders in the power systems industry. The aims of the event included:

- Developing an understanding of the evolving power system, its new challenges, and alternative solutions to meeting those challenges
- Surveying the existing grid storage technologies, their current applications and business models, and looking into future trends
- Exploring the synergistic effects between storage, distributed generation, and microgrids, and how these can alter the structure and operation of the grid
- Developing an understanding of the current state and challenges of grid storage regulation and market design in order to suggest actionable policy and regulatory recommendations

Expert insight was presented on each of these topics, provoking discussion and debate among the participants. A summary of the discussion, without attribution, along with key takeaways and contributed materials will be published by MITEI this fall to guide future research efforts and inform policy-making. Contributed materials, with authors, will be posted on the symposium website to inform stakeholders engaged in power systems and energy storage implementation, market design, and regulation.

Women in Clean Energy Symposium: Urban Strategies for a New Energy Future

In support of developing national-level capacity, MITEI is partnering with the Department of Energy to fulfill the US commitment to the Clean Energy Ministerial's Clean Energy Education and Empowerment initiative launched by nine governments in 2010. The US Women in Clean Energy program includes the naming of 30 Energy Ambassadors, an awards program, and an annual major conference. The third annual, invitation-only Women in Clean Energy Symposium, Urban Strategies for a New Energy Future, took place in September 2014 at MIT. Over 200 participants gathered to continue the broader effort of supporting and enhancing educational and career opportunities for women in clean energy, building on the foundation established at the first symposium in 2012.

The symposium's speakers ranged from those working on smart grid and urban transportation policy and technology solutions to those working on financing models to support "green" urban infrastructure. Key participants pointed out that globalization and rapid urbanization are presenting an opportunity to make a critical impact by responding to growing energy demand with efficient and clean sources. Forward-looking leaders shared success stories regarding how they balance the competing goals of productive, affordable, and low-carbon energy by establishing partnerships and programs to make their cities smarter and greener.

Eight mid-career women received awards for their work in clean energy, and Sue Tierney, senior advisor, Analysis Group, received a Lifetime Achievement Award. Tierney's four decades of service span government, the private sector, and academia, including serving as assistant secretary for policy at the US Department of Energy, state cabinet officer for environmental affairs, and state public utility commissioner.

Independent Activities Period

Each year, MITEI sponsors a number of energy events during IAP and helps publicize other energy-related activities organized by faculty and students across campus. This year, MITEI's offerings included tours of Veolia Energy North America's cogeneration station at Kendall Square, Cambridge; the Massachusetts Department of Transportation Highway Operations Center and the MBTA Operations Control Center facilities and tunnels; the Aramco Research Center; the LEED Platinum-certified Artists for Humanity building; and the Massachusetts Clean Energy Center's Wind Technology Testing Center. MITEI also offered information sessions for undergraduate students interested in learning more about energy-related undergraduate research opportunities and the Energy Studies minor.

IHS CERAWeek

Each year, IHS CERAWeek brings together an international group of industry, policy, technology, and financial leaders to participate in one of the world's preeminent energy conferences. MIT was the only academic institution invited to partner in IHS CERAWeek 2015, and MIT researchers played leading roles in several sessions.

The keynote session on Friday, April 24, which spotlighted cutting-edge research by four MIT energy researchers, was led by Robert Armstrong and moderated by IHS

vice chairman Daniel Yergin. The session "Frontiers of Science and Innovation: What Game-Changing Technologies Are on the Energy Horizon?" explored the frontiers of innovation, transformation, systems, and tools that will reshape the energy future, and underscored the important role universities play in the innovation pipeline as incubators of talent and technology.

IHS CERA also sponsors the monthly MITEI seminar series that brings thought leaders from colleges and universities across the country to inform the MIT community about critical areas of energy research and analysis that will help the nation and the world meet the enormous energy challenges in the coming decades.

Crowds and Climate

MITEI again co-sponsored the Climate CoLab's Crowds and Climate Conference, a thought-provoking program that explored the role that new technology-enabled approaches—such as crowdsourcing, social media, and big data—can play in developing creative new ideas and taking action on climate change. Held November 6–8 on the MIT campus, the second annual conference was attended by more than 200 people, with an additional 1,000 joining virtually via livestream and Google Hangout. A key element of the conference was a series of presentations by winners of contests run by the Climate CoLab, an online platform developed by the MIT Center for Collective Intelligence, which seeks to crowdsource creative new ideas to address climate change.

MIT Energy Club Conference

MITEI co-sponsored the student-run MIT Energy Club annual gathering (which celebrated its 10th anniversary this year) and was instrumental in securing keynote speakers. Robert Armstrong delivered the welcoming address to a full house.

The conference and the MIT Energy Club—now the Institute's largest student group—were co-founded by David Danielson PhD '08, then an MIT graduate student and now the US assistant secretary of energy and director of the Department of Energy Office of Energy Efficiency and Renewable Energy. Danielson returned to campus both as a keynote speaker and as moderator of the final panel discussion at this year's conference.

MITEI-Sponsored Public Seminars and Colloquia, 2014–2015 Academic Year

September 30, 2014: "How to Think about Energy and Climate," Former Secretary of State and MIT Professor George P. Shultz, Distinguished Fellow at the Hoover Institution at Stanford University

October 6, 2014: "The Growth Imperative: Plotting a Sustainable Energy Future for India," Jairam Ramesh, Former Indian Minister for Rural Development and Visiting Fellow at the Harvard Kennedy School

February 26, 2015: "Chevron: Differentiating Performance Through Technology," Barbara Burger, President, Chevron Technology Ventures

April 8, 2015: "An Evening with Power Africa and Off-Grid Electric," hosted by e4Dev (energy for human development). Speakers: Andrew Herscowitz, Power Africa and Trade Africa Coordinator; Kate Steel, Power Africa/Trade

Africa Energy Sector Team Lead; Graham Smith, Vice President of Business Development at Off-Grid Electric

April 13, 2015: "Pricing Carbon to Combat Climate Change: What Can the United States Learn from British Columbia?" Mary Polak, Environment Minister, British Columbia

April 16, 2015: "Pathways to Decarbonization in China and India: Evidence of Integrated Governance Solutions," Bruce Gilley, Associate Professor, Portland State University

May 1, 2015: "The Role of Energy Storage in a Low-Carbon Energy Mix," Bernard Salha, Chief Executive Officer of Research and Development, EDF

May 18, 2015: "Smaller and Sooner: Accelerating Fusion Energy's Development with Technology and Science Innovation," Dennis Whyte, Director of the MIT Plasma Science and Fusion Center and Professor of Nuclear Science and Engineering

Communications Outreach

MITEI's Communications Office seeks to add value to all of MITEI's efforts, for example by creating strategic communications plans that span print and online communications, social media, and by involving key constituents and stakeholders. The communications staff reaches out to the press to promote and disseminate MITEI's work; provides communications support for MITEI's stakeholders, MIT faculty, and MITEI staff; produces a variety of print and online publications and marketing and promotional collateral; and engages in social media outreach with an integrated approach. For the recent study *The Future of Solar Energy,* the communications team created and executed a comprehensive strategy that included extensive outreach to the press, a social media campaign, and strong coordination with the MIT News Office.

Publications

Energy Futures, MITEI's semiannual print magazine, features in-depth research stories and coverage of news, energy education, and events. The magazine is also shared online via MITEI's website, and select content is shared via social media.

MITEI's monthly e-newsletter, inaugurated four years ago, now has over 6,600 subscribers. The newsletter updates the community on MITEI activities and progress, particularly about events welcoming public involvement, and highlights profiles of faculty and students.

Affiliated Groups

MITEI is affiliated with faculty members in several MIT centers, departments, and laboratories pursuing interdisciplinary energy and environmental activities. MITEI supports the financial administration of certain projects and collaborates on research and education activities with these organizations.

Center for Energy and Environmental Policy Research

Established in 1977, the Center for Energy and Environmental Policy Research (CEEPR) funds research on energy and environmental policy to support sound decision making by government and industry. It is directed by Christopher Knittel and jointly sponsored by MITEI, the Department of Economics, and the Sloan School of Management.

Affiliated faculty and research staff as well as international research associates contribute to empirical research on policy issues related to coal, oil, gas, and electricity markets; nuclear power; transport; energy infrastructure; investment finance and risk management; and environmental and carbon constraints. CEEPR cooperates closely with associates in government and industry from around the globe to enhance the relevance of its research.

Output includes working papers, policy briefs, and research input; larger, interdisciplinary studies; two annual research workshops in Cambridge, Massachusetts; and a European energy policy conference organized jointly with the Energy Policy Research Group at the University of Cambridge.

Joint Program on the Science and Policy of Global Change

The Joint Program on the Science and Policy of Global Change integrates natural and social sciences to study the interactions among human and earth systems to provide a sound foundation of scientific knowledge. Co-directed by Professors John Reilly and Ronald Prinn, the program combines traditional strengths in science and economics to aid decision makers in confronting the interwoven challenges of future food, energy, water, climate, and air pollution issues, among others. The 23-year-old program is recognized as a world-leading center for integrated assessment of global change.

The program has developed unique analytical capabilities for investigating the complex connections among human activities and the global environment, as well as associated uncertainties. At the heart of this work is the MIT Integrated Global System Modeling framework. This linked set of computer models analyzes interactions among human and earth systems, enabling the program to undertake quantitative analyses of global changes and their social and environmental implications. A team of faculty, professional research staff, postdoctoral fellows, and graduate students carries out the work and communicates the research results, analysis methods, and assessment conclusions to a broad range of audiences.

Through publications, presentations, workshops, and briefings, the program's work is conveyed to policymakers in the United States and other countries, industry leaders, other analysis groups in the climate community, environmental organizations, journalists, students, educators, and the public at large. The effort is supported by 10 US federal agencies and an international consortium of industrial, foreign government, and foundation sponsors in North America, Europe, Japan, and China.

Office of Sustainability

In August 2013, the Office of Executive Vice President and Treasurer (EVPT) established MIT's first Office of Sustainability, reporting directly to Executive Vice President and Treasurer Israel Ruiz. Julie Newman, director of sustainability, and her staff are spearheading an expansion and coordination of campus energy and sustainability programs across campus and in the community. MITEI and the Office of Sustainability are continuing the already strong collaboration with the EVPT's office and the Department of Facilities in campus energy education, faculty engagement, and student projects both inside and outside the classroom.

Analysis Group for Regional Energy Alternatives

MITEI's research in the area of integrated planning for local and regional energy infrastructures is centered in the Analysis Group for Regional Energy Alternatives (AGREA), led by Stephen Connors. Collaborations include the MIT-Portugal Program and the Engineering Systems Divion's Center for Complex Engineering Systems along with the King Abdulaziz City for Science and Technology, as well as MITEI's own projects.

AGREA focuses on how to dramatically reduce energy use and emissions on the local and regional scale. Technology portfolios incorporating high penetration renewables, smart energy uses—including electric transportation, energy storage, and transformations of the built environment—require a detailed understanding of local energy system operations and of the combined dynamics of solar, wind, and other renewables and how they match the dynamics of local energy needs. This includes structural changes in energy demand resulting from the deployment of "smart technologies" as well as from rapidly growing demands for other commodities, such as potable water from desalination plants.

The scenario-based tradeoff-analysis approach (developed in the early 1980s by MIT Energy Laboratory researchers) is the primary tool used by AGREA. Ongoing and recent research activities include projects in the MIT-Portugal Program's Sustainable Energy and Transportation Systems focus area, as well as efforts elsewhere in Europe and the Middle East, including Saudi Arabia. AGREA's bottom-up, scenario-based approach helps both policymakers and private-sector innovators identify new market niches for clean energy technologies, taking into consideration local economic and resource dynamics.

In addition, Professor Connors advises numerous graduate and undergraduate students in other projects and programs across MIT looking at fuel consumption and emissions impacts among renewables and fossil fuels. Some of these projects involve challenges to the development of new renewable industries such as offshore wind, the electrification of transportation, energy storage, and smart grid technologies; the potential impacts of the widespread deployment of distributed generation to electrification in developing countries; and real options applications to energy investments involving climate change, economic growth, and energy security.

MultiScale Material Science for Energy and Environment Laboratory

MITEI continues to host MultiScale Material Science for Energy and Environment, an international joint unit or UMI (Unite Mixte Internationale) between the French National Center for Scientific Research (CNRS) and MIT. The UMI, led by director Roland Pellenq and co-director Franz Ulm, plays a critical role in MIT's ability to respond to the research challenges of sustainable shale gas exploration. Specifically, in collaboration with Shell, Schlumberger, MIT, and the X-SHALE project, UMI carbon scientists and Materials Science and Civil Engineering faculty are leading the development of the fundamental nanoscale knowledge required for a sustainable asset management of shale gas.

Through the affiliation of the UMI with CNRS (with financial support from the Laboratory of Excellence ICoME2 funded by the Commissariat pour les Investissemements d'Avenir and l'Agence Nationale pour la Recherche), MIT has become a partner in various CNRS labs in France, including the SOLEIL synchrotron in Paris (the last generation of synchrotron combining and exceeding the performance of Berkeley and Berlin synchrotrons) and the Centre Interdisciplinaire de Nanosciences de Marseille Laboratory, the last-generation transmission electron microscope and a unique time-resolved setup to study, in situ, the kinetics of the dissolution/precipitation reaction of cement.

The affiliation of UMI researchers as visiting professors supports successful project integration into the educational landscape of MIT. Specifically, UMI researchers are contributing to MIT's educational offerings at the graduate level through out-of-the-box topics such as "Soft Matter Physics of Muds," an offering in the Department of Civil Environmental Engineering. The UMI facilitates research collaborations for MIT faculty seeking research relationships with France.

Carbon Capture and Sequestration Technologies Program

MITEI's continuing work on carbon capture and sequestration (CCS) technologies focuses on three areas: assessment, education/outreach, and research. MITEI Senior Research Engineer Howard Herzog leads this effort. Active internal collaborations include Ahmed Ghoniem (Mechanical Engineering) on oxy-combustion and gasification technologies, Alan Hatton (Chemical Engineering) on stimulus-response sorbents for CO_2 capture, Ruben Juanes (Civil and Environmental Engineering) on geologic storage modeling, and John Parsons (Sloan School of Management) on CCS regulatory frameworks and business organization.

The core of the program is the Carbon Sequestration Initiative, an industrial consortium on carbon management. The 12 members are Alstom Power, American Petroleum Institute, Chevron, ConocoPhillips, Duke Energy, Electric Power Research Institute, Entergy, ExxonMobil, Shell, Southern Company, Suncor, and Vattenfall. The initiative funds research and hosts an annual two-day Carbon Sequestration Forum to examine critical technical and policy issues related to CCS.

Highlights from the past year include:

- The 16th MIT Carbon Sequestration Forum, November 2014
- Graduation of two master's students in the Technology and Policy program
- Publication of several commentary pieces, including one in the Wall Street Journal (November 23, 2014)
- Publication of the quarterly CCS Regulatory Newsletter
- Maintenance of an online CCS Demonstration Projects database

The group's strong interactions with the national and international CCS community include:

- Participation in the Coal Utilization Research Council's CCS Technology Collaborative
- Membership in an international network on CCS costs
- Membership on the steering committee and program committee of the premier international meeting on CCS, the 12th International Conference in Greenhouse Gas Control technologies (GHGT-12), held on October 2014 in Austin, TX

From 1989 to 2008, CCS saw a significant year-to-year growth, but has seen a major slowdown in growth and expenditures since 2008. The major cause is the disarray in climate policy at both the national and international level, which creates much uncertainty about the development of commercial markets for CCS technology. MITEI recognizes that CCS is a key component to successfully mitigating climate change, and it is developing a strategy to strengthen and grow the program.

Robert C. Armstrong
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