



Laboratory for Energy and the Environment: Merger Strengthens, Broadens MIT's Sustainability Research

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Introduction

With this issue, we introduce *e-lab's* new home, the Laboratory for Energy and the Environment (LFEE). The LFEE was formed on July 1, 2001, when MIT merged the Energy Laboratory with the Center for Environmental Initiatives, thus strengthening its commitment to tackling energy and environmental problems that cross disciplinary boundaries.

The LFEE brings together collaborating faculty and staff in 14 departments to address the complex, long-term, multifaceted problems of sustainable development and its needs for energy and other resources. These multidisciplinary teams work not only on technological solutions but also on the environmental, economic, political, and social aspects associated with their realization. Collaboration with developed and developing nations alike fosters the implementation of sustainable practices worldwide. Educational and outreach programs serve MIT students as well as other academic researchers, industry professionals, and policy makers at home and abroad.

In this issue of *e-lab*, we present the perspectives of some of the LFEE's principal contributors. We asked them:

- What are some of the most important and exciting issues, challenges, and/or technologies in your field for the next five years?

- What research do you hope to undertake to address them?
- How will the new LFEE mission and structure help you and your colleagues address those issues?

Taken together, the articles demonstrate the wide-ranging activities and topics that are being tackled by the LFEE and its affiliated laboratories, centers, and academic departments. Future issues of *e-lab* will contain in-depth research reports on those activities.

Challenges and Opportunities

David H. Marks

Morton '42 and Claire Goulder Family Professor of Engineering Systems and Civil and Environmental Engineering; Director, Laboratory for Energy and the Environment

The founding of the Laboratory for Energy and the Environment (LFEE) is a dream come true for me. It is the culmination of a ten-year effort to bring together researchers across MIT to cooperate on problem solving and innovative management in support of a sustainable future. We now have experts in a variety of disciplines studying the complex interrelationships between energy and the environment as well as other global environmental challenges to

sustainable development. Research focusing on the supply and demand sides of energy and resource use is linked with studies of related



David H. Marks

economic and social issues. Our expertise is such that we can look not just at single technologies in depth but also across technologies; and we can study how improving and using technologies

can lead to better management and policy formation. It is an exciting time, and bringing many of MIT's main multidisciplinary energy and environmental groups together into one campus location will lead to increased synergy.

We are working all over the world, especially in the developing nations, to seek ways to foster economic development while limiting and mitigating the social and environmental impacts of that growth. For example, through the Alliance for Global Sustainability, we work with collaborators at the Swiss Federal Institutes of Technology, University of Tokyo, and Chalmers University of Technology (Sweden). Our research focuses on helping megacities worldwide cope with issues of mobility, energy, basic infrastructure, and water and air pollution.

Many of our research programs have outreach and educational components, so we're working to spread sustainable thinking and practices worldwide. Through our Program for Environmental Education and Research we are increasing the environmental awareness of the MIT community as well as practicing environmental professionals.

Laboratory for Energy and the Environment

Centers, Laboratories, and Programs

Alliance for Global Sustainability

Center for Advanced Nuclear Energy Systems

Center for Airborne Organics

MIT/AGS

Program for Environmental Education and Research (PEER)

Program in Science, Technology, and Environmental Policy

Sloan Automotive Laboratory

Research Areas/Groups

Alternative Fuels

Analysis Group for Regional Electricity Alternatives

Carbon Management and Sequestration

Competitive Power Systems Group

Energy Conservation

Green Chemistry

Regulation and Policy

Renewable Energy Technologies

Education (PEER)

Advanced Technology Environmental Education Center-MIT Partnership

Martin Family Society of Graduate Fellows for Sustainability

Urban Focus: MIT-Cambridge Collaboration on Education for the Environment

Wallenberg Foundation Postdoctoral Fellowship Program on Sustainability and the Environment

Youth Environmental Summit

Related Centers, Laboratories, and Programs

Building Technology Program

Center for Energy and Environmental Policy Research

Global System for Sustainable Development

Integrated Program on Urban, Regional, and Global Air Pollution

What are the main challenges that LFEE will tackle in the coming years? I believe that a central one is to develop integrated solutions to complex problems. We need better methods of understanding and explaining the trade-offs and cause-and-effect relationships among activities in different energy-use sectors and the social systems they serve.

Another challenge is changing people's behavior. How can human behavior about resource and energy use be brought in line with long-term sustainability goals? What drives consumption? Will economic instruments alone be successful in influencing consumer behavior as population growth and life-style improvements put more stress on our natural and environmental resources?

Another challenge is how best to apply technology. How can technology be used to lessen the impacts of energy and resource use and to narrow the gap between the developed and the developing world in terms of accessibility to jobs, economic development, and a clean environment?

Finally, what is the role of science and technology in solving major societal problems, and how can MIT aid in clarifying and serving that process?

The LFEE is in an excellent position to tackle all of those challenges comprehensively, both by performing a wide set of focused projects and by managing large-scale initiatives on environmental problem solving.

An area in which we're addressing many of those challenges—and an area of particular interest to me personally—is sustainable mobility. How are people and goods to be moved in an increasingly constrained urban and intercity

setting while maintaining the economic benefits derived from mobility? Access to knowledge, goods, jobs, and social activities is a cornerstone of our society. How will future developments in urban areas, in freight movement, and in intercity travel be made consistent with environmental and social goals? How can information technologies help build access to jobs and knowledge and support personal interactions without physically moving people? How might the physical movements of people and goods be coordinated through smarter infrastructure to avoid congestion and environmental impacts? I see this set of problems as a formidable—and exhilarating—challenge for the future.

Spreading Sustainable Ideas and Practices: LFEE Education and Outreach

Jeffrey I. Steinfeld

Professor of Chemistry; Director, Program for Environmental Education and Research

Education and outreach are integral components of the mission of the LFEE. The Program for Environmental Education and Research (PEER) has responsibility for carrying out this mission. Goals include the following:

- Education of our own students. All students at MIT need to understand what is happening in the world that we inhabit, to be aware of how human activities are influencing this world, and to acquire a sense of responsibility for the planet and its inhabitants. A major objective of PEER is to ensure that environmental issues and concerns are part of the



Jeffrey I. Steinfeld

- education of every MIT student, not just those who will go on to be environmental scientists, engineers, and planners.
- Education of our own faculty. In order to educate our students, faculty in all fields and disciplines must recognize that the ability to change or affect a natural system carries with it the responsibility to consider the effects of such a change on everything and everyone that relies on that system.
- Education of industry leaders, policy makers, and elected officials. MIT has traditionally played a role in the policy arena and engaged in issues that have major implications for global prosperity. Among those issues, few are more critical than safeguarding the natural environment.
- Education of the public and the media. Conveying these ideas to the general public—and maximizing the effectiveness of the media to do so—will be essential for bringing about the changes in attitudes and behavior necessary to achieve a truly sustainable society.

PEER carries out a wide range of activities and programs in support of this mission, including:

- Developing, testing, and disseminating curriculum modules for courses and subjects taught at MIT and elsewhere. Case studies have been prepared that bring together science, engineering, health, and policy aspects of environmental issues such as polychlorinated biphenyl (PCB) contamination, use of MTBE additives in automotive fuels, energy, and climate change.

- An Environmental Fellows Program, which includes the Martin Family Society of Graduate Fellows for Sustainability and the Wallenberg Foundation Postdoctoral Fellows on Sustainability and the Environment. These Fellows will develop a heightened awareness of environmental concerns and sustainability issues. In addition, they will create a life-long, international network of colleagues to call on as they work on complex, multidimensional environmental issues.
- The Youth Environmental Summit (YES), a summer institute of the Alliance for Global Sustainability. The YES brings students from many different countries together each summer for an intensive two-week seminar and learning program on environmental and sustainability issues. YES alumni have formed the AGS World Student Community to continue their interactions and project work.
- Outreach to community colleges and high schools, state and local legislators, and others seeking insights from the LFEE's extensive research programs.

MIT is undertaking a campus-wide initiative to improve the environmental performance of our own practices and to become a leader in environmentally sustainable operations. Education is a key component of this initiative. As part of the recent settlement between MIT and the US Environmental Protection Agency, PEER is managing "Education for the

Environment,” a collaboration between MIT and the Cambridge Public Schools that is intended to address past problems and to serve as a model for such collaborations elsewhere.

The mission and structure of the new LFEE will provide greatly expanded opportunities and resources for carrying out PEER’s mission and for developing new programs and approaches.

Global Climate Change: Clarifying the Debate

Henry D. Jacoby

William F. Pounds Professor of Management (retired); Co-Director, Joint Program on the Science and Policy of Global Change

After a decade of effort in the search for a common response to global climate change, international negotiations threaten to bog down in



Henry D. Jacoby

disagreement and recrimination. Some nations, led by the European Union, believe there is no choice but to proceed with the Kyoto Protocol negotiated in 1997. Others, importantly including the United

States, have rejected the Kyoto text and suggest that some better approach must be found. Thus, the world likely faces several years of confusion as nations work out their own individual responses to greenhouse emissions and continue to seek some way to knit the larger contributors

into a common framework. Domestic and international discussions, for many years focused on the Kyoto structure, are again wide open; and the issues at stake are not just the details of common control measures but the very architecture of global agreement.

In this circumstance, it is crucial that facilities be provided for competent and neutral assessment of proposed solutions and that debate—naturally focused on short-term policy concerns—not lose sight of the long-term climate threat and our evolving knowledge of the science of the earth system. The MIT Joint Program on the Science and Policy of Global Change, founded in 1991, continues its mission of providing analysis that integrates the science of the climate system, the economic and ecological aspects of human intervention and potential control mechanisms, and assessment of technologies that may help manage this threat.

In this period of uncertainty about a global approach, understanding the potential for technological advance, particularly of energy supply and use technologies, takes on special importance. In the long term, the international goal of stabilizing greenhouse gas emissions in the atmosphere cannot be met without dramatic advances in energy technology. With no agreement on an approach to emissions control, on the other hand, the desire for a technological “fix” can cloud judgment about policy development in the short term. It is in this latter domain that the close collaboration between the Joint Program and the LFEE is particularly productive. Realistic assessments of potential future technological developments—drawing on LFEE work in areas such as carbon capture and sequestration,

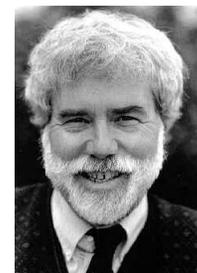
advanced nuclear power, and advanced end-use devices—are crucial inputs both to the modeling activities of the Joint Program and to the integrated assessments that are its ultimate purpose.

Food for the Future: Assessing the Sustainability of Agriculture in Developing Countries

Dennis B. McLaughlin

H.M. King Bhumipol Professor of Civil and Environmental Engineering

During the next 50 years, global population is expected to increase from 6 billion to about



Dennis B. McLaughlin

9 billion—a change that will require a substantial increase in food production. Thus far, global food production has kept pace with population growth, in part due to increases in inputs such as fertilizer and irrigation water. But there are indications that water and soil resources in certain arid and semi-arid areas, especially in Africa and South Asia, are being depleted to the point where they may not be able to sustain existing production levels, let alone the higher levels needed to feed a growing population.

The sustainability of the world’s food supplies is the subject of considerable conjecture and debate but relatively little quantitative analysis. To help fill that gap, my group at the

Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics at MIT is working to construct an accurate accounting of water resources in critical areas of Asia. This work is supported by federal agencies such as the National Aeronautics and Space Administration and the National Science Foundation as well as by the LFEE and the Alliance for Global Sustainability.

Existing ground-based data are generally too limited and uncertain to enable us to accurately characterize hydrologic fluxes over large areas. We are therefore supplementing traditional data sources with new information compiled for global climate analysis. Included are satellite-based remote sensing data that can be used to characterize seasonal variations in vegetation (important for estimation of evapotranspiration) and to map river basin boundaries. New remote sensing data sources likely to come on-line over the next few years should also enable us to obtain better information on important variables such as precipitation, soil moisture, snow cover, and groundwater storage.

Our research has several aspects, including the construction of water budgets for large river basins and groundwater aquifers and the development of advanced methods for analyzing remote sensing data. The common goal of this work is to assess regional water supplies and demands, both now and in the future, so that we can identify areas where resources are being critically depleted.

While resource depletion is a major concern, other factors will also affect future food supply in developing countries. For example, the amount of food available in developing regions

of the world is influenced by technological changes such as new irrigation methods and genetically modified crops; by rural-to-urban migration; by the trend toward larger, more capital-intensive, and more productive farms; by the growing dependence on imports and thus international trade policy; and by the potential impact of global climate change on regional agriculture. We hope to assemble teams that can undertake parallel studies of the impacts of those factors on global food production. Such studies will also help to define effective technological, economic, and policy responses for dealing with impending problems. The LFEE is a natural setting in which to pull together the needed teams of scientists and engineers as well as economists with expertise in resource, trade, and development issues.

Global resource issues affecting poor rural and urban populations are likely to become increasingly important in the environmental field. Indeed, such issues may well eclipse more conventional concerns regarding environmental regulation for industry. Our role in this work is to help policy analysts take advantage of promising new data sources that will finally enable us to assess resource availability and monitor environmental change on a global scale.

Developing Nations: Sustainable Approaches to Economic Growth

Mario Molina

Institute Professor

Many issues are coming into focus as the international community tries to respond to global environmental issues such as climate change. Of particular interest to me is the role of the developing nations, where most of the new economic growth will occur. In the past, economic



Mario Molina

growth has meant higher energy consumption. The United States and other developed countries must therefore work hard not only to develop their own energy policies but also to help developing countries find energy-efficient ways to accomplish economic growth.

For several years, we have been working with the Mexican government to alleviate Mexico City's severe air pollution—a serious problem in many rapidly developing cities. We are studying the local benefits attainable from increased energy efficiency and cleaner energy use and also determining the “co-benefits” in terms of global impacts. Improving the local environment will affect the global environment and thus the role played by Mexico in international climate negotiations.

Our main focus has been on transportation, the dominant source of Mexico City's air emissions. Much of the city's fleet is old and must be retired or replaced. Possible approaches include improving the public transportation system and replacing existing buses with cleaner hybrid or natural-gas-fueled buses.

Defining, evaluating, and implementing such approaches requires addressing scientific, engineering, social, and economic issues. The Mexico City Program therefore involves investigations by experts in transportation systems, health effects and epidemiology, atmospheric modeling, economic and institutional systems and policy-making, and other major emissions sources such as power plants. Other collaborators bring all the components together to perform integrated assessments of possible policies. Program participants include faculty, staff, and students from various departments at MIT, from the Harvard School of Public Health and the Kennedy School of Government, and from academic institutions and the government in Mexico.

To better understand the air-pollution problem and the potential effectiveness of various responses to it, my group also conducts basic research on various aspects of atmospheric chemistry. We are characterizing the chemical properties of small particles found in emissions

and known to be a potential health risk. We are determining how they change in the atmosphere—a prerequisite to understanding their impacts on human health. Our findings may also help to clarify how such particles interact with clouds and how they may affect the climate system, which is one of the major uncertainties in the current global climate debate.

The new LFEE is a natural setting for bringing together all the people and pieces of the Mexico City Program as well as other major MIT programs that address today's increasingly complex and multifaceted problems. At MIT, academic departments are naturally very powerful because they are at the core of the university's function. It is therefore important to have organizations like the LFEE that are orthogonal to the departmental setup. Through them, faculty with a common goal but different perspectives and knowledge can find one another and work together without worrying about their institutional affiliations. The LFEE is thus a framework for gathering MIT's wisdom and expertise to tackle complex challenges such as air pollution and climate change.

Transportation Systems: Pathways to Sustainability

John B. Heywood

Sun Jae Professor of Mechanical Engineering;
Director, Sloan Automotive Laboratory

Malcolm A. Weiss

Senior Research Staff, Laboratory for Energy
and the Environment

Our vast transportation systems provide us with lots of mobility, but they have serious drawbacks: they emit pollutants that degrade the air; they consume large amounts of petroleum-derived fuels; and they emit correspondingly large amounts of carbon dioxide. What research themes will members of the LFEE be focusing on to deal with those challenging problems?

We will be working hard to improve the performance of current transportation technology. Today's internal combustion engines can be improved significantly. Our studies will focus on critical processes such as engine friction (which has a big impact on efficiency), on combustion modifications that will improve driveability and emissions, and on ways to improve the total system performance of engines and their exhaust-catalyst-based emission controls. We will also be exploring how to improve gasoline and diesel fuels to help meet ever-stricter limits on air-pollutant emissions without degrading other aspects of engine operation. The total potential for improving fuels is substantial and can affect engine performance in the near term.



John B. Heywood

We will also be examining new internal combustion engine concepts that may improve engine efficiency and reduce emissions levels as well. One such concept uses a combustion process called homogeneous charge compression ignition (HCCI). In this process, a mixture of fuel vapor and air is compressed so that its temperature rises and it begins to burn spontaneously.



Malcolm A. Weiss

Since HCCI combustion starts via autoignition (rather than by a well-defined spark discharge or by the start of fuel injection, as in a diesel), much work needs to be done to assess whether such a combustion process can be adequately controlled in an engine on a vehicle.

A second promising new engine concept is a hydrogen-augmented gasoline-fueled spark-ignition engine that the Sloan Automotive Laboratory and Plasma Fusion Research Center at MIT are jointly developing. Key to the new engine is the plasmatron, a small on-board device that—aided by an electrical discharge—converts some of the gasoline into hydrogen-rich gas. Mixing small amounts of such gas with the gasoline flowing into the engine allows the engine to operate very “fuel-lean,” thus much cleaner and more efficiently.

More broadly, our engine and fuels specialists will continue to work together assessing hybrids, fuel cells, and other new technologies that may make possible larger reductions in

energy consumption and undesirable emissions including carbon dioxide. Results from our work will enable MIT to provide well-reasoned advice on how our society can start to deal with major environmental sustainability issues associated with transportation.

Buildings: Developing and Using Sustainable Approaches

Leon R. Glicksman

George Macomber Professor of Construction Management; Professor of Building Technology; Director, Building Technology Program

Buildings now consume more than a third of the total energy and half the total electricity used in the United States. Also, indoor air quality is an increasing concern. I believe that we can find ways to build buildings that consume substantially less energy than today’s do while providing improved air quality and good comfort—all at little or no increase in initial cost.

In the Building Technology Program, one of our goals is to improve existing sustainable technologies and encourage their more widespread use. For example, new building designs used in Europe maximize the use of natural ventilation, reducing or eliminating the need for air conditioning and providing better interior ventilation. Our assessments show that the same design philosophy could succeed in many types of buildings and many geographical areas in the United States. We’re developing innovative

designs and control systems for natural ventilation and examining more advanced ventilation approaches that can ensure cleaner air near building occupants. Other investigations focus on improving and implementing advanced window systems that control solar energy and insulation levels.

One problem with implementing sustainable practices is that architects do not have adequate simulation tools to guide them. Sophisticated simulation programs can predict the energy performance of a building, given details of its design and operation. But critical decisions are



Leon R. Glicksman

already made before those details are available. For example, an architect may wonder what happens to energy consumption or natural lighting if he turns his building to face south rather than west. We’re

developing a Web site that will enable architects to evaluate such choices quickly and easily before proceeding with a more detailed building design.

Building energy-efficient structures is a global challenge, so we work with collaborators in several countries. Our work with Chinese developers, Tsinghua University, and our partners in the Alliance for Global Sustainability (AGS)—University of Tokyo and the Swiss Federal Institutes of Technology at Zürich and Lausanne—has produced several large-scale building designs that demonstrate the advantages of sustainable practices. We are now planning collaborative programs with colleagues at Chalmers University of Technology in Sweden.

Both of those activities are part of the AGS. Through the Cambridge-MIT Institute, we are working with Cambridge University to develop sustainable designs for major commercial buildings in Europe.

Here at home, we are working toward making the MIT campus a model of good, sustainable practices attainable at a reasonable cost. Working with MIT's facilities department, we have retrofitted advanced ventilation systems in office spaces and are incorporating a natural ventilation system demonstration into a dormitory now under construction. In addition, we are preparing sustainable guidelines for architects and engineers to use as they develop plans for the MIT campus. These on-campus activities provide a valuable educational opportunity for MIT students, including undergraduates.

Overall, our program and activities fit well into the structure and goals of the new LFEE. Our work combines concern for energy and the environment (in our case, both outdoor and indoor). It is multidisciplinary, with technology and architectural design as well as economic and policy aspects. It has a strong international component. And it helps educate people—from students to working professionals—about sustainable approaches and how to put them into practice.

Assessing Strategies for a Sustainable Energy Future

Stephen R. Connors

Coordinator, Multidisciplinary Research, Laboratory for Energy and the Environment; Director, Analysis Group for Regional Electricity Alternatives

One of the greatest challenges concerning energy and the environment is society's ability to understand complex, long-term problems well enough



Stephen R. Connors

to identify and implement equally long-term, often dispersed solutions. It has long been recognized that "silver bullet" solutions to our energy and environmental problems do not exist. Robust solutions

must therefore be identified and implemented, usually over decades-long time frames. As such, the successful transition to a sustainable energy future can be thought of as an "infrastructure management" set of activities. Included is the management of not only the physical energy supply and consumption infrastructure but also the "knowledge infrastructure," in this case, knowledge of the environmental burdens associated with various energy alternatives and society's changing needs for energy services.

Recognizing those challenges, the LFEE is undertaking integrated assessments and other multidisciplinary research programs that develop this knowledge infrastructure both for ourselves and for our stakeholder audiences. Our research

uses a "scenario-based tradeoff analysis" approach to identify long-term, cost-effective emissions-reduction strategies. We are now applying the approach in two ongoing programs in the Alliance for Global Sustainability (AGS): the China Energy Technology Program and the Mexico City Integrated Assessment.

Working with Chinese and Mexican stakeholders, we use our tradeoff analysis approach to determine the comparative performance (emissions, cost, health, and ecological impacts) of various multi-option strategies. In the China project, life-cycle analysis is performed by our AGS colleagues in Switzerland to identify the full impacts of each strategy. The approach thus integrates scientific and institutional concerns and incorporates diverse disciplines. We define the strategies to be studied and assemble other information in close collaboration with local and regional decision makers in China and Mexico, thereby improving the chances that our analyses will actually help local energy and environmental efforts.

The China and Mexico projects are showing that addressing interactions between old technologies and new is critical to bringing down pollutant emissions in a cost-effective manner. One cannot simply focus on which new technologies to add to the system. Much of the environmental burden is associated with existing infrastructure components. Whether attempting to retire old power plants or swap old diesel trucks for new,

policy makers must deal with an existing infrastructure and many entrenched interests. Therefore, assessment of the technical, economic, and political feasibility of multi-option strategies is a fundamental aspect of our approach.

As the 21st century progresses, it is likely that the technologies with which we generate our electricity, cool and heat our houses, produce our goods, and move them from here to there will become as energy efficient as technically feasible. Therefore, to identify long-term solutions, we plan to expand our analyses to include an information technology component that permits “smart use” of technologies in addition to “efficient provision.” With such inherently distributed solutions, examining the role of the competitive marketplace in deploying these sustainable technologies will also be necessary.

If we are to move successfully to a sustainable energy future, we must assess our multi-option strategies well in advance, and we must undertake educational and outreach activities to encourage implementation of the “best” strategies. The LFEE is structured to tackle those very issues and to foster integration of work in different disciplines, both within MIT and with other leading research institutions, decision makers in government and industry, and the public.

Product Manufacture: Relating Cost to Environmental Effects

Joel P. Clark

Professor of Materials Systems; Center for Technology, Policy, and Industrial Development

Frank Field III

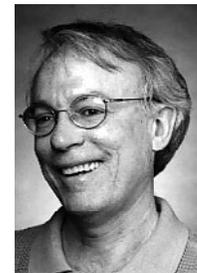
Senior Research Engineer, Center for Technology, Policy, and Industrial Development; Associate Director, Technology and Policy Program

The environmental impacts of a product over its lifetime—like many other attributes—are strongly influenced by the choices made in product development: design, material composition, and production method. Product developers are giving increased attention to the environmental effects of these early-stage choices. However, many efforts to characterize the environmental impacts of alternative product and process choices do not simultaneously consider the cost and the performance and other engineering implications of those choices, thereby limiting the decision-making utility of such analyses.

Our group, the Materials Systems Laboratory (MSL) in the Center for Technology, Policy, and Industrial Development, has been working to develop a systematic framework to integrate environmental, engineering, and economic analysis. Engineering models are routinely used to estimate the performance, processing, and, to a lesser extent, economic consequences of changes in products and their manufacture. Now we are extending those tools to allow analysts to construct a cost analysis concurrently with a “life-cycle inventory.” The focus of our effort is to ensure that a consistent cost analysis

can accompany the development of a life-cycle inventory (i.e., the volume of chemicals and other materials released and consumed during the lifetime of a product, from manufacture through use and disposal) through the use of published sources of environmental data.

Of course, developing a life-cycle emissions inventory is only the beginning of a credible environmental assessment of design or process alternatives. The key issue is the use of such data to evaluate the comparative merits of those alternatives without imposing gigantic environmental assessment tasks on product developers. Toward that end, we have been developing



Joel P. Clark



Frank Field III

“metrics”—standards of comparison—for interpreting the potential consequences of an emissions inventory, including effects on global climate, water quality, and human health.

In order to be able to make industrially useful comparisons, one must construct environmental metrics along with economic and engineering metrics such as manufacturing cost and product performance.

Using this approach, we reduce the large, diverse set of inventory data to a manageable collection of indicators that decision makers can use to compare strategic choices on a consistent basis. Moreover, the logic and methodology

used to derive each metric is transparent to users, increasing the credibility of the results and clarifying the interrelationships among the technological, economic, and environmental indicators of each strategy's performance.

Our current work is focused on the automotive industry. We have begun to build a framework for analyzing the impact of automotive design, manufacturing technology, and materials selection on (a) emissions to the air, land, and water; (b) energy and resource consumption; and (c) the cost of manufacturing, using, and disposing of (or recycling) specific automobiles. We are also beginning a series of case studies, including the temporal analysis of emissions of greenhouse gases from automobile fleets; investigation of the economic impacts of European automotive recycling regulations; and examination of the cost and environmental impacts of producing and using automobile bodies made from alternative materials.

Education Linking Science, Engineering, and Environmental Policy

Thomas W. Eagar

Thomas Lord Professor of Materials Science and Engineering; Co-Director, Program in Science, Technology, and Environmental Policy

Joanne M. Kauffman

Principal Research Scientist, Laboratory for Energy and the Environment; Co-Director, Program in Science, Technology, and Environmental Policy

Environmental regulation is at a crossroads. For decades, regulatory actions and standard-setting have involved command-and-control directives aimed at specific emission sources. Today, many analysts both within and external to government agree that more holistic approaches are needed to improve environmental performance. Yet there has been limited success in recent attempts to "reinvent" regulations to provide incentives for better performance. Progress toward sustainable development is being hindered by inefficiencies in command-and-control policies, fragmented regulations that shift risks from one source or medium to another, and a failure to focus public resources on the highest priority risks. Moreover, although most environmental regulations are by their nature science- and technology-intensive, many public officials and the public at large lack understanding of the role technology can and must play in solving environmental problems.

If those problems are going to be overcome in the future, we believe it is crucial that institutions like MIT have a voice in the policy arena and that our students be prepared to address



Thomas W. Eagar



Joanne M. Kauffman

environmental issues holistically—no matter where their careers take them. Thus, students will need a better understanding of the gap between technology and policy that pervades much of environmental decision-making and standard-setting today. Traditional engineers receive inadequate training in and exposure to policy, government, and the social sciences. Their views therefore may be underweighted in the process of formulating and promulgating regulations. Consequences for the environment and the manufacturer, obvious or discoverable to an engineer, too often are not even addressed in the decision-making process.

Motivated by those concerns and by a desire to contribute to the preparation of new engineering leaders, we have begun putting together a research-based program that will bridge the gap between engineering and the social and management sciences with a focus on environmental policy. The Program in Science, Technology, and Environmental Policy

(P-STEP) will provide masters and doctoral students with an opportunity to perform thesis work involving multifaceted analyses of specific regulatory issues and standards that exist or are being considered. Their research will be jointly supervised by engineering and social sciences faculty.

By understanding both technology and policy and how they interact, MIT graduates will be prepared to participate in the process of formulating and promulgating regulations and standards. As well-trained engineers, they will be able to analyze proposed regulations and standards and observe or discover consequences for the environment or for manufacturers that might not otherwise be recognized in the traditional policy-making process. When such results are made available to relevant decision makers in the policy arena, negative consequences may be avoided rather than corrected after standards are put in place—often a difficult and costly undertaking.

We believe that MIT is one of the most effective places to bring together teams of engineers, health specialists, economists, and political scientists to carry out multidisciplinary research to address critical environmental issues. The results of this research and the engagement of students in conducting it will contribute to the policy debate on these issues and simultaneously prepare the next generation of environmental leadership for government, industry, and society.

Political Economy and Technology Policy: Developing Responses to Environmental Problems

Kenneth A. Oye

Associate Professor of Political Science; Director, Political Economy and Technology Policy Group

By combining expertise on scientific and technical issues with expertise on problems of political economy, the Political Economy and Technology Policy Group—a joint program of the LFEE and the Center for International Studies—may help improve the quality of public and private responses to critical environmental problems.

In the coming years, government, the private sector, and nongovernmental organizations will face environmental issues marked by substantial and rising uncertainty, as summarized in the table below. Conventional wisdom supports two



Kenneth A. Oye

contradictory responses to environmental problems characterized by uncertainty. Some observers invoke the precautionary principle, arguing that because environmental and health consequences may be irreversible, delaying action to acquire information may mean waiting too long. Others take the existence of uncertainty as a justification for not

SOME SOURCES OF UNCERTAINTY IN ENVIRONMENTAL DECISION-MAKING

Type of Uncertainty	Source of Uncertainty	Examples of Issues Affected by Source of Uncertainty
Uncertainty over environmental and health risks	Emerging technologies with hard-to-assess risks	Nuclear fission in 1945 GMO certification in 2001
	Complex environmental effects of technology	Greenhouse gases => climate change
	Low-dose exposure with possible long latency periods	Pesticide residues => long-term health effects
Uncertainty over the efficacy and costs of ways of reducing risks	Technologies for reduction of risks	Efficacy of three-way catalysts and sensors reduced by sulfur in fuel
	Substitution of inputs and products	Costs of emission controls => slower auto fleet turnover
	Effects of policy on firms/sectors/nations	Effect of fuel standards on refiner margins and capacity
Uncertainty over unintended effects of actions to reduce risks	Unanticipated side costs	MTBE => water quality degradation
	Complex interaction effects	NO _x reduction => ozone elevation (weekend effect)
	Unanticipated side benefits	Sulfur cuts to reduce acid rain => unexpected health benefits

acting, arguing that because policies tend to lock into place, acting on precaution may entail living with substantial continuing costs of inappropriate policies. In fact, conflict over environmental policy is most pronounced in situations with unproven but potentially irreversible cumulative risks and unproven but potentially irreversible responses to risks.

The structure of the LFEE will help improve the quality of decision-making on environmental problems by fostering research and outreach in several directions.

First, LFEE research seeks to improve the quality of initial public decision-making in areas marked by uncertainty. With scientists assessing environmental and health risks, engineers developing technologies that may reduce or increase risks, and social scientists seeking to improve the performance of economic markets and political institutions, the LFEE is well positioned to identify gaps in knowledge, to engage in integrated appraisals of policy options, and to credibly assess risks in areas of controversy.

Second, LFEE research seeks to improve the capacity of political institutions to adapt to new information. Under conditions of uncertainty, initial policies will be in error. The key is to modify initial decisions as information emerges concerning unintended side costs and benefits, complex interaction effects, or unexpected risk-reduction options. The LFEE is well positioned to suggest ways of developing incentives for regulators and legislators to acquire information in key areas of uncertainty and to respond to information by improving policies.

Third, LFEE research seeks to assess the private effects of public environmental policies,

with specific attention to the competitive position of firms, sectors, and nations. The Political Economy and Technology Policy Group is launching a study of links among regulation, the utilization of technologies, and industrial structure. The group of engineers and social scientists will begin with sectoral studies on automobiles and fuels, food processing, pharmaceuticals, and pulp and paper. A particular focus will be on ways that public environmental policies may redistribute or contain private business risks associated with technological, financial, and market uncertainty.

Sustainable Development and International Environmental Policy

Joanne M. Kauffman

Principal Research Scientist, Laboratory for Energy and the Environment; Lecturer, Department of Political Science; Coordinator, Alliance for Global Sustainability

Sustainable development and international environmental policy are closely linked. Development that leads to improved quality of life is supported by robust environmental policies that protect the environment without compromising the capacity to create economic well-being. Although the concept of sustainability is inherently vague, it can nevertheless help guide the creation of such robust policies. To foster sustainability, we need to redefine “development” to bring environmental and social concerns into the sphere of economic planning and policy-making at all levels.

Academic institutions, especially those that specialize in science and engineering, have an important role to play in identifying emerging environmental and economic problems and in conceptualizing and articulating methodologies and policies for responding to them. Scientific research can help us understand pressures that activities today are putting on natural ecosystems. Engineering studies can clarify our understanding of existing technologies and of trajectories for new technology development. The combined results can help guide technological innovation and deployment—an important key to putting mankind on a more sustainable path.

In the LFEE, we are working to foster sustainability by taking a new approach to understanding environmental challenges and their relationship to sustainable development. That approach requires a balancing of scientific and technological factors with economic considerations and a set of predominantly social issues including equity, governance, communications, and human behavior. Accordingly, we support a systems approach that takes account of multiple dimensions of a problem and options for its solution.

We also recognize that many if not most of today’s environmental and sustainability issues are international and even global in scope. Dealing with them poses significant challenges to governments and multinational industry alike. The key is finding ways to better align government policies and industry interests to support sustainable global development.

These concerns suggest a set of important questions that LFEE-based research in collaboration with our international partners in the Alliance for Global Sustainability (AGS) can address. Examples include the following:

- What are the strengths and weaknesses of current methodologies used for incorporating scientific and technological knowledge into the decision-making process, and how might they be improved? While it is generally understood that global markets today are increasingly subject to the provision and deployment of such knowledge through international supply chains, means of accelerating the transformation of that knowledge into sustainable productivity are poorly understood.
- What are the means and effective mechanisms by which knowledge for sustainable development can be captured and shared within firms, between academic scholars and firms, and across geographical and cultural borders?
- What are the barriers and constraints to the use of such knowledge, and what is the role of innovation in the information technology and communications sectors in overcoming them?
- What are the economic, institutional, and political constraints to the deployment of robust environmental policies that emerge from our research?
- How do policies to promote sustainable development in specific sectors—such as energy or mobility—affect the strategies of relevant firms, nongovernmental organizations, and others under conditions of uncertainty?

Developing methods and means to address those questions is a central activity of the LFEE and its AGS partners in academia, industry, government, and civil society around the world. The AGS has supported more than 60 multidisciplinary international research projects involving hundreds of faculty and graduate students. In addition, international educational

opportunities supported by the AGS are building an international network of knowledgeable and committed young leaders in developed and developing countries alike. Through this and other international partnerships, the LFEE is bringing a global perspective to all our efforts and helping to create a new network of environmental leaders throughout the world.

Designing Competitive Markets for Electricity and Emissions Trading

A. Denny Ellerman

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Increasing reliance on competitive markets in industries that were previously heavily regulated has become a characteristic of our times.



A. Denny Ellerman

The Center for Energy and Environmental Policy Research (CEEPR) focuses its research on understanding the markets that are created in this process, in particular, markets for electricity

and for emission rights.

In the past, regulatory or administrative procedures determined investment in electricity-generating capacity and the provision of electricity and related services to customers. Current efforts to restructure the electric utility industry aim to increase the role of markets in accomplishing those tasks. In effect, markets for electricity are being created where none existed before,

and we have little practical knowledge of how those markets will operate. Yet the performance of those new markets is key to providing the cheaper but equivalent services that many observers presume will result from restructuring. Using its own funds and a recent three-year grant from the Cambridge-MIT Institute, CEEPR will continue to evaluate how the markets being created for electricity and for related transmission and ancillary services around the world have performed thus far. Insights gained should help regulators, participants, and policy makers to make better decisions in restructuring the electric utility industry.

The process of restructuring environmental regulation through the use of market-based instruments such as emissions trading is not so far along, but a few examples are available for study. Two multiyear grants from the US Environmental Protection Agency will allow CEEPR to continue studies concerning the US Acid Rain Program, which imposed a cap on total sulfur dioxide emissions in the United States and permits the trading of rights to emit sulfur dioxide among electric utilities. As in the case of electricity, a market has been constructed where none existed before; and to many observers' surprise, it has worked. The Acid Rain Program has become the exemplar in the United States—and increasingly abroad—for addressing new environmental problems, whether they pertain to conventional pollutants or to greenhouse gases. CEEPR's studies of this market seek to explain how it works and how applicable it is for addressing other environmental problems.

How markets function is closely related to how the goods being traded are produced. As a result, any complete understanding of electricity or emissions markets requires a solid grounding in the underlying production technologies. Thus, restructuring electricity and environmental regulation requires not only an understanding of the historical precedents in electric utility and environmental regulation but also a sound appreciation of the scientific, engineering, and economic considerations unique to each of those markets. The new LFEE will facilitate the integration of these several perspectives.

Designing the Competitive Electric Power Industry from the Wires Up

Marija Ilić

Senior Research Scientist, Department of Electrical Engineering and Computer Science

The electric power industry has entered uncharted territory. It is transforming from a fully regulated monopoly to a competitive structure in which electricity is treated as a traded commodity. Thus



Marija Ilić

far, this transformation has not been smooth. The ownership and operational responsibilities are changing, but the fundamental physics of power systems operation has not. It is becoming increasingly clear that changing the design of the industry will be necessary to meet the requirements of

both the physics of power generation and delivery and the competitive market. Moving forward will require major reassessment and redesign of interactions among the economic, engineering, and regulatory processes that run the industry.

In the Competitive Power Systems Group (CPSG), we view these times as both exciting and overwhelming. We recognize that electric power systems are among the most complex man-made systems in existence and as such offer a test bed for a variety of theoretical breakthroughs in systems theory, control, operations research, computer science, economics, and so on. At the same time, we feel an urgent sense of responsibility for coming up with innovative industry designs essential to the successful transition to the new industry paradigms.

During the past five years, the CPSG has performed extensive systematic modeling and analysis of operations and planning in the electric power industry under the new regulatory environment (see *e-lab*, January–March 2001). Our published findings have predicted several major issues and problems that have been experienced by the industry, in particular, the volatile prices and rolling blackouts in California.

Based on our findings, we are convinced that much work is needed to design and implement truly open, competitive electric power markets. In such markets, the penetration of a new technology must be directly driven by the value that that technology provides, whether by generating electricity or implementing customer choice or permitting flexible delivery of electricity. Of critical importance is the ability of customers to select prices linked to quality of service (e.g., reliability, voltage, and frequency specifications), price volatility, and/or environmental perfor-

mance. To be successful in the long run, the restructured industry will need new engineering and economic concepts and software that are capable of transmitting price information and implementing variable levels of service.

In the current industry climate, no one seems to fully recognize this challenge. Even more striking, none of the top universities in the country has taken a leadership role by nurturing the multidisciplinary education and research required for this work.

The LFEE is in a unique position to pull together the wide-ranging intellectual capability and financial support needed to move MIT into this leadership role. MIT has the resources to tackle the problem: it has world-class electric power engineers, economists, financial engineers, policy analysts, and computer experts. However, the problems the industry faces are beyond anyone's single expertise. Only teams in which individual knowledge is complemented and synergies are built have potential for success.

We in the LFEE need a vision of how we can create an exciting, supportive environment in which such teams can assemble and develop creative concepts and solutions for the electric power industry. We then need to communicate our vision across MIT and to key sponsors. The undertaking will require major commitments from all involved, but it will be both challenging and rewarding to help rebuild and revitalize the electric power industry for the 21st century.

Renewable and Alternative Energy Supply Technologies

Jefferson W. Tester

Herman P. Meissner Professor of Chemical Engineering

Environmental concerns and energy security issues are motivating a growing interest in the development and deployment of alternatives to fossil fuels. Among the options for generating electricity and heat are renewable sources such as direct solar, wind, hydro, biomass, and geothermal. Options for transportation use include using cleaner-burning fuels—for example, hydrogen and biodiesel produced from renewable energy sources—that produce lower emissions of particulates, nitrogen oxides, sulfur oxides, hydrocarbons, and carbon dioxide. Such renewable energy technologies will be able to penetrate international energy markets only if they offer high performance in both a technical and economic sense. Favorable policies that promote larger-scale manufacture and deployment and provide credit for the favorable environmental attributes of renewable energy systems will accelerate this transition. Such policies will



Jefferson W. Tester

reduce the costs of renewable systems so that they can compete with conventional coal, gas, and oil—fuels that for the near term are in good supply and reasonably inexpensive.

Considerable expertise exists among LFEE faculty and research staff to improve specific alternative energy technologies, to provide in-depth analyses of evolving energy options, and to perform integrated energy assessment across many disciplines. MIT has the capacity to provide enabling technologies that could significantly improve the performance and lower the cost of alternative technologies. For example, one of the major barriers to widespread deployment of geothermal heat-mining technologies is the high cost of drilling wells. Drilling costs escalate exponentially rather than linearly with depth, so the cost barrier can be quite severe, especially in the eastern United States, where deposits are low-grade and deep wells are necessary to attain commercially useful energy for generating electricity. My LFEE colleagues and I are studying advanced drilling concepts using rock fusion and spallation methods. If successful, such methods could change the cost-depth relationship from exponential to linear, making development costs for geothermal energy in low-grade areas commercially competitive.

Research in the area of bioenergy could bring about fundamental improvements in our ability to convert biomass into useful fuels. Modern metabolic engineering and genomics methodologies are now being successfully applied elsewhere at MIT in the health and agricultural areas. Those methodologies could also lead to new, more efficient methods of using biomass to synthesize clean biofuels and

other important chemicals that have traditionally been derived from petroleum feedstocks. The impacts of such enabling technologies would be substantial in the United States as well as in many developing countries.

Other opportunities exist in the area of materials science. MIT teams have developed methods of designing materials at a molecular level and then scaling them up to produce bulk materials that can be fabricated into energy-related devices. In one notable example, researchers have developed advanced polymers and used them to fabricate a lithium-ion polymer battery that has both high efficiency and structural flexibility. A similar approach to materials development could yield high-performance photovoltaic cells that convert a larger fraction of the sun's photon energy to electricity than is possible today. This approach could also lead to more efficient fuel cells that convert the chemical energy stored in hydrocarbons directly to electricity, making unnecessary the energy-consuming intermediate step of chemically reforming the hydrocarbon to hydrogen.

Members of the LFEE have also demonstrated an unusual capacity for conducting quantitative energy technology assessment and modeling, including properly accounting for life-cycle effects and developmental uncertainties. Such multidisciplinary work connects well to more focused energy technology research by providing both context and a means of evaluating new ideas at an early stage of their development.

Fuels and Energy Conversion, Environmental Technology, and Clean Chemical Processing

William A. Peters

Principal Research Engineer, Laboratory for Energy and the Environment

A major challenge facing today's energy sector is how to maintain and broaden the economic prosperity made possible by abundant and



William A. Peters

affordable energy while protecting the environment from present and future harm. My research goals are to help create technically viable, publicly acceptable solutions to this problem by providing

new scientific and engineering understanding of chemical processes to enable "sustainable" use of energy and energy-intensive substances such as mineral ores, water, and chemicals.

By sustainable, I mean practices that responsibly utilize, conserve, recycle, or substitute raw materials, products, wastes, and technologies so as to preserve and extend economic progress and protect the environment now and in the future.

My work is about making sustainable development practical. Thus, I seek to understand the benefits and shortcomings of existing process technologies and to discover new products and

processes that are more economical, less polluting, and more efficient in energy and raw materials use. For example, I am interested in production of clean fuels such as hydrogen and diesel liquids from biomass and fossil resources (coal, natural gas, heavy oil); decontamination or recycle of polluted soils, water, and wastes; and environmentally friendly synthesis of metals, chemicals, and materials.

My approach is to identify and understand factors that determine how well a process performs and whether it emits significant quantities of adverse by-products. Small-scale experiments simulate existing technology (for example, solid fuel combustion) or a potential new process (for example, electrical recycle of pulping chemicals and organic waste from paper making) to learn how fast and how completely substances undergo desired as well as unwanted chemical and physical changes. I collaborate with analytical chemists and toxicologists to determine the chemical composition and potential human health impacts of process effluents, and I study special mathematical tools (probability density functions) to simplify simulations of chemical reaction rates.

I am especially interested in learning how to use diverse chemical environments for sustainable processing. Examples are high-temperature mixtures of gases and solids for fuel decontamination, "reengineered" water (modestly heated but appreciably compressed H₂O) for waste destruction and products synthesis, liquids bombarded with ultrasound to

create a mosaic of cavities that stimulate useful chemical reactions, and controlled electrical discharges (harnessing lightning in a test tube) for producing fuels and metals. The last two provide process energy electrically and thus from non-greenhouse sources (e.g., nuclear, solar, geothermal), if desired.

My research contributes to the LFEE's research mission by providing new understanding to enable sustainable processing of natural and anthropogenic resources such as fuels, chemicals, mineral ores, water, and wastes. My work also generates information applicable in LFEE assessments of alternative energy technologies and policies. In support of the LFEE's educational program, several colleagues and I are writing a textbook and teaching a graduate course called "Sustainable Energy."

Advanced Nuclear Energy Systems: An Agenda for the 21st Century

Mujid S. Kazimi

TEPCO Professor of Nuclear Engineering;
Director, Center for Advanced Nuclear Energy
Systems

Fulfilling the world's growing need for new electric generation capacity in the 21st century is a significant challenge, especially given the concerns about climate change. I believe that



Mujid S. Kazimi

nuclear energy can play an important role in meeting that need and in helping us move toward a sustainable energy future. In particular, using nuclear power plants in place of fossil-fuel-fired plants will

reduce future atmospheric emissions of airborne particulates and greenhouse gases and will ease the increasing pressure now evident in the United States to find new sources of fossil fuels. Already nuclear plants provide nearly 18% of the world's electricity, and the reliability and safety of those plants have improved significantly in recent years. As a result, the public attitude toward nuclear energy has become more positive.

What will it take for nuclear energy to fulfill its promise as an energy supply option worldwide? We will need new nuclear plant technology options that enhance safety, reduce spent-fuel production, reduce the cost of building new

plants, and provide intelligent ways to perform more efficiently plant operations and their regulation. The potential for achieving such advances is enormous. After all, the current nuclear plants were mostly designed two decades ago. Since that time, revolutionary changes have occurred in materials and in remote sensing and information technology, and we have learned important lessons from operating and regulating existing reactors.

In the Center for Advanced Nuclear Energy Systems (CANES), we are undertaking research on several fronts. To enhance the reliability of existing nuclear power plants, we are developing improved methods for determining leading indicators of plant performance and for scheduling plant upgrades and maintenance. We are trying to reduce the amount of spent fuel that must be stored and disposed of by finding economic ways to extract more energy from the nuclear fuel. One of our boldest ideas in this regard is to replace today's cylindrical fuel pins with annular (ring-shaped) pins that are internally cooled. The new fuel will run at higher power density but much lower temperatures so it will be able to increase plant safety while reducing total waste. We have also been examining the possibility of using thorium as well as uranium as fuel—a change that would expand the resources available for energy production and reduce the plutonium content of the spent fuel, thereby reducing weapons-proliferation concerns.

In the longer term, more dramatic expansion of nuclear power use will be possible with advanced nuclear reactors and fuel cycles. Of particular interest to CANES researchers is the helium-cooled pebble-bed reactor. If properly

designed and operated and limited to a small size (about 100 MWe), such a reactor has excellent safety features. If its coolant is lost, the plant shuts down automatically and dissipates its stored heat without engineered safety systems. When mass produced and coupled with a high-efficiency gas turbine, this small reactor could become economically viable and an attractive non-fossil option for developing nations seeking to build electric grids.

In the future, nuclear power plants may have to produce not only electricity but also transportation fuels such as hydrogen. The use of nuclear energy for such industrial applications will require high-temperature working fluids. An exciting idea is the use of a power cycle that involves gas turbines driven by supercritical carbon dioxide—a cycle with high power efficiency at low enough temperatures to enable us to use more conventional structural materials than are possible with helium.

Finally, we are performing assessments of current and proposed nuclear options, including their technical, economic, and environmental implications within national and global contexts. We will share our evaluations with nuclear engineers, energy professionals, and national and international policy makers so that they can make informed decisions about future energy choices.

Carbon Capture and Sequestration: One Approach to Protecting Our Climate

Howard J. Herzog

Principal Research Engineer, Laboratory for Energy and the Environment

Developing strategies, technologies, and policies to address global climate change concerns will be a major challenge for many years to come. The solution does not lie with a single strategy or technology but with a range of options,



Howard J. Herzog

including improved efficiency, increased use of low- or no-carbon fuels, and carbon sequestration. The LFEE has projects in all these areas, but my primary focus is on carbon capture from large stationary sources with subsequent sequestration in geologic formations or the deep ocean.

The MIT Energy Laboratory was one of the first research organizations to look seriously at the carbon sequestration option. During the past 10 years, we have worked closely with the US Department of Energy (DOE) to build a foundation for a major research effort in this area. The DOE budgets for carbon capture and sequestration have grown from near zero to more than \$40 million annually, and they are still growing. It was gratifying to hear

President Bush say in a speech on June 11, 2001, “We believe all technology offers great promise to reduce emissions, especially carbon capture, storage, and sequestration technologies.”

Research into carbon capture and sequestration technologies requires multidisciplinary teams—a cornerstone of the LFEE approach. I work with civil, chemical, and materials engineers, chemists, oceanographers, atmospheric chemists, geologists, economists, and political scientists. We are also starting to work closely with industry, which has growing interest in potential opportunities provided by carbon sequestration.

As we move forward, we face three major challenges. First is cost. While carbon capture is feasible today, large-scale implementation could cost \$250–300 per tonne of carbon avoided (about \$75 per tonne of carbon dioxide avoided). While some may consider this acceptable, many feel that significant (50–75%) cost reductions are required. The second challenge is to demonstrate that various reservoirs—depleted oil and gas wells, unmineable coal seams, deep brine formations, the deep ocean—are safe, effective, and environmentally sound. Finally, we must work with social scientists to assure that the technology we develop will be accepted by the public.

With increased research support and interest, I see research efforts in this area expanding from theoretical and laboratory studies to field experiments and large-scale demonstrations. Carrying out those efforts will require large projects involving increasing numbers of collaborating sponsors and participants. I foresee that research into carbon capture and sequestration technologies will continue to be as challenging and as gratifying in the coming decade as it has been during the past decade.

Publications

The following publications covering Laboratory for Energy and the Environment (LFEE) and related research became available during the past period. Center for Advanced Nuclear Energy Systems (CANES) reports are available from Michael Messina, MIT Department of Nuclear Engineering, Room 24-215, Cambridge, MA 02139-4307 (tel.: 617-253-7407). MIT theses may be ordered from the Libraries Document Services, MIT, Room 14-0551, Cambridge, MA 02139-4307. Other publications may be ordered from LFEE Publications, MIT, Room E40-473, Cambridge, MA 02139-4307 only if a price is assigned and only if prepaid by check payable to "MIT Laboratory for Energy and the Environment." Prices are postpaid surface mail. For air delivery, add 15% to US, Canada, and Mexico, and 30% elsewhere. A list of publications is available on request.

Publications marked by an asterisk (*) can be found or are forthcoming on-line via the following addresses:

Laboratory for Energy and the Environment:

<http://lfee.mit.edu>

Energy Laboratory:

<http://web.mit.edu/energylab/www/>

Center for Energy and Environmental Policy Research:

<http://web.mit.edu/ceepr/www/>

Joint Program on the Science and Policy of Global Change:

<http://web.mit.edu/globalchange/www/>

Instructions for ordering paper copies of the reports and working papers are also available at the above listed sites or by telephoning 617-258-0307 for LFEE and Energy Laboratory publications, 617-253-3551 for Center publications, and 617-253-7492 for Joint Program publications.

Reports and Working Papers

Babiker, M., L. Viguier, J. Reilly, A. Ellerman, and P. Criqui. *The Welfare Costs of Hybrid Carbon Policies in the European Union*. Joint Program on the Science and Policy of Global Change Report No. 74. 22 pages. June 2001.*

Ballinger, R., J. Lim, and M. Kazimi. *A Review of US Research Activities on Material Compatibility Issues in Nuclear Systems Using Heavy Liquid-Metal Coolant and Needs for Improved Materials*. CANES Report No. MIT-ANP-TR-080. 45 pages. July 2001.

Buongiorno, J., N. Todreas, M. Kazimi, and K. Czerwinski. *Conceptual Design of a Lead-Bismuth Cooled Fast Reactor with In-Vessel Direct-Contact Steam Generation*. CANES Report No. MIT-ANP-TR-079. 351 pages. March 2001.

Dostal, V., N. Todreas, P. Hejzlar, and M. Kazimi. *Plant Design and Cost Assessment of a Forced Circulation Lead-Bismuth Cooled Reactor with Conventional Power Conversion Cycles*. CANES Report No. MIT-ANP-TR-082. 93 pages. September 2001.

Ellerman, A., and N. Tsukada. *CO₂ Abatement by Multi-fueled Electric Utilities: An Analysis Based on Japanese Data*. Joint Program on the Science and Policy of Global Change Report No. 76. 32 pages. July 2001.*

Forest, C., P. Stone, A. Sokolov, M. Allen, and M. Webster. *Quantifying Uncertainties in Climate System Properties using Recent Climate Observation*. Joint Program on the Science and Policy of Global Change Report No. 78. 16 pages. July 2001.*

Fullerton, D., and G. Metcalf. *Cap and Trade Policies in the Presence of Monopoly and Distortionary Taxation*. Joint Program on the Science and Policy of Global Change Report No. 72. 20 pages. March 2001.*

Hejzlar, P., N. Todreas, M. Kazimi, and M. Driscoll. *Evaluation of a Once-Through Lead-Bismuth-Cooled Reactor Concept*. CANES Report No. MIT-ANP-TR-081. 46 pages. September 2001.

Holian, G., A. Sokolov, and R. Prinn. *Uncertainty in Atmospheric CO₂ Predictions from a Parametric Uncertainty Analysis of a Global Ocean Carbon Cycle Model*. Joint Program on the Science and Policy of Global Change Report No. 80. 25 pages. September 2001.*

Hori, T. *Creating the Wholesale Market for Electricity in Japan: What Should Japan Learn from Major Markets in the United States and Europe?* Center for Energy and Environmental Policy Research Working Paper No. MIT-CEEPR 2001-005WP. 59 pages. July 2001.*

Hu, L.-W., K. Nagasawa, P. Hejzlar, and M. Kazimi. *Thermal Striping in LWR Piping Systems*. CANES Report No. MIT-NSP-TR-007. August 2001.

Joskow, P. *California's Electricity Crisis*. Center for Energy and Environmental Policy Research Working Paper No. MIT-CEEPR 2001-006WP. 56 pages. July 2001.*

Joskow, P. *US Energy Policy During the 1990s*. Center for Energy and Environmental Policy Research Working Paper No. MIT-CEEPR 2001-004WP. 105 pages. July 2001.*

Kamenkovich, I., A. Sokolov, and P. Stone. *Feedbacks Affecting the Response of the Thermohaline Circulation to Increasing CO₂. A Study with a Model of Intermediate Complexity*. Joint Program on the Science and Policy of Global Change Report No. 75. 21 pages. July 2001.*

Montero, J.-P. *Multipollutant Markets*. Center for Energy and Environmental Policy Research Working Paper No. MIT-CEEPR 2001-008WP. September 2001.*

Oggianu, S., K. Hansen, and M. Kazimi. *Modeling the Dynamic Complexity of the Nuclear Policymaking Process and System: The High Level Nuclear Waste Issue*. CANES Report No. MIT-NFC-TR-033. 101 pages. August 2001.

NEW AND RENEWED PROJECTS, APRIL – SEPTEMBER 2001

Topic	Donor or Sponsor	Investigators (Department)
GIFTS AND CONTRIBUTIONS		
Alliance for Global Sustainability	Avina Foundation; E.I. DuPont DeNemours & Co.	
Center for Energy and Environmental Policy Research (CEEPR) membership	BP Amoco; Hidroelectrica del Cantabrico Foundation; Mannheimer Versorgungs Verkehrsge MBH; Saudi Aramco Services Co.; Swiss Reinsurance Co.	
Sloan Automotive Laboratory (for Fuels and Emission Research)	Cosmo Research Institute	V. Wong (Laboratory for Energy and the Environment)
Martin Fellowships	Martin Foundation Inc.	
NEW PROJECTS		
Energy Price Dynamics and Environmental Policy	CEEPR	R. Pindyck (Sloan School of Management)
Stabilization Funds, Simple Rules, and Fungibility	CEEPR	R. Rigobon (Sloan School of Management)
Electric Utility Restructuring	CEEPR	P. Joskow (Economics)
To Study Feasibility of Proposal on Risk Management in Energy Corporations	CEEPR	S. Kothari (Sloan School of Management)
Multigas Contributors to Global Change	The Pew Center for Global Climate Change	J. Reilly (Laboratory for Energy and the Environment)
Natural Ventilation, Solar Heating, and Integrated Low-Energy Building Design	Cambridge-MIT Institute	L. Glicksman (Architecture and Mechanical Engineering)

Oggianu, S., H. No, and M. Kazimi. *High Burnup Fuels for Advanced Nuclear Reactors*. CANES Report No. MIT-NFC-TR-029. 161 pages. May 2001.

Pindyck, R. *Dynamics of Commodity Spot and Futures Markets: A Primer*. Center for Energy and Environmental Policy Research Working Paper No. MIT-CEEPR 2001-002WP. 38 pages. May 2001.*

Pindyck, R. *Optimal Timing Problems in Environmental Economics*. Center for Energy and Environmental Policy Research Working Paper No. MIT-CEEPR 2001-001WP. 29 pages. March 2001.*

Pindyck, R. *Volatility and Commodity Price Dynamics*. Center for Energy and Environmental Policy Research Working Paper No. MIT-CEEPR 2001-007WP. 39 pages. August 2001.*

Reilly, J., M. Babiker, and M. Mayer. *Comparing Greenhouse Gases*. Joint Program on the Science and Policy of Global Change Report No. 77. 20 pages. July 2001.*

Sobeski, R., K. Hansen, and M. Kazimi. *Modeling the Dynamic Complexity of the Nuclear Energy Policymaking Process: The Nuclear Proliferation Issue*. CANES Report No. MIT-NFC-TR-030. 72 pages. June 2001.

Sweeting, A. *The Effect of Falling Market Concentration on Prices, Generator Behaviour and Productive Efficiency in the England and Wales Electricity Market*. Center for Energy and Environmental Policy Research Working Paper No. MIT-CEEPR 2001-003WP. 51 pages. May 2001.*

Visudhiphan, P., P. Skantze, and M. Ilić. *Dynamic Investment in Electricity Markets and Its Impact on System Reliability*. Energy Laboratory Working Paper No. MIT-EL 01-012WP. 22 pages. July 2001.*

Webster M., M. Babiker, M. Mayer, J. Reilly, J. Harnisch, R. Hyman, M. Sarofim, and C. Wang. *Uncertainty in Emissions Projections for Climate Models*. Joint Program on the Science and Policy of Global Change Report No. 79. 29 pages. August 2001.*

Xu, Z., M. Driscoll, and M. Kazimi. *Systematic Study of Moderation Effects on UO₂ Fueled Lattices*. CANES Report No. MIT-NFC-TR-028. 63 pages. May 2001.

Yoon, Y., and M. Ilić. *A Possible Notion of Short-Term Value-Based Reliability*. Energy Laboratory Working Paper No. MIT-EL 01-013WP. 18 pages. August 2001.*

Zhao, X., M. Driscoll, and M. Kazimi. *Micro-Heterogeneous Thorium Based Fuel Concepts for Pressurized Water Reactors*. CANES Report No. MIT-NFC-TR-031. August 2001.

NEW AND RENEWED PROJECTS, CONTINUED

Topic	Donor or Sponsor	Investigators (Department)
RENEWED PROJECTS		
Engine and Fuels Research Consortium	Exxon Mobil Research and Engineering Corp.	J. Heywood (Mechanical Engineering)
International Collaboration on CO ₂ Sequestration	US Department of Energy	H. Herzog (Laboratory for Energy and the Environment)
CO ₂ Capture and Sequestration	Electric Power Research Institute; Peabody Energy	H. Herzog (Laboratory for Energy and the Environment)
Technology Assessment of Fuels and Propulsion Systems for Road Transportation	Exxon Mobil Corp.; Norsk Hydro AS	M. Weiss (Laboratory for Energy and the Environment) J. Heywood (Mechanical Engineering)

Other Publications

- Adams, E. *Evaluation of Tracers for Use in the International Field Experiment on CO₂ Ocean Sequestration*. Presented at First National Conference on Carbon Sequestration, Washington, DC, May 14–17, 2001. 9 pages. \$10.00
- AuYeung, F., J. Heywood, and A. Schafer. *Future Light-Duty Vehicles: Predicting their Fuel Consumption and Carbon-Reduction Potential*. SAE Paper No. 2001-01-1081. Presented at the Society of Automotive Engineers 2001 World Congress, Detroit, Michigan, March 5–8, 2001. Ordering instructions at <<http://www.sae.org>>.
- Barker, J. *Planning for Economically and Environmentally Sound Electricity Service in Shandong Province, China*. MCP thesis. MIT Department of Urban Studies and Planning. June 2001.
- Buongiorno, J., N. Todreas, and M. Kazimi. *Thermal Design of a Lead-Bismuth Cooled Fast Reactor with In-Vessel Direct-Contact Steam Generation*. Forthcoming in *Proceedings of ICONE 9*, Nice, France, April 8–12, 2001. 12 pages. \$10.00
- Buongiorno, J., N. Todreas, and M. Kazimi. "Void fraction prediction for the Pb-Bi/water direct contact nuclear reactor." In *Proceedings of ICONE 8*, Baltimore, Maryland, April 2–6, 2000. American Society of Mechanical Engineers. 2000.
- Caldeira, K., H. Herzog, and M. Wickett. *Predicting and Evaluating the Effectiveness of Ocean Carbon Sequestration by Direct Injection*. Presented at the First National Conference on Carbon Sequestration, Washington, DC, May 14–17, 2001. Available as PDF on the Web at <<http://web.mit.edu/energylab/www/hjherzog/publications.html>>.
- Chisholm, S. "Stirring times in the Southern Ocean." *Nature*, v. 407, pp. 685–687, 12 October 2000.
- Driscoll, M., and P. Hejzlar. "A negative reactivity feedback device for actinide burner cores." *Transactions of the American Nuclear Society*, v. 84, pp. 241–242, June 2001.
- Ellerman, A. "Le defi europeen: Issues in the implementation of greenhouse gas emissions trading in Europe." *Revue de l'Energie*, no. 524, pp. 105–110, February 2001.
- Ellerman, A. "The US SO₂ allowance trading program." *Revue de l'Energie*, no. 527, pp. 315–320, June 2001.
- Ellerman, A., T. Stoker, and E. Berndt. "Sources of productivity growth in the American coal industry: 1972–95." In *New Developments in Productivity Analysis*, C. Hulten, E. Dean, and M. Harper, eds., v. 63 of *Studies in Income and Wealth*, pp. 373–418, 2001.
- Hallgren, B., and J. Heywood. *Effects of Oxygenated Fuels on DI Diesel Combustion and Emissions*. SAE Paper No. 2001-01-0648. Presented at the Society of Automotive Engineers 2001 World Congress, Detroit, Michigan, March 5–8, 2001. Ordering instructions at <<http://www.sae.org>>.
- Hejzlar, P., M. Driscoll, M. Kazimi, and N. Todreas. *Minor Actinide Burning in Dedicated Lead-Bismuth Cooled Fast Reactors*. Forthcoming in *Proceedings of ICONE 9*, Nice, France, April 8–12, 2001. 12 pages. \$10.00
- Herzog, H. "What future for carbon capture and sequestration?" *Environmental Science and Technology*, v. 35, no. 7, pp. 148A–153A, April 1, 2001.
- Herzog, H., K. Caldeira, and E. Adams. "Carbon sequestration via direct injection." In *Encyclopedia of Ocean Sciences*, J. Steele, S. Thorpe, and K. Turekian, eds. London: Academic Press, pp. 408–414, September 2001. Available as PDF on the Web at <<http://web.mit.edu/energylab/www/hjherzog/publications.html>>.

Jacoby, H., and D. Reiner. "Getting climate policy on track after The Hague." *International Affairs*, v. 77, no. 2, pp. 297–312, April 2001.

Joskow, P. *Statement before the US Senate Committee on Governmental Affairs*, June 13, 2001. Center for Energy and Environmental Policy Research Reprint Series No. 154, 15 pages, 2001.*

Joskow, P., and J. Tirole. "Transmission rights and market power on electric power networks." *RAND Journal of Economics*, v. 31, no. 3, Autumn 2000.

Kim, D., M. Kazimi, M. Driscoll, and N. Todreas. *The Economics of Transmutation Fuel Cycles*. Presented at IAEA Technical Committee Meeting, November 28–30, 2000. 14 pages. \$10.00

Kobayashi, T., M. Kazimi, and S. Connors. *The Role of Nuclear Energy in Southeast Asia*. Presented at the IAEA International Seminar on the Status and Prospects of Small and Medium Sized Reactors, Cairo, Egypt, May 27–31, 2001. 12 pages. \$10.00

Long, Y., Y. Yuan, E. Pilat, C. Rim, and M. Kazimi. *Modeling Fission Gas Release in High Burnup ThO₂-UO₂ Fuel*. Forthcoming in *Proceedings of ICONE 9*, Nice, France, April 8–12, 2001. 12 pages. \$10.00

Marcinkowski, K., G. Apostolakis, and R. Weil. "A computer-aided technique for identifying latent conditions (CATILaC)." *Cognition, Technology & Work*, v. 3, pp. 111–126, 2001.

McFarland, J., H. Herzog, J. Reilly, and H. Jacoby. *Economic Modeling of Carbon Capture and Sequestration Technologies*. Presented at the First National Conference on Carbon Sequestration, Washington, DC, May 14–17, 2001. Available as PDF on the Web at <<http://web.mit.edu/energylab/www/hjherzog/publications.html>>.

Pindyck, R. "The dynamics of commodity spot and futures markets: a primer." *The Energy Journal*, v. 22, no. 3, pp. 1–29, 2001.

Quiviger, G., and H. Herzog. *A Case Study from Norway on Gas-Fired Power Plants, Carbon Sequestration, and Politics*. Presented at the First National Conference on Carbon Sequestration, Washington, DC, May 14–17, 2001. Available as PDF on the Web at <<http://web.mit.edu/energy-lab/www/hjherzog/publications.html>>.

Rabute, R., and T. Tian. "Challenges involved in piston top ring designs for modern SI engines." *Transactions of the ASME*, v. 123, pp. 448–459, April 2001.

Rublewski, M., and J. Heywood. *Modeling NO Formation in Spark Ignition Engines with a Layered Adiabatic Core and Combustion Inefficiency Routine*. SAE Paper No. 2001-01-1011. Presented at the Society of Automotive Engineers 2001 World Congress, Detroit, Michigan, March 5–8, 2001. Ordering instructions at <<http://www.sae.org>>.

Skantze, P., and M. Ilić. *Valuation, Hedging and Speculation in Competitive Electricity Markets: A Fundamental Approach*. Norwell, Massachusetts: Kluwer Academic Publishers. 2001.

Steinfeld, J. "Climate change and energy options: decision making in the midst of uncertainty." *Fuel Processing Technology*, v. 71, pp. 121–129, 2001.

Swift, B. "How environmental laws work: an analysis of the utility sector's response to regulation of nitrogen oxides and sulfur dioxide under the Clean Air Act." *Tulane Environmental Law Journal*, v. 14, pp. 309–425, Summer 2001.

Tolsma, J., and P. Barton. "Process simulation and analysis with heterogeneous models." In *European Symposium on Computer Aided Process Engineering-11*, R. Gani and S. Jorgensen, eds. Elsevier Science BV. 2001.

Trout, B., J. Tester, Z. Cao, and M. Bazant. *Development and Application of High Accuracy Methane-Water Potentials from ab initio Calculations for Modeling of Gas Hydrates*. Presented at Division of Physical Chemistry, 221st ACS National Meeting, San Diego, California, April 2001. \$10.00

World Business Council for Sustainable Development (WBCSD). *Mobility 2001: World Mobility at the End of the Twentieth Century and its Sustainability*. Prepared for the Sustainable Mobility Working Group of the WBCSD by the Massachusetts Institute of Technology and Charles River Associates Inc. 188 pages. 2001.*

Yilmaz, E., et al. *Analysis of Oil Consumption Behavior During Ramp Transients in a Production Spark Ignition Engine*. SAE Paper No. 2001-01-3544. Presented at the Society of Automotive Engineers 2001 World Congress, Detroit, Michigan, March 5-8, 2001. Ordering instructions at <<http://www.sae.org>>.

Zhao, X., M. Driscoll, and M. Kazimi. *Neutronics Characteristics of Micro-Heterogeneous ThO₂-UO₂ PWR Cores*. Forthcoming in *Proceedings of ICONE 9*, Nice, France, April 8-12, 2001. 11 pages. \$10.00

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