Report of the Energy Research Council

MIT Energy Research Council

Robert C. Armstrong Chemical Engineering, Co-Chair
Ernest J. Moniz Physics and Engineering Systems Division, Co-Chair

May 3, 2006

Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

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Council Members

Stephen Ansolabehere	Political Science
Robert C. Armstrong	Chemical Engineering, Co-Chair
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Daniel G. Nocera	Chemistry
Karen R. Polenske	Urban Studies and Planning
Yang Shao-Horn	Mechanical Engineering

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[1] Some sections dealing with internal MIT resources have been omitted from this printing of the report.

Executive Summary

This report describes a response by MIT to the need for new global supplies of affordable, sustainable energy to power the world. The need for workable energy options is perhaps the greatest single challenge facing our nation and the world in the 21st century. The acuteness of the challenge at this point in time results from the "perfect storm" of supply and demand, security, and environmental concerns:

- a projected doubling of energy use and tripling of electricity demand within a half century, calling for a substantial increase in fossil fuel supplies or dramatic transformation of the fossil fuel-based energy infrastructure
- geological and geopolitical realities concerning the availability of oil and, to some extent, natural gas – specifically the concentration of resources and political instability in the Middle East - underlie major security concerns
- greenhouse gas emissions from fossil fuel combustion are increasingly at the center of decisions about how the global energy system evolves – one that carries on in the "business as usual" overwhelming dependence on fossil fuels or one that introduces technologies and policies that greatly improve efficiency, dramatically expand use of less carbon-intensive or "carbon free" energy, and implement large scale carbon dioxide capture and sequestration.

MIT's history of success as an institution in bringing science, technology, and policy to bear in addressing major societal challenges, our strength of human resources in these areas, our capacity to work across disciplinary boundaries, our long-standing focus on innovation and "technology transfer", and our demonstrated willingness to work with industry and government gives us a special responsibility and opportunity to focus our resources on this energy challenge. Above all, the enthusiasm and commitment of faculty, students and staff manifested during the Council's work augur well for substantial contributions in the coming years to resolution of the energy/environmental challenge. We advocate an approach that combines research, education, and MIT-campus energy programs.

The interests and capabilities of our faculty ultimately determine the specific energy research that will be done at MIT, and they have come forward with a rich set of interests that will draw upon multiple disciplines. We cannot predict exactly how this will end up in a fully formed energy initiative. However, we have reached consensus on the need for a broad initiative that

1. provides the enabling basic science and technology that may underpin major transformation of the global energy system in several decades,
    a. renewable energy (solar, biofuels, wind, geothermal, waves)
    b. energy storage and conversion
    c. application to energy of core enabling science and technology that have made dramatic strides in the last decade or so (e.g., superconducting and cryogenic components, nanotechnology and materials, biotechnology, information technology, transport phenomena)

2. develops the technology and policy needed to make today's energy systems more effective, secure, and environmentally responsible
    a. advanced nuclear reactors and fuel cycles that address cost, safety, waste, and nonproliferation objectives
    b. affordable supply of fossil-derived fuels (oil, natural gas, coal) from both conventional and unconventional sources and processes
    c. key enablers such as carbon sequestration
    d. thermal conversion and utilization for dramatically enhanced energy efficiency, including in industrial uses
    e. enhanced reliability, robustness, and resiliency of energy delivery networks
    f. system integration in energy supply, delivery, and use
    g. learning from the past and understanding current public attitudes towards energy systems
    h. sound economic analysis of proposed policies for energy development and greenhouse gas mitigation
    i. understanding and facilitating the energy technology innovation process
    j. in-depth integrative energy and technology policy studies that draw upon faculty across the campus
3. creates the energy technology and systems design needed for a rapidly developing world.
    a. science and policy of climate change
    b. advanced energy-efficient building technologies
    c. advanced transportation systems, from novel vehicle technologies and new fuels to systems design, including passenger and freight networks
    d. "giga-city" design and development, particularly in the developing world.

Because of the magnitude of the proposed program at MIT, we advocate phasing in research thrusts in these three areas over the next several years. Because we are fortunate at MIT to have significant breadth and depth, we have many options for structuring the portfolio. A starting set of projects might include solar power, nuclear power systems, and integration of the science and policy of climate change as lead thrusts in the three categories above. At the same time it is important to seed other initiatives to bring them on-line as additional research thrusts in subsequent years, and the extensive lists above demonstrate a wealth of candidates for early focus. Likely areas for these projects include electrochemical storage and conversion and biofuels in the first category, multiscale modeling and simulation (e.g., for energy conversion and high efficiency) and subsurface energy science and engineering (e.g., for enhanced oil recovery and carbon dioxide sequestration) in the second category, and energy efficient buildings and transportation technology and systems in the third.

MIT is an ideal place to demonstrate the power of combining education and research in producing leaders for tomorrow in energy. Not only should we engage both undergraduate and graduate students in integrative, multidisciplinary energy-related projects as part of their education, but we should also produce and deploy educational content and materials for use here and beyond the borders of MIT. To guide development of an integrated set of educational options and to incorporate interdepartmental and interschool education work into the energy initiative, an Energy Education Task Force should be established.

Improving campus energy management holds promise for lowering energy use and cost, reducing emissions, and providing an important learning environment for faculty, students, and staff. A number of options for achieving these goals have been suggested. It is recommended that as a next step a comprehensive assessment and analysis of these approaches and alternatives be conducted in order to understand fully the opportunities, trade-offs, benefits and costs before committing to a course of action.

The energy initiative outlined in this report is ambitious, but appropriate for MIT. To ensure its success, we recommend creation of an organization with a clearly defined responsibility to steer the initiative and to serve as a focal point for cross-department and school initiatives and activities in energy. We envision a different organizational structure than MIT has used in the past for energy research. An Energy Council should be created to guide this organization and have broad representation from the five schools at MIT. Several subgroups will report to the Energy Council. These include the research thrusts, educational task force, campus energy management task force, and LFEE. The Energy Council should move towards the creation of a permanent energy laboratory or center within five years of the launch of the initiative. It is critical that the new organization have central research space to facilitate its mission.

1 MIT and the Energy Challenge

MIT President Susan Hockfield, in her May 2005 inaugural address, called for a renewed Institute commitment to energy-related research and education:

> "[A] great opportunity, and a great obligation, is our institutional responsibility to address the challenges of energy and the environment. Over the last thirty years, these two words – energy and the environment – have gotten a little tired, tired not from overuse but from lack of progress. I believe that the time for that progress is now. I believe that the country and the world may finally be ready to focus on these matters seriously. And again, it is our responsibility to lead in this mission.
>
> Tackling the problems that energy and the environment present will require contributions from all of our departments and schools. Many MIT faculty are working already on new routes to renewable and sustainable energy. We need to advance this scientific and engineering work, while focusing our efforts and magnifying their impact, through our world-class expertise in economics, architecture and urban planning, political science and management.
>
> To this end, we have begun working with the faculty to develop a major new Institute-wide initiative on energy. This initiative will foster new research in science and technology aimed at increasing the energy supply and bringing scientists, engineers, and social scientists together to envision the best energy policies for the future. We will seed this initiative with resources for new interdisciplinary faculty positions. And I believe that, working together, we will make an enormous difference."

This report of the MIT Energy Research Council, which is made up of faculty from all five MIT Schools, presents recommendations for advancing the Institute's energy research and educational agenda.

The urgency for this energy focus lies principally with three overarching drivers, often viewed as presenting conflicting demands in a "business as usual" world:

- The aspirations and needs of billions of people in both developed and emerging economies call for dramatic increases in global affordable energy supply, which is currently dominated by fossil fuel combustion, and for major gains in conservation and energy efficiency.

- Diverse security challenges associated with energy supply will be exacerbated as energy use expands significantly, from competition for limited conventional oil and natural gas resources often located in politically volatile areas, to protection of increasingly extended energy delivery systems, to the possibility of misuse of nuclear power development to advance nuclear weapons programs.

- The growing concerns about climate change may call for a fundamental transformation of the global fossil-fuel dominated energy infrastructure, an impact much greater than that associated with mitigation of other environmental challenges.

There is considerable uncertainty as to how each of these issues will develop, but certainty that a set of options, broader than what we have available today, must be developed relatively soon to address these challenges over the next several decades. Those options are rooted in science, technology, and synergistic policies that both stimulate timely technology development and condition the marketplace for the public good. Timing is crucial. The capital intensity of energy supply and delivery systems has historically led to slow turnover of energy infrastructure, with a characteristic time scale approaching fifty years. Yet each of the challenges indicated above plausibly calls for significant change within that time frame, so that new directions need to be set beginning today. A key feature of a successful MIT initiative will be the joining of fundamental research and analysis in science, engineering, energy economics, and corporate and public policy to advance real-world solutions to this "perfect storm" of energy challenges. We will elaborate briefly on these challenges so as to frame the ensuing research and educational agenda.

1.1 Energy supply and demand

The enormity of the global energy supply chain, and its centrality to nearly every societal activity, conditions all discussions of energy technology and policy. A multi-trillion dollar/year business supplies about 450 Exajoules (EJ, or 10^{18} joules); equivalently, we "burn" energy at a rate over 14 Terawatts (TW, or trillion watts). About 86% is supplied by fossil fuels – coal, oil, and natural gas. The United States uses about a quarter of the total.

Figure 1.1 shows per capita GDP and energy use for a representative set of countries. The correlation is apparent and underscores the developing world's drive to increase aggressively affordable energy supply. This economic impulse will be the principal driver for the anticipated doubling of global energy use by mid-century. China alone has been increasing energy use at about 10%/year, with profound impacts on global energy markets.

The situation for electricity is even more challenging. The United States National Academy of Engineering chose electrification as the greatest engineering achievement of the twentieth century, thereby acknowledging its pervasive role in enhancing quality of life. Globally, about 16 trillion kWh of electricity are generated annually, with per capita use shown in Fig. 1.2 against the United Nations Human Development Index (HDI) – a measure of health, education, and economic well-being. Developing country needs are again apparent. "Business as usual" scenarios suggest a tripling of electricity generation in fifty years. Even then, 1.4 billion people will still be without electricity in a quarter century, and many more than that still well down the "HDI trajectory" at mid-century.

The supply challenge can be mitigated dramatically by demand-side action. Despite the overall correlation of energy and GDP, Figure 1 displays meaningful variations in "energy intensity" in different societies with comparable standards of living, such as

Western Europe and the United States. The consequences for energy supply depending on what trajectory is followed by developing and emerging economies are enormous. The difference in Chinese energy supply alone when its GDP/person is doubled (likely in only ten to fifteen years) is equivalent to 10% of today's global energy market, depending on whether China has the US or Western Europe energy intensity.

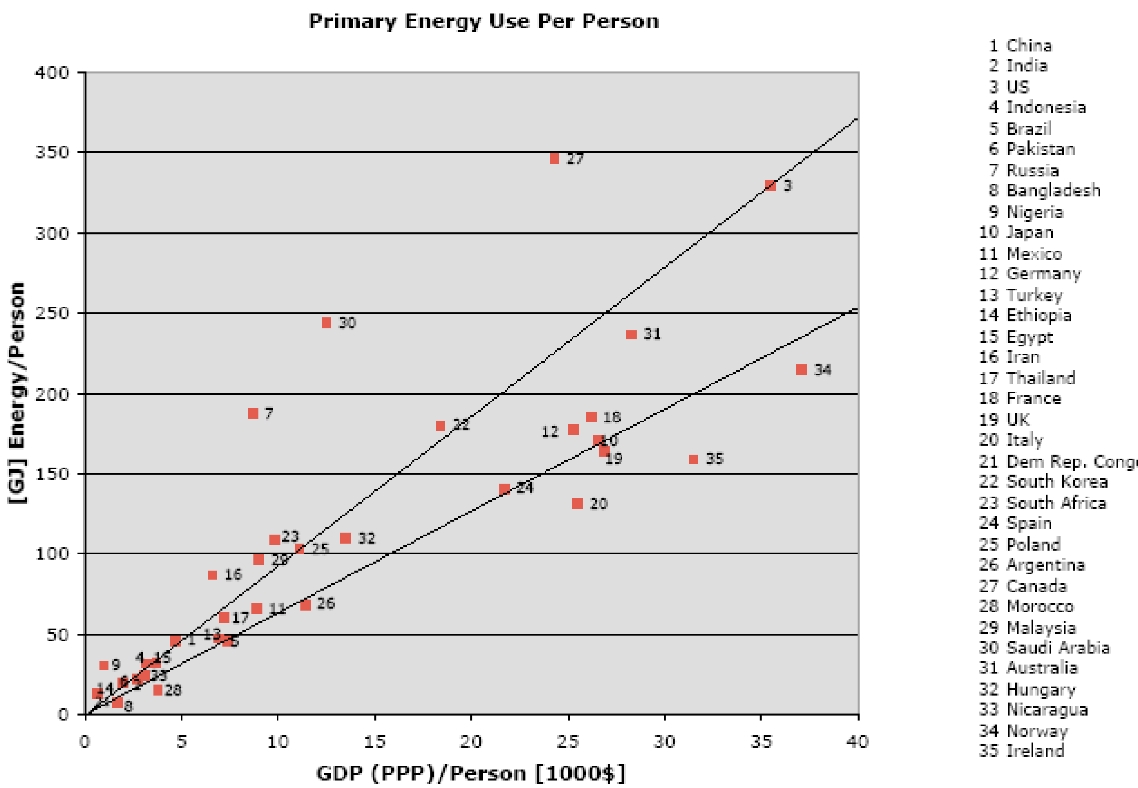

Figure 1.1 Energy use (in gigajoules) vs. GDP (on a purchasing power parity basis) for selected countries on a per capita basis. Data from the International Energy Agency. Upper line indicates ratio for the US; lower line indicates ratio for Japan and several Western European countries.

Not only do fossil fuels dominate energy consumption today, but "business as usual" scenarios predict that will be the same for many tomorrows. Of course, the availability of these relatively inexpensive, high energy density fuels has driven profound societal transformation since the Industrial Revolution. However, the continued availability of oil at low cost over the next decades has been cast in doubt, and demand may simply not be met at acceptable cost without major change in how we supply and use energy.

1.2 Energy and security

These challenges to oil supply raise familiar security issues since our transportation sector is almost totally dependent on petroleum-derived liquid fuels and because of geological and geopolitical realities about their availability. Increasingly, similar concerns are voiced about natural gas. Competition for supplies, such as that emerging in the Far East, can directly and indirectly raise regional and global security problems. These realities place a premium on new technologies and policies that lead to diversification of oil and gas supplies and that develop alternate transportation technologies and fuels that require less oil and gas consumption. The challenge is considerable. For example, the "solution" that largely preserves the current transportation and fuels paradigm is large-scale introduction of alternative liquid fuels derived from coal, gas, or biomass. However, the sheer magnitude of the energy content in today's use of oil, over 150 EJ/year (or almost 5 TW), together with conversion efficiencies, means that any substantial displacement of oil in this way will have profound implications on other energy and land uses. Multiple technology and policy approaches will be essential.

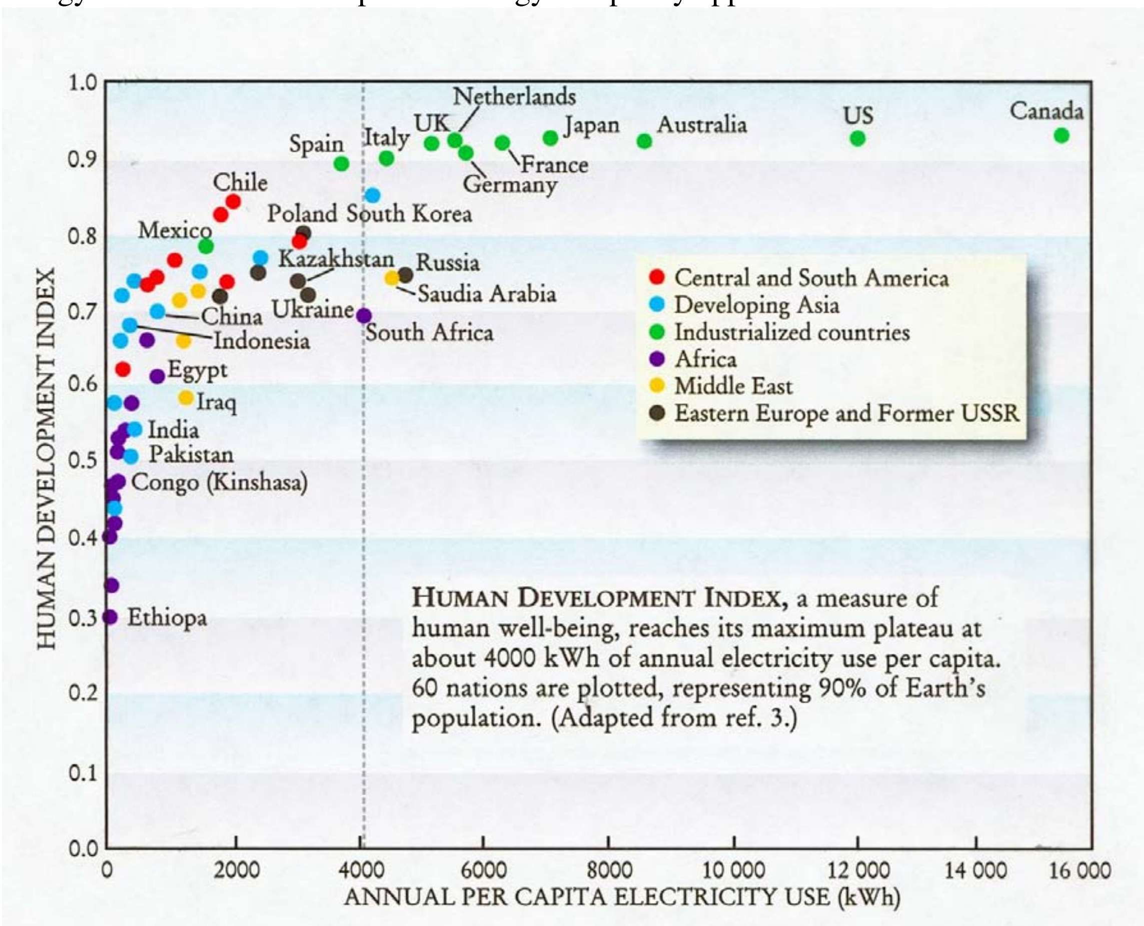

Figure 1.2. Human development index vs. per capita electricity use for selected countries. Taken from S. Benka, *Physics Today* (April 2002), pg 39, and adapted from A. Pasternak, Lawrence Livermore National Laboratory rep. no. UCRL-ID-140773.

This is not the only security concern associated with energy supply and use. Extended energy delivery systems are vulnerable to disruption, whether by natural occurrences such as hurricanes or by intentional sabotage. There are also concerns about nuclear weapons proliferation facilitated by the expansion worldwide of nuclear power and components of the nuclear fuel cycle. In particular, high natural gas prices and climate change concerns have led to considerable global interest in new nuclear fuel cycle development, potentially with substantial deployment in new parts of the world and a risk that some might use the expansion to disguise nuclear weapons ambitions.

1.3 Energy and environment

Environmental concerns arising from fossil fuel combustion have a long history, reaching back to regulations on coal burning in thirteenth century London imposed by Edward I. More recently, local and regional effects such as urban smog and acid rain have led to new pollution policies and technologies. However, the more challenging problem of greenhouse gas emissions, and specifically the emission of carbon dioxide from fossil fuel combustion, is now front and center in the international evaluation of energy options. Clearly, serious attempts at carbon control in a world dominated by fossil fuels cannot be implemented in a "business as usual" scenario. The basic choices are improved efficiency in the continuing use of fossil fuels, dramatic expansion of less carbon-intensive or "carbon-free" technologies, and potentially large-scale use of carbon dioxide capture and sequestration.

Again, the magnitude of the challenge deserves comment. As a benchmark for discussion, we take limiting atmospheric greenhouse gas concentrations below a doubling of pre-industrial levels as a reasonable target. While such a target does not have a rigorous basis in terms of climate modification and societal cost and disruption, the great majority of engaged scientists would view this as a prudent limit at our current state of knowledge. Because of the cumulative nature of CO_2 in the atmosphere, the target can be translated into a CO_2 "emissions budget" that is somewhat offset by CO_2 uptake in the oceans, plants, and soils. With today's understanding of the global carbon cycle, a business-as-usual approach to energy supply and use will exhaust that "budget" shortly after mid-century. Practically speaking, the increase in emissions must be slowed in the immediate future, and then reduced back to or below today's emissions rate by mid-century, in the face of a projected doubling of energy use at that time. This can be thought of as adding another global energy infrastructure of today's scale (recall, 14 TW!) but without greenhouse gas emissions, and at acceptable economic and environmental cost. A significant "de-linking" of energy supply growth and conventional fossil fuel dependence is called for. Once again, multiple supply and end-use technologies will be required – both megawatts and "negawatts". There is no silver bullet. Further, the inertia of the system – the inertia of large sunk capital costs, atmospheric inertia, policy and political inertia –requires strong action now if we envision success over many decades. Multiple technologies and policies must work together.

This "perfect storm" of supply and demand, security, and environmental concerns calls for a strong science, technology, and policy research focus at MIT and elsewhere. Interdisciplinary research efforts bringing together the talents of many faculty, students, and staff can bring new impetus. A portfolio of such efforts is needed to address central questions for an uncertain future, a future that will require a robust set of options. It is clearly an agenda well beyond the reach of any single institution, but one to which MIT, with its depth and breadth of science and engineering and history of interdisciplinary research and of industry collaboration, can make major contributions while educating the next generation of leaders.

1.4 The research agenda

A large number of MIT faculty, students, and staff have helped the Energy Research Council discussions with thoughtful suggestions and proposals for priority research and educational activities through which they and their colleagues can make a sustained commitment to working on key elements of the complex energy challenge. From this, we envision a portfolio of multidisciplinary research activities being developed that is shaped so as to address the linked supply and demand, security, and environmental challenges.

1.4.1 Science and technology for a clean energy future

Enabling basic research is needed to underpin 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 individual firms and because it prepares future leaders of forefront research. Many of the expressed faculty interests fall in this part of the portfolio:

- renewable energy sources (wind, solar, geothermal, waves, biofuels),
- electrochemical energy storage and conversion,
- core enabling science and technology (e.g., superconducting and cryogenic components, nanotechnology and materials, transport phenomena), and
- nuclear fusion

1.4.2 Improving today's energy systems

Needless to say, the impact of MIT's energy research activities, now and in the future, will be measured not only by how they contribute to the science and technology base for the long term energy system transformation, but also by how they help evolve today's energy infrastructure towards lower cost, enhanced security, and less environmental impact over the next decade or two. This work is inherently closer to the marketplace and will need especially close coordination and partnership with industry. Again, many faculty are committed to enhanced efforts in this context:

- advanced nuclear reactors and fuel cycles that address cost, safety, waste, and nonproliferation objectives;
- affordable supply of fossil-derived fuels (oil, natural gas, coal) from both conventional and unconventional sources and processes;
- key enablers such as carbon sequestration;
- thermal conversion and utilization for dramatically enhanced energy efficiency, including in industrial uses;
- enhanced reliability, robustness, and resiliency of energy delivery networks; and
- system integration in energy supply, delivery, and use.

In addition to technology advances, near term progress hinges critically on better understanding of societal and policy opportunities and barriers to energy system development. MIT has a strong faculty cadre experienced in the integration of technology, policy, and analysis that can help shape the public debate on energy system development and advance an "honest broker" role in complex societal decisions. Some policy work will be integrated directly with technology development programs, while other areas of interest include:

- learning from the past and understanding current public attitudes towards energy systems,
- sound economic analysis of proposed policies for energy development and greenhouse gas mitigation,
- understanding and facilitating the energy technology innovation process, and
- in-depth integrative energy and technology policy studies that draw from faculty across the campus.

1.4.3 Energy utilization in a rapidly evolving world

The large projected increases in global population and energy demand, led by those in developing and emerging economies, are a defining need for new energy technology and policy and serve as a reminder that an international perspective is central to framing the research agenda. Issues such as functioning of oil markets or climate change are inherently global in nature. And yet, 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 solutions are advanced promptly enough. Demographic trends, such as significant urbanization, will also call for creative approaches to energy delivery. Examples of multidisciplinary faculty interest include:

- science and policy of climate change;
- advanced, energy-efficient building technologies;
- advanced transportation systems, from novel vehicle technologies and new fuels to systems design including passenger and freight networks; and
- "giga-city" design and development, particularly in the developing world.

These portfolio elements and specific areas of interest may not represent the full range of activity sometime down the road, but they do capture a range of capability and interest that augurs well for a heightened and sustained MIT focus on the energy challenge.

1.5 Why MIT?

The principal response to the question "Why MIT?" for an energy initiative is the extraordinary interest of hundreds of faculty, students, staff, and alumni. They, together with Institute leadership, have understood the energy challenge as a leading opportunity to bring science, engineering, and policy to bear on human needs in the 21st century.

MIT is not unique among research universities in sharpening its focus on energy-related research, and there will be some common challenges in meeting expectations and aspirations. The last twenty years have seen inadequate and inconsistent funding for university-based, energy-related research. Faculty renewal at a significant scale will be critical over the next several years. Interdisciplinary research, spanning multiple departments and schools, will be an essential supplement to ongoing research conducted by individual investigators. Infrastructure must be developed to advance the technology innovation process, when appropriate, beyond the traditional laboratory scale.

We believe MIT is well positioned to take on these tasks. MIT has a track record of impact when the Institute commits to focus multiple disciplines on an important societal challenge. This initiative is specifically about supplementing ongoing discipline-based research with a portfolio of multidisciplinary, multi-faculty, multi-year, sustained research efforts. In addition, the Institute has long been a leader in technology innovation and a well-documented catalyst for establishing technology-based enterprises. This, together with extensive experience in partnering with industry, will be important for overcoming the "valley of death" syndrome that often lies between basic research and energy technology scale-up and deployment. Needless to say, the faculty renewal, resource development, and infrastructure needs will have to be met.

In short, delivering on the promise of this energy initiative will call upon many of the Institute's attributes beyond excellence in research – a creative but grounded approach to complex problems; interdisciplinary research tradition; exceptional faculty, staff, and students; long-established experience with industrial collaboration; international partnerships; convening power for key conversations; and a practiced ability to serve as "honest broker" in framing and analyzing important societal issues with significant scientific and technological content. The energy challenge, while formidable, will yield to dedicated application of such capabilities.

2 Background

2.1 Membership and Charge

Shortly after President Hockfield's inaugural address, Provost Robert Brown formed the Energy Research Council, with the following membership representing all five of MIT's Schools:

Stephen Ansolabehere	Political Science
Robert Armstrong	Chemical Engineering, Co-Chair
Angela Belcher	Biological Engineering and Materials Science & Engineering
Vladimir Bulovic	EECS
Gerbrand Ceder	MS&E
John Deutch	Chemistry
William Green	Chemical Engineering
John Heywood	Mechanical Engineering
Henry Jacoby	Sloan School of Management
Mujid Kazimi	Nuclear Science and Engineering
Steven Leeb	EECS
Ernest Moniz	Physics & Engineering Systems Division, Co-Chair
Dale Morgan	EAPS and Director of Kuwait Center
Daniel Nocera	Chemistry
Karen R. Polenske	Urban Studies and Planning
Yang Shao-Horn	Mechanical Engineering

In its charge, the council was

> "… asked to develop the outline of a strategy for MIT's response to this energy challenge. In doing so the council should:
>
> 1. Develop a picture of the current state of MIT energy-related research and expertise. It would be helpful to engage the broad community in small-group discussions of perceived opportunities as well as barriers to success.
> 2. Develop a list of promising science and engineering research areas that match global needs and MIT capabilities. What top-level commitments are needed to enable success by MIT in these areas? Are there area-specific needs for junior and senior faculty hiring to invest in these research areas?
> 3. Comment on what organizational structure would best facilitate success in these energy areas. In light of the multi-disciplinary nature of the issues and the importance of interdisciplinary research, are there organizational changes that would better enable the research agenda and knitting together the "energy community" at MIT? Are there implications for the evolution of LFEE?"

The Energy Research Council (ERC) met for the first time on June 17, 2005 with the Provost and Vice-President for Research, Alice Gast, to discuss the charge and process.

One notable outcome of that meeting was the unanimous agreement that the charge of the ERC should be expanded to include explicitly education.

2.2 Process followed

The Energy Research Council began its work with an initial data gathering phase. During this period we sought to understand the current status of energy research and education at MIT as well as to gather the views of our stakeholders with respect to the issues, challenges, and opportunities facing MIT as we moved into this initiative. The data gathering included

- summer/fall small group faculty discussions
- polling of departments, laboratories, and centers for current status of energy research/education at MIT
- discussions with graduate students via the Energy Club
- discussions with undergraduates through meetings with living groups
- one-on-one meetings with alumni and meetings with several alumni clubs
- one-on-one meetings with key industry leaders
- a workshop with leaders from industry

Beginning in the fall the ERC met a minimum of twice a month. Early fall sessions were focused on refined data gathering and input based on analysis of initial discussions. These were organized around a number of ERC Subcommittees formed on the basis of the input we received over the summer and on our early deliberations:

- Undergraduate students (Leeb, Armstrong),
- Graduate students (Moniz, Armstrong),
- Alumni/ae (Armstrong, Moniz),
- Industry (Deutch, Ceder, Heywood, Polenske, Shao-Horn, Armstrong, Moniz),
- Research White papers (Green, Armstrong, Moniz, Nocera),
- Education/curriculum (Jefferson Tester, Elisabeth Drake, Ahmed Ghoniem, Michael Golay, Leon Glicksman, Amanda Graham, Don Lessard, Donald Sadoway, Jeffrey Steinfeld and Nafi Toksoz), and
- MIT facilities/campus activities (Bulovic, Ansolabehere, Kazimi).

Brief summaries of the work of these subcommittees are given in Appendix 8.1. Chapters 3, 4, and 5 are based on the work of the last three of these groups, respectively.

Results from these inputs were debated and discussed in series of all-day ERC meetings in January. Based on these discussions we approached some faculty groups to get shorter, two-page research white papers that clarified priorities and goals in some of the original white papers and in some cases sought to achieve synergistic synthesis of two or more related white papers.

The web was a great help to the ERC in conducting its work thus far, and we believe that it will be an important tool for the energy initiative at MIT as we go forward. The ERC maintained both an internal web site for distributing work product to Council members, e.g., minutes of our meetings, summaries of each faculty discussion group, progress reports of the various subcommittees of the Council, and emails and letters sent to the

Council with advice on process or direction, as well as a public (MIT-only) site. The public site has been used to date to distribute the white papers to the entire MIT community.

In parallel with our data gathering and discussions over the past nine months we have been constructing a new, public energy web site. We anticipate that this web site will go live about the time this report is released. The purpose of the external web site is to provide a coherent portal into MIT energy activities for the external world. It should also be useful as a one-stop source of energy information for the MIT community, including information on educational opportunities, research (with links to departments, laboratories, and centers), energy related seminars on campus, UROP opportunities, energy classes taught across the Institute, etc. The web site contains a time line with a history of energy research at MIT going back to its founding and a section that will spotlight exciting recent research in the energy area at MIT.

As an additional means to stimulate energy discussion on campus, the ERC has sponsored an energy colloquium this year, featuring leaders from different parts of the energy field. Speakers include:

- Dr. Steve Koonin, Chief Scientist BP, “Energy for the Coming Decades: Trends and Technologies” (September 22, 2005)
- Dr. Lee Lynd, Professor of Engineering at Dartmouth College, “The Role of Biomass in America's Energy Future” (February 2, 2006)
- Dr. Amory Lovins, Founder and CEO of Rocky Mountain Institute, “Winning the Oil Endgame” (February 27, 2006)
- Dr. Samuel Bodman, Secretary of Energy (May 9, 2006)

The attendance and lively discussion at these seminars demonstrates the intense interest on the MIT campus today. We look forward to continuing this series.

3 Energy Research at MIT – a Strong Tradition, an Enhanced Commitment

MIT was established in 1861 as a "polytechnic" with an explicit commitment to the application of scientific knowledge to industry's challenges and society's needs. With such a mission, it is not surprising that advancements in energy supply, delivery and use have been a persistent feature of the Institute's research and education programs since its early days. Today, the faculty carry out cutting-edge research in numerous energy-related science, engineering, and policy areas, a snapshot of which can be accessed at http://web.mit.edu/erc.

We now aim to supplement this work by bringing together multi-disciplinary groups of faculty, students, and staff. We anticipate that considerable progress will follow from joint application of recently developed tools, capabilities, and results in different fields.

As described in Chapter 2, the Council solicited input from faculty, students, and staff and received many expressions of interest to carry out such research. Here we provide a very brief summary of these interests, as it is important for understanding where the faculty may ultimately lead this effort. Clearly, a phased approach will be needed to realize a significant part of this agenda over time; that will be discussed in Chapter 7.

3.1 Electricity supply, delivery, and use

Electricity demand growth is predicted to outpace that for energy overall by a substantial amount over the next decades. This is especially so for the developing and emerging economies where electricity supply today is often unreliable or even unavailable, seriously limiting quality of life gains and economic development options. By mid-century, most projections anticipate that electricity production will account for about 40% of global carbon dioxide emissions. If such emissions are dramatically restricted in coming years, it is clear that power plants will be a major focus for mitigation programs. This in turn calls for significant technical and policy development.

The nature of such a challenge in the United States can be seen from today's fuel mix for electricity generation: 50% coal, 20% nuclear fission, 18% natural gas, 7% hydroelectric, 3% petroleum, and 2% other renewables. The other renewables are 75% biomass (primarily wood/wood waste and municipal solid waste/landfill gas), 17% geothermal, 7% wind, and 0.6% solar. In a greenhouse gas constrained world, coal use raises issues of much higher efficiency and of CO_2 capture and sequestration; nuclear, of public acceptance and waste management; natural gas, of supply and price; renewables, of cost, intermittency (wind and solar), and land use. In addition, major issues of electricity delivery and associated regulatory structures remain unresolved. Similar issues apply globally, with some regional variation in the balance of concerns. The options need to become more attractive in the near term and expanded for the long term.

3.1.1 Efficient generation, delivery and use

3.1.1.1 Buildings

The residential and commercial sectors in the US consume about 40% of all primary energy, and three-quarters of that derives from electricity use. The developing world is building at an unprecedented pace. Major steps to reduce energy needs for the built environment are essential.

Several faculty in Architecture, Urban Planning, Mechanical Engineering, and Electrical Engineering are engaged in building technology development (e.g., design tools, materials, natural ventilation, controls). Going forward, an important step will be development of integrative tools and demonstrations that draw upon innovations such as anidolic collectors, controllable thermal mass matched to irregular occupancy patterns, equipment sensing and controls responsive to occupancy spatial patterns, etc. An integrated "Virtual Building" web-based platform that integrates all aspects of a sustainable energy-efficient building would be a first step. It would accommodate many parameter variations (climate, orientation, local materials,…), providing applicability in many regions. This could then lead to a research laboratory for demonstration and validation of integrated solutions – new façade systems, insulating materials, lighting schemes, controls, materials, and energy consumption assessment strategies. Finally, these considerations can be extended to a larger urban context. These activities lend themselves to campus-based student research and education.

3.1.1.2 System integration

There can be great benefits in efficiency, functionality, and/or cost through integrated energy system design. This can consist of integrating components optimized for different operating conditions (e.g., combined cycle power plants, hybrid drive trains), or of system component design, normally addressed individually within different engineering disciplines, as an integrated whole (e.g., photovoltaic and building technology, fuel cell and heat engine technologies). Current efforts in modeling and simulation, systems analysis and control, novel thermal and chemical conversion technologies, manufacturing and materials, and materials science will contribute to a high-efficiency systems integration focus area.

3.1.1.3 Enabling technologies

Superconducting and cryogenic technology can play a greatly expanded role in energy conversion, energy use, energy transmission, energy storage, and power system stabilization. The Plasma Science Fusion Center has a leadership role in superconducting magnet design for the US fusion program, and MIT faculty have previously played a significant role in applying superconductivity to energy, including spinning out commercial activity. Building on this foundation and infrastructure, faculty from Nuclear Science and Engineering, Electrical Energy and Computer Science, Materials Science and Engineering, Mechanical Engineering, Physics, and others are poised to initiate new research on the use of superconducting and cryogenic technology to important issues such as DC power transmission, power control and grid stabilization, high power conditioning, and high efficiency electrical machinery.

3.1.1.4 Reliability, robustness, and resiliency of critical energy networks

Several recent events – the 2001 energy disruptions in California, the 2003 Northeast blackout, the 2005 cascading fuel and electricity network failures following Hurricane Katrina – serve to remind us of the need to upgrade our energy delivery systems, most especially the electric grid. Part of the solution is new technology. Another is system design for reliability, robustness, and resiliency. Faculty from all five MIT Schools will contribute to a critical energy networks project that would start by improving the theory and practice of infrastructure network analysis and design, integrating analysis of the physical, information, and control/communications layers. The focus will be on developing tools for decision-oriented multi-resolution dynamic models for distributed feedback control. Associated with this will be improving real-time monitoring and management and investigation of new approaches to economic and regulatory incentives for system improvement.

3.1.1.5 Efficient thermal energy direct conversion and utilization

More than 90% of primary energy sources (fossil and nuclear) are converted into mechanical and electrical energy through thermal processes. The vast majority of energy usage in industrial processes is in the form of heat. Much of the heat is released into the environment (about two thirds for today's power plants), so improved energy efficiency of thermal systems can have a major impact.

A multi-disciplinary group of faculty is prepared for a substantial program of nanotechnology-enabled investigations of thermal energy conversion and use technologies. Thermoelectric and thermophotovoltaic science and technology will be explored at the nano-level, perhaps in collaboration with Lincoln and/or Draper Laboratories. Also, liquids are ubiquitous in heat transfer systems, and most work has focused on engineering heat transfer surfaces to increase performance. The work here will instead focus on improving the heat transfer characteristics of the liquids themselves, through research on suspended nanomaterials.

3.1.2 Nuclear power

Nuclear power currently supplies about a sixth of world electricity demand and, after a period of little new construction, may be at the threshold of significant expansion globally. The drivers for this upsurge in interest range from high and volatile natural gas prices to concern about climate change. In the US, the Energy Policy Act of 2005 provided substantial financial incentives for 6000 Megawatts of "first mover" plants, and the Administration is proposing a major expansion of nuclear energy research and development for advanced technologies that might better address the concerns about nuclear waste management and nuclear proliferation.

MIT has long been prominent in nuclear science and engineering, from advanced reactor design to development of risk assessment methodology. The MIT research reactor has been extensively used to study material degradation issues under simulated conditions of power reactors. A faculty group from the Schools of Engineering and of Science has laid the groundwork for new directions that address key challenges for new nuclear technologies.

A core activity would be working with colleagues at DOE laboratories and at other universities to develop in-depth modeling and simulation capability for advanced fuel cycles. Such fuel cycles can address the key obstacles to nuclear power expansion, but will require years of development and integrated analysis of the many component technologies (e.g., reactor, fuel forms, and separations). A powerful simulation tool can guide research and development as well as deployment and policy development.

Other program elements would involve extending a modeling approach to design of high temperature irradiation-resistant materials, including advanced fuel materials and designs; developing specific technologies for advanced reactors and fuel cycles (including high burn-up fuel, modular constructability techniques, and advanced sensor/control systems); exploring separations process design; and developing alternative waste disposal approaches (e.g., deep boreholes for very long lifetime minor actinides).

3.1.3 Coal and carbon sequestration

Coal is the most abundant energy resource in the US, China, and India. It is also relatively inexpensive and supplies half of US electricity use. In China, coal use has risen rapidly over the last decade, now double that of the US. The challenges for coal-based power generation are environmental. Considerable progress has been made in cleaning up conventional pollutant emissions at reasonable cost. However, CO_2 capture at conventional pulverized coal plants is very expensive and today is not carried out at any commercial scale power plant. Since coal is so carbon-intensive, this leads to significant CO_2 emissions – about 80% of US emissions from electricity production. Of course, even if the CO_2 is captured, it would still need to be stored safely and economically, and long-term geological sequestration remains to be understood and demonstrated at the necessary scale. A multi-disciplinary faculty group plans to work together on science, engineering, and policy issues associated with near-zero emissions coal use.

3.1.3.1 Advanced coal technologies/coal gasification

The research plan relies heavily on systems integration and optimization based on advanced simulation, including analyses of the complex policy, regulatory, and economic issues affecting decisions about this technology. Simulations of coupled chemistry and transport in turbulent multi-phase flows will be used to develop accurate process models for gasification design and system integration. Advanced power plant analysis will be carried out for both air- and oxygen-blown plants, including CO_2 capture.

In addition, optimal designs will be explored for correctly integrating chemical, fuels, and hydrogen production in conjunction with power production. This raises economic/policy issues, such as the incentives for a utility to participate (or not) in the fuels/chemicals markets, and how such incentives might apply in China or India.

3.1.3.2 Carbon sequestration

MIT already has a significant sequestration program. New efforts would considerably broaden the scope of research, developing the scientific basis and tools for site selection and reservoir characterization, for real time monitoring of the storage process and the long-term verification of CO_2 repository integrity, and for understanding the ultimate fate of the CO_2. Systems integration studies will also be carried out, including questions such as storage impurity requirements, alignment with regulatory approaches and liability concerns, and design of the sequestration infrastructure at large scale (about a billion tons of carbon per year).

3.1.4 Renewables

The transition from wood to coal in the second half of the nineteenth century marked the beginning of our dependence on fossil fuels as the principal energy source. This was followed by large scale introduction of oil and natural gas. Today, many argue that "conventional" oil and gas supplies will be unable to meet anticipated demand, and concomitantly will be much more expensive, within decades. This lies at the core of major security concerns. The contribution of large scale coal use without major environmental consequences is uncertain. Renewables hold the promise of addressing these security and environmental concerns; this has been characterized as moving from hunting and gathering fossil resources to farming renewable resources. However, many challenges must be met successfully if a renewables transition is to be accelerated appreciably. The scale-up required for an appreciable (non-hydro) renewables contribution is two to three orders of magnitude. Cost reduction is essential. Further, the diffuse nature of renewable resources means that, with current technology, very large land areas would be required for the scale-up. Environmental impact must be understood. In addition, intermittent renewables will need solution to the energy storage challenge for large scale deployment. And finally, policy considerations are important for managing an infrastructure transition to renewables. While this is a complex and difficult set of issues, it is a crucial one for long-term development of a global energy infrastructure that can address simultaneously supply, security and environmental concerns. It is an appropriate challenge for MIT and other research universities, and several faculty groups are engaged in various facets of renewable energy development.

3.1.4.1 Wind energy

Wind power has been growing rapidly, with attractive economics in the best wind locations. Nevertheless, it faces challenges for truly large scale deployment. Intermittency is one. Public acceptance in visible locations is increasingly problematic. This has led to great interest in over-the-horizon off-shore wind platforms. There are vast wind resources 5-50 miles off our coastlines, in water depths 30-100 meters, and close to load centers. An MIT group is pursuing innovative floating wind platforms. It will investigate floater concepts and mooring systems, wave induced loads, fully coupled dynamic response including wind, wave and current effects, and simulation methods for preparing design standards. Economic and operational issues will also be evaluated.

3.1.4.2 Geothermal energy

Geothermal energy does not suffer the intermittency problem of wind or solar, and deployed worldwide capacity today is about 250,000 MWt. However, it is very location specific, relying on the presence of active, high-grade hydrothermal systems relatively close to the surface. The MIT interest is in universal geothermal systems, requiring engineering of artificial systems that can emulate the characteristics of hydrothermal reservoirs. The research agenda includes reservoir characterization, reservoir design and stimulation using chemical and hydraulic methods, advanced drilling and well completion methods, production and energy conversion technology, and overall systems integration and life cycle analysis to optimize performance.

This research agenda is clearly applicable to other sub-surface energy-related science and engineering challenges, such as CO_2 sequestration, seismic risk assessment, gas and oil recovery, non-conventional hydrocarbon resource recovery, and deep borehole isolation of nuclear waste. This suggests such a cross-cutting sub-surface research effort.

3.1.4.3 Solar

The solar opportunity represents a high payoff research direction with significant reward (potentially hundreds of terawatts), but substantial breakthroughs are needed. Today there are many options but no obvious silver bullet for dramatically reducing the cost-to-efficiency ratio. There are many MIT faculty working on various parts of the challenge, and a comprehensive program that can have impact at various time scales is now contemplated. It would have several elements. Further work on improved manufacturing process technologies is important for reducing costs and enhancing performance in the relatively near term. An aggressive program is needed to develop nascent technologies based on inorganic, organic, and photobiological photovoltaics, such as the recent advances in controlled assembly of hybrid organic/inorganic nanostructures. Another direction will be solar photochemical methods for fuel storage; a focus here is to develop catalysts capable of translating the light capture and charge separation function of photovoltaics into useful fuel forming reactions. There are basic science problems that need to be solved before these reactions can be carried out efficiently.

3.1.4.4 Wave energy

Wave energy technologies have reached the demonstration stage at some sites, but still face considerable challenges for widespread large scale deployment. These challenges include large daily to seasonal variations, the need to go beyond linear concepts of resonance at or close to one frequency (since sea waves are nonlinear and random), and the ability to operate safely in hostile weather. MIT expertise in coastal and offshore engineering, and in wave-structure interactions, can bring nonlinear tools to optimization of wave-power system performance. A comprehensive grid system that collects and distributes power from sea-waves will be evaluated.

3.1.5 Electrochemical energy conversion and storage technologies

Energy storage permeates the discussion of the world's future energy sources. Large-scale inexpensive storage can significantly change the landscape of energy markets. Electrical storage can lead to more efficient use and distribution of energy, and allow for very large scale renewables deployment. Electrical storage on board vehicles will increase efficiency and open up a path towards reduced oil dependence for liquid transportation fuels. Major advances are needed in energy density, cost, and durability.

The research plan anticipated here builds on existing strength in electrochemistry and has three core initiatives: fundamental studies of electrocatalysis at the molecular level; nanoscience enabled high-energy lithium storage materials; and materials for hydrogen storage. The first will include novel processes to produce electrocatalysts, such as nanoscale self-assembly, and advanced characterization tools to probe the mechanism of interfacial and bulk electron and ion transfer in the electrocatalytic process. The lithium battery research focus will include study of the potential of nano-materials to optimize reversible capacity of high-energy positive electrode materials. The objective is also to investigate radically new paradigms for the storage and release reactions of hydrogen in materials, combining atomistic ab-initio modeling methods with high-resolution surface and structural techniques.

3.1.6 Fusion

Nuclear fusion remains a technology that could provide an immense energy source if challenging science, technology, and cost issues are overcome over the next few decades. It should be emphasized that, as fusion researchers pursue the energy goal, much basic plasma science and advanced technology development is explored. MIT has long had a major fusion program, the Department of Energy-supported Plasma Science Fusion Center (PSFC), which houses a significant technical infrastructure that serves faculty and students from several departments. The PSFC carries out major experiments, such as the Alcator C-Mod Current Drive Experiment. This is an ambitious effort at creating non-inductively driven steady-state plasmas using RF waves. The program also involves testing several concepts for protection of the first wall facing the plasma from the effects of escaping particles. Through the center, considerable knowledge about superconducting magnets has been developed. These, and other work at the Center, supports the next generation international tokamak facility (ITER). The key issue for the MIT fusion program is faculty renewal for sustaining this continuing program.

3.2 Transportation and fuels

The global transportation sector is almost completely dependent on petroleum-based liquid fuels. As already discussed, this is at the core of the oil security problem. It is likely to be exacerbated as transportation demands in the developing and emerging economies grow dramatically, while “conventional” oil resources may prove more difficult to find and produce.

There are several technology-based objectives that can be pursued to alleviate the problem:

1. resource diversification, e.g., expanded use of heavy oil/tar sands that are plentiful in the Americas
2. alternative fuels, e.g., coal- or natural gas-derived liquid fuels; biofuels
3. increased vehicle efficiency, e.g., hybrids, advanced diesels with appropriate environmental performance
4. changed paradigm/different fuel infrastructure, e.g., plug-in hybrids electric vehicles, hydrogen vehicles

MIT has a long history of involvement in transportation. Examples are the development of the engineering science behind engine behavior and pioneering the modern field of transportation system analysis. Its researchers have been instrumental in developing the system-oriented planning and analytical techniques in widespread use today. MIT researchers have also made major contributions to research and development in motor vehicle propulsion technologies and fuels through the Sloan Automotive Laboratory and to jet engine developments through the Gas Turbine Laboratory. MIT researchers are actively involved in improving the efficiency and reducing the emissions of engines, exploring different fuel options, exploring more robust and efficient fuel cell and battery technologies, and achieving vehicle weight reduction through use of new materials. They have also worked on developing strategic metropolitan and regional analytical frameworks for the study of (passenger and freight) transportation energy futures. They have focused on these transportation distributional issues in a wide-range of contexts and are identifying the more promising pathways (technological, behavioral, and institutional) for reducing energy consumption. An important task is to develop feasible strategies for embarking on those pathways and to measure the energy efficiency of proposed alternatives. In addition, there are innovative programs, such as the “concept car” and “car and the city” projects of the Media Lab. A focus will now be to galvanize the diverse range of these transportation and fuels research activities, spanning many departments and schools, so as to provide new research opportunities and advances.

3.2.1 Hydrocarbons: sustaining domestic and global resources

A key issue for addressing petroleum availability is enhanced recovery from existing reservoirs, where recovery rates have typically been in the 30-40% range. Capillary forces, wettability, surface chemical processes, complex pressure/temperature fields, and poorly understood spatial variability in solid and fluid properties contribute to these recovery factors. MIT faculty from EAPS, Mechanical/Ocean Engineering, and Chemical Engineering form the core of a research initiative to address this issue through new approaches based on physical and biological stimulation of existing reservoirs. Pore/molecular scale understanding of solid-fluid surface chemistry will be combined with these stimulation methods. Focus areas will include geophysical stimulation using focused acoustic and electromagnetic energy for activating fluid boundary layers and overcoming capillary forces; biological stimulation (microbes) for increasing production and/or converting heavy oils into more useable fluids; and advances in fundamental understanding of rock-fluid chemical interactions and downhole chemical processes.

Another focus will be on oil and natural gas production in ultra-deep water and in unconventional reservoirs. Natural gas is not a major transportation fuel, but it shares many of the exploration and production issues and is beginning to develop a global market structure with some similarities to that for oil. For ultra-deep water, the focus will be on integration of new remote imaging and characterization methods with the knowledge of deep-water currents and seafloor robotics for construction and production engineering. New imaging and monitoring methods together with enhanced fracture engineering methods will expand the tight gas sands and coalbed methane resource base.

3.2.2 Hydrocarbon fuels for the future

Emerging technologies, in particular coal gasification, may enable coal to produce a wide spectrum of products including liquid fuels. Coal gasification also has the advantage of lowering costs for CO_2 capture and subsequent sequestration. Three complementary research thrusts will be pursued by a cross-disciplinary team: advanced modeling and simulation of processes and systems for feedstock conversion, decarbonization, and new fuel utilization; experimental studies of new processes and fuels; economic, policy, and infrastructure analysis, and system-level modeling tools. MIT is a leader in quantitative modeling and simulation, with particular strengths in simulation technology for process systems engineering, fuel chemistry, gas turbines, internal combustion engines, materials science, electrochemical processes, and environmental sciences. With current computational capabilities, issues related to optimally integrated "coal refineries", plant design with flexibility at both ends (feed supply and products specification), and reduction in environmental footprint with minimal energy and economic cost can all be addressed much more effectively than one or two decades ago.

3.2.3 Biomass to biofuels

The most abundant renewable resource that has the potential to make a substantial difference in liquid fuel supply is biomass. One can certainly imagine an impact of two to three million barrels per day of biofuels in the intermediate term. This would contribute substantially to elasticity in the transportation fuels market. However, overall product yields and productivity must be improved, as they are key factors of the overall process economics.

The research planned will focus primarily on the engineering of microorganisms for optimal biomass-to-biofuels conversion and related bioprocessing issues. An enabling technology residing at the core of this effort is metabolic engineering, an area in which MIT faculty have played a leading role in advancing its principles and methodologies over the past fifteen years. The central theme is engineering of microorganisms using modern genetic tools in order to optimize their metabolic pathways for the overproduction of useful products.

3.2.4 Transportation power trains

There are numerous opportunities to improve performance of internal combustion engines and of hybrid systems. This has been pursued at MIT for many years, but there remain new ideas for the coming years. For example, there are important consequences in maintaining or improving the fuel economy of diesel engine vehicles while meeting increasingly stringent regulations on emissions of air pollutants. The use of onboard fuel reformer technology is a promising approach for addressing these issues in a ten year time frame. A new initiative along these lines would have several elements: after-treatment systems for reduction of NOx, using spatially selective hydrogen regeneration of NOx traps; after-treatment systems for reducing particulate emissions, again using hydrogen-rich gas for regeneration of particulate traps; and use of reformer technology to control auto-ignition in homogeneous charge compression ignition engines.

3.2.5 Freight systems and energy

Worldwide, freight uses about 43% of all transportation energy. Improving the energy efficiency of freight transportation has immediate impact, since supply chains and logistical decisions respond exceptionally fast to incentives. MIT has considerable freight transportation and supply chain expertise to bring to bear on a comprehensive look at the energy-saving opportunities in the freight system. The project will start with an extensive database for several countries/regions in order to assess trends relevant to freight energy consumption. Technical and operational opportunities to reduce energy use will then be identified. Approaches that will be investigated include productivity improvements through supply chain design, modal shifts, infrastructure investment to streamline the transfer of materials, pricing policies and fuel taxes to influence demand and modal choice, congestion pricing, improved communication/tracking systems, and technological innovation in improved propulsion systems.

3.2.6 Developing country metropolises: transportation energy futures

Over the next fifty years, assuming business-as-usual, the use of energy for transportation will double. The growth in transportation energy use will be particularly high in metropolitan areas of the developing world: virtually all net global population growth will take place in developing world cities. A research project will focus on developing strategic metropolitan and regional analytical frameworks for the study of (passenger and freight) transportation energy futures. The focus will be on transportation distributional issues in a wide-range of contexts and to identify the more promising pathways (technological, behavioral, and institutional) for reducing energy consumption for transportation. An important task is to develop feasible strategies for embarking on those pathways and to measure the energy efficiency of proposed alternatives. The research will proceed by selecting "archetype" cities and regions, developing an integrated suite of transportation and land-use supply and demand models, and identifying potential futures and assessing metropolitan transportation energy performance under those futures.

3.3 Science and policy of climate change

When considering the "environment" part of the energy-environment challenge, the dominant issue now and for the decades to come is the threat of global climate change. Existing MIT capability in climate studies is very substantial. Integrated studies of the climate system — involving over a dozen faculty from all five schools and some twenty-five research staff, post-docs and graduate and undergraduate research assistants — are organized under the Joint Program on the Science and Policy of Global Change (joint between the Center for Global Change Science and the Center for Energy and Environmental Policy Research). A fifteen-year effort has been carried out in coupled modeling of the global economy, atmospheric chemistry, climate dynamics (ocean, atmosphere, land) and terrestrial and marine ecosystems. Given the centrality of the climate issue to the evolution of energy infrastructure in the coming decades, the Joint Program is a major asset for MIT's energy initiative. Some expansion in scope and, most important, addressing faculty succession issues are called for, particularly in the areas of reservoir geology, aerosols, climate dynamics, and economics and policy.

Several enhancements of the program are needed. One is the expanded CO_2 sequestration program that was described earlier. Another is in the area of terrestrial ecosystem dynamics, which is important to the study of climate-ecosystem interactions, biomass fuels, and ecosystem carbon sequestration. The program will also contribute to evaluating the problems of scale in the deployment of energy technologies – i.e., in the climate context, proposals for future energy generation must be judged on their feasibility at the Terawatt or greater scale. Multi-disciplinary teams will assess the economic and environmental viability of each candidate energy "solution" through integrated system modeling.

3.4 Understanding energy systems

Many of the research areas discussed above involve combinations of science, engineering, and policy studies. However, some research studies entail critical insights on the entire energy system from political, policy, economic, social and historical perspectives. These studies are important components of the overall initiative since timely deployment of technologies often depends upon public attitudes and public policy.

3.4.1 Learning from the past: energy and society

We must learn from history. MIT faculty have established strong programs studying science and technology in their social contexts. These have revealed how the success or failure of a new technology depends not only upon its intrinsic value but also on the political, economic, and cultural values of society. Historical analysis of energy policy may have valuable lessons for guiding future policy that promotes the public good. Three fields of historical research will be pursued: energy and consumption; energy and the environment; the basic economic and political structures that frame energy in the modern world.

3.4.2 Public attitudes about energy technologies

Public attitudes will guide how and whether governments respond to challenges such as those of climate change or energy security. Public opinion expresses national priorities and the acceptability of alternative policies and technologies. Over the coming decade, public awareness and concern about energy and the environment could change dramatically, if energy prices continue to rise and national policy initiatives and international agreements push countries to take aggressive actions to stem carbon emissions and water and air pollution. Academic research has documented little about what people know and believe about energy and the environment, what tradeoffs they are willing to make, and what policies they find acceptable. Initial MIT energy and environment surveys serve as a foundation for a larger program tracking public opinion on this subject over the coming decades. The overall objective will be to determine the nature of people's preferences about future energy sources and attitudes about economic and environmental tradeoffs.

3.4.3 Energy technology innovation

The provision of fuels, electricity, and energy services is largely a private sector activity in the US and in most other countries. Therefore, decisions on whether to invest in new energy technologies will ultimately be made by private, profit-seeking firms. Yet there is little chance that technological change on the scale needed could be achieved without a major government presence in the energy innovation system. This is problematic for several reasons: the current set of US government policies affecting new energy technology adoption falls short of what would be needed for major change; the record of US government promotion of energy technologies has been very mixed; there is no consensus on the appropriate scope, scale, and institutional design of new government policies in support of energy technology innovation. It is also the case that there will be many different kinds of innovation pathways for new energy technologies. Two broad research tasks will be undertaken: methods for measuring and monitoring the performance of the overall energy innovation system will be devised; new approaches (funding mechanisms, institutions,…) designed to address specific problems and weaknesses in different parts of the energy innovation system will be developed and analyzed.

3.4.4 Energy security

Energy security encompasses a wide range of concerns that are key to the deployment of particular technologies or the provision of energy generally. Of particular importance is research on three subjects. First, worldwide deployment of nuclear power risks proliferation of weapons technologies and materials. Second, energy provision infrastructures, such as grids and pipelines, may be vulnerable to attack and disruption. Third, worldwide dependence on oil for transportation and the globalization of oil markets makes US national security dependent on disruptions in oil supplies due to political unrest in the Middle East, Africa, and elsewhere. MIT offers general expertise in the development of public policies in the national and international arenas that address security issues arising from each of these three key aspects of energy provision. MIT research, particularly that conducted in the Center for International Studies (CIS) and the Center for Transportation and Logistics (CTL), has made and will continue to make fundamental contributions to the development of policies to tackle important energy security issues. Given the wide range of often disparate issues, we see that a sound strategy for investment in this area is to invest in the activities of several centers currently engaging these issues, particularly CIS and CTL, rather than a single effort that attempts to bring these different technology areas under one umbrella.

3.4.5 Energy provision and regulation

Cultural, political, and economic factors have often inhibited or facilitated the application of emerging technologies to energy problems in the past. This research will look ahead to see how such factors are likely to affect the introduction of current emerging technologies. Energy regulation case studies would be used to elucidate several issues: estimates of public costs and benefits (what factors lead to recurring miscalculations of technology benefits?); estimates of private costs and benefits (what changes in regulation or standards of compensation might induce power providers to favor energy efficient technologies?); estimates of health, safety, and environmental risks (how can one overcome the lack of public credibility given to official risk assessments?); and estimates of conditions under which regulation is beneficial and the optimal regulatory structure.

4 Education[2]

Education and research are inextricably woven together at MIT. Major research themes are dealt with elsewhere in this report. This chapter focuses on the classroom, laboratory, project, UROP, and other aspects of the education of our students. We are mindful of the fact that more than the specific research discoveries that come from MIT, our major product is people. It is important that our energy education activities develop the leaders that ensure a bright outlook for the energy future of our nation and world.

Core science disciplines provide essential fundamental concepts important to energy systems whereas engineering and social science disciplines deal with energy technology and choices at both the component and integrated systems levels. Today several multi-disciplinary subjects are offered at MIT that focus on the environment with a connection to energy systems, but the coverage of energy technology and policy is uneven. More subjects with a technology and/or policy focus on energy could be developed within or cutting across all five schools.

At both undergraduate and graduate levels, effective programs begin with core disciplinary subjects, perhaps with an integrative project that provides context and motivation at the same time that students are acquiring these competencies. Then the courses students study spiral upwards through more specialized disciplinary and multidisciplinary subjects and activities such as cross-cultural interactions within and outside MIT. At the end of the program students pursue capstone projects or theses that are both integrative and focused on real problems. These problems can be taken from the MIT campus, the nation, and the world at large.

4.1 Present status and limitations of energy education at MIT

Many students at MIT (and at other universities in the Boston area) have expressed strong interest in energy topics, as evidenced by formation of energy-related clubs and cross registration in a broad range of energy related subjects. The growth of interest in energy has been recent, and mirrors the increased public and political attention given to energy in recent years. For reasons described in Chapter 1, we do not think this interest or attention to energy by students is transient; more likely it will continue to increase over the coming years. At MIT many energy-related subjects exist, attracting a broad range of students from many different backgrounds. Although MIT has strong offerings, the Institute has an opportunity to develop a much more coherent and comprehensive response to these new interests. The current educational offerings exist more as niche activities than as integrated educational programs leading to well recognized energy-relevant degrees. Nonetheless, these provide a solid base for developing new subjects and/or programs.

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[2] Adapted from the white paper, *Energy Education at MIT*, submitted by the ERC Education Subcommittee [Jefferson Tester (chair), Elisabeth Drake, Ahmed Ghoniem, Michael Golay, Leon Glicksman, Amanda Graham, Donald Lessard, Donald Sadoway, Jeffrey Steinfeld and Nafi Toksoz] and the supplement entitled "Ideas and Initial Pathways for Implementing the Proposed Energy Education Initiative."

Factors explaining this situation include a low level of public and political interest in energy problems until the past five years, the traditional disciplinary focus of the Institute's departments, and the lack of a clearly identified group to coordinate energy education and transparent mechanisms for resourcing multidisciplinary education of this sort. The issue of low interest appears no longer to be a problem. The immense disciplinary strength of the Institute's departments can be built on to provide foundational content on which we can construct advanced project, laboratory, and cross disciplinary subjects and experiences. However there is a clear need for an MIT-wide group to guide energy education that cuts across departmental and school boundaries. This group would be important for identifying and addressing opportunities for energy education in the first year and more generally in the GIRs, for developing educational programs that build on the offerings of several different departmental programs, and for providing service and guidance to our students to take advantage of the energy offerings at MIT.

A difficult current problem for delivering interdisciplinary subjects in energy is the provision of teaching resources, particularly teaching assistants. Several very successful subject offerings of this type have had difficulty obtaining TA support, because the large enrollments come from many different departments. The result is that no single department has an obvious responsibility to commit TA resources. Given MIT's past resourcefulness in launching and dealing with new interdisciplinary initiatives, we are confident that issues like this can be resolved. However, it will be helpful to have a core group thinking about best practices and advocating for these core needs.

4.2 Opportunities

There are significant educational opportunities for MIT at both the undergraduate and graduate levels. Below we discuss opportunities in each of these categories.

Given the current review of the General Institute Requirements that is underway, it is timely to consider how energy subject matter could be included in the undergraduate common curriculum. We believe that infusion of content on energy science, technology, and policy into the first year experience would be very valuable in exciting students about learning and provide them context for other parts of the curriculum. Indeed two educational experiments – "Physics of Energy" and "Energy, Environment, and Society" – which were recently approved for funding by the D'Arbeloff Fund, will pilot test approaches for doing this.

There are numerous other possibilities that come to mind, including developing HASS energy subjects or even a core energy theme within HASS as an option for students to pursue. The HASS core could include subjects in energy economics, ethics, and environmental and energy policy, for example. The overarching theme would be to think broadly about specific technology and science opportunities in a broad societal context – using an integrative approach that involves life cycle assessment, decision and risk assessment, system dynamics, and trade-off analytic tools to frame alternatives.

Within existing departmental offerings there is a great opportunity to include energy examples, case studies, projects, and laboratory experiments. For example design projects for the past two years in one department have been taken from the MIT Coal Study. This provides students the opportunity to contribute to an important study, and at the same time provides very timely problems for learning design. In collaboration with the "Walk the Talk" initiatives described in Chapter 5, there is a great opportunity to involve undergraduate (and graduate) students in laboratory, design, and research projects directed at improving MIT's on-campus energy management. We have a great chance to increase the use of the MIT campus as a learning laboratory for energy efficiency and behavior management.

One outreach opportunity for such practice-based learning, with potential for real world impact, is energy projects focused on the needs of developing world countries. MIT already is involving students and faculty in bringing useable technology to the developing world through D-Lab and other faculty/student projects. Developing these types of project activities with a focus on energy and an emphasis on making a difference in the practical world will broaden the world-view of our community, and especially our students, in important ways.

Another significant opportunity lies in developing coherent courses of study in energy that build on existing departmental offerings, perhaps augmented by select new subjects. A useful institutional structure for accomplishing this would be an interdepartmental minor. Given the breath of energy content and issues, there may need to be several flavors of this minor to serve the entire Institute. Since the minor would cut across departments, it would need to be managed by a cross departmental unit, such as the group we have proposed here. Eventually we would like to have a spectrum of subjects that cover the five energy categories: "where it comes from," "making it available," "better ways to use it," "impact on people and the planet," and "making choices."

There is already a wide range of energy subjects and research opportunities across the five schools at MIT, and given the increased focus on energy this situation is likely to get worse (or better depending on your point of view) in the near future. It is important to develop a clearing house of information on energy subjects and UROP opportunities to help students and faculty advisors in designing customized programs of study with emphasis on energy. An energy subject database[3] has recently been launched as a first step. Keeping this information up-to-date and accurate will require regular oversight.

At the graduate level, one of MIT's great strengths is the faculty depth to enable offering a variety of advanced subjects that prepare graduate students for research in specific areas of interest. MIT has the opportunity to create an unparalleled set of advanced graduate subjects in energy that can serve as the basis of text books and education outside of MIT. A research database would be a significant aid to new graduate students at MIT seeking to identify research opportunities for thesis work. The energy subjects database should also be valuable to graduate students.

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[3] http://energyclasses.mit.edu/about.php.

4.3 Recommended strategies and actions

A key issue raised in Section 4.1 is the need for a group to coordinate MIT-wide educational initiatives. Indeed exploiting many of the opportunities identified in the preceding section will depend on such a group. For this purpose we recommend the formation of a cross-school group to guide education efforts in energy at MIT. We call this group the Energy Education Task Force; it would be part of the larger MIT energy initiative. The Energy Education Task Force should be charged with pursuing the opportunities described above and with identifying other educational targets. Priorities for initial work include

- Undergraduate
    - integration of energy content into the first year subjects
    - energy project-based subjects for first year students, e.g., the experiments supported by the D'Arbeloff Fund.
- Undergraduate minor(s)
    - define by January 2007
    - determine if there should be one or several minors
- Graduate
    - identify a set of advanced graduate energy subjects that will facilitate work by graduate students in MIT energy initiative areas
    - determine how to provide resources for developing and offering these new subjects
    - prioritize rollout of the new subjects
- Outreach
    - energy focused student projects in developing world countries
    - couple these student projects with MIT research

Private fundraising for energy education should be pursued as part of the overall energy initiative resource development strategy. These funds will be important for providing faculty support (e.g., summer salary or teaching release during a regular semester) for curriculum development on new energy subjects, projects, case studies, etc. They are also important for supporting additional teaching assistants to cover multidisciplinary subjects with large enrollments across campus.

5 Walking the Talk

The power of leading by example is important to MIT and for facilitating change…While the Energy Initiative itself and the Energy Research Council is envisioned primarily as research and education focused, I very much hope that we will also lead by example and develop programs, adopt technologies, and innovate approaches that model sustainable energy practices on our campus.

- President **Susan Hockfield**, November 14, 2005

5.1 Leading by example

Our campus environment should reflect our commitment to sustainable energy practices. Leading as educators and innovators, we should offer the MIT campus to our students and faculty as a model teaching and research tool, a place they can affect and improve, an energy-conscious place they can embrace as a reflection of their own aspirations for an energy-conscious world. MIT should consider and design a Sustainable Campus Energy Initiative that would entail the following three actions:

- increase MIT campus energy efficiency through feasible approaches that reduce environmental impacts and energy costs,
- take a leadership role in shaping energy practices for energy-intensive research institutions, and
- foster student creativity and activism, inspired by the energy-conscious campus environment, and allow them to develop new ideas for energy-sustainable living that are applied on the evolving MIT campus.

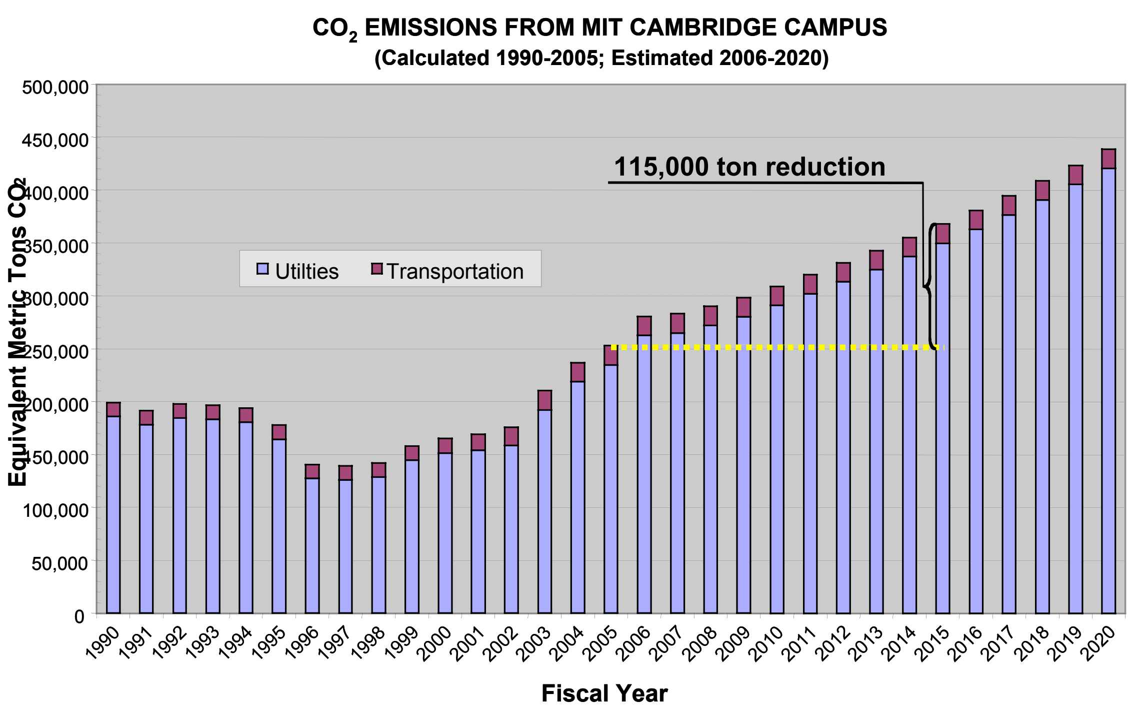
The significant recent development of the MIT campus, undertaken to meet research, educational, and institutional needs, has been accompanied by substantially increased energy use and cost, increased emissions, higher per capita energy use, and frankly, minimal energy conservation practices. Future campus growth, however, can and should better reflect our commitment to sustainable energy practices. We should recognize the present opportunity to embrace a sustainable campus energy initiative rooted in technology, and demonstrate that it is feasible to develop and implement an integrated and cost effective conservation, research, and education program, while not compromising institutional growth. Given MIT's prominence as a technology innovator, such an effort can stimulate sustainable energy practices elsewhere. Entrusted to the hands of our faculty, students, and staff, our campus buildings and grounds could become a teaching and research tool of exceptional effectiveness. Additionally, this effort would also mitigate some of the financial risk associated with rising and volatile energy prices. It can serve as a highly visible campus effort that rallies the entire MIT community including faculty, staff, and students to search jointly for solutions to this important, applied problem, thereby reinforcing the intent of the energy initiative as one that cuts across the whole campus.

A tangible metric of progress of such an initiative is campus greenhouse gas (GHG) emissions. Using this metric has the advantage of linking directly to one of the core challenges that motivates the energy initiative, while indirectly reflecting other goals such as pollutant reduction, waste management, and conservation. It is also an easily articulated metric and thus helpful for measuring and communicating program goals and accomplishments.

5.2 Energy use at MIT

Energy use on campus is characterized by dramatic and steady increases in net energy consumption and energy use intensity, as well as in soaring costs. MIT's predominant energy use is for utility services: providing electricity, heating, and cooling to the 158 academic buildings on campus. Since 1998, MIT's electricity and fossil fuel use has grown by over 60%, while student, faculty, and staff count increased by only 9% and building area by 14%. This represents a significant increase in energy intensity per capita and per square foot. In addition, it is estimated that energy costs will have increased 75% from 1998 by the end of 2006. This upward trend in use and cost is expected to continue in a "business-as-usual" approach.

The increasing energy use inevitably leads to increasing campus greenhouse gas emissions as reflected in a comprehensive analysis[4] conducted at MIT. This inventory was updated to reflect GHG emissions for years 2004 and 2005. Utility emissions account for 93% of total campus GHG emissions, while transportation and solid waste emissions account for 7% and <1% respectively.



[4] Tiffany Groode and John Heywood, "A Methodology for Assessing MIT's Energy Use and Greenhouse Gas Emissions," LFEE Report 2004-002 RP, May 2004.

As shown in the figure, campus GHG emissions have risen dramatically from 1998 through 2005. However, prior to that, there was a substantial emissions drop of about 30%. This was the consequence of the 1995 installation of a combined heat and power generation system (co-generation) that provides a concrete example of major energy and emissions reductions driven by institutional intervention to increase efficiency (the co-gen plant has a net efficiency of about 70%) and to reduce energy costs by several million dollars a year. Since then growing building square footage, increasing energy intensity, and surpassing the maximum capacity of the current co-generation facility have combined to cause our greenhouse gas emissions to grow rapidly. The projections to 2020, shown in the figure, assume campus growth as planned in 2003. The "business as usual" projection is for 46% higher emissions in 2015 as compared to 2005.

5.3 A proposed MIT sustainable campus energy initiative

With a deep institutional commitment to campus wide adoption of sustainable energy practices we can evolve into a model, energy sustainable campus. A group drawn from the ERC, the Department of Facilities, and the Environmental Programs Office developed a detailed quantitative road map for a sustainable campus energy initiative that includes reducing our energy intensity and operating costs, adopting advanced energy technologies, and offering diverse research and educational opportunities. The principal goal of the road map is to demonstrate that through campus efforts MIT's GHG emissions in 2015 (ten years from the start of President Hockfield's energy initiative) can be less than or equal to its value today, even as the campus continues to grow. This is a 32% reduction (115,000 tons of CO_2) from the "business as usual" expectation, and a significant reduction in the projected energy costs. Following 2015, a subsequent 10-year goal and plan would be established to maintain reduced emission levels by adopting the newest of technologies and sustainable energy practices.

Our preliminary analysis indicates that stabilizing emissions to 2005 levels in 2015 could be achieved through a concerted and aggressive energy-management program consisting of co-generation utility plant expansion; infrastructure renewal; energy conservation measures for existing buildings and transportation systems; aggressive sustainable design for all new construction; and campus-focused research. Preliminary analysis has indicated that attractive pay-back periods and significant positive returns on investment are expected for most energy-related projects, ultimately saving the Institute millions of dollars annually in energy costs.

5.4 Assessment

To ensure that the most energy and cost efficient approaches to the development and design of this campus energy initiative are pursued and to understand fully the opportunities, trade-offs, benefits and costs of such an initiative, it is recommended that a comprehensive assessment and analysis of MIT's energy situation and a full financial analysis of the proposal above be conducted. The assessment should compare the proposal with other options with respect to energy effects, cost efficiency, and educational impact. We should select the appropriate activities and develop a detailed implementation plan that emphasizes our institutional values, enhances our educational mission, and demonstrates MIT commitment and leadership. The campus subgroup of the

MIT Energy Council recommended in the next Chapter would be charged with the analysis.

Based on this assessment, there may be many feasible approaches going forward. One may be the creation of a Resource Efficiency Investment Fund and Innovation Center to support educational and research efforts aimed at creating a more energy efficient campus. Analogous to the MIT Deshpande Center for Technology Innovation, the Innovation Center would drive infrastructure efficiency improvements and innovation; support sustainable and high performance design; drive down energy costs; and enable faculty and student researchers to use MIT campus as a learning laboratory. Additionally, efforts supported by the Innovation Center would intimately link MIT's academic endeavors with the daily efforts of the Department of Facilities, unifying the campus across these traditional institutional boundaries. Several MIT student organizations – including the Energy Club, Students for Global Sustainability, SAVE, MIT Student Pugwash, and Design for Change – have all expressed interest and support for this energy initiative, thereby laying the groundwork for substantial student collaboration. The education subcommittee of the Energy Research Council has fully endorsed this idea as an important and valuable vehicle to provide energy-focused educational opportunities for students.

A revolving loan fund would be established that would be replenished by savings achieved from project-related reductions in utility consumption, waste generation, and operating costs. By using the accrued interest portion of the loan, the fund would also be able to provide grants for faculty and student research and education projects that support campus resource efficiency and innovation, GHG reductions, and other energy and environmental objectives. In addition, the Innovation Center would raise additional funding for applicable faculty and student research.

There are clearly many barriers to implementation of the proposed plan for a sustainable campus energy initiative. Funding is perhaps foremost. Investments for conservation and infrastructure renewal, which compete with many other demands for funds from both capital and operating budgets, would have to be raised in priority. If departments, labs, and other units could capture some of the savings from reduced energy use, results might improve. It may also be necessary for MIT and other institutions to work with government to revise indirect cost accounting rules so as to provide or increase incentives for energy efficiency and conservation. Indeed, working with other institutions with similar energy challenges and sharing best practices and lessons learned on all aspects of "walking the talk," especially research universities, is likely to be very productive.

6 Organization

6.1 A Brief History

In 1972 MIT created the Energy Laboratory to provide a focused program to bring together its breadth of expertise in natural and social sciences, engineering, planning, and management and to expand both the technical and social-science aspects of research in the field of energy. The Energy Laboratory was organized as a special research center reporting to the MIT Vice President for Research. For three decades the Energy Laboratory conducted research, educated students, and performed public service in support of economically sound, globally conscious, and environmentally responsible energy policies and technologies. Laboratory activities engaged multidisciplinary groups of faculty, professional staff, students, and visiting investigators in research on a wide range of topics related to energy supply, technology, utilization, and policy. Research volume of the Energy Laboratory grew robustly in its initial decade, driven by the "energy crisis" of the late 1970's, going from about $600,000 in FY '73 to a peak of about $13 million in FY '81. However, a declining sense of urgency in the nation's energy research agenda in the subsequent decades was matched by a declining funding base for the Energy Laboratory.

In 2001 the Energy Laboratory and the Center for Environmental Initiatives were merged to create a new Laboratory for Energy and the Environment (LFEE). As described in the 2003-2004 LFEE Report to the President[5]:

> "The 2001 founding of LFEE culminated MIT's 10-year effort to bring together researchers from all corners of the Institute to collaborate on problem solving and innovative management in support of a sustainable future. LFEE includes 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. LFEE scholars look at single technologies in depth and also across technologies to see how their use and improvement might lead to better management and policy formation.
>
> "The Laboratory for Energy and the Environment (LFEE) supports, coordinates, and conducts research and education on sustainability issues that influence development and welfare worldwide. A central theme running through all of LFEE's initiatives is the role of science and technology in shaping better environmental policy at all levels in both the public and private sectors. The education program of LFEE is committed to educating the next generation of environmental and sustainability leaders worldwide through joint projects locally and nationally and through participation in international education programs with our partners around the world."

Thus in the early 2000's there were both intellectual and fiscal drivers for creating the merged laboratory. Like the Energy Laboratory that preceded it, LFEE has an MIT-wide charter for organizing research and educational activities.

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[5] MIT Reports to the President 2003-2004, p. 3-53 (also http://web.mit.edu/annualreports/pres04/03.05.pdf.)

Given the compelling need for MIT to take a global leadership role in energy research and education coupled with outstanding opportunities for these identified in the previous chapters, there is a clear need for a *distinct* MIT organization to seed, foster, and nurture these activities. The desire for a clear focus on energy coupled with the need for a number of attributes not found in LFEE, e.g., control of core central space, leads us to conclude that a new organization is needed at MIT. In the next section we describe the new organizational structure, and in the following section we discuss the path from our current structures to the new one.

6.2 A New Organization

If MIT is to develop over several years a balanced portfolio of multiple, interdisciplinary, energy research thrusts, and if it is to project leadership in energy research and related student training, a strong inter-school laboratory or center is needed. This laboratory should *not* subsume all energy-related research at MIT (e.g., individual investigator efforts or department-focused laboratories and centers), but should act as an umbrella for developing sustained interdisciplinary research thrusts identified with the MIT President's energy initiative and for supporting affiliated centers and programs.

It would be confusing (both internally and externally) and inefficient for MIT to have multiple organizations charged with a common mission of organizing cross-disciplinary research and education in energy at MIT. The new center should be a focal point for senior MIT Administrators, Deans, Department Heads, and key faculty to shape the portfolio of interdisciplinary research thrusts. It must have a director who provides leadership in advancing the key "conversations" that match important energy research areas, faculty interests, department recruiting interests and opportunities, and resource development.

6.2.1 Attributes

A number of key attributes important to the success of a new center are:

1. Central space. We do not envision central space to house all energy research and education at MIT, but rather space to provide unique, central facilities of value to a broad cross-section of energy research on campus as well as to provide a location for demonstration/pilot projects of a scale larger than can fit ordinarily in individual faculty research laboratories. The need for central space is particularly important and will distinguish the new energy laboratory or center from previous energy organizations at MIT.
2. A strong professional staff (research scientists and engineers…), chosen to meet the needs of faculty-driven research efforts, that can devote full time to development and execution of sponsored, sustained interdisciplinary research efforts. There needs to be leadership and professional development opportunities for these staff members.
3. Substantial discretionary/seed funding (e.g., graduate student and postdoc support) for kicking off promising new multi-faculty thrust areas.
4. A strong MIT steering committee to work with the Director on key decisions. An important element for the success of the laboratory is the stringent and

regular review of its programs. The steering committee should work with the Director in the seeding of significant new areas of energy research and in increasing, decreasing, or ceasing existing research activities.

5. A strong external advisory committee, with significant industry representation, for input on major research directions as well as other activities of the center.
6. A Visiting Committee reporting to the Provost/VP for Research evaluating progress and performance on a regular basis.
7. A focal point for interdisciplinary discussion/communication both internally and externally. Examples of useful activities to be undertaken include managing an Institute energy web site/portal, convening workshops with industry, sponsoring a colloquium and seminar series, facilitating discussions across schools and department on hiring needs and opportunities in the energy area, and organizing educational programs in energy that involve multiple academic units.

6.2.2 Education

The center should have an important educational mission in addition to its research focus. There are several aspects to this educational mission. First, there is an obvious and natural connection between the energy research carried out by graduate and undergraduate students and the educational mission of MIT. Second, there are educational functions that do not fall well within a single department, which could be more naturally handled by the new laboratory. Examples cited in Chapter 4 include the creation, administration, and evolution of an undergraduate minor(s) in energy and the allocation of central teaching resources (TAs) to multidisciplinary subjects in energy. Third, there is a need for a central information source on subject offerings in energy; given the broad range of subject matter offered and the diversity of the offering departments, students need a central source (database) to help in identifying subject offerings relevant to their individual programs.

To integrate interdepartmental and interschool education work into the energy initiative, an Energy Education Task Force should be established to guide development of an integrated set of educational options. This task force would also be a natural resource to coordinate with the numerous student groups and student initiatives on campus. The Energy Education Task Force is one of several standing committees reporting to the Director and Executive Steering Committee. Members of the Task Force are appointed by the Director.

6.2.3 MIT energy management

An MIT Energy Management Task Force, comprised of faculty, MIT Facilities representatives, Environmental Office representatives, and students, should be established to coordinate the on campus energy initiatives discussed in Chapter 5. The MIT Energy Management Task Force is one of several standing committees reporting to the Director and Executive Steering Committee. Members of the Task Force are appointed by the Director.

6.2.4 Energy Council

An Energy Council, with faculty from all MIT Schools, should be established and charged with continuing oversight of the energy initiative. Membership on the Council is to be selected by the Provost in consultation with the Director and the Deans of the five Schools at MIT. This Council should be appropriately charged by the Provost consistent with its role in implementing the energy initiative. In Section 6.3 elements of this charge are enumerated. It will serve as the laboratory Executive Steering Committee.

6.3 Path forward

How do we get to the structure envisioned in the previous subsection? We do not believe that it is feasible or desirable to attempt to create this laboratory or center immediately. On the other hand, we do believe that it is essential to put in place immediately a committed leadership group to guide actively the transition to the new structure. We therefore recommend the creation of an independent steering organization, named the MIT Energy Council (MITEC), which would be charged with carrying out MIT's new energy initiative. The structure in which this Council functions is shown in Fig. 1; it mirrors the ultimate structure of the new laboratory. The MITEC will have the authority and power to carry out the MIT energy initiative, including constructing the appropriate interdepartmental laboratory structure. That is, we envision an evolutionary process. It is the goal to have a self-sufficient laboratory in place within five years from the creation of MITEC.

There are a number of attributes of the construction and charge of this Council that we feel are important to its success. These include

1. The chair/director has sufficient authority and responsibility for carrying out the mission of the Council.
2. The Council has broad, competent membership from across MIT.
3. There needs to be a commitment of initial space for the energy initiative.
4. The Council (and energy initiative) should not be monopolistic, in the sense that there is no attempt to bring all energy research and education at MIT under the auspices of this Council.
5. The Council has a strong External Advisory Board, consisting of leaders from industry, academia, and government, to advise the chairman/director on issues such as major research directions. This Board should meet at least twice a year.
6. A long-term commitment, at least five years, is made to this Council.
7. The External Advisory Board serves in the role of a Visiting Committee and reports regularly to the Provost/VP for Research to evaluate progress and performance on a regular basis. At such time as a permanent laboratory or center is established, a Visiting Committee should be appointed; the Visiting Committee would meet less frequently than the External Advisory Board.

We furthermore feel that it is important that the charge to the Council contain among other elements

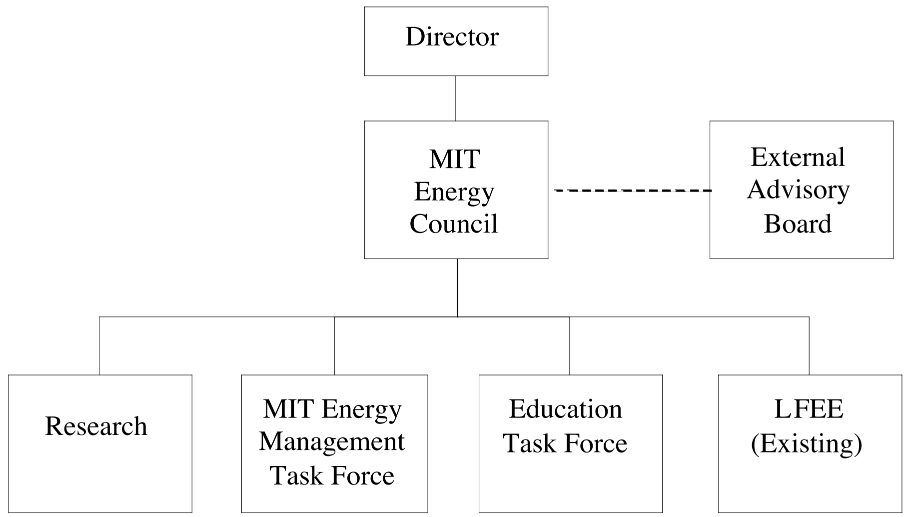

Figure 6.1. Organizational structure for the energy initiative.

1. The Council successfully implements the research and educational initiatives set forth in other parts of this report.
2. The Council evolves an interdepartmental laboratory for the long-term conduct of the MIT energy initiative.
3. The Council works with the faculty and senior administration to develop financial resources to ensure self-sufficiency of the MIT energy research initiative within five years. To this end, the Council is expected to assist actively in fund-raising for energy at MIT.
4. The Council should provide a home for interdepartmental educational initiatives in energy at MIT.
5. The Council should allocate resources, financial and space, to fulfill its mission. This includes distribution of research funding to faculty groups conducting research that is part of the initiative and providing seed funding for new, promising research and education ventures of potential benefit to MIT broadly. The Council should also work to ensure that adequate teaching resources, e.g., teaching assistants, be provided to large, Institute-wide energy subjects.
6. The Council should serve as a focal point for interdisciplinary discussion and communication in energy (manage web site/portal, workshop convener with industry, colloquium and seminar series …).

7 Launching the Initiative

MIT clearly has many opportunities for responding to the energy challenge

- expanded multidisciplinary research that helps to provide technology and policy options for an uncertain energy future
- a focused effort to increase and organize energy curricula and educational opportunities for tomorrow's innovators and leaders
- campus energy management projects and practices that lower operating costs, reduce emissions, and generate exciting student research and education.

Realistically, the portfolio development will – and should – take time. The portfolio will grow according to evolving faculty and student interest, ongoing recruitment of new faculty, and resource development from individuals, foundations, industry, and government.

A major multidisciplinary, multi-faculty, multi-year, research program will typically call for sustained support in the one to several million dollars per year range, requiring commitment from faculty, sponsors, and administration. Educational and campus energy initiatives will also take resources.

This clearly suggests a phased approach, an initiative that grows over several years through a process that continuously nurtures new research collaborations and the associated resource development. Significant resources will be needed early to launch some research areas that have well developed plans and collaborations, together with seed funding to support multiple developing research initiatives that can then grow into new major sustained programs. It is important that the portfolio consists of robust program elements, rather than a collection of subcritical efforts (of course, a multitude of individual investigator programs will be going on in parallel, as is the case today).

The criteria for guiding this portfolio development will include:

- committed faculty groups: multidisciplinary participation, leadership, track record in related areas and/or in key enabling disciplines
- importance of the proposed research to the energy challenges outlined in Chapter 1, including scale of and time scale for potential impact, and overall portfolio balance in addressing the challenges
- comparative advantage and coherence of the research plans
- prospects for adequate support, both financial support from donors, industry, and/or government, and also support of relevant departments (faculty hiring, space,…).

We cannot predict today how this process will evolve, any more than we can "pick winners" for the global energy system later in this century. Nevertheless, we can suggest what an initial research portfolio might look like, one that we are well poised to launch in the near term. Each of the research areas alluded to here was discussed in Chapter 3.

These represent our judgments for good starting points for building up the initiative over several years in light of the above criteria.

7.1 A phased research agenda

As outlined in Chapter 1, we envision a balanced portfolio, aligned with our faculty's interests and capabilities, that addresses the enabling basic science and technology that may underpin major transformation of the global energy system in several decades, that develops the technology and policy needed to make today's energy systems more economic, secure, and environmentally responsible, and that develops the energy technology and systems design needed for a rapidly developing world.

7.1.1 Science and technology for a clean energy future

Solar power is often recognized as the renewable resource with the greatest long term potential, well over a hundred TW, but in many ways with the longest technology road to travel to large scale impact. Major issues include the need for substantial cost reductions and for major advances in inexpensive energy storage so as to overcome intermittency for a functioning system (a problem for wind systems, as well).

MIT has a considerable spectrum of relevant activities – production manufacturing design for cost reduction, new photovoltaic materials development (such as organic semiconductors), basic science (conversion of water into hydrogen and oxygen by sunlight), and policy aimed at advancing innovation and deployment. Most likely with a combination of donor and industry support, such work could be expanded significantly and quickly, and then broadened further with new faculty in selected areas.

There are many additional areas of interest that could be developed relatively quickly with significant near-term seed funding of multidisciplinary faculty groups, and we mention two. Electrochemical storage and conversion, one of the pathways mentioned above to address the intermittency of certain renewables, is an area of considerable faculty strength and activity and is ripe for expansion. Research in electrocatalysis, nanoscience-enabled storage, and new materials for hydrogen storage would be at the core of the program. A biofuels group, centered mainly in chemical engineering and in biology, has come together to propose a research thrust that builds on unique MIT core competencies in bioengineering – optimized metabolic pathways.

7.1.2 Improving today's energy systems

MIT has a strong science, technology, and policy base for expanded research in nuclear power systems and a key relationship for partnership with the DOE national laboratory system and its extensive infrastructure. There are indications that government-sponsored research in this area will, after a long period of very modest support on a narrow range of problems, dramatically increase in size and scope. In addition, a multidisciplinary group of MIT faculty has performed an extensive analysis of nuclear power issues, including an analysis of strategic research and development directions. An expanded program here would include research in advanced fuel cycle simulation and technology, materials development for high temperature reactor conditions, advanced modular reactors, and analysis of international institutional approaches to support the nonproliferation regime. As the program develops, some specific faculty hiring needs would have to be addressed.

Significant faculty groups can be seeded to develop crucial cross-cutting tools and applications that are difficult for individual firms to develop because of the inherently multi-disciplinary nature of the problems. One such theme brought forward by the faculty repeatedly is multi-scale modeling and simulation – from molecular to engineering scale, from technology component to complex integrated systems. Examples of applications are: "coal refineries" that yield a suite of hydrocarbon-based, high-value products; highly efficient integrated systems made up of different energy conversion components optimized for different operating conditions; and network architectures integrating advanced sensors, communications, and controls. The expectation is that such a program would also serve to guide and stimulate laboratory work on key science and engineering work on these systems, perhaps selectively growing into pilot scale campus facilities. Hydrocarbon conversion to power, chemicals, and fuels is a likely early focus.

Another integrating focus area is subsurface energy science and engineering. This would bring together faculty from several departments (EAPS, mechanical engineering, chemical engineering, nuclear engineering,…) to bring new capability to studies of enhanced oil and gas recovery, carbon dioxide sequestration, geothermal energy, enhanced nuclear waste isolation, methane hydrates, and other important energy issues. While starting with a strong faculty core, targeted faculty recruitment in several departments would be needed over a few years to have these programs reach their full potential.

7.1.3 Energy systems for a rapidly evolving world

Integration of the science and policy of climate change is central to understanding how the global energy system will evolve, particularly in the face of developing and emerging economic (China, India, Brazil, Indonesia,…) demand. MIT has a strong foundation and well-recognized efforts in climate change, bringing together natural science, computation, economics and policy, and integrated assessments. A first step would be to extend the scope of this effort with enhanced support and targeted faculty recruitment over a few years.

Next steps can advance strong programs in energy efficiency and in transportation to new levels of activity, scope, and cross-campus integration. These are programs that can have particular importance for developing and transition economies, reflecting the inherently global nature of the energy challenge in the next several decades. Research in building design and operation has spawned collaborations from Cambridge-MIT to China and addresses enormous opportunities for energy conservation and efficiency, especially electricity. Such research would also integrate very well into an enhanced effort at campus energy management and student (specifically including undergraduate) research. Thermal management for industrial processes also offers major benefits, with research spanning core technologies such as thermoelectrics to system analyses of process design. Also regional and income distributional issues in a wide range of contexts need to continue to be studied by developing strategic metropolitan and regional analytical frameworks for determining (passenger and freight) transportation energy futures. The aim will be to identify the more promising pathways (technological, behavioral, and institutional) for reducing energy consumption for transportation.

In transportation research MIT has had considerable strength and impact for a long time, spanning propulsion system and vehicle technology development to transportation fuels and systems and policy studies. This strength continues and can be amplified with enhanced cross-campus collaboration. Opportunities range from improving vehicle efficiency and emissions control technologies to addressing infrastructure issues for alternative fuels to system analysis of global freight delivery networks. The systems studies would draw in faculty from areas such as the Sloan School, ESD, and supply chain management.

7.2 Education

MIT is an ideal place to demonstrate the power of combining education and research in producing leaders for tomorrow in energy. Not only should we engage both undergraduate and graduate students in integrative, multidisciplinary energy-related projects as part of their education, but we should also produce and deploy educational content and materials for use here and beyond the borders of MIT. To guide development of an integrated set of educational options and to integrate interdepartmental and interschool education work into the energy initiative, an Energy Education Task Force should be established. This task force will report to the MITEC.

Priority actions for education at the undergraduate level include the integration of energy content into the undergraduate first year experience and GIR's and the creation of an interdepartmental energy minor. We encourage experiments on the use of energy project-based subjects for the first year as exemplified by two underway next year: "Physics of Energy" and "Energy, Environment, and Society." An energy minor (or minors) offers a low-overhead mechanism for exploiting the energy strengths across campus to provide our students with a formal means to specialize in energy. UROPs provide a natural connection between undergraduate education and research. We need to work to make these more available to our students by providing listings on an energy education web site and by supporting additional UROPs. At the graduate level, we should identify a set of advanced graduate energy subjects that will facilitate research work by graduate students (and advanced undergraduates) in MIT energy initiative areas. These will need to be prioritized to facilitate their systematic introduction.

7.3 Walking the talk

Improving campus energy management holds promise for lowering energy use and cost, reducing emissions, and providing an important learning environment for faculty, students and staff. Following a thorough assessment and analysis, a Resource Efficiency Investment Fund and Innovation Center might be established within an MIT Sustainable Campus Energy Initiative. The fund would be structured as a revolving fund for energy saving projects with reasonable pay-back periods. In addition, it would enable faculty and student research that uses MIT's campus as a laboratory for energy efficiency and conservation. The Center would be a focal point for sharing best practices and lessons learned with other institutions and for recommending both internal and government policies that incentivize individual departments, laboratories, and other units for improved energy use.

Campus greenhouse gas emissions can provide a useful metric for such an initiative, since it is easily articulated and communicated, encompasses other environmentally motivated activities (such as pollutants and recycling), and links directly to one of the core energy challenges that motivate the energy initiative. Indeed, it is quite possible that a mandatory greenhouse gas emission program will be implemented nationally within a decade, and perhaps sooner regionally. A target of returning to today's emissions levels in ten years is challenging (a 32% reduction from projected levels) but doable with about 20% energy use efficiency improvements, expansion of the high-efficiency cogeneration plant to meet increased campus needs, and energy efficient design of all new buildings. Steps needed to implement such a program are discussed in Chapter 5.

7.4 Organization

The energy initiative outlined in this report is ambitious, but appropriate for MIT. To ensure its success, an organization needs to be created with clearly defined responsibility to steer the initiative and to serve as a focal point for cross-department and school initiatives and activities in energy. We envision a different organizational structure than MIT has used in the past for energy research. An Energy Council should be created to guide this organization and have broad representation from the five schools at MIT. The Council will be led by a Director with responsibility for the successful implementation of the initiative and its programs and be advised by an External Advisory with leaders from industry, academia, and government.

Several subgroups will report to the Energy Council. These include the research thrusts, educational task force, and campus energy management task force. In addition we recommend that the existing LFEE be moved inside of this organization and also report to the Council. This will help MIT to maintain a single, clear interface to the world on energy and help to integrate quickly current LFEE activities with the new energy initiative.

The Energy Council should move towards the creation of a permanent energy laboratory or center within five years of the launch of the initiative. It is critical that the new organization have central research space to facilitate its mission.

8 Appendices

8.1 Summary of input from ERC subcommittees

8.1.1 Undergraduate student input (Leeb, Armstrong)

To solicit comments and ideas from MIT undergraduate students across the Institute regarding energy issues and undergraduate education, three seminar-style open forums were held at three different locations across MIT in September of 2005. These seminar forums were organized as study breaks with food. Two were held in dormitories (Baker House and Simmons House) and one was held in the Grier Room in MIT Building 34. In every case, the forums were advertised across the campus with posters and e-mail. The Simmons event was advertised to every MIT undergraduate via e-mail from the Registrar. The Grier room event was advertised via e-mail through the departments and the undergraduate academic support office (to include freshmen). Professor Leeb organized and ran the Simmons and Grier events with assistance from Professor Muriel Medard and Anne Hunter. Professor Les Norford organized and ran the Baker house event with assistance from Professor Dava Newman. There were approximately 60 students in attendance at the Baker event, 60 students in attendance at the Simmons event, and over 160 students at the Grier Room event.

Each of the three events followed a similar agenda. The program began with a 25 minute lecture delivered by the event coordinator (either Professor Leeb or Professor Norford) reviewing the operation of an electric vehicle. With a fresh or renewed appreciation for the energy storage capabilities of petrochemicals, students and the coordinator discussed the petroleum production peak question ("Hubbert's peak"), and expanded into a more general discussion of energy sources, environmental impact of energy production and consumption, and the possible roles and responsibilities of MIT students and graduates in answering future challenges arising from energy and environment problems. Students met in breakout groups to review the questions on a survey form for approximately 20 to 30 minutes. Then, a one-to-two-hour open discussion was held to review thoughts on the survey questions and any other topics of interest. Each event lasted two to four hours. The discussions at all three events were spirited. The event coordinators collected comments in two different ways: by notes taken during verbal discussions and by survey forms distributed at the events.

8.1.2 Graduate student input (Moniz, Armstrong)

Input from the graduate students was facilitated by the Energy Club. Ideas from the graduate students were collected by an Energy Club committee co-chaired by Greg Singleton and Libby Wayman. Results were summarized in an Energy Club White Paper[6]

[6] *White Paper to the Energy Research Council* submitted by the MIT Energy Club, by David Danielson (Materials Science and Engineering), Greg Singleton (Technology and Public Policy), Libby Wayman (Mechanical Engineering), Mike Berlinski (Technology and Public Policy), Mark Bohm (Technology and Public Policy), Kristian Bodek (Mechanical Engineering), Will Bradshaw (Urban Studies and Planning), Nolan Browne (Sloan School of Management), Chris Jones (Office of Graduate Students), Nick McKenna (Engineering Systems Division), David Miller (Engineering Systems Division).

and presented and discussed with the ERC at one of our regular meeting. The graduate students had thoughtful comments and recommendations on a wide range of issues covering organization, education, research, Institute energy goals, and activities beyond the classroom and laboratory.

8.1.3 Alumni input (Armstrong, Moniz)

With the help of the Alumni Office and the Resource Development Office, Professors Moniz and Armstrong held individual meetings with a number of interested alumni during visits to campus. Professor Moniz also met with MIT Alumni Clubs in San Francisco and Washington DC to discuss the work of the Council and to solicit ideas and input.

8.1.4 Industry input (Deutch, Ceder, Heywood, Polenske, Shao-Horn, Armstrong, Moniz)

The primary mechanism for industry input was the ILP Industry Energy Workshop held on campus December 6 and 7, 2005. The workshop was structured to inform the industry attendees about the MIT Energy Initiative goals and objectives and describe some of the exciting energy research underway at MIT today. Most importantly, breakout sessions were included to engage industry in a very active discussion to learn from industry its ideas on

- significant science and technology needs/barriers for affordable, sustainable energy,
- where MIT can make a difference, and
- how MIT and industry can best work together on the challenges identified.

Approximately 80 leaders from industries representing the fuels, transportation, electrical utility, and consumer products sectors attended.

8.1.5 Research White papers (Green, Armstrong, Moniz, Nocera)

We solicited white papers describing major multidisciplinary research areas MIT should pursue in the short term (5-10 years) and long term (10-30 years) and outlining the institutional resources and actions required to make these practical. Each white paper was limited to five pages and authors were requested to use the following format:

1) A one-page description of the motivating energy problem in non-specialist language, i.e. why is this important?
2) No more than three pages briefly summarizing the state of the art in addressing this problem globally and at MIT and outlining outline the sorts of short- and/or long-term research or other activities that should be done by MIT to contribute significantly to solving the problem.
3) A one-page conclusion estimating the level of investment required to perform this research, including the rough annual funding level required, the number of faculty required (and whether achieving this number would require new faculty hires in the near future), any organizational/ institutional change required to make it practical to address this problem effectively, and any major space or facility requirements beyond that normally available to MIT faculty. Those submitting were asked to identify likely sponsors for the activity, if known, and mention any major issues associated with working with those sponsors.

In order to foster broad engagement in the submissions, the white papers were posted on the web and one-page responses from the faculty to any of the submitted papers were invited and also posted. We were very pleased by the broad and extensive response of the faculty to this call.

Subsequent to discussion of the five-page white papers by the Council, we requested follow-on two-page write-ups on proposed, focused, major, multidisciplinary research initiatives. In many cases these were used to clarify or combine ideas in the original white papers. We specifically sought information on available faculty resources for conducting the research, leadership, additional faculty hires or succession issues relevant to the program, potential for significant impact of the research, and brief specifics about the research approach.
Forty-five white papers and two-page proposals were submitted, and a complete listing of these is given in Appendix 8.2 below. A brief summary and discussion of these submissions is given in Chapter 3.

8.1.6 Education/curriculum (Jefferson Tester, Elisabeth Drake, Ahmed Ghoniem, Michael Golay, Leon Glicksman, Amanda Graham, Don Lessard, Donald Sadoway, Jeffrey Steinfeld and Nafi Toksoz)

From the early deliberations of the Energy Research Council and from broad input from faculty, undergraduate students, and graduate students, it was clear that any energy initiative at MIT should include education (interpreted broadly) as well as research. This committee was asked to make recommendations to the Council on what MIT should do in energy education. They produced a white paper, *Energy Education*, as well as a two-page addendum recommending specific actions in education, which together serve as the basis of Chapter 4 of this report.

8.1.7 MIT facilities/campus activities (Bulovic, Ansolabehere, Kazimi)

MIT Facilities was eager to participate with the ERC in exploring avenues for MIT to be an example of energy efficiency and responsibility as well as a source of new ideas, science, technology, and policy. These discussions led to a white paper, *Leading and Educating by Example: A Greenhouse Gas Reduction Initiative for MIT Campus Operations*, and serves as the basis of Chapter 5 of this report.

8.2 White papers submitted to the Energy Research Council

1. *Carbon Dioxide Capture and Storage* - Howard Herzog (Laboratory for Energy and the Environment), Arthur Baggeroer (Mechanical Engineering), Gerbrand Ceder (Materials Science and Engineering), Herbert Einstein (Civil and Environmental Engineering), Julio Friedmann (Lawrence Livermore National Lab and visitor in EAPS), William Green (Chemical Engineering), Charles Harvey (Civil and Environmental Engineering), Alan Hatton (Chemical Engineering), Jim Katzer (Laboratory for Energy and the Environment), Gregory McRae (Chemical Engineering), David Mohrig (Earth, Atmospheric and Planetary Sciences), Peter Stone (Earth, Atmospheric and Planetary Sciences), Bernhardt Trout (Chemical

Engineering), Franz Ulm (Civil and Environmental Engineering), Andrew Whittle (Civil and Environmental Engineering)

2. *Clean, High Efficiency Diesel Engine Vehicles Using Onboard Fuel Reformer Systems* - Dan Cohn (Plasma Science and Fusion Center), Leslie Bromberg, (Plasma Science and Fusion Center), Jeff Freidberg (Nuclear Science and Engineering; Plasma Science and Fusion Center), John Heywood (Mechanical Engineering and Sloan AutoLab), Rick Temkin (Plasma Science and Fusion Center), Victor Wong (Laboratory for Energy and the Environment), Gerald Fink (Biology and Whitehead Institute), Kristala Prather (Chemical Engineering), Chokyun Rha (Biomaterials)

3. *The Climate Project* – Ronald Prinn (Earth Atmospheric and Planetary Sciences)

4. *Converting Biomass to Biofuels through Biotechnology* - Gregory Stephanopoulos (Chemical Engineering), Charles Cooney (Chemical Engineering), Anthony Sinskey (Biology), Graham Walker (Biology)

5. *Developing Country Metropolises: Transportation Energy Futures* – Christopher Zegras (Urban Studies and Planning), Cynthia Barnhart (Civil and Environmental Engineering/Engineering Systems Division), Moshe Ben-Akiva (Civil and Environmental Engineering), Stephen Connors (Laboratory for Energy and the Environment), Ralph Gakenheimer (Urban Studies and Planning), Carl Martland (Civil and Environmental Engineering), Karen R. Polenske (Urban Studies and Planning), Fred Salvucci (Civil and Environmental Engineering), Joseph Sussman (Civil and Environmental Engineering/Engineering Systems Division), Nigel Wilson (Civil and Environmental Engineering)

6. *Efficient Thermal Energy Direct-Conversion and Utilization Technologies* – Gang Chen (Mechanical Engineering), M.S. Dresselhaus (Electrical Engineering and Computer Science and Physics), J. Buogiorno (Nuclear Science and Engineering), L. Glicksman (Architecture), J. Lienhard (Mechanical Engineering), B. Mikic (Mechanical Engineering), M. Kazimi (Nuclear Science and Engineering), R. Ram (Electrical Engineering and Computer Science), Sidney Yip (Nuclear Science and Engineering)

7. *Electrochemical Conversion Technologies* - Yang Shao-Horn (Mechanical Engineering), George Barbastasthis (Mechanical Engineering), Kimberly Hamad-Schifferli (Mechanical Engineering), Nicola Marzari (Materials Science and Engineering), Daniel Nocera (Chemistry), Jefferson Tester (Chemical Engineering)

8. *Electrochemical Energy Conversion and Storage Technologies* – Gerbrand Ceder (Materials Science and Engineering) and Yang Shao-Horn (Mechanical Engineering), Gang Chen (Mechanical Engineering), Nicola Marzari (Materials Science and Engineering), A. Mayes (Materials Science and Engineering), Donald

Sadoway (Materials Science and Engineering), Harry Tuller (Materials Science and Engineering)

9. *Emerging Technology and Energy Security: Looking Back to Look Ahead* - Kenneth Oye (Department of Political Science)

10. *Emissions Control from Mobile Sources* - Bernhardt L. Trout (Chemical Engineering)

11. *Energy Club White Paper* - David Danielson (Materials Science and Engineering), Greg Singleton (Technology and Public Policy), Libby Wayman (Mechanical Engineering), Mike Berlinski (Technology and Public Policy), Mark Bohm (Technology and Public Policy), Kristian Bodek (Mechanical Engineering), Will Bradshaw (Urban Studies and Planning), Nolan Browne (Sloan School of Management), Chris Jones (Office of Graduate Students), Nick McKenna (Engineering Systems Division), David Miller (Engineering Systems Division)

12. *Energy Education* - Jefferson Tester (Chemical Engineering), Elisabeth Drake (Laboratory for Energy and the Environment), Ahmed Ghoniem (Mechanical Engineering), Michael Golay (Nuclear Science and Engineering), Leon Glicksman (Architecture), Amanda Graham (Laboratory for Energy and the Environment), Don Lessard (Sloan School of Management), Donald Sadoway (Materials Science and Engineering), Jeffrey Steinfeld (Chemistry), Nafi Toksoz (Earth Atmospheric and Planetary Sciences)

13. *Energy Future of the Built Environment* - Leon Glicksman, (Architecture and Mechanical Engineering), Marilyne Andersen (Architecture), Yung Ho Chang (Architecture), John Fernandez (Architecture), David Geltner (Urban Studies and Planning), David Laws (Urban Studies and Planning), Steve B. Leeb (Electrical Engineering and Computer Science), Les Norford (Architecture), Karen R. Polenske (Urban Studies and Planning), Andrew M. Scott (Architecture), David Wallace (Mechanical Engineering), Jan Wampler (Architecture)

14. *Energy Security* - Steve Ansolabehere (Political Science), John Deutch (Office of the Institute Professors)

15. *Fossil Fuel Electric Power Generation* - Janos Beer (Chemical Engineering)

16. *Freight Transportation and Energy* - Daniel Roos (Engineering Systems Division), Yossi Sheffi (Civil & Environmental Engineering, ESD), Chris Caplice (Center for Transportation and Logistics), Randolph Kirchain (Materials Science & Engineering), Henry Marcus (Mechanical Engineering), Carl Martland (Civil & Environmental Engineering), Karen Polenske (Urban Studies and Planning), Joseph Sussman (Civil & Environmental Engineering, ESD)

17. *Fuels for the Future: Options & Consequences* - William Green (Chemical Engineering), Ahmed Ghoniem (Mechanical Engineering), Rob van der Hilst (Earth Atmospheric and Planetary Sciences), Gregory McRae (Chemical Engineering), Kenneth A. Smith (Chemical Engineering), Jefferson Tester (Chemical Engineering), Nafi Toksoz (Earth Atmospheric and Planetary Sciences), Ian Waitz (Aeronautics and Astronautics)

18. *Fusion Energy* - Jeffrey Freidberg (Nuclear Science and Engineering)

19. *High Efficiency Power and Energy Systems Using Superconducting and Cryogenic Technology* - Joseph Minervini (Plasma Science and Fusion Center), Joel Schultz (Plasma Science and Fusion Center), Leslie Bromberg (Plasma Science and Fusion Center), Ron Ballinger (Nuclear Science and Engineering), John Brisson (Mechanical Engineering; Cryogenic Engineering Lab), Michael Cima (Materials Science and Engineering), Jeffrey Freidberg (Nuclear Science and Engineering; Plasma Science and Fusion Center), James Kirtley (Laboratory for Electromagnetic & Electronic Systems), Thomas Keim (Laboratory for Electromagnetic & Electronic Systems)

20. *Hydrocarbon Fuels for the Future: Unleashing the Conventional and Unlocking the Unconventional* – Dale Morgan (Earth, Atmospheric, and Planetary Sciences), William Green (Chemical Engineering), Daniel Burns (Earth, Atmospheric, and Planetary Sciences)

21. *Hydrocarbons: sustaining domestic and global resources* – Dale Morgan (Earth Atmospheric and Planetary Science), Jefferson Tester (Chemical Engineering), Chryssostomos Chryssostomidis (Mechanical Engineering)

22. *The 3R's of Critical Energy Networks: Reliability, Robustness, and Resiliency* - Richard Larson (Engineering Systems Division), David Marks (Laboratory for Energy and the Environment), Munther Dahleh (Electrical Engineering and Computer Science), Marija Ilic (Engineering Systems Division)

23. *Integrated Design for Efficient Energy Provision and Use* - David Marks (Laboratory for Energy and the Environment), Steve Connors (Laboratory for Energy and the Environment)

24. *Integrated Energy Conversion Systems* - Ahmed Ghoniem (Mechanical Engineering)

25. *Integrating Electric Energy Sub-Systems* - Gerald Wilson (Electrical Engineering & Computer Science) Larry Susskind (Urban Studies and Planning), Phil Clay (Chancellor's Office), Penny Chisolm (Civil and Environmental Engineering), Matt Gardener (Earth System Initiative), Ken Oye (Political Science), Nick Ashford (School of Engineering), David Staehlin (Electrical Engineering and Computer Science)

26. *Integrating Environmental and Social Contexts into the Search for Energy Innovation* - David Marks (Laboratory for Energy and the Environment), Phil Clay (Chancellor's Office), Phil Gschwend (Civil and Environmental Engineering), Larry Susskind (Urban Studies and Planning), Penny Chisolm (Civil and Environmental Engineering), Matt Gardener (Earth System Initiative), Ken Oye (Political Science), Nick Ashford (School of Engineering), David Staehlin (Electrical Engineering and Computer Science)

27. *Leading and Educating By Example: A Greenhouse Gas Reduction Initiative for MIT Campus Operations* - Steven Lanou (Environmental Program & Risk Management), Peter Cooper (MIT Department of Facilities)

28. *Learning from the Past: Energy and Society at MIT* - Peter Shulman (Program in Science Technology & Society), Meg Jacobs (History), Merritt Roe Smith (Program in Science, Technology and Society), Rosalind Williams, (Program in Science, Technology and Society)

29. *Low-C Energy from Coal: Integrated Electricity and Fuel Production* – Ahmed Ghoniem (Mechanical Engineering), William Green (Chemical Engineering), and Gregory McRae (Chemical Engineering)

30. *Macro Organizational Structure of MIT Energy Entities* – Dale Morgan (Earth Atmospheric and Planetary Science)

31. *Needed! A Campus-Wide Energy Strategy with Student Participation* - Samantha Sutton (Students for Global Sustainability)

32. *Novel Science and Technology to Enable Energy Storage* - Gerbrand Ceder (Materials Science and Engineering), Steve Connors (Laboratory for Energy and the Environment), Elisabeth Drake (Laboratory for Energy and the Environment), Ahmed Ghoniem (Mechanical Engineering), Yang Shao-Horn (Mechanical Engineering), Donald Sadoway (Materials Science and Engineering), Jefferson Tester (Chemical Engineering)

33. *Nuclear Energy / Advanced Fuel Cycles* – Mujid Kazimi (Nuclear Science and Engineering), Ronald Ballinger (Nuclear Science and Engineering), Michael Golay (Nuclear Science and Engineering), Pavel Hejzlar (Nuclear Science and Engineering), Andrew Kadak (Nuclear Science and Engineering), Linn Hobbs (Materials Science and Engineering), Jefferson Tester (Chemical Engineering), and Sidney Yip (Nuclear Science and Engineering)

34. *Nuclear Fission Energy* - Mujid Kazimi (Nuclear Science and Engineering), Jacopo Buongiorno, Andrew Kadak (Nuclear Science and Engineering), Richard Lester (Nuclear Science and Engineering), Neil Todreas (Nuclear Science and Engineering), George Apostolakis (Nuclear Science and Engineering), Ronald

Ballinger (Nuclear Science and Engineering), Michael Driscoll (Nuclear Science and Engineering), Michael Golay (Nuclear Science and Engineering), Pavel Hejzlar (Nuclear Science and Engineering), Linn Hobbs (Materials Science and Engineering), Eduardo Kausel (Civil and Environmental Engineering), John Lienhard (Mechanical Engineering), Franz Ulm (Civil and Environmental Engineering), and Sidney Yip (Nuclear Science and Engineering)

35. *Oil and Natural Gas* - Robert van der Hilst (Earth, Atmospheric, & Planetary Sciences), Daniel Burns (Earth, Atmospheric, & Planetary Sciences), Arthur Baggeroer (Ocean and Electrical Engineering), William Green (Chemical Engineering), Gordon Kaufman (Sloan School of Management), David Mohrig (Earth, Atmospheric, & Planetary Sciences), Dale Morgan (Earth, Atmospheric, & Planetary Sciences), Roger Summons (Earth, Atmospheric, & Planetary Sciences), Jeff Tester (Chemical Engineering), Nafi Toksoz (Earth, Atmospheric, & Planetary Sciences), Kim Vandiver (Ocean Engineering), Michael Fehler (Los Alamos National Laboratory)

36. *The Problems of Scale in the Energy/Environmental Challenge* - Ronald Prinn (Earth, Atmospheric, & Planetary Sciences), John Reilly (Laboratory for Energy and the Environment)

37. *Production of Liquid Fuels by Biotechnological Conversion of Lignocellulosic Biomass* – Gregory Stephanopoulos (Chemical Engineering), Charles Cooney (Chemical Engineering), Gerald Fink (Biology, Whitehead Institute), Kristala Jones Prather (Chemical Engineering), Chokyun Rha (Provost's Office), Anthony Sinskey (Biology), Graham Walker (Biology), Daniel Wang (Chemical Engineeering)

38. *Refueling America -- The Coal Refinery of the Future* - Gregory McRae (Chemical Engineering)

39. *Renewable Energy: From Hunter-Gatherer to Farmer* - Emanuel Sachs (Mechanical Engineering)

40. *The Solar Opportunity* - Daniel Nocera (Chemistry)

41. *Transportation Energy* - John Heywood (Mechanical Engineering), Christopher Zegras (Urban Studies and Planning), Cynthia Barnhart (Civil and Environmental Engineering/Engineering Systems Division), Peter Belobaba (Aeronautics & Astronautics), Moshe Ben-Akiva (Civil and Environmental Engineering), Stephen Connors (Laboratory for Energy and the Environment), Joseph Ferreira (Urban Studies and Planning), Ralph Gakenheimer (Urban Studies and Planning), Henry Marcus (Mechanical Engineering), Carl Martland (Civil and Environmental Engineering), Amadeo Odoni (Aeronautics & Astronautics), Karen R. Polenske (Urban Studies and Planning), Fred Salvucci (Civil and Environmental Engineering), Yang Shao-Horn (Mechanical Engineering), Joseph Sussman (Civil

and Environmental Engineering/Engineering Systems Division), Ian Waitz (Aeronautics & Astronautics), Nigel Wilson (Civil and Environmental Engineering).

42. *Transport Phenomena in Energy Engineering* - John Lienhard (Mechanical Engineering), Bora Mikic (Mechanical Engineering)

43. *Universal Geothermal Energy* - An Opportunity for Sustainable Energy - Jefferson Tester (Chemical Engineering) with ideas from Nafi Toksoz (Earth, Atmospheric, & Planetary Sciences), Dale Morgan (Earth, Atmospheric, & Planetary Sciences), Rob van der Hilst (Earth, Atmospheric, & Planetary Sciences), Kenneth Smith (Chemical Engineering), Mike Driscoll (Nuclear Science and Engineering), Mujid Kazimi (Nuclear Science and Engineering), Mike Golay, Ahmed Ghoniem (Mechanical Engineering), Emanuel Sachs (Mechanical Engineering), Herbert Einstein, Chiang Mei (Mechanical Engineering), William Green (Chemical Engineering), Jeffrey Friedberg (Nuclear Science and Engineering), Bernhardt Trout (Chemical Engineering), William Peters (ISN) and Elisabeth Drake (Laboratory for Energy and the Environment).

44. *Wave Energy* - Chiang Mei (Civil and Environmental Engineering)

45. *Wind Energy* - Paul Sclavounos (Mechanical Engineering), Stephen Connors (LFEE), Mark Drela (Aeronautics and Astronautics), Ahmed Ghoniem (Mechanical Engineering), Pat Keenan (Mechanical Engineering), James Kirtley (Electrical Engineering and Computer Science) Jeffrey Lang (Electrical Engineering and Computer Science), Emanuel Sachs (Mechanical Engineering), Alex Slocum (Mechanical Engineering), Kim Vandiver (Mechanical Engineering)

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