Creating a National Network of Energy Discovery-Innovation Institutes: A Step Toward America's Energy Sustainability

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Abstract

The United States economy, our national security, and the well being of our citizens are dependent upon the availability of clean, affordable, secure, and sustainable energy resources. Yet our current energy infrastructure, heavily dependent upon fossil fuels, is characterized by rising costs, harmful environmental impact, and increasing dependence upon energy imports from politically unstable regions of the world. While the development of alternative energy sources has become a critical national priority, the current federal policies, programs, and investment aimed at conducting the research necessary to develop and implement new energy technologies are inadequate when measured against the urgency, complexity, and scale of the challenges in building a sustainable energy infrastructure for the nation.

This paper summarizes the severity of the current energy challenges faced by the nation and the inadequacies of the current federal energy research effort. It joins many others in calling for a major increase in federal energy R&D comparable in scale to earlier national efforts such as the Manhattan Project or the Apollo Program. While such a massive effort would require dramatic increase in research activity on the part of national laboratories and industry, this paper suggests this effort could also benefit by launching a new paradigm for energy research based upon regionally located *energy discovery-innovation institutes*. These institutes, characterized by an intimate partnership among multiple participants including federal agencies, research universities, established industry, entrepreneurs, investors, and the states, would be charged with performing both the basic research and technology development necessary to rapidly deploy highly innovative energy technologies in the marketplace. Such institutes would enable a more comprehensive approach to the energy challenge that would include attention to public policy, economic, legal, and behavioral issues in addition to energy science and technology.

These institutes would be organized into a *National Energy Research Network* to address national priorities and coordinated using modern management and information technology, while the regional character of the energy discovery-innovation institutions would allow them to focus on the unique assets, challenges, and opportunities for energy research, development, and implementation at the local level, thereby stimulating strong regional economic development and job creation. In effect, this proposed element of a national energy R&D program could be viewed as a 21st century adaptation of the highly successful model of the agricultural and engineering

experiment stations established across the United States through the Land Grant Acts (particularly the Hatch Act of 1887) to build a modern industrial nation in the 20th century to the contemporary challenges of achieving a sustainable national energy infrastructure for the 21st century.

Executive Summary

The United States economy, our national security, and the well-being of our citizens are dependent upon the availability of clean, affordable, secure, and sustainable energy resources. Yet our current energy infrastructure, heavily dependent upon fossil fuels, is unsustainable. Global oil and gas production is expected to peak within the next several decades. While there are substantial reserves of coal and tar sands, the mining, processing, and burning of these fossil fuels poses increasingly unacceptable risk to both humankind, particularly within the context of global climate change. Furthermore, the security of our nation is threatened by an addiction to oil that has created a reliance on energy imports from politically unstable regions of the world that threatens both our national economy and security. Clearly securing reliable and sustainable energy for the nation must become among the highest priorities of the federal government if it is to meet its responsibilities for national security, economic prosperity, and social well-being.

Unfortunately, current federal energy research strategies, policies, and investments seem woefully inadequate when measured against the urgency, complexity, and scale of the challenges in building a sustainable energy infrastructure for the nation. The severity of the looming energy crisis facing the United States, viewed within the context of the federal R&D effort characterizing other national priorities such as health care ($30 B/y) and defense ($80 B/y), would call for a federal energy R&D effort on the order of $30 to $40 B/y, roughly ten times the current federal effort. There are increasing calls for just such a federal energy R&D effort, comparable in scale to earlier national efforts such as the Manhattan Project or the Apollo program.

Such a massive effort will require a dramatic increase in federally-funded energy research activity on the part of national laboratories and industry. In addition, the unusual complexity of the nation's energy challenges suggest the need for new research organizations capable of spanning the broad array of scientific, technological, economic, legal, and behavioral issues necessary to develop and deploy new energy technologies on the scale required by the nation. To this end, a new energy research paradigm is proposed as an element of a greatly expanded federal effort. The proposal is to create a national network of regionally-based *energy discovery-innovation institutes*, a concept recently developed by the National Academy of Engineering for linking fundamental scientific discoveries with technological innovations to create the products, processes, and services needed by society.

These energy discovery-innovation institutes would be characterized by an intimate partnership among multiple participants – federal agencies, research universities, established industry, entrepreneurs, the investment community, and state and local government. The institutes would be capable of developing and rapid transferring highly innovative technologies into the marketplace and stimulating regional economic development. Furthermore, since the challenge of a sustainable energy infrastructure depends as much on economic, behavioral, policy, and political issues as upon science and technology, these institutes would be charged with employing a more comprehensive approach to scientific research, technology development, and commercialization than existing research organizations such as national laboratories or corporate R&D centers. Disciplines such as the social and behavioral sciences, business administration, law, and environmental and public policy will join science and engineering in addressing the nation's energy challenges.

The institutes would also assume the role of contributing to the human resources – the scientists, engineers, managers, and entrepreneurs – necessary to support and sustain the nation's energy infrastructure. Each institute would create, in effect, an "R&D commons", where strong, symbiotic partnerships could be created and sustained not only among the disciplines but among organizations with quite different missions and cultures (universities, industry, entrepreneurs, government agencies) joining together to build the knowledge base and human capital necessary to address the nation's highest priorities.

More specifically, it is proposed that each regional energy research discovery-innovation institute be created and managed by a regional consortia led by research universities with strong participation by industry, entrepreneurs and investors, state and federal government. Each institute would have with a particular theme, such as renewable energy technologies, advanced petroleum extraction, carbon sequestration, biofuels, transportation energy, carbon-free electrical power generation and distribution, energy efficiency or economic, behavioral, and policy energy studies. The institutions will also be charged with addressing the economics, policy, business, and behavioral challenges required to successfully diffuse technological achievements into society. Each energy discovery-innovation institute would be provided with core support from one or more federal agencies at a level growing to $200 million per year, with significant additional funding from state governments, industry, the investment community, foundation, and university sources. Each would have numerous participants and affiliates from industry, federal and state agencies, and other research universities from around the nation in both participation and management.

Each energy discovery-innovation institute or cluster of institutes would be set up to respond to the unique energy needs and capabilities of its region. For example, the large urban populations and energy-intensive nature of the Great Lakes states, dependent upon heavy manufacturing, agriculture, and transportation, would lead naturally to research in areas such as energy efficiency technologies, alternative transportation fuels and technology, and carbon-free electricity generation–including such important technologies as carbon sequestration. In contrast, an energy research cluster formed in the West and Mountain states would address the needs of rapid population growth and economic activity widely dispersed over fragile ecosystems with limited water resources but significant primary energy sources (oil, gas, shale, hydro), while taking advantage of the presence of a large number of national laboratories, with research in areas such as renewable energy technologies (such as solar, wind, and geothermal sources) and energy distribution. Similar energy research clusters would be formed to address the unique needs and opportunities in other regions, such as the Northeast, Southeast, and Midwest states. The regional character of these institutes and the strong participation by industry and the investment sector would also stimulate local economic growth through new energy technology business development and job creation.

To be sure, the total federal investment in such a novel effort would be significant – estimated eventually to grow to $4 to $6 billion per year. Yet this would be a relatively modest fraction (10% to 15%) of the total federal investment in R&D necessary to adequately address today's energy challenges, most of which would be conducted through more conventional mechanisms such as national laboratories and industry R&D ($30/y B to $40 B/y). Furthermore the federal funds necessary for such energy R&D could be derived from the reallocation of federal subsidies of ineffective energy development efforts or from the revenues created by new programs aimed at controlling greenhouse gas emissions such as carbon cap-and-trade auctions or taxes.

Today our increasingly economically fragile and environmentally damaging energy infrastructure is putting at great risk this nation's economic prosperity and security and perhaps even the very future of humankind on Earth. New energy technologies must be rapidly developed and deployed that are sustainable for the long term and characterized by acceptable environmental impact. The consequences of failing to make such investments would be far greater, if not catastrophic, for our nation, not to mention the world.

A century ago the United States responded to challenges of modernizing American agriculture and industry through the Hatch Act of 1887, which created a network of agricultural and engineering experiment stations through a partnership involving higher education, business, and state and federal government that developed and deployed the technologies necessary to build a modern industrial nation for the 20th century while stimulating local economic growth. The proposed National Energy Research Network of regional energy discovery-innovation institutes is remarkably similar to this earlier national effort, both in spirit and structure. It would create a partnership among research universities, business and industry, entrepreneurs and investors, and federal, state, and local government to conduct the research, development, and commercialization of new energy technologies necessary to build a sustainable national energy infrastructure for the 21st century while stimulating strong regional economic growth and job creation.

The Most Serious Challenge of the 21st Century

There are few contemporary challenges facing our nation – indeed, the world – more threatening than the unsustainable nature of our current energy infrastructure. Every aspect of contemporary society is dependent upon the availability of clean, affordable, flexible, and sustainable energy resources. Yet our current energy infrastructure, heavily dependent upon fossil fuels, is unsustainable. Global oil and natural gas production are expected to peak within the next several decades. Substantial reserves of coal and tar sands do exist, however, the mining, processing, and burning of these fossil fuels poses increasingly unacceptable risk to humankind, particularly within the context of global climate change.

Furthermore, the security of our nation is threatened by oil addiction and the consequent reliance on foreign energy imports from unstable regions of the world. Our growing trade imbalance, driven primarily by petroleum imports coupled with the increasing control of oil reserves by nation states rather than commercial markets, puts the United States at great economic and geopolitical risk. If the federal government is to meet its responsibilities for national security, economic prosperity, and social well being, it must move rapidly and aggressively to address the need for a sustainable energy future for the United States. Yet time is not on our side.

Recent analyses of world petroleum production and known reserves suggest that global oil production could peak as early as the next decade (with gas production peaking roughly a decade later). Despite new discoveries, oil companies continue to report declining production of both oil (e.g., Exxon-Mobil down by 6 to 8% a year) and natural gas (down 15% a year). Furthermore, while recent large discoveries of several billion barrels sound encouraging, they represent only a few months of additional resources at the current global consumption rate of 86 million bbl/day. As a recent assessment noted, "Holding off the peak (of global petroleum production) until 2040 would require both a high – and much less certain – total oil resource and adding more production each year than ever before, despite having already produced all of the world's most easily extractable oil." (Science, 2007)

The timing of a peak in global oil production is actually less important than the approaching imbalance between supply and demand. This imbalance could occur if the development of new reserves and extraction technologies can no longer keep production rates adequate to meet growing demand. Oil prices would rise dramatically higher than today's levels with corresponding increases at the pump, triggering an even more massive impact on the U.S. trade deficit and further destabilizing capital markets.

The rapidly increasing oil and gas demands from developing economies such as China, India, and Latin America make this imbalance more likely in the near term, particularly since the United States currently consumes 25% of world production while large commercial oil companies control less than 18% of reserves. (Goodstein, 2004) An assessment by the U. S. Department of Energy warned, "The world has never faced a problem like this. Without massive mitigation more than a decade before the fact, the problem will be pervasive and will not be temporary. Previous energy transitions (wood to coal and coal to oil) were gradual and evolutionary; oil peaking will be abrupt and revolutionary." (Hirsch, 2005)

To be sure, our nation has substantial reserves of other energy resources such as coal, tar sands, and oil shale. Yet the mining, processing, and burning of these fossil fuels with current technologies is characterized by substantial environmental impact both because of carbon emissions and land and water utilization. While "clean coal" is the current mantra of the day, it is still an elusive goal without new technologies for emission controls and carbon sequestration that will require very substantial research and development – not to mention adding considerably to electrical generation costs. The United States also has access to significant uranium resources that could enable a substantial growth in nuclear power capacity, comparable to coal with current technology and an order of magnitude larger with advanced breeder reactor technologies. Yet here, too, there remain serious challenges including the development of facilities for disposing of the radioactive products in spent nuclear fuel, public perceptions of nuclear reactor safety, and the reluctance of the financial markets to invest in new nuclear plants.

Moreover there is a growing consensus in the scientific community that utilization of fossil fuels in energy production is already a significant contributor to global climate change. Evidence of global warming is now incontrovertible. Increasing global surface and air temperatures, receding glaciers and polar ice caps, rising sea levels, and increasingly powerful weather disruptions all confirm that unless the utilization of fossil fuels is sharply curtailed in the very near future, humankind could be seriously threatened. The recent Intergovernmental Panel on Climate Change concluded that: "Global atmospheric concentrations of carbon dioxide, methane, and nitrous oxide have increased markedly as a result of human activities since 1750 and now far exceed pre-industrial values. The global increases in carbon dioxide concentration are due primarily to fossil fuel use and land-use change." (IPCC, 2007) Add to this the possibility of truly cataclysmic nonlinear events such as a massive release of carbon dioxide from melting Arctic tundra or a change in the Earth's albedo from melting of the polar ice caps, and it is clear why Lewis characterizes our current energy practices as "the biggest experiment on Planet Earth than humans ever have done, and we get to do that experiment exactly once!" (Lewis, 2007)

Although there continues to be disagreement over particular strategies to slow global climate change – whether through international agreements (e.g., Kyoto), regulation that restricts carbon emissions, or market pressures (e.g., "cap and trade" strategies) – there is little doubt that energy utilization simply must shift away from the current use of fossil fuels to meet over 85% of all our energy needs and move toward alternative, non-hydrocarbon energy sources. "We are not talking any more about what climate models say might happen in the future. We are experiencing dangerous disruption of the global climate, and we are going to experience more. Yet we are not starting to address climate change with the technology we have in hand, and we are not accelerating our investment in energy technology R&D," warns John Holdren, president of the American Academy for the Advancement of Science. (AAAS, 2007)

While efforts to control greenhouse gas emissions through international agreements or economic incentives are essential, the anticipated growth in energy demand from developing economies and growing populations will require clean and more efficient energy technologies that have yet to be developed. The most immediate impact will be from new technologies that improve the efficiency of energy utilization, e.g., low energy illumination, high efficiency buildings, fuel-efficient automobiles, and low power computers. New technologies are also needed to mitigate the harmful impact and resource constraints of existing energy sources such as carbon sequestration for coal combustion, more efficient methods for petroleum and natural gas exploration and extraction, and advanced nuclear energy systems with enhanced safety and reduced radioactive waste toxicity and lifetime.

Addressing long-term energy needs will require the development of new, carbon-free renewable energy technologies, such as solar, wind, and biofuels. Yet the intermittency inherent in renewable energy sources will also require massive development and deployment of central and distributed energy storage technologies such as batteries. And while such alternative energy sources based upon current technology are prominently featured in most "green energy" proposals, there remains a very substantial gap in achieving both the scale and cost structures necessary for major impact. In fact a recent report by the International Energy Agency on Energy Technology noted that the IPCC goal of limiting global warming to 2.4°C will require virtual decarbonization of the power sector at an estimated cost of $4.5 trillion between now and 2050. (IEA, 2008) Clearly alternative energy technologies such as electric or hybrid cars, hydrogen fuels, advanced nuclear power, and renewable energy sources such as solar, wind, or biofuels still require considerable research and development before they evolve to the point of the massive utilization required for substantially reducing our dependence upon fossil fuels.

In summary, the United States must move rapidly to develop and implement the technologies necessary to achieve a sustainable energy infrastructure that dramatically reduces oil imports and environmental impact. The nation's economic strength and security demands a massive commitment similar in magnitude to those of other national priorities, such as health care and national defense, if it is to stimulate the scientific research and technology development and deployment necessary to address our energy challenges.

The Inadequacy of Current Federal Policies, Programs, and Investments

Past transitions in energy utilization, e.g., from wood to coal to oil to electricity, have been driven primarily by the private sector. They have occurred over timescales of generations or even centuries, involving gradual changes in energy technologies and utilization that allowed producers, consumers, and markets to adjust. However today's energy challenges are characterized by a magnitude, timescale, and dimensionality that requires strong government intervention.

The magnitude of the necessary transformation of our energy infrastructure is immense. It is estimated that over $16 trillion in capital investments over the next two decades will be necessary just to expand energy supply to meet growing global energy demands, compared to a global GDP of $44 trillion and a U.S. GDP of $12 trillion. Put another way, to track the projected growth in electricity demand, the world would need to bring online every day for the next 20 years a new 1,000 MWe powerplant costing several billion dollars! (Lewis, 2007)

Furthermore while the timescale of decades required to deploy new energy technologies appears long, the consequences of failing to respond to the environmental or geopolitical impact of our current carbon-based energy infrastructure require more immediate attention. As noted earlier, we are already experiencing serious impact from global climate change, including intensification of disruptive weather (e.g., hurricanes) and melting of polar ice and glaciers. Furthermore the impact of rapidly rising petroleum prices and increasing dependence on imported oil from politically unstable regions seriously threatens both our economy and national security.

As if the scale of the energy challenge is not enough, there are few technology infrastructures more complex than energy, interwoven with every aspect of our society. Large-scale deployment of sustainable energy technologies will involve not simply advanced scientific research and the development of new technologies. We must pay careful attention to social, economic, legal, political, behavioral, consumer, and market issues – all characterized as well by complex regional, national, and international relationships. Little wonder that one commonly hears the complaint that "the energy crisis is like the weather; everybody complains about it, but nobody does anything about it!" Hence government intervention is clearly necessary to address the inability of the private sector to deal with the magnitude, urgency, and complexity of the energy crisis facing our nation.

Numerous studies, from groups such as the National Academies, the President's Council of Advisors on Science and Technology, and the American Association for the Advancement of Science, have given the very highest priority to launching a massive federal R&D effort to develop sustainable energy technologies. (National Academies, 2005). In fact, a high level task force created by the Secretary of Energy's Advisory Board (SEAB) stated in the strongest possible terms:

> America cannot retain its freedom, way of life, or standard of living in the 21st century without secure, sustainable, clean, and affordable sources of energy. America can meet its energy needs if and only if the nation commits to a strong and sustained investment in research in physical science, engineering, and applicable areas of life science, and if we translate advancing scientific knowledge into practice. The nation must embark on a major research initiative to address the grand challenge associated with the production, storage, distribution, and conservation of energy as both an element of its primary mission and an urgent priority of the United States. (Vest, 2005)

Yet today there is ample evidence that both the magnitude and character of federal energy R&D programs are woefully inadequate to address the urgency of the current energy challenges faced by this nation.

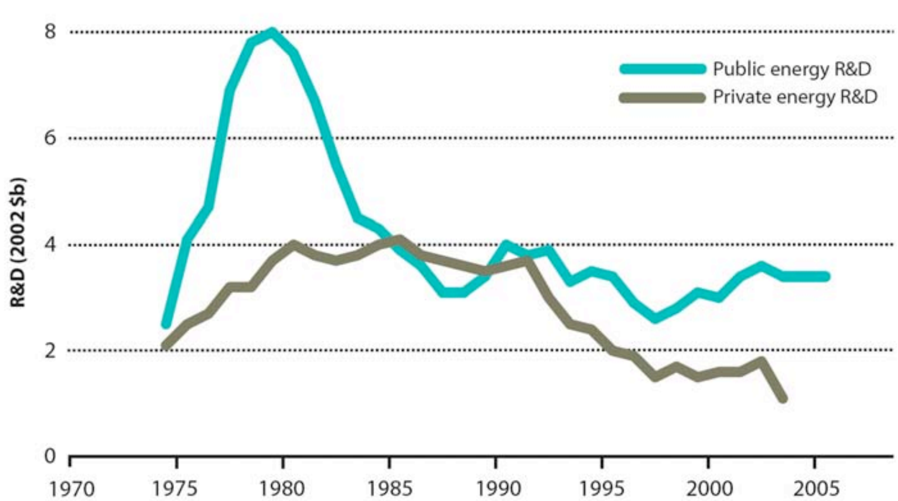
How much should the federal government be investing in energy R&D to deal with such challenges? One approach would be to compare current investments in energy R&D with those in other technology-dependent economic sectors such as health care, defense, and space. As the table below indicates, this year the federal government will invest $31 B in R&D for the health care sector (which accounts for 16% of GDP or

$2.3 T), $84 B of R&D for defense (5% or 0.7 T), and $12 B of R&D for space (2% or $0.2 T). Since the energy sector is comparable in size to health care, corresponding to 10% of GDP or $1.4 T in 2008, and intensely dependent upon new technologies, one could argument a comparable federal investment in energy R&D, amounting to $30 B or more a year.

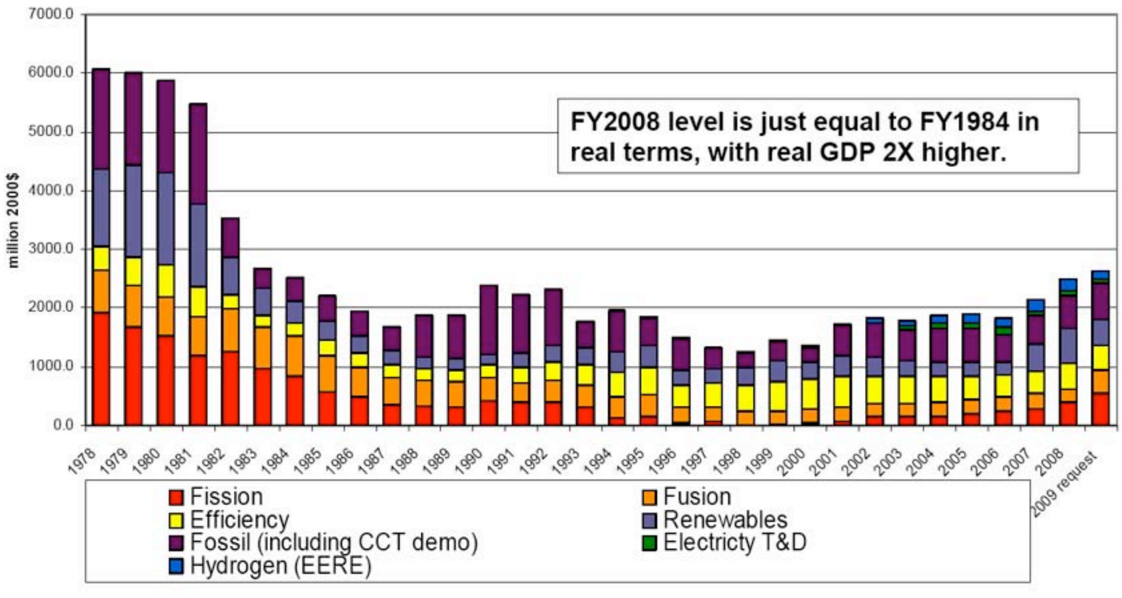
Sector	% GDP	$ GDP	Federal R&D*	Industrial R&D
Health	16%	$2.3 T	$31 B	$35 B
Defense	5%	$0.7 T	$84 B	$25 B
Space	2%	$0.2 T	$12 B	$5 B
Energy	10%	$1.4 T	$3 B	$1.5 B

*(NSF Science and Engineering Indicators, 2008;AAAS, 2008)

Today federal energy research amounts to $3 B/y, less than 10% of the federal investment in other areas of comparable significance to the nation's prosperity and security. Over the past two decades, energy research has actually been sharply curtailed by the federal government (75% decrease), the electrical utility industry (50% decrease), and the domestic automobile industry (50% decrease). (Kammen, 2005) Today the federal government effort in energy R&D is less than 20% of its level during the 1970s in constant dollars! Clearly, Washington has yet to take the energy crisis seriously, at least as measured by its commitment to energy R&D. As a consequence our nation remains at very great risk.



Declining energy R&D by economic sector (Kammen, 2005)



U.S. DOE energy R&D (Kerry Galligher, February, 2008)

Returning again to the DOE Secretary's Energy Advisory Board (SEAB) Task Force study, there is growing realization that besides the seriously inadequate level of federal investment in energy R&D, that nation's existing paradigms for federal energy research are simply not up to the task. Currently the lead federal agency for energy research is the Department of Energy, with the bulk of its research conducted by its national laboratories. Yet the SEAB Task Force warns: "The Department of Energy has a historically poor reputation as being badly managed, excessively fragmented, and politically unresponsive. The current organization of the Department is not appropriate to the magnitude and centrality of scientific and advanced technological research required by our energy challenges." (Vest, 2005)

The organizational separation of DOE's basic and applied energy research programs makes the migration of basic research findings to applied research solutions difficult and undisciplined, with those successes that do emerge often simply serendipitous. The DOE R&D offices and programs are organized around fuel sources, e.g., coal, oil, gas, nuclear, and renewables, all too often characterized by an "energy technology of the year" approach and internal competition that disrupts longer-term strategic efforts. This lead to stove-pipe organizations that focus on incremental or discrete technologies as opposed to systems that integrate R&D supply, distribution, and end use needs for the set of energy sources and associated infrastructures. This can result in energy policies that seriously underestimate threats and consequences, are all too frequently risk-adverse and parochial, and tend to seriously misjudge the potential for new high-risk, high-payoff, technologically-enabled opportunities and threats. (ARPA-E Testimony, 2007)

The DOE SEAB Task Force also raised a concern about an insular culture characterizing the DOE laboratories arising from the security constraints of their past and present work in atomic energy. It concluded the laboratories are too far removed from the marketplace and too focused on their existing portfolios to effectively support "transformational" research targeted at new energy technologies. Most DOE labs are ill-suited to conduct the market analysis and public policy research required for large-scale deployment of renewable energy sources, significant gains in energy efficiency, or reduction in fossil fuel consumption. Early efforts in developing new technologies capable of transforming energy infrastructure by the national laboratories and industry have had limited success in the marketplace (e.g., synfuels, Freedom Car, the hydrogen economy, nuclear power, and FutureGen, to name only a few).

Diffusing technology through our social system in a rational and planned way will be critical to a rapid transformation of our energy systems. Poorly planned introduction of technology has resulted in a history of unintended consequences that often do more to damage the growth of that technology than to help it. A new approach to technology development and deployment is badly needed to avoid the obvious mistakes and costly false starts that the nation can ill afford.

Since energy challenges have important implications for the nation's scientific and engineering workforce, human capital development has also become a particularly critical issue that requires immediate attention. It is well known that one of the most effective technology transfer mechanisms is the knowledge and skills carried by graduates of the nation's research universities. Yet most DOE activities are relatively isolated from education (aside from campus-based research programs sponsored by the DOE Office of Science). Furthermore, since the complexity of the nation's energy challenges involve socioeconomic and political issues as much as science and technology, unusually broad multidisciplinary research efforts are required that encompass important areas such as social and behavioral sciences, professional programs in business administration, law, medicine, and public and environmental policy, all areas where national laboratory expertise is limited. While the national laboratory model has been effective in conducting large-scale scientific R&D in areas such as nuclear weapons development and high energy physics, the isolated, laboratory-centric culture has not proven particularly effective in meeting other important national needs. The track record is lacking in technology transfer into the commercial marketplace with seamless connections with public policy, business interests, and social behavior, or in human resource development through the education of scientists and engineers.

Yet the DOE laboratories are an essential component of the nation's research enterprise and must remain a critical asset in America's effort to achieve energy sustainability. They must be adequately funded so as to play a key role in any Manhattan Project-scale approach to energy R&D.

But it should also be recognized that the national laboratories have neither the mission nor the capacity to build and maintain necessary energy infrastructure. That properly remains the role of industry. Nor can the national laboratories play a prominent role in producing the human capital – in the form of scientists, engineers, managers, and entrepreneurs –necessary to develop, build, and manage the nation's energy infrastructure. That task most properly belongs' to the nation's universities.

The DOE SAEB Task Force concluded, "The federal government alone cannot meet the nation's energy related R&D needs. The Department of Energy must partner with universities, industry, and other federal agencies. It should seek the best balance of national laboratory, university, and industrial research, and form partnerships with industry and academia to drive innovation in its mission areas." (Vest, 2005) The capabilities of DOE mission-focused divisions and national laboratories must be significantly augmented by other research organizations and programs.

Other organizations have reached similar conclusions. For example, the nation's electrical utilities have proposed (through the Edison Electric Institute) than revenue raised from a carbon tax or cap-and-trade program should be earmarked for energy research directed by an affiliated industry research organization, such as the Electric Power Research Institute. Other groups, such as the Gas Research Institute, recommend that industry groups be established to play the lead role in the conduct of the nation's energy R&D, push technology deployment, and develop the huge infrastructures needed to change the way the United States produces and utilizes energy.

However, investor pressures on near-term, bottom line results have shifted most corporate R&D activity away from basic research conducted in years past by large corporate R&D laboratories, such as Bell Laboratories, IBM Research Laboratory, Ford Scientific Laboratory, and Dupont Research Laboratory. Today, corporate resources are focused on product development. So while industry participation is certainly necessary to augment the national laboratory role, industry, too, does not have the capacity to conduct the deep basic research required for advanced energy technologies, address the broad policy issues, and to play a major role in developing the human capital needed for the energy industry.

As for universities, traditional research programs also suffer from disciplinary silos and insular cultures, though often not as difficult to overcome as those resident within the national laboratories and industry. Universities have the advantage that their educational mission provides a highly effective technology transfer mechanism through large-scale deployment of their graduates and through faculty involvement via joint research or short-term consulting. Yet universities are frequently hindered by complex intellectual property policies that inhibit the commercialization of campus-based discoveries.

In summary, it is clear that a federal research program adequate to respond to the urgency, scale, and complexity of the nation's needs for a sustainable energy infrastructure will require a massive increase in federal funding for energy research and development involving the entire national research enterprise. It will also require augmenting the existing national laboratory, industrial, and university R&D enterprise with new research paradigms characterized by highly multidisciplinary scientific research, the development of highly innovative technology commercialization approaches capable of rapid deployment into the marketplace, and the agility necessary to respond to ever changing challenges and opportunities.

Such a national program must involve an intimate and balanced partnership among multiple players from the outset, including federal agencies, research universities, established industry, entrepreneurs, the investment community, and state and local government. A new research culture must be developed based on the nonlinear flow of knowledge and activity among scientific discovery, technological innovation, entrepreneurial business development, and economic, legal, social, and political imperatives, all coordinated across the spectrum of energy technologies contributing to a comprehensive national energy policy.

A New Paradigm for National Energy Research

Discovery-Innovation Institutes

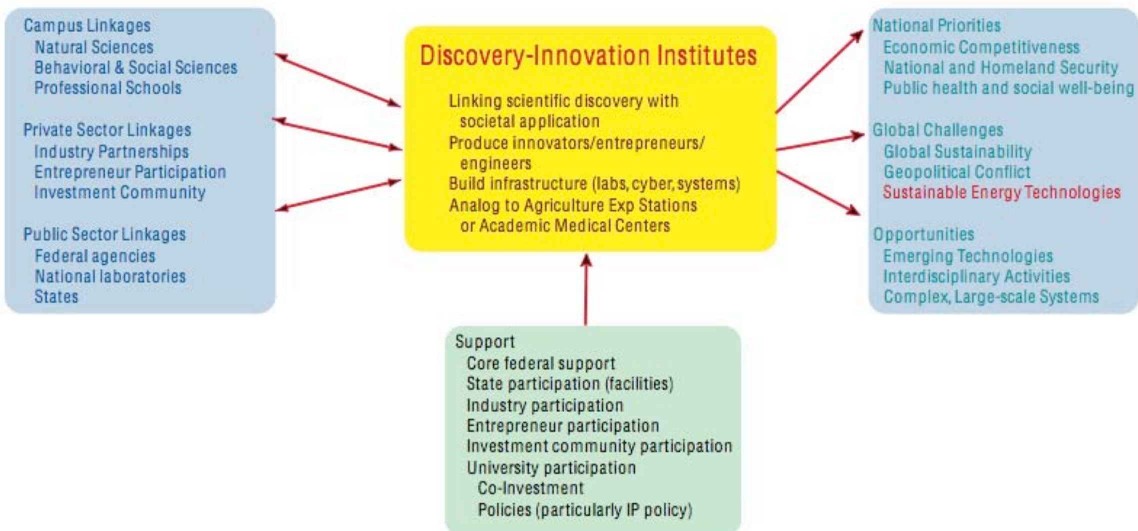
In recent years an array of alternative research and technology development paradigms have been explored, such as SEMATECH for the electronics industry, the Advanced Technology Program of NIST, the Small Business Innovation Research grant programs, the I-ARPA and In-Q-Tel efforts within the intelligence community, and the proposed ARPA-E for energy research, the DOE Office of Science analog to the highly successful Defense Advanced Research Projects Agency (DARPA). However, each of these models also seems to fall somewhat short of responding adequately to the scale, complexity, and urgency of the energy research needs of the nation.

In 2005 a National Academy of Engineering task force on engineering research and American competitiveness concluded that to meet challenges such as energy sustainability, the United States required a new research paradigm based not only upon new organizational structures and multidisciplinary activities. The task force called for far more robust relationships among various institutional sectors, such as federal and state governments, established and startup business and industry, investors, foundations, and academia. (NAE, 2005)

To this end, the NAE task force recommended the establishment of university-based *discovery-innovation institutes* capable of linking fundamental scientific discoveries with technological innovation to create the products, processes, and services needed by society and addressing national priorities such as energy sustainability. Such institutes would be managed by consortia of universities and industry, with federal and state governments, industry, foundations, entrepreneurs and the investment community, and higher education involved as both participants and sponsors.

The discovery-innovation institutes were envisioned as the foci for long-term, applications-driven research aimed at building the knowledge base necessary for technological innovation drawing on an array of academic and professional disciplines, including the natural sciences, engineering, social sciences, and professional disciplines such as business administration, law, and medicine. The institutes would be characterized by partnership, interdisciplinary research, technology commercialization, education, and outreach. (For a more detailed description of the NAE discovery-innovation institute concept, see the excerpt from the NAE report provided in the Appendix.)

The make-up of discovery-innovation institutes have been seen as similar in character and scale to academic medical centers and agricultural experiment stations that combine research, education, and professional practice and drive transformative change. As experience with academic medical centers and other large research initiatives suggests, discovery-innovation institutes could stimulate significant regional economic activity, such as the location nearby of clusters of start-up firms, private research organizations, suppliers, and other complementary groups and businesses. The institutes would take advantage of the ability of American research universities to conduct cutting-edge basic research (as evidenced by scientific breakthroughs and Nobel prizes created on their campuses) and world-class scientists, engineers, and other knowledge professions. The institutes would also tap the unusual capacity of research universities to build and manage large, complex, and mission-focused enterprises (e.g., academic medical centers, federal R&D facilities, and international development programs).



The Discovery-Innovation Institute: An R&D Commons

The unusually broad mission of discovery-innovation institutes would require the active involvement of industry, entrepreneurs, government agencies, federal research organizations, and universities. Importantly, the institutes could provide a safe zone where issues such as intellectual property could be worked out in advance. In a sense, they would create an "R&D commons", where strong, symbiotic partnerships could be created and sustained among the disciplines and among organizations with quite different missions and cultures joining together to build the knowledge base necessary to address the nation's highest priorities.

Here it is interesting to note that the concept of a discovery-innovation institute actually represents a contemporary adaptation of a highly successful paradigm for research and technology development created over a century ago through the sequence of land-grant acts passed by the United States Congress. The Hatch Act of 1887 provided revenue from the sale of federal lands to create a network of university-based agricultural and engineering experiment stations on university campuses to help modernize American agriculture and industry. This effort was based on a partnership involving higher education, business, and state and federal government, and the program was instrumental in developing and deploying the technologies necessary to build a modern industrial nation for the 20th century while stimulating local economic growth.

The discovery-innovation institutes proposed by the National Academy of Engineering are remarkably similar both in spirit and structure to the agricultural and engineering experiment stations created by the Hatch Act, since they also emphasize partnerships to address national priorities while stimulating strong regional economic growth. Of course the scale of the research and the necessity of commercialization to larger, more complicated, and more centralized industries such as energy (rather than agriculture) make the discovery-innovation institutes a more complex concept, but still very much in the same spirit as the earlier effort.

The proposed creation of such discovery-innovation institutes in key areas of national interest has received unusually strong support by the membership of the National Academy of Engineering – particularly noteworthy, since 45% of the Academy membership is drawn from industry. Furthermore, language to establish such institutes was included in Senate bills introduced in both 2006 (S. 2197 – Protecting America's Competitive Edge through Energy Act) and 2007 (S. 771 The American COMPETES Act).

A National Network of Discovery-Innovation Institutes for Energy Research

Any national effort to build an energy R&D program at the level of the Manhattan Project or the Apollo program, as some have suggested (Alexander, 2008), should augment the existing national laboratory and industrial R&D infrastructure with new research paradigms that i) provide a broader intellectual span, from science and engineering to the social and behavioral sciences and professional disciplines such as business administration, law, and public policy, ii) add more robust educational efforts at the college and graduate level capable of producing the human capital required by the emerging energy sector, and iii) address the particular needs and opportunities characterizing different regions of the country. To this end it is proposed that the nation create a highly coordinated *national network of discovery-innovation institutes* focused on energy research, with each institute located adjacent to a major research university and coordinated at both the national and regional levels to address both national energy objectives and regional challenges and opportunities.

More specifically, it is proposed that each energy research discovery-innovation institute be created and managed by a regional consortia led by research universities with strong participation by industry, entrepreneurs and investors, and state and federal government. Each institute would have a particular theme, such as renewable energy technologies, advanced petroleum extraction, carbon sequestration, biofuels, transportation energy, carbon-free electrical power generation and distribution, energy efficiency or economic, behavioral, and policy energy studies. The institutes would be charged with addressing the technical, economic, policy, business, and social challenges required to successfully diffuse innovative energy technologies into society.

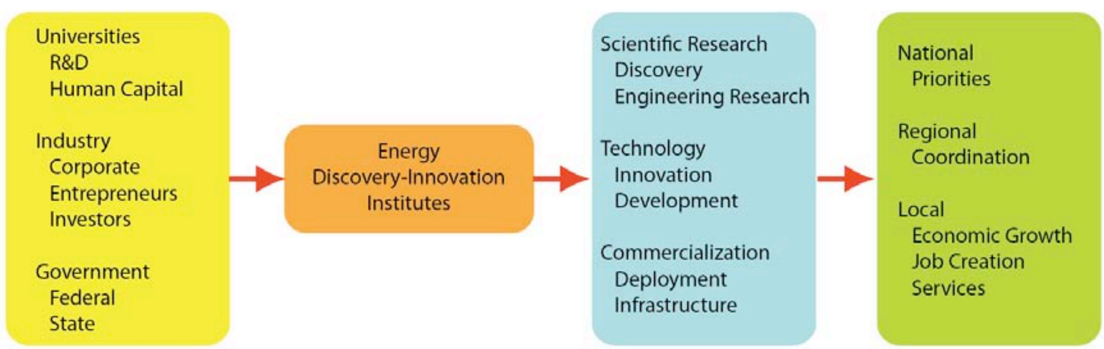
Each energy discovery-innovation institute would be provided with core support from one or more federal agencies at a level growing to $200 million per year, with significant additional funding provided by state governments, industry, the investment community, foundation, and university sources. Each would have numerous participants and affiliates from industry, federal and state agencies, and other colleges and universities. Although each energy discovery-innovation institute would be associated with a lead research university or consortium, clusters of such energy research institutions would be coordinated at the regional level, with strong participation by industry, entrepreneurs, and the investment community.

To achieve a critical mass of activities, the proposed National Energy Research Network would consist of 20 to 30 such energy discovery-innovation institutes. Hence the scale of the proposed federal investment, assuming core support building to $200 M/y for each energy discovery-innovation institute, would total $5 to $6 B/y, an amount that seems not only necessary for significant impact in view of the complex and compelling nature of the nation's need for sustainable energy, but also compatible with both existing and future federal resources.

It is further recommended that a competitive award process be adopted involving rigorous merit review at the level of both individual discovery-innovation institutes and regional clusters. Proposals would be evaluated by a cross-agency panel and subjected to comprehensive internal and external (peer) review. Successful proposals would receive core support either by individual federal agencies, such as the Departments of Energy, Commerce, Defense, Transportation and Agriculture, or through interagency agreements, similar to that provided by the National Nanotechnology Initiative or the Global Climate Change Initiative.

Core support would consist of sustained federal funding to support and anchor the main programs of the institute and to provide for infrastructure, similar to the way in which the national laboratories are supported. Here it is important that the federal government, perhaps with the assistance of independent advisors such as the National Academies, develop a framework of energy research strategies and priorities to guide such a competitive award decision process, as well as a process for ongoing evaluation and assessment of progress toward benchmarks at both the level of individual energy discovery-innovation institutes, regional clusters, and the National Energy Research Network itself. The program could be staged by launching the first of several energy discovery-innovation institutes as regional experiments and then following with more institutes and eventually clusters as the concept matures.

Support would also be provided by states, industry, venture capital firms, and universities. States would be encouraged to contribute land, capital facilities for research and development, and other infrastructure. Industry would fund student internships and provide direct financial support for facilities and equipment. The venture capital and investment community would provide expertise in licensing and in creating new companies and would provide support for technology commercialization. Each of these partners would have a presence at the institute so that commercialization specialists are in contact with researchers. Finally, universities would commit to providing faculty and staff time and to encouraging the engagement of students at all levels of the institute. They will also provide a policy framework (e.g., transparent and efficient intellectual property policies, flexible faculty appointments, responsible financial management, etc.), educational opportunities (e.g., integrated curricula, multifaceted student interaction), knowledge and technology transfer (e.g., publications, industrial outreach), and additional investments (e.g., in physical facilities and cyberinfrastructure).



The partners, roles, and impact of energy discovery-innovation institutes

It is important that this new federal energy R&D effort be established and managed as an interagency effort rather than the responsibility of a single federal department, similar to other federal initiatives such as nanotechnology, high performance computing, and global climate change. The challenge of a sustainable energy infrastructure depends as much on socioeconomic, political, and policy issues as upon science and technology. Hence, energy R&D requires a comprehensive approach encompassing the social and behavioral sciences, business administration, law, and environmental and public policy.

Since the proposed national network of discovery-innovation institute clusters represents a radical departure from existing research paradigms, it would require a new, independent management structure consisting of research university and industry consortia committed to rapid deployment of new technologies. While this energy research network would be closely coordinated with existing activities, such as those by the Department of Energy and its national laboratories, it would have a parallel, interagency reporting structure (e.g., Energy, Defense, Commerce, EPA, Transportation, Agriculture, as well as basic research agencies such as NSF and NIH). In fact, beyond coordination and collaboration, some degree of competition between the proposed network of discovery-innovation institutes and existing R&D organizations, such as the national laboratories, would be encouraged, much as it has been in defense R&D.

The university consortia managing each regional energy discovery-innovation institutes would be responsible for the operation and the budget of the institute along with management of the relationships among the various participants. Each institute would have a management structure consisting of a director and several associate directors, each responsible for the major activities of the institute (basic research, applied research, technology transfer and commercialization, outreach, etc.). The institute leadership would be advised by an external advisory board representing the participating partners -- government (federal and state), industry, national laboratories, and universities. In order to promote high-risk, high-reward research, a component of the institute budget (perhaps 10%) would be reallocated each year to promising new ideas and directions, at the expense of those that are not showing progress. In this way, the institute would be continually pushing the forefront on new ideas, weeding out stale projects and yet allowing good ideas to make progress and continue to move forward.

The cooperative nature and regional focus of each discovery-innovation institution would allow a much broader range of research opportunities to be addressed than those involving national or industrial laboratories alone. For example, consider the possibility of using heat from a nuclear power plant (co-generation) to power a bio-refinery producing a range of energy products. Here, beyond technology, much of the challenge is in scheduling, regulating, and financing such an effort. While one can build an ethanol or biodiesel plant in a year, it could take several years to get a design-certification and license from the Nuclear Regulatory Commission to build a small nuclear plant. It would also take a large capital investment to finance the effort. This kind of project presents a major interdisciplinary challenge across many constituencies, e.g., the transportation and agricultural industry, electrical utilities, nuclear equipment vendors, federal agencies such as the NRC, the financial industry, all with a strong regional character. The partnership character of a discovery-innovation institute, coupled with its regional focus, would give it the capacity to launch such a project that would be beyond the capability of a national laboratory or industry consortium alone.

Of course, ramping up such a national network of energy discovery-innovation institutes to the suggested level over a something like a five-year period will be a challenge, both to generate the necessary funding and to develop an effective management strategy. Yet we have seen similar initiatives both from industry (e.g., British Petroleum's massive investment in biofuel research at the Universities of California and Illinois) and the states (e.g., the state-funded research institutes at the University of California). The federal government has also launched activities at similar levels in other areas of priority such as defense and biomedical research.

As noted earlier, the complexity and urgent nature of the nation's energy challenges require both a very substantial increase in federal energy R&D spending ($30 B/y or greater). The 2008 presidential campaign raised calls for national investments in "green energy" technology at a level of $150 B/y. At the international level the G-8 and other wealthy nations have been urged to invest from $100 B/y to $250 B/y in technology innovation and infrastructure. While these may seem like ambitious targets during difficult economic times and constrained budgets, it should be noted that the nation is already investing tax dollars of this magnitude in subsidizing energy development programs whose effectiveness has been questioned (e.g., the subsidy of corn-based ethanol production). Furthermore, a carbon tax or the auction of carbon cap-and-trade certificates resulting from legislation such as the Lieberman-Warner bill are estimated to yield $100 B/y at the outset, growing to as much as $500 B/y over the next several decades. (Thompson, 2008)

It is very important to stress that both the proposed National Energy Research Network and regional clusters would be characterized not only by the novel research paradigm of discovery-innovation institutes but also by their highly integrated character as a research <u>network</u>. Undergirded by powerful information and communications technology, i.e., cyberinfrastructure (hardware, software, scientists and engineers, organizations, and polices), and overlaid by a network of virtual organizations involving scientists, engineers, industrial management, and federal participants, the national network would provide a powerful test-bed for the new types of research organizations enabled by rapidly evolving cyberinfrastructure. It would utilize cyberinfrastructure-enabled research paradigms, such as collaboratories and immersive virtual environments, to reduce unnecessary duplication of costly research facilities and cumbersome management bureaucracy. Here again there is considerable experience available from earlier government-funded joint ventures involving research universities and industry.

The proposed National Energy Research Network would nucleate activities from federal and state government, academia, large and small business, and the investment community, marking the beginning of a knowledge revolution that would contribute greatly to the economic base of the nation. It would also begin to move the federal government toward more progressive energy policies and new research paradigms that would lead to an integrated effort to address the nation's challenges for sustainable energy production and associated distribution infrastructure.

Regional Focus

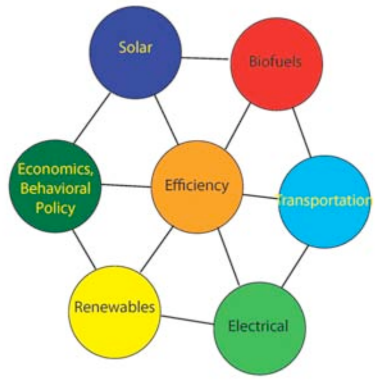
The proposed national network of energy discovery-innovation institutes would be coordinated on a regional basis to respond to the unique energy needs and opportunities characterizing various regions of the United States, e.g., Northeast, Southeast, Great Lakes, Midwest, and Intermountain West states. For example, the region of the United States currently most vulnerable to the unsustainable nature of our current energy infrastructure and federal energy policy spans the Great Lakes states. These states are home to the nation's largest concentration of energy-intensive industries – manufacturing, agriculture, and transportation – clustered about large urban populations, and heavily dependent upon fossil fuel energy sources, e.g., petroleum-based fuels and coal-fired power plants. Not only does this region comprise the nation's largest energy consumer, but its industry and business contributes a very significant fraction of the nation's economic activity, employment, and trade. Today the industries and residents of the region utilize 38% of the nation's electricity, produced primarily from coal-fired plants. Should electrical power generation from fossil fuels be sharply curtailed or should prices skyrocket through regulatory requirements for carbon sequestration or through market geopolitical instabilities, there is little likelihood that the region's industrial capacity would remain competitive in global markets.

Furthermore, this region as the hub of the nation's automobile industry is at particular risk. Over one million jobs, directly or as a multiplier, are dependent upon energy and related industries (e.g., transportation and electrical power generation). Spiking of gasoline prices to Asian and European levels (currently $8 per gallon and above) would likely obliterate what remains of the American automobile industry, since it is unlikely that domestic companies would be able to shift rapidly enough to the small, fuel-efficient cars produced by Asian manufacturers or adapt enough to exploit hybrid, electric, or hydrogen fuel technologies on a short timescale. While it is certainly appropriate that the federal government implement far more aggressive fuel mileage standards, it is also increasingly clear that without massive federal investment in the energy R&D to develop new technologies, such as biofuels, advanced battery technology, hydrogen fuel cycles, or other low carbon propulsion systems, such standards by themselves will almost certainly amount to a death sentence for one of the nation's most important industries.

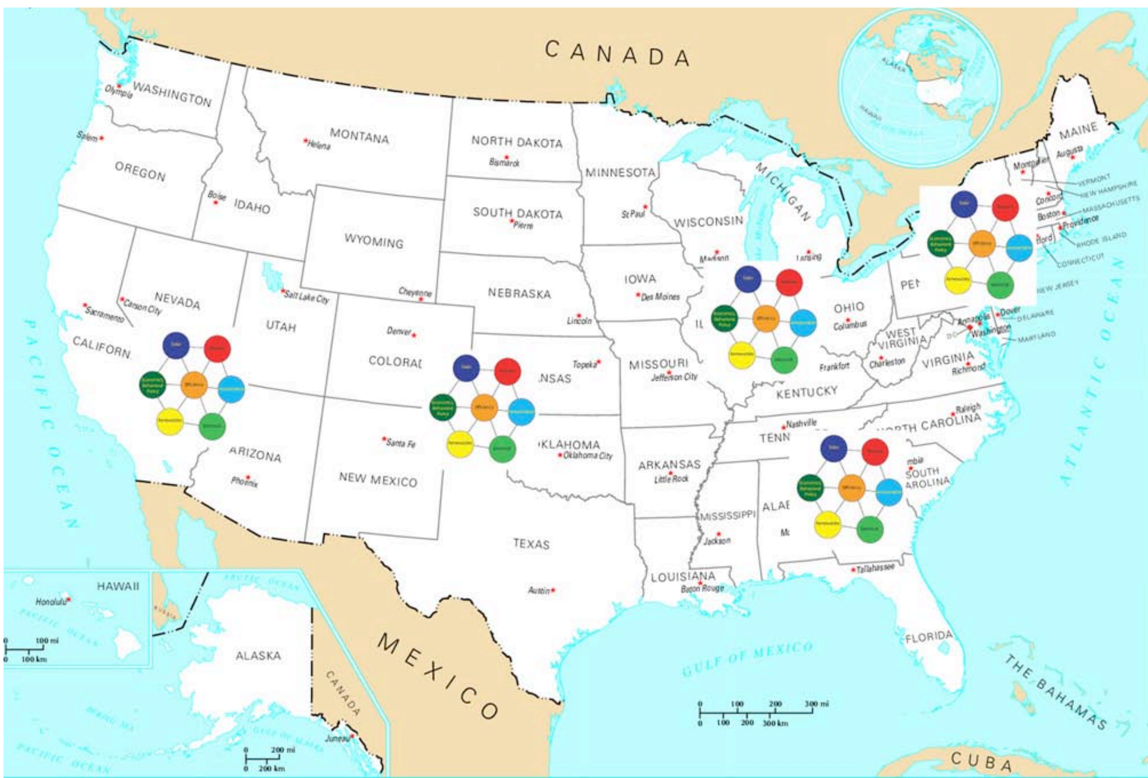
During the 20th century, the Great Lakes states became not only the economic engine of the global economy but also the arsenal of democracy that sustained the nation through two world wars. But today finds the Great Lakes region in the midst of a huge and difficult transition from an industrial to a knowledge economy. Yet, migrating the region's economy from old, fossil-fuel-based to new, clean technologies while creating a culture of innovation in the region to help solve energy challenges in the United States is a significant economic opportunity.

The challenges and opportunities characterizing the Intermountain West states suggest an alternative model of an energy research cluster. Much of the nation's current DOE national laboratory-based research is concentrated in the western (California and Washington) and intermountain states (New Mexico, Arizona, Nevada, Idaho, and Colorado), which also comprise the nation's fastest growing region in both population and economic activity. Given its massive projected future development, the Intermountain West will contend in the next two decades with challenging questions of energy intensity and economic sustainability and will struggle with some of the nation's most extreme needs for clean and affordable energy, new energy efficiency techniques and technologies, and scalable sources of renewable energy.

With strong commitment to interest in its university research capacity as an economic leverage point, an energy research cluster formed in the Intermountain West region would address the needs of rapid population growth and economic activity. The cluster would also address the challenges related to the regions fragile ecosystems and the proximity to significant primary energy sources (oil, gas, shale, hydro). Geography also suggests an unusually strong potential for solar and wind energy in this region, as does the presence of a large number of national laboratories with particularly strong research capability in areas such as renewable energy technologies, energy distribution, and carbon mitigation and sequestration.



A typical regional cluster of discovery-innovation institutes



The proposed National Energy Research Network

The energy needs and capabilities of the Northeast, Southeast, and Midwest states similarly provide strong rationale for clusters of energy discovery-innovation institutions in these regions. In the Northeast, large urban populations with intensive energy needs, the relative absence of national laboratories, and the presence of many of the world's strongest research universities will dictate the design of the region's discovery-innovation institutes. The priorities of the Southeast cluster are growing populations and economies, a strong agricultural and manufacturing base, and sophisticated national laboratories and nuclear utilities. In the Midwestern states, priorities will be shaped by the presence of primary energy sources, a rapidly changing economic base, and significant environment challenges–not the least of which is from weather disruptions. Clearly other regional clusters are also worthy of consideration for the launch of this effort.

A Roadmap for Federal Action

So what steps should the federal government consider in order to create an R&D program commensurate with the seriousness of the threats to our nation posed by an unsustainable energy infrastructure? Although the nation will soon have a new administration and Congress, there are some general recommendations in terms of a legislative agenda, federal management organization, and R&D policy that seem appropriate even at this early stage. These are based upon the premise that the nation must move rapidly to launch a federal energy R&D effort of the scale and urgency of earlier initiatives such as Manhattan Project, and that the specific proposal put forward in this paper for a National Energy Research Network of energy discovery-innovation institutes would be one component of this broader effort.

The legislative effort should begin with a general authorization bill similar to the Hatch Act of 1887 that creates the energy discovery institutes as a component of the nation's energy research activities along with a proposed funding and program evaluation plan, e.g., building up over a five-year-period and initially sustained for 20 years with five-year reviews of both individual innovation-discovery institutes and the entire program. In addition to stand-alone legislation to establish a network of energy discovery-innovation institutes, a rare opportunity to move the National Energy Research Network concept closer to reality presents itself at the start of the new Administration and Congress. In the first months, Washington is expected to debate the establishment of a cap-and-trade system. Already, prior to the elections, key members of Congress have laid out proposals for such a system. It is recommended that a significant proportion of the funds generated by a cap-and-trade system be allocated to competitive energy research. The proposed National Energy Research Network could utilize a share of these new funds in a way that ensures they are best allocated to cutting-edge innovations that are quickly brought to the marketplace. In tandem, legislative campaigns should be started to ensure that any system of energy discovery-innovation institutes authorized by Congress receives funding to operate successfully.

Here a key issue is where the National Energy Research Network (or a larger Manhattan-Project-scale energy research program) would fit within the federal government. One might consider a strong interagency committee in OSTP overseeing the program similar to those for nanotechnology and climate change, consisting of a project director and representatives from OSTP and OMB (probably at the associate director level), with a reporting line to the National Science and Technology Council. But it is also likely that any such program would need a lead agency, such as the Department of Energy, that could drive and promote the project with OMB, Congress, and the public. Of course, locating this program entirely within DOE also raises several of the concerns noted earlier in this paper. To break with the status quo and achieve a truly government-wide effort balance among intramural and extramural participants (e.g., DOE labs vs. industry, higher education, and the states), it would probably be necessary to create a new senior position in DOE such as an Under Secretary or even a Level II Presidential appointment similar to the Deputy Secretary with responsibility for total energy program (e.g., "Director of the Energy 2020 Project"). The strong role of the discovery-innovation institutes in R&D as well as in working with industry to commercialize technology suggest that this should not be the Under Secretary for Science.

It is important that this cuts across existing DOE programs, e.g., fossil, nuclear, renewables, science, as well as the national laboratories, if it is to take on the scale of a Manhattan Project more broadly, with the NERN as a component. If the new "Energy 2020" office is placed within DOE, it probably needs to be legislatively freed of much of the contract, legal, and other procedures of DOE, perhaps with even a direct relationship with OMB. It should also have monies appropriated to it that are for pass-through/coordination to other agencies so that a true interagency character can be developed. An alternative would be to appropriate funds directly to other relevant federal agencies (DOD, Commerce, Interior, Agriculture) to enable them to launch their own set of energy discovery-innovation institutes, although this would create the additional complexity of coordinating among multiple appropriations subcommittees. In any case there should be a strong external advisory committee to assist in oversight and policy development for the program.

More specifically, since the National Energy Research Network is based upon clusters of regionally-based energy discovery-innovation centers, it would be possible to adopt a phased approach, perhaps launching five institutes a year over a five-year period to create the full network, with the early institutes being viewed as prototypes to refine both policy and operational issues (e.g., management, intellectual property, and coordination). Each institute would be subject to a rigorous evaluation at regular intervals, together with an ongoing assessment of the effectiveness of the entire program in terms of research results, funding matches, commercial spinoffs, and human resource production. Although long-term energy research would require sustained funding of the research network, it would also be possible to place a sunset of 12 to 15 years on each individual discovery-innovation institute so that a re-competition for federal support would occur.

Conclusion

Today an economically fragile and environmentally damaging energy infrastructure has put at great risk this nation's economic prosperity and security, and perhaps even the very future of humankind on Earth. New energy technologies must be rapidly developed that are sustainable for the long term, characterized by acceptable environmental impact, and linked to the legal and social infrastructures to properly take advantage of these technology innovations. As many others have suggested, the current level of federal investment, policies, and programs is seriously inadequate to this challenge, and a national effort of the scale and urgency of other earlier initiatives such as the Manhattan Project or the Apollo program is justified.

This will require an order of magnitude increase in the federal investment in research conducted by the national laboratories and industry, perhaps at the level of $30 to $40 billion a year and comparable to federal investment in other R&D priorities such as health care ($30 billion/y) and defense ($80 billion/y). In addition to substantial increases in federal investment in research through conventional funding mechanisms, the unusual complexity and scale of the nation's energy challenges requires new research paradigms better able to integrate scientific research, technology development and commercialization, and the production of human resources across a broad range of scientific, technological, economic, behavioral, and public policy considerations.

To address these broader requirements, this paper has proposed augmenting the R&D programs of the national laboratories and industry with an entirely new research paradigm recently proposed by a task force of the National Academy of Engineering: a national network of multidisciplinary *discovery-innovation institutes* capable of linking fundamental scientific discoveries with technological innovations to create the products, processes, and services needed by society. Funding would be provided by an interagency federal program, augmented by contributions from state governments, industry, foundations, venture capital and investing community, and universities. Each institute would be closely linked with an adjacent research university (or consortium); supported by core federal funding building to a level of $200 million per year; augmented with significant additional funding from state, industry, foundation, and university sources; and managed by a consortium of research universities and industrial partners. Beyond addressing critical national energy priorities in a coordinated fashion, the energy discovery-innovation institutes would be responsive to unique regional challenges and opportunities and would furthermore be designed to stimulate local economic growth through spinoff activities, new business formation, and job creation.

When completed, the proposed National Energy Research Network would consist of 20 to 30 discovery-innovation institutes, organized into regional clusters, with interagency federal funding building to a total level of $4 to $6 billion a year. While this may seem ambitious in view of current federal budget constraints, it is modest indeed compared to the federal R&D funding provided other federal priorities such as health care, defense, and manned spaceflight, and represents only 10%-15% of the total federal energy R&D investment estimated to be necessary to respond to this nation's urgent needs for creating a sustainable energy infrastructure. Furthermore, there are ample options for funding such a major federal energy R&D effort, both through reallocation of funds from existing federal energy development programs of questionable value (e.g., subsidies for corn-based ethanol production) or from the revenues generated by future programs aimed at constraining greenhouse gas emissions (e.g., the auctions of carbon cap-and-trade certificates or from a carbon tax).

A century ago the United States took bold action through the Hatch Act of 1887 to establish a network of university-based experiment stations to assist in modernizing American agriculture and industry. Remarkably similar in both spirit and structure to this earlier highly successful effort, the proposed National Energy Research Network of regional energy discovery-innovation institutes would create a partnership among research universities, business and industry, entrepreneurs and investors, and federal, state, and local government, working together across a broad spectrum of scientific, engineering, economic, behavioral, and policy disciplines, to build a sustainable national energy infrastructure for the 21st century while stimulating strong regional economic growth.

Today our national energy infrastructure, based primarily upon fossil fuels and heavily dependent upon an unsustainable dependence on foreign energy imports, simply must be replaced with new technologies before our economic prosperity, national security, and natural environment are severely damaged. It is time once again for the federal government to make a major commitment to investing adequately in the

R&D necessary to develop new energy technologies that will secure prosperity and security for future generations while protecting the sustainability of Planet Earth for humankind. The National Energy Research Network, comprised of regional energy discovery-innovation institutes, would represent an important element of this broader national effort to achieve a sustainable energy future for both our nation and the world.

References

Alexander, Lamar, "A New Manhattan Project for Clean Energy Independence", *Issues in Science and Technology*, Summer, 2008.

American Association for the Advancement of Science, "R&D in the FY 2009 Budget", R&D Budget and Policy Program, http://www.aaas.org/rd/fy09.htm

Atkins, Daniel E. (chair), *Revolutionizing Science and Engineering Through Cyberinfrastructure*. Report of the National Science Foundation Blue-Ribbon Advisory Panel on Cyberinfrastructure. Washington, D.C.: National Science Foundation, 2003

Augustine, Norman (chair), National Academies Committee on Prospering in the Global Economy of the 21st Century, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*, National Academies Press, Washington, D.C., 2005.

Austin, John and Britany Affolter-Caine, *The Vital Center: A Federal-State Compact to Renew the Great Lakes Region*, Brookings Institution Metropolitan Policy Program, Washington, D.C. 2006.

Caltech, "The Energy Wars", Caltech *Engineering Applied Science Magazine*, Interview with Nathan Lewis, Harry Gray, and other Caltech Faculty, May, 2007.

Council on Competitiveness, National Innovation Initiative. Washington, DC: Council on Competitiveness, 2004. http://www.compete.org/nii/

Friedman, Thomas, *The World Is Flat: A Brief History of the 21st Century*. New York: Farrar, Strauss, and Giroux, 2005.

Goodstein, David, *Out of Gas: The End of the Age of Oil*. New York: W. W. Norton, 2004

Hirsch, Robert, Peaking of World Oil Production: How Do We Mitigate the Problem, SAIC Study, Department of Energy (2005)

IPCC, Climate Change 2007, Intergovernmental Panel on Climate Change, 2007

International Energy Agency. "Energy Technology Perspectives 2008: Scenarios and Strategies to 2050. Paris: OECD/IEA, 2008.

Kammen, Daniel M. and Gregory F. Nement. "Reversing the Incredible Shrinking Energy R&D Budget", Issues in Science and Technology, Fall, 2005, pp. 88

Kerr, Richard A., "The Looming Oil Crisis Could Arrive Uncomfortably Soon", *Science* Vo. 316, April 20, 2007, p. 351

Lewis, Nathan S., "Powering the Planet", Caltech *Engineering & Science*, No. 2 (2007), p. 13

National Academy of Engineering Task Force on Research, *Assessing the Capacity of the*

U.S. Engineering Research Enterprise. Washington: National Academy of Engineering, 2005. (http://books.nap.edu/catalog.php?record_id=11393)

National Academies, America's Energy Future: Technology Opportunities, Risks and Tradeoffs, Study under way (2008)

National Science Board, *Science and Engineering Indicators 2008*, Arlington, VA: National Science Foundation, 2008)

PCAST, Energy Technologies, President's Council of Advisors on Science and Technology, 2006.

Schellenberger, Michael and Ted Nordhaus, "Scrap Kyoto". *Democracy Journal*, Summer, 2008.

Schlesinger, William, Carbon Trading, Science, Vol 314, November 25, 2006, p. 1217; William Chameides, Michael Oppenheimer, Carbon Trading Over Taxes, Science, Vol 315, March 23, 2007, p. 1670

Thompson, Clive, "A Green Coal Baron", New York Times Magazine. June 22, 2008.

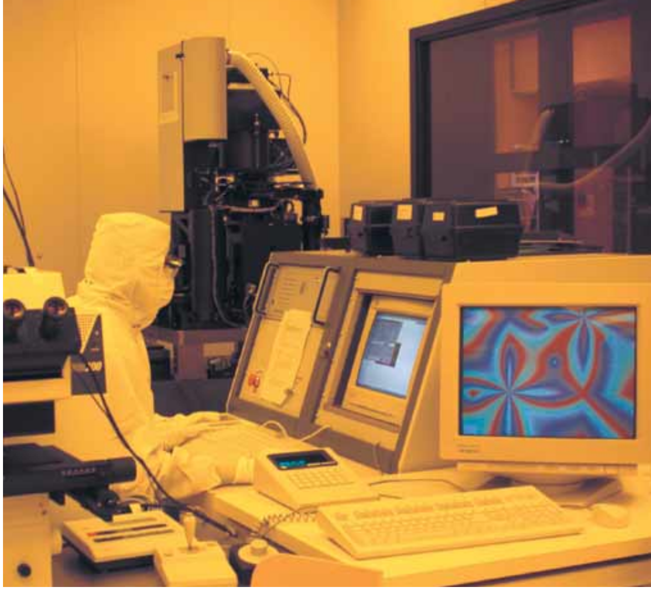
Vest, Charles M., Chair, *Critical Choices: Science, Energy, and Security*. Final Report of the Secretary of Energy's Advisory Board Task Force on the Future of Science Programs at the Department of Energy, October 13, 2003.

DISCOVERY-INNOVATION INSTITUTES: A PATH AHEAD

U.S. leadership in innovation will require commitments and investments of funds and energy by the private sector, federal and state governments, and colleges and universities. The committee believes that a bold, transformative initiative, similar in character and scope to initiatives undertaken in response to other difficult challenges (e.g., the Land Grant Acts, the G.I. Bill, and the government-university research partnerships) will be necessary for the United States to maintain its leadership in technological innovation. The United States will have to reshape its engineering research, education, and practices to respond to challenges in global markets, national security, energy sustainability, and public health. The changes we envision are not only technological, but also cultural; they will affect the structure of organizations and relationships between institutional sectors of the country. This task cannot be accomplished by any one sector of society. The federal government, states, industry, foundations, and academia must all be involved.

Research universities are critical to generating new knowledge, building new infrastructure, and educating innovators and entrepreneurs. The Land-Grant Acts of the nineteenth century and the G.I. Bill and government-university research partnerships of the twentieth century showed how federal action can catalyze fundamental change. In the past, universities dealt primarily with issues and problems that could be solved either by a disciplinary approach or by a multidisciplinary approach among science and engineering disciplines (e.g., ERCs). To meet future challenges, however, universities will need a new approach that includes schools of business, social sciences, law, and humanities, as well as schools of science, engineering, and medicine. Solving the complex systems challenges ahead will require the efforts of all of these disciplines.

RECOMMENDATION 9. Multidisciplinary discovery-innovation institutes should be established on the campuses of research universities to link fundamental scientific discoveries with technological innovations to create products, processes, and services to meet the needs of society. Funding should be provided by federal and state governments, industry, foundations, the venture capital and investing community, and universities.



Discovery-innovation institutes would be foci for long-term fundamental and applied engineering research on major societal challenges and opportunities, would create new models of sectoral and disciplinary interaction on university campuses, and, indeed, would change the culture of research in this country. The committee envisions a large number of diverse institutes, some based at single universities, some involving consortia of institutions, and some focused on strengthening the research and educational capacity of a wide variety of institutions. With the participation of many scientific disciplines and professions, as well as various economic sectors (e.g., industry, federal and state governments, foundations, entrepreneurs, and venture capitalists), the institutes would be similar in character and scale to academic medical centers and agricultural experiment stations. In scope and transformational power, discovery-innovation institutes would be analogous to the agricultural experiment stations created by the Hatch Act of 1887 and the complementary creation of cooperative extension programs authorized by the Smith-Lever Act of 1914.

Operationally, discovery-innovation institutes would be comparable to academic medical centers, which combine research, education, and practice in state-of-the-art facilities and address significant national priorities rather than applications-driven research and technology centers, such as engineering experiment stations and federally funded R&D centers (e.g., MIT's Lincoln Laboratory and Carnegie Mellon's Software Engineering Institute). Like academic medical centers and other large research initiatives, discovery-innovation institutes would stimulate significant commercial activity, as clusters of start-up firms, private research organizations, suppliers, and other complementary groups and businesses locate nearby; in this way, the institutes would stimulate regional economic development. Some of the existing NSF-sponsored ERCs could serve as starting points for the development of discovery-innovation institutes. An effective way to initiate a discovery-innovation institute program on a pilot basis might be to expand the charter of one or two ERCs to include the multidisciplinary scope and scale of the research, education, innovation, and technology transfer activity of fully developed discovery-innovation institutes.

Discovery-innovation institutes would require the active involvement of industry and national laboratories to fulfill their missions of conducting long-term research to convert basic scientific discoveries into innovative products, processes, services, and systems. They would stimulate the creation of new infrastructure, encourage (in fact, require) interdisciplinary linkages, and lead to the development of educational programs that could produce new knowledge for innovation and educate the engineers, scientists, innovators, and

entrepreneurs of the future (Figure 3). Discovery-innovation institutes would be characterized by partnership, interdisciplinary research, education, and outreach.

FIGURE 3 Discovery-innovation institutes.

CAMPUS LINKAGES
Sciences
Professional schools

PRIVATE-SECTOR LINKAGES
Industry partnerships
Entrepreneur participation

PUBLIC-SECTOR LINKAGES
Federal agencies
National laboratories
States

DISCOVERY-INNOVATION INSTITUTES

Link scientific discovery with societal applications

Educate and train innovators, entrepreneurs, and engineers

Build infrastructure (laboratories, cybersystems, etc.)

Analogous to agricuture experiment stations and acdemic medical centers

NATIONAL PRIORITIES
Economic competitiveness
National and homeland security
Public health and social well-being

GLOBAL CHALLENGES
Global sustainability
Geopolitical conflict

OPPORTUNITIES
Emerging technologies
Interdisciplinary activities
Complex large-scale systems

SUPPORT
Core federal support (e.g., Hatch Act)
State participation (physical facilities)
Industry participation
Entrepreneur participation
University participation
Co-investment
Policies (e.g., for intellectual properry)

Partnership

The federal government would provide core support for the discovery-innovation institutes on a long-term basis (perhaps a decade or more, with possible renewal). States would be required to contribute to the institutes (perhaps by providing capital facilities). Industry would provide challenging research problems, systems knowledge, and real-life market knowledge, as well as staff who would work with university faculty and students in the institutes. Industry would also fund student internships and provide direct financial support for facilities and equipment (or share its facilities and equipment). Universities would commit to providing a policy framework (e.g., transparent and efficient intellectual property policies, flexible faculty appointments, responsible financial management, etc.), educational opportunities (e.g., integrated curricula, multifaceted student interaction), knowledge and technology transfer (e.g., publications, industrial outreach), and additional investments (e.g., in physical facilities and cyberinfrastructure). Finally, the venture capital and investing community would contribute expertise in licensing, spin-off companies, and other avenues of commercialization.

Interdisciplinary Research

Although most discovery-innovation institutes would involve engineering schools (just as the agricultural experiment stations involve schools of agriculture), they would require strong links with other academic programs that generate fundamental new knowledge through basic research (e.g., physical sciences, life sciences, and social sciences), as well as other disciplines critical to the innovation process (e.g., business, medicine, and other professional disciplines). These campus-based institutes would also attract the participation (and possibly financial support) of established innovators and entrepreneurs.

Education

Engineering schools and other programs related to the discovery-innovation institutes would be stimulated to restructure their organizations, research activities, and educational programs. Changes would reflect the interdisciplinary team approaches for research that can convert new knowledge into innovative products, processes, services, and systems and, at the same time, provide graduates with the skills necessary for innovation. These changes would also generate strategies for retaining undergraduates in engineering programs and attracting and retaining students from diverse backgrounds. Discovery-innovation institutes would provide a mechanism for developing and implementing innovative curricula and teaching methods.

Outreach

Just as the success of the agricultural experiment stations depended on their ability to disseminate new technologies and methodologies to the farming community through the cooperative extension service, a key factor in the success of discovery-innovation institutes would be their ability to facilitate implementation of their discoveries in the user community. Extensive outreach efforts based on existing industry and manufacturing extension programs at engineering schools would be an essential complement to the research and educational activities of the institutes. Outreach should also include programs for K–12 students and teachers that would build enthusiasm for the innovation process and generate interest in math and science.

Research Priorities

This initiative would stimulate and support a very wide range of discovery-innovation institutes, depending on the capacity and regional characteristics of a university or consortium and on national priorities. Some institutes would enter into partnerships directly with particular federal agencies or national laboratories to address fairly specific technical challenges, but most would address broad national priorities that would require relationships with several federal agencies. Awards would be made based on (1) programs that favor fundamental research driven by innovation in a focused area; (2) strong industry commitment; (3) multidisciplinary participation; and (4) national need. Periodic reviews

BOX 4 LARGE COMPLEX SYSTEMS

The development of methodologies for creating very large, complex systems would be an ideal focus for a discovery-innovation institute. Experience shows that the development of such systems always costs more and takes longer than anticipated, and usually results in less capability than desired. The solutions require the integration of knowledge from many disciplines and the modification of plans based on experience gained from the implementation of subsystems.

To create systems on a "learn as you go" basis requires a strategy for collecting and analyzing information from the early use of subsystems and dynamic management of budgets and schedules, without compromising accountability. However, there are no accepted methodologies for this type of sequential management of systems based on incremental implementation. Even selecting the sequence of subsystem implementation based on where the most valuable experience is likely to be gained as early as possible is not standard practice.

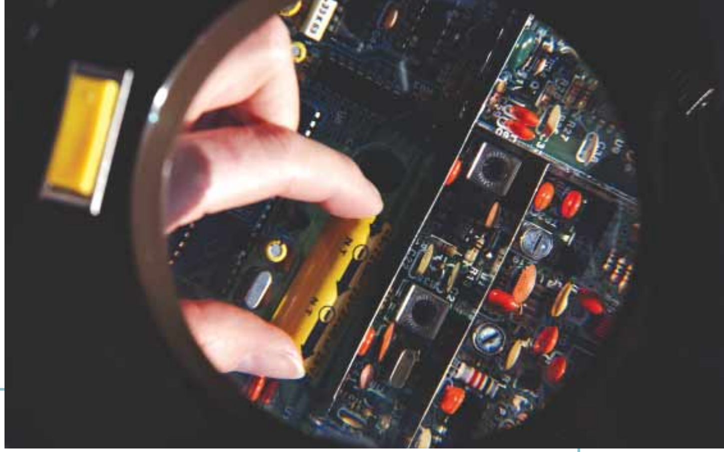
Although computer-based tools are emerging to improve collaboration among large teams working on common problems, analogous tools for the development of large, complex systems are not available. Systems-engineering researchers at the nation's universities could integrate research from many disciplines to develop new methodologies and tools for the creation and management of large, complex systems. Faculty members who work on these projects would gain direct experience with the pressures and problems of system development.

System development could lead to new approaches to embedding automated information-collection capabilities into systems, using collaborative computing to gain early insight into system performance, broadening the education of engineers to include exposure to management complexities, and developing new materials for research and education.

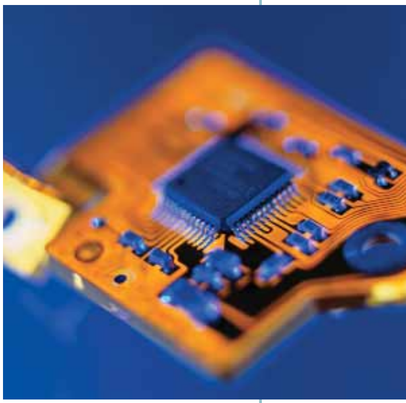
These systems reside and operate in a complex environment that raises financial, political, social, and ethical issues. Mobilizing multidisciplinary teams to address these issues would be an important step toward maximizing their social and economic benefits.

would ensure that the institutes remain productive and continue to progress on both short- and long-term deliverables. The examples below suggest some areas of focus for institutes (see also Boxes 4 and 5):

- Institutes linking engineering with the physical sciences, social sciences, environmental sciences, and business programs to address the urgent national challenge of developing sustainable energy sources, including, for instance, the production, storage, distribution, and uses of hydrogen-based fuels for transportation.
- Institutes linking engineering with the creative arts (visual and performing arts, architecture, and design) and the cognitive sciences (psychology, neuroscience) to conduct research on the innovation process per se.
- Institutes linking engineering systems research with business schools, medical schools, schools of education, and the social and behavioral sciences to address issues associated with the knowledge-services sector of the economy.



BOX 5 BEYOND CMOS



Semiconductors represent a critical foundational technology for innovation in most industries and have helped the United States achieve unprecedented economic prosperity and defense superiority. Most semiconductor products are based on CMOS technology, which is likely to reach its fundamental limits—primarily for power dissipation and reliability—in about 15 years. Because there is typically a 15-year lag from research to production, the time to initiate the successor to CMOS is now. The successor technology will be in the broad area of nanoelectronics, but currently it is neither defined nor understood.

The Semiconductor Industry Association has proposed the concept of a nanoelectronics research initiative (NRI) to meet this urgent need. The objective of the NRI is: "By 2020 to discover and reduce to practice via technology transfer to industry novel non-CMOS devices, technology, and new manufacturing paradigms which will extend the historical cost/function reduction, along with increased performance and density for another several orders of magnitude beyond the limits of CMOS."

Like the discovery-innovation institutes initiative, the NRI is envisioned as a partnership of industry, government, and academia. The NRI would be primarily university-based, with federal funds leveraged by state and industry contributions. Industry assignees will effectively and swiftly move results from universities to companies.

Source: Apte and Matisoo, 2004.

- Institutes linking engineering with social sciences and professional schools to conduct research on communication networks to determine capacity, identify bottlenecks, estimate extendibility, and define performance characteristics of complex systems that comprise terrestrial, wired, wireless, and satellite subnets, as well as the legal, ethical, political, and social issues raised by the universal accessibility of information.
- Institutes linking engineering, business, and public policy programs with biomedical sciences programs to develop drugs, medical procedures, protocols, and policies to address the health care needs and complex societal choices for an aging population.

Funding

The committee recognizes that federal and state budgets are severely constrained and are likely to remain so for the foreseeable future. Nevertheless, with revised national R&D investment priorities and public understanding of the critical need for public investment in research to sustain national security and prosperity, the required sums could be made available. The level of investment and commitment would be analogous to the investments in the late nineteenth century that created and sustained the agricultural experiment stations, which endure to this day and have had incalculable benefits for agriculture and the nation as a whole. We expect similar results from discovery-innovation institutes.

On the federal level, the discovery-innovation institutes should be funded jointly by agencies with responsibilities for basic research and missions that address major national priorities (e.g., NSF, DOE, NASA, DOD, DHS, DOT, U.S. Department of Commerce, Envirnmental Protection Agency, and U.S. Department of Health and Human Services).

States would be required to contribute to the institutes (perhaps by providing capital facilities). Industry would provide challenging research problems, systems knowledge, and real-life market knowledge, as well as staff who would work with university faculty and students in the institutes. Industry would also fund student internships and provide direct financial support for facilities and equipment (or share its facilities and equipment). Universities would commit to providing a policy framework (e.g., transparent and efficient intellectual property policies, flexible faculty appointments, responsible financial management, etc.), educational opportunities (e.g., integrated curricula, multifaceted student interaction), knowledge and technology transfer (e.g., publications, industrial outreach), and additional investments (e.g., in physical facilities and cyberinfrastructure). Finally, the venture capital and investing community would contribute expertise in licensing, spin-off companies, and other avenues of commercialization.

CONCLUSION

Exciting opportunities in engineering lie ahead. Some involve rapidly emerging fields, such as information systems, bioengineering, and nanotechnology. Others involve critical national needs, such as sustainable energy sources and homeland security. Still others involve the restructuring of engineering education to ensure that engineering graduates have the skills, understanding, and imagination to design and manage complex systems. To take advantage of these opportunities, however, investment in engineering education and research must be a much higher priority.

"We are not graduating the volume [of scientists and engineers], we do not have a lock on the infrastructure, we do not have a lock on the new ideas, and we are either flat-lining, or in real dollars cutting back, our investments in physical science. The only crisis the U.S. thinks it is in today is the war on terrorism. It's not!" Craig Barrett, CEO of Intel and current chairman of the National Academy of Engineering (Friedman, 2004).

The United States has the proven ability and resources to take the global lead in innovation. Scientists and engineers can meet the technological challenges of the twenty-first century, just as they responded to the challenges of World War II by creating the tools for military victory and just as they mounted an effective response to the challenge of Sputnik and Soviet advances in space. With adequate federal investment and the participation of other stakeholders in engineering research, education, and professional practice, we can realize this vision.

The country is at a crossroads. We can either continue on our current course—living on incremental improvements to past technical developments and gradually conceding technological leadership to trading partners abroad—or we can take control of our destiny and conduct the necessary research, capture the intellectual property, commercialize and manufacture the products, and create the high-skill, high-value jobs that define a prosperous nation.