CHAPTER 16

# New University Paradigms for Technological Innovation

*James J. Duderstadt*

In today's global, knowledge-driven economy, leadership in innovation is essential to a nation's prosperity and security. In particular, technological innovation — the transformation of new knowledge into products, processes and services of value to society — is critical to economic competitiveness, national security and an improved quality of life. The United States has long benefited from a fertile environment for innovation, such as a diverse population continually renewed through immigration, democratic values that encourage individual initiative, and free market practices that drive the ongoing process of creative destruction (à la Schumpeter). But history has shown that public investment is necessary to produce the key ingredients for technological innovation including: new knowledge (research and development), human capital (education, particularly at the advanced level), infrastructure (physical and now cyber) and supportive policies (tax, intellectual property) (Augustine, 2005).

Although the flow of knowledge from scientific discovery through development and technological innovation, commercialization and deployment was once thought of as a linear, vertical process, it is now viewed as far more complex, both vertical and horizontal, and involving many interacting disciplines and participants. As Nam Suh has suggested in his paper for this Glion Colloquium (Suh, Chapter 19), for innovation to occur, there cannot be any missing steps or elements in the continuum of necessary activities.

Traditionally, one thinks of the appropriate activities for each of the key factors in the innovation continuum — namely, government, industry and universities — in terms such as basic research, applied research, development, commercialization and deployment. For example, basic research activities, usually speculative, long term and driven by scientific curiosity, are usually viewed as the proper role of research universities, while use-driven basic research, applied research and development are more commonly roles for government or industrial laboratories. Commercialization and deployment are similarly viewed most appropriate for industry (both established and entrepreneurial).

Yet, there are other types of research important to the innovation continuum. In his theory of scientific revolution, Thomas Kuhn suggested that major progress was achieved not through gradual evolution of conventional disciplinary research, but rather through revolutionary, unpredictable transformations after the intellectual content of a field reaches saturation (Kuhn, 1963). The U.S. National Science Foundation refers to such activities as *transformative research*, "research driven by ideas that stand a reasonable success of radically changing our understanding of an important existing concept or leading to the creation of a new paradigm or field of science. Such research is also characterized by its challenge to current understanding or its pathway to new frontiers" (National Science Board, 2007). While it might be assumed that such transformative research would most commonly occur in research universities, ironically the peer pressure of merit review in both grant competition and faculty promotion can discourage such high-risk intellectual activities. In fact, transformative research occurs just as frequently in some industrial research laboratories (e.g., Bell Laboratories in the past and Google Research today) where unusually creative investigators are freed from the burdens of grant seeking or commercial deadlines. It also occurs in a small number of unique government agencies such as the Defense Advanced Research Project Agency (and hopefully in its spinoffs of ARPA-E and IARPA), where path-breaking research is shielded from the pressures of grant competition and application deadlines.

At the other end of the innovation continuum is translational research, aimed at building the knowledge base necessary to link fundamental scientific discoveries with the technological innovation necessary for the development of new products, processes and services. While translational research is both basic and applied in nature, it is driven by intended application and commercial (or social) priorities rather than scientific curiosity. Such translational research is a common feature of the biomedical industry, moving "from bench to bedside" or from laboratory experiments through clinical trials to actual point-of-care patient applications. While it is also a necessary component of the innovation continuum in other areas, particularly in corporate and federal R&D (with Bell Laboratories and the U.S. Department of Energy Laboratories as prominent examples), it has generally not been identified as a specific activity of research universities.

## DISCOVERY-INNOVATION INSTITUTES

Over the past several years, there has been an increasing recognition that U.S. leadership in innovation will require commitments and investments of resources by the private sector, federal and state governments, and colleges and universities. In 2005, the U.S. National Academies issued a series of reports suggesting 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 post-WWII government-university research partnerships) will be necessary for the United States to maintain its leadership in technological innovation (Augustine, 2005). The United States will have to reshape its research, education and practices to respond to challenges in global markets, national security, energy sustainability and public health. The changes envisioned were not only technological, but also cultural; they would affect the structure of organizations and relationships between institutional sectors of the country.

To this end, it was the recommendation of the U.S. National Academy of Engineering that a major federal initiative be launched to create translational research centers aimed at building the knowledge base necessary for technological innovation in areas of major national priority (Duderstadt, 2005). These centers, referred to as *discovery-innovation institutes*, would 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. With the participation of many scientific disciplines and professions, as well as various economic sectors (industry, government, states and institutions of higher education), discovery-innovation institutes would be 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 has shown, discovery-innovation institutes would have the potential to 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.

More specifically, discovery-innovation institutes would be characterized by partnership, interdisciplinary research, education and outreach:

*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 investment 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:* Universities hosting 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. 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 established by the U.S. Land Grant Acts 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 universities 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:* The National Academy report envisioned 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 favour fundamental research driven by innovation in a focused area; (2) strong industry commitment; (3) multidisciplinary participation; and (4) national need. Periodic reviews would ensure that the institutes remain productive and continue to progress on both short- and long-term deliverables.

*Funding:* To ensure that the discovery-innovation institutes lead to transformative change, they would be funded at a level commensurate with past federal initiatives and current investments in other areas of research, such as biomedicine and manned spaceflight. Federal funding would ultimately increase to several billion dollars per year distributed throughout the university research and education enterprise, with states, industry, foundations and universities investing comparable amounts in these research centers. To transform the technological innovation capacity of the United States, the discovery-innovation institutes would be implemented on a national scale and backed by a strong commitment to excellence by all participants. Most of all, they would become engines of innovation that would transform institutions, policies and cultures, and enable our nation to solve critical problems and maintain its leadership in the global, knowledge-driven society of the 21st century.

## A CASE STUDY: ENERGY RESEARCH

Sustainability and security challenges plague the world's energy production and delivery system. The global economy currently relies on fossil fuels for nearly 85% of its energy. By 2030, global energy use is projected to grow by 50% over 2010 levels. At the same time, recent analyses of world petroleum production, known reserves, and the impact of rapidly developing economies suggest that an increasing imbalance between supply and demand will drive up global oil and gas prices, placing a nation's economy and security at risk. While the world has substantial reserves of other fossil-fuel resources, such as coal, tar sands and oil shale, the mining, processing and burning of these fossil fuels with current technologies are expensive and characterized by increasingly unacceptable environmental impact in light of climate change concerns and intensive land and water utilization (IPCC, 2008; Friedman, 2008).

Today's energy challenges stem from an unsustainable energy infrastructure, largely dependent on fossil fuels characterized by unacceptable environmental impact and supply constraints, with clear implications for a nation's economic, public health and national security. Addressing these challenges will require substantial investments in clean and efficient energy technology, much of which has yet to be developed, making innovation the centerpiece of successful energy policy (Lewis, 2007).

Transformative innovation will be required to address fundamental energy challenges. As Presidential Science Advisor John Holdren warns, the multiplicity of challenges at the intersection of energy with the economy, the environment and national security — led by excessive dependence on petroleum and the dangerous consequences of energy's environmental impact, particularly global climate change — requires a major acceleration of energy-technology innovation that, over time, can reduce the limitations of existing energy options, bring new options to fruition and reduce the tensions among energy-policy objectives and enable faster progress on the most critical ones (Holdren, 2006).

Near term impact can be achieved from adopting existing technologies and practices that improve the efficiency of energy utilization, bringing fuel savings and creating new jobs. Yet, large and sustained efficiency investments in existing technologies will not be enough to achieve global sustainability goals. New technologies and practices are needed to mitigate the harmful impact and resource constraints of existing energy sources. Of longer term importance is the deployment of affordable, carbon-free renewable energy technologies, which will require energy storage technologies and an expanded electricity grid. With today's renewable technologies, a substantial gap remains in achieving the scale and cost structures necessary for major impact.

Here, innovation is needed not only through greatly increasing R&D in energy technologies but to demonstrate these on a commercial scale and deploy them rapidly into the marketplace. Yet, over the past two decades, energy research in the United States has actually been sharply curtailed by the federal government (75% decrease), the electrical utility industry (50% decrease), and the domestic automobile industry (50% decrease). The energy industry has the lowest level of R&D investment (relative to revenues) of any industrial sector. In 2009, federal investment in energy R&D amounted to less than $3 billion, compared to the federal R&D effort characterizing other national priorities such as health care ($30 B/y) and defense ($80 B/y) (Kammen, 2005; Friedman, 2008).

Furthermore, today's United States energy research program does not have the mission, capacity or the organizational structure to equip the nation to meet the full span of its challenges. It continues to be primarily conducted by national labs that are not only fragmented and insulated from the marketplace, but fail to tap the considerable resources of the nation's industry and research universities (Vest, 2003). Major innovation in research paradigms, policy and management will be necessary to bring about the needed pace of energy-technology innovation (Holdren, 2006):

- To provide the scale, continuity and coordination of effort in energy R&D and demonstration needed to bring an appropriate portfolio of improved options to be commercialized in a timely way.

- To tap the nation's top scientific and engineering talent and facilities, which are currently distributed throughout the nation's research universities, corporate R&D centers and federal laboratories.
- To address adequately the unusually broad spectrum of issues involved in building a sustainable energy infrastructure, including, in addition to science and technology, attention to complex social, economic, legal, political, behavioral, consumer and market issues.
- To build strong partnerships among multiple players — federal agencies, research universities, established industry, entrepreneurs and investors, and federal, state and local government.
- And to launch robust efforts capable of producing the human capital and public understanding required by the emerging energy sector at all education levels.

In view of these market and governance challenges, it is clear that the search for breakthrough technologies and practices should be placed at the center of energy research efforts. This will require a far more comprehensive and interactive engagement of the entire national research enterprise: research universities, corporate R&D laboratories and federal laboratories.

To address these challenges, a recent report by the Brookings Institution made two important recommendations (Duderstadt, 2009):

The United States should first commit itself to increasing federal investments in energy R&D to a level appropriate to address the dangerous and complex economic, environmental and national security challenges presented by the nation's currently unsustainable energy infrastructure. Comparisons with federal R&D investments addressing other national priorities such as public health, national defense and space exploration suggest an investment in federal energy R&D, an order of magnitude greater than current levels, growing to perhaps $20 to $30 billion per year, with most of this flowing to existing research players and programs (e.g., national laboratories and industry).

A significant fraction of this increase should be directed toward a new research paradigm consisting of a national network of regionally-based *energy discovery-innovation institutes* (e-DIIs) that serve as hubs in a distributed research network linked through spokes to concentrations of the nation's best scientists, engineers and facilities.

Recall that the discovery-innovation institute concept is characterized by institutional partnerships, interdisciplinary research, technology commercialization, education and outreach. In this sense, the e-DII paradigm would place a very high priority on connection and collaboration rather than competition to achieve deeper engagement of the nation's scientific, technology, business and policy resources in an effort to achieve a sustainable energy infrastructure for America.

As envisioned here, therefore, the proposed e-DIIs would do the following:

*Organize around a theme*, such as renewable energy technologies, advanced petroleum extraction, carbon sequestration, biofuels, transportation energy, carbon-free electrical power generation and distribution, or energy efficiency. Each e-DII would be charged with addressing the economic, policy, business, and social challenges required to diffuse innovative energy technologies of their theme area into society successfully. This mission would require each e-DII to take a systems-approach to technology development and help to transcend the current "siloed" approach common at DOE and its national labs.

*Foster partnerships* to pursue cutting-edge, applications-oriented research among multiple participants, including government agencies (federal, state and local), research universities, industry, entrepreneurs and investors. The e-DIIs would encourage a new research culture based on the nonlinear flow of knowledge and activity among scientific discovery, technological innovation, entrepreneurial business development and economic, legal, social, and political imperatives. In a sense, e-DIIs would create an "R&D commons" where strong, symbiotic partnerships could be created and sustained among partners with different missions and cultures. Building a sustainable energy infrastructure depends as much on socioeconomic, political and policy issues as upon science and technology. The e-DIIs would encompass disciplines such as the social and behavioral sciences, business administration, law and environmental and public policy, in addition to science and engineering.

*Act as the hubs of a distributed network*, linking together as spokes, the basic research programs of campus-based, industry-based and federal laboratory-based scientists and engineers, research centers and facilities, to exploit the fundamental character of discovery-innovation institutes to couple fundamental scientific research and discovery with translational research, technology development and commercial deployment. But the hub-and-spoke network architecture would go further by enabling the basic research group spokes to interact and collaborate among themselves (through exchanges of participants, regularly scheduled meetings and cyberinfrastructure). Just as the rim of a bicycle wheel greatly strengthens its hub-and-spoke structure, the direct interaction of the basic research groups (the spokes) would greatly facilitate collaboration and research progress, creating a basic energy research community greater than the sum of its individual parts and with sufficient flexibility, synergy and robustness to enable the participation of leading scientists and engineers to address the unusual complexity of the nation's energy challenges.

*Develop an effective strategy for energy technology development, commercialization and deployment*, working closely with industry, entrepreneurs and the investment community. For example, this might draw on the experience of major medical centers (the commercialization of translational research through business startups), agricultural and industrial extension programs, federal initiatives for regional economic development or entirely new paradigms for technology transfer.

*Build the knowledge base, human capital, and public awareness necessary to address the nation's energy challenges.* The e-DIIs are envisioned as the foci for long-term, applications-driven research aimed at building the knowledge base necessary to address the nation's highest priorities. Working together with industry and government, the e-DIIs would also lead to the development of educational programs and distributed educational networks that could produce new knowledge for innovation and educate not only the scientists, engineers, innovators and entrepreneurs of the future, but learners of all ages, about the challenge and excitement of changing the U.S. energy paradigm. Thus, the e-DIIs would have a fundamental educational mission of public education through the involvement of their scientists and engineers in sharing best educational practices and developing new educational programs in collaboration with K-12 schools, community colleges, regional universities and workplace training that lead to significantly increased public engagement.

*Develop and rapidly transfer highly innovative technologies into the marketplace.* The treatment of intellectual property is critical to the rapid and efficient transfer of energy technologies to the marketplace. The e-DIIs should provide a safe zone where intellectual property issues could be worked out in advance. Technology transfer within e-DIIs should be structured to maximize the introduction and positive societal impact of e-DII technologies, learning from successful industry-university partnerships (e.g., BP and the Universities of California and Illinois).

*Encourage regional economic development.* With the participation of many scientific disciplines and professions as well as various economic sectors, e-DIIs are similar in character and scale to academic medical centers and agricultural experiment stations that combine research, education and professional practice and drive transformative change. This organizational form has been successful at generating jobs and stimulating regional economic activity, by the nearby location of clusters of start-up firms, private research organizations, suppliers and other complementary groups and businesses. The e-DIIs should have an explicit mission to focus, at least in part, on the unique energy needs and opportunities characterizing their home regions, to ensure that new technologies would respond to local challenges and thus could be rapidly deployed.

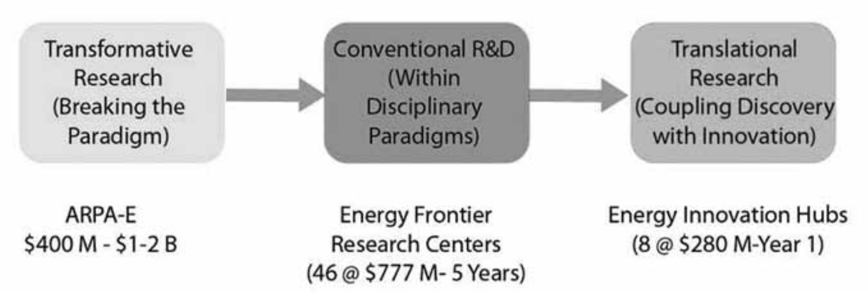
*Expand the scope of possible energy activities.* The partnership character of the e-DII, involving a consortium of universities, national laboratories, industry, investors, state and federal government, coupled with its regional focus, would give it the capacity to launch projects that are beyond the capability of a national laboratory or industry consortium alone.

To achieve a critical mass of activities, our report recommended the creation over the next several years of a national network of several dozen energy discovery-innovation institutes distributed competitively among the nation's research universities and federal laboratories:

- *University-based e-DIIs:* Those e-DIIs located adjacent to research university campuses would be managed by either individual universities or university consortia, with strong involvement of partnering institutions such as industry, entrepreneurs and investors, state and local government, and participating federal agencies. While most university-based e-DIIs would focus both on research addressing national energy priorities and regional economic development from new energy-based industries, there would also be the possibility of distributed or virtual e-DIIs (so-called "collaboratives") that would link together institutions on regional or national bases. As mentioned earlier, each e-DII would also act as a hub linking together investigators engaged in basic or applied energy research in other organizations.
- *Federal laboratory-based e-DIIs:* There should be a parallel network of e-DIIs associated with federal laboratories. To enable the paradigm shifts represented by the discovery-innovation institute concept, these e-DIIs would be stood up "outside the fence" to minimize laboratory constraints of security, administration and overhead and driven by the bottom-up interests of laboratory scientists. Like university-based e-DIIs, their objectives would be the conduct of application-driven translational research necessary to couple the extraordinary resources represented by the scientific capability of the national laboratories with the technology innovation, development and entrepreneurial efforts necessary for the commercial deployment of innovative energy technologies in the commercial marketplace. A given national laboratory might create several e-DIIs of varying size and focus that reflect both capability and opportunities. There might also be the possibility of e-DIIs jointed, created and managed by national laboratories and research universities.
- *Satellite energy research centers:* The large e-DIIs managed by research university consortia or national laboratories would anchor "hub-and-spoke" sub-networks linking satellite energy research centers comparable in scale to DOE's Energy Frontier Research Centers or NSF's Engineering Research Centers, thereby enabling faculty in less centrally-located regions or at institutions with limited capacity to manage the large e-DII hubs to contribute to the nation's energy R&D as an element of the national e-DII network.

A merit-based competitive process would award core federal support ranging from \$5 M/y to \$10 M/y for modest centers in single institutions to as much as $100 M/y to $200 M/y for large e-DIIs managed by consortia of universities and national laboratories. Federal funding would be augmented with strong additional support and participation from industry, investors, universities and state governments, for a total federal commitment growing to roughly $6 billion/y (or 25% of the recommended total federal energy R&D goal of $20 to $30 billion/y estimated to be necessary to address adequately the nation's energy challenge.)

In May 2009, the U.S. Department of Energy announced the first step of building just such a significant energy research program by launching a new *transformational* research program patterned after the U.S. Department of Defense's Advanced Research Projects Agency (DARPA) known as ARPA-E and funded at an initial level of $400 M/y; funding 46 new Energy Frontier Research Centers on university campuses and national laboratories for small research teams; and creating an initial set of eight "energy innovation hubs", similar in concept to the energy discovery innovation institutes, for *translational* research funded at $280 M for the first year. President Obama has also committed to increasing federal energy research by at least $15 B/y, hence beginning to approach the target set by our Brookings report (Chu, 2009).




Interestingly enough, this strategy has important antecedents in American history. In earlier times during periods of great challenge or opportunity, the United States responded to the changing needs of the nation with massive investments in the nation's research capacity. The Land Grant Acts of the 19th century created, through the great land-grant universities, the capacity to assist the nation's transition from an agricultural to an industrial economy. The Manhattan Project developed the nuclear technology to protect the nation during a period of great international peril. The post-WWII research partnership between the federal government and the nation's universities was not only critical to national security during the Cold War, but drove much of America's economic growth during the latter half of the 20th century. The Apollo Program fulfilled mankind's dream to conquer space by sending men to the moon.

Most analogous to the present situation was the visionary action taken by Congress to respond to the challenge of modernizing American agriculture and industry with the Hatch Act of 1887. This act 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 network of regional "energy innovation hubs" is remarkably similar both in spirit and structure, since it will bring together 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, behavioural, and policy disciplines to build a sustainable national energy infrastructure for the 21st century while stimulating strong regional economic growth. It will represent an important element of a broader national effort to achieve a sustainable energy future for both our nation and the world.

## CONCLUDING REMARKS

The role of research universities in contributing to the innovation necessary to compete in a knowledge-driven global economy is widely recognized. Clearly, the traditional approaches to fundamental research and education are essential for creating the new knowledge and knowledge professional to this effort. Yet, this paper suggests that something more is necessary: *transformational* research to stimulate the breakthrough discoveries that create entirely new economic activities and *translational* research and development to transfer new knowledge generated on the campuses into products, processes and systems capable of addressing the needs of society. These, in turn, will likely require new paradigms for university research similar to those suggested in recent U.S. National Academy and National Science Foundation studies and currently being applied to address the urgent need for sustainable energy technologies.

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