Blueprint for American Prosperity
Unleashing the Potential of a Metropolitan Nation

ENERGY DISCOVERY-INNOVATION INSTITUTES: A STEP TOWARD AMERICA'S ENERGY SUSTAINABILITY

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EXECUTIVE SUMMARY

The need to renew America's economy, foster its energy security, and respond to global climate change compels the transformation of U.S. energy policy. Innovation and its commercialization must move to the center of national reform. Not only must a broad range of carbon pricing and regulatory responses be adopted, but major increases in federal R&D are essential along with the deployment of bold new research paradigms. To that end, the federal government should establish a national network of regionally based **energy discovery-innovation institutes (e-DIIs)** to serve as the hubs of a distributed research network linking the nation's best scientists, engineers, and facilities. Through such a network, the nation could at once increase its current inadequate energy R&D effort and complement existing resources with a new research paradigm that would join the unique capabilities of America's research universities to those of corporate R&D and federal laboratories.

America's Challenge

Massive sustainability and security challenges plague the nation's energy production and delivery system. Transformational innovation and commercialization will be required to address these challenges. However, current innovation efforts remain inadequate to ensure the development and deployment of clean energy technologies and processes. States and localities lack the wherewithal to make the needed investments. Additionally, numerous market failures prevent private firms from investing sufficiently in clean energy. Because firms cannot capture all the benefits of their innovative activity, they underinvest and focus on short-term, low-risk research and product development.

Limitations of Existing Federal Policy

Federal energy efforts, meanwhile, suffer from two key shortcomings. First, the federal government spends less than 1 percent of its R&D budget on energy—a level less than one-fifth of expenditures in the 1970s and 1980s—clearly insufficient in light of coming challenges. Beyond that, federal energy efforts are also based on an obsolete research paradigm. Most federal energy research is conducted within "siloed" labs that are too far removed from the marketplace and too focused on their existing portfolios to support "transformational" or "use-inspired" research targeted at new energy technologies and processes.

A New Federal Approach

The federal government should create a national network of several dozen e-DIIs. An interagency process should establish the network and competitively award core federal support of up to $200 million per year for each major e-DII operated by university or national laboratory consortia, along with funding for smaller e-DIIs and distributed energy networks connected to the large e-DII "hubs." Federal funding would be augmented with participation by industry, investors, universities, and state governments, for a total federal commitment growing to roughly $6 billion per year (or 25 percent of a recommended total federal energy R&D goal of $20 to $30 billion per year). The e-DIIs would:

- **Foster partnerships to pursue cutting-edge, applications-oriented research among multiple participants and disciplines**
- **Develop and rapidly transfer highly innovative technologies** into the marketplace
- **Build the knowledge base and human capital** necessary to address the nation's energy challenges
- **Encourage regional economic development** by spawning clusters of nearby start-up firms, private research organizations, suppliers, and other complementary groups and businesses

I. Introduction

The need to renew America's economy, foster its energy security, and respond to global climate change all compel the transformation of U.S. energy policy.

It is now largely agreed that massive technology changes will be needed to stabilize greenhouse gas emissions worldwide.

Innovation and its dispersal through commercialization must therefore move to the center of national reform. Not only must a broad range of pricing, regulatory, and infrastructure responses be adopted, but massive direct investments in the innovation process are essential.

And yet, the scale and intensity of current energy innovation efforts in the United States remain inadequate to produce the needed technological progress and human capital development. Both private and public sources have underinvested in energy research in the past and now the nation faces acute, increasingly urgent challenges as it moves to address the complex challenges posed by global climate change.

In all of this, serious market and government failures in the U.S. and elsewhere have so far prevented the private and public sectors from making sufficient investments in energy innovation. Most notably, relatively low energy prices—in the absence of national carbon-pricing interventions and notwithstanding several oil price spikes over the past 40 years—have for decades reduced the incentive for companies to invest in clean and efficient energy technologies and processes. Similarly, the reality of spillover benefits and other market realities mean that individual firms can rarely capture all of the benefits of their innovative activity, which also leads to underinvestment and a focus on short-term, low-risk research and product development. Uncertainty and insufficient information on energy pricing, policy, and the features of new technology or processes may further delay innovation. Additionally, states and localities usually lack the wherewithal to engage systematically over the long time horizons needed to catalyze inventions.

The upshot of all this is clear: The insufficiency of private investment and the inability of most states and local governments to engage adequately—in the absence of a high price on carbon or sufficient regulatory interventions—places the responsibility for guaranteeing adequate levels of energy innovation largely in the lap of the federal government.

Such an assignment of responsibility is appropriate, moreover, given the federal government's historic responsibilities for environmental protection and economic and national security. However, both the magnitude and character of federal energy innovation programs remain inadequate to address the development of a sustainable energy economy in America.

Current industry and government investments in energy-sector research and development (R&D) are clearly too low, given the urgency of the energy challenges facing the nation. For its part, the energy industry lags most other major U.S. industries in the fraction of its revenues devoted to R&D. For that reason, private firms should be enticed both through federal tax incentives and other investments to increase R&D activities to a level comparable to other technology-intensive industries such as electronics, defense, and health care.

On the government side, meanwhile, which is dominated by the federal government's activities, the federal investment in energy R&D today amounts to a bit more than $2 billion per year—less than one-fifth of the funding levels of the 1970s and 1980s. Given the large size of the energy sector ($1.4 trillion per year) and the sheer complexity and urgency of the nation's energy challenges, it would seem that the federal investment in energy R&D should be increased substantially to levels comparable to those associated with other compelling national priorities such as health care, national defense, and space exploration. Such a prioritization argues for federal energy investment in the neighborhood of $20 to $30 billion per year.

In response, this report proposes a significant increase in the scale of the federal government's energy R&D activities. To be specific, the pages that follow call for an order of magnitude growth in annual federal investments that would increase to $20 to $30 billion the nation's roughly $2 billion-plus current effort on non-defense energy-related R&D. Along these lines, the paper assumes that the bulk of the nation's needed new investment would flow to the nation's existing federal laboratories and associated corporate R&D centers.

However, both the complexity of America's energy challenge argue that the nation should not simply spend more on the same sort of efforts in which it is already engaged. Instead, the multidisciplinary nature of the problem suggests that a portion of the needed growth in federal funding should be reserved for mobilizing additional assets (beyond the laboratories and corporate centers) in new ways capable of contributing to the development, commercialization, and deployment of energy technologies. These assets include the nation's research universities, entrepreneurs, and investors, as well as state and regional economic development organizations. In this connection, the federal laboratories represent a formidable concentration of scientists and engineers capable of addressing scientific and technological challenges such as nuclear deterrence, high-energy physics, and space exploration. However, the fact is that large-scale deployment of sustainable energy technologies will involve not only advanced scientific research and the development of new technologies, but also careful attention to complex market, economic, social, legal, political, behavioral, and consumer issues. Developing and deploying new energy technologies is, furthermore, frequently characterized by complex regional, national, and international dynamics. Building, operating, and maintaining a sustainable energy infrastructure will require, in this sense, a rather considerable expansion of the nation's human capital, which will only be developed through strengthening math and science education at all levels and the training and intense collaborations not only of world-class scientists and engineers but also entrepreneurs, venture capitalists, business professionals, legal experts, and others capable of dealing with the myriad legal, business, behavioral, and environmental issues that characterize energy development.

In view of all this, the pages that follow argue not just for a step-change in the *amount* of federal energy R&D spending but for the use of *new paradigms* for that investment—new paradigms that build on the current considerable R&D capabilities of the federal laboratories and industry but also seek to create new forums for high-intensity collaboration among multiple players.

And here, one such paradigm that appears to be particularly well-suited for the purpose of accelerating technology development and deployment is the discovery-innovation institute concept developed in 2005 by the National Academy of Engineering.[1] This paradigm was designed to link fundamental scientific discovery with use-inspired research capable of stimulating the innovation necessary to create, commercialize, and deploy new products, processes, and services. In addition, the innovation centers were intended 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, then, this paper proposes that the federal government should experiment with a new paradigm in energy research by establishing a national network of regionally based **energy discovery-innovation institutes** (e-DIIs) as one part of an expanded national energy effort.[2] The e-DIIs—characterized by results-oriented partnerships among multiple participants—including federal agencies, research universities, established industry, entrepreneurs, investors, and the states—would be charged with performing the basic research and technology development necessary to rapidly deploy highly innovative energy technologies into 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. In addition, e-DIIs would focus on the unique assets, challenges, and opportunities for energy research, development, and implementation within their home regions, thereby stimulating regional economic development and job creation.

In effect, the e-DIIs would stand as 21st-century successors to the highly successful agricultural and engineering experiment stations, and their associated extension services, established across the United States through the Land Grant Acts to build a modern industrial nation.

And as it happens, the new discovery centers would also serve as a new stimulus to metropolitan prosperity—the crucial goal of the *Blueprint for American Prosperity*, a multi-year initiative of the Metropolitan Policy Program at Brookings. U.S. metropolitan areas are already the leading repositories of the research, workforce, infrastructure, and capital resources that will be needed to drive innovation and usher in a new generation of energy technologies. By situating highly collaborative, commercialization-oriented new innovation centers in metro areas, a concerted push to deploy a network of e-DIIs would serve as a powerful new boost to local and regional economic development. In this way, the proposed national network of e-DIIs would at once lead the nation in responding to a series of crucial boundary-crossing problems and empower U.S. metropolitan areas—and so make a major contribution to the prosperity and sustainability of the nation.

Thus, this report at once reviews the enormity and complexity of the nation's energy challenges, surveys the limitations of current responses, and details the outlines of a new research approach and paradigm that would join the unique capabilities of America's research universities to those of corporate R&D centers and the nation's renowned federal laboratories. First, the report lays out the sustainability and security challenges posed by the nation's current energy infrastructure and the need for enhanced energy research and development (R&D). Next, the report discusses the multiple barriers that prevent sufficient private investment in energy R&D and makes the case for why the government—and then specifically the federal government—must take the lead in ensuring adequate energy R&D commitments. A new federal energy research paradigm is then proposed and similar paradigms already in use internationally and at the state and regional level are examined. Finally, a national network of e-DIIs is proposed, followed by a discussion of the steps needed to implement the new network, and a look at some options for financing and organizing it. Through it all, the paper endeavors to supply some fresh thinking on one portion of the nation's energy research, development, and deployment continuum, which is itself but one portion of several needed responses to the nation's energy challenge.

II. THE NATION FACES SERIOUS ENERGY SUSTAINABILITY AND SECURITY CHALLENGES

Today's energy challenges stem from an unsustainable energy infrastructure, largely dependent on fossil fuels, with clear implications for America's economic and national security. Addressing these challenges will require substantial—and creative—investments in clean and efficient energy technology, much of which has yet to be developed.

Innovation, therefore, must become the centerpiece of any successful long-term energy policy.

1. Supply, security, and sustainability challenges plague the world's energy production and delivery system.

The global economy currently relies on fossil fuels (e.g., oil and other petroleum products, natural gas, and coal) for nearly 85 percent of its energy.[3] However, the hard fact is that fossil-fuel dependence cannot be sustained over the long term due to supply constraints, security concerns, and increasingly unacceptable global climate impacts.

By 2030, global energy use is projected to grow by 50 percent over 2005 levels.[4] The International Energy Agency (IEA) estimates that $20.2 trillion in capital investments will be needed to meet this growing demand.[5] Approximately half of the needed investments will be required in developing countries, with nearly 20 percent in China alone. North America is projected to need $4.1 trillion of capital investments. More than half of the world's projected new energy investment will be needed to provide electricity. To meet projected growth, the world would need to bring online every day for the next 20 years a new 1,000-megawatt-equivalent power plant costing several billion dollars.[6]

In this regard, a sustained imbalance between oil supply and demand could occur if the development of new reserves and extraction technologies fail to keep production rates on pace with growing demand. Currently, annual global oil and natural gas production lags consumption.[7] With the long-term oil and gas demands of developing economies such as China, India, and Latin America rising, long-term supply and demand imbalances will likely drive up global oil and gas prices. The American economy, meanwhile, is particularly at risk from high oil prices: The United States accounts for one-quarter of the world's oil consumption despite producing just 10 percent of the world's oil supply.[8] Nearly 60 percent of the nation's petroleum supply is imported, up from around 30 percent in the 1970s.[9] With few affordable and scalable alternatives, periodically spiking oil prices can disrupt industrial production and reduce consumer purchasing power, threatening to push the nation into an economic recession, as has regularly occurred since World War II.[10] Higher oil prices also threaten the U.S. trade balance, which has been running a deficit since 1992. Nearly 50 percent of the increased trade deficit from 2002 to 2006 was due to higher oil prices and associated higher net import costs.[11]

Furthermore, America's economic and national security is threatened by its dependency on oil imports from politically unstable regions of the world. Although Canada is currently the largest supplier of oil to the United States, 45 percent of the nation's oil in June 2008 was imported from OPEC nations and 18 percent was imported from the Persian Gulf.[12] Many oil-exporting countries are politically volatile, including Venezuela, Nigeria, and recently Russia.[13] In addition, nearly 77 percent of the world's oil reserves are controlled by national oil companies (NOCs) and only 10 percent are controlled by Western international oil companies, such as Exxon or BP.[14] American vulnerability to oil supply decisions by oil-exporting countries and NOCs has led to costly military engagements in areas such as the Persian Gulf, which continue to pose an immediate threat to the nation's security.[15] Additional security threats arise from terrorist organizations (supported in part by oil wealth), piracy, and underdeveloped security over critical energy infrastructure within the U.S. and abroad.[16]

And then there are the daunting environmental side-effects of world carbon dependency. To be sure, the world has substantial reserves of other fossil fuel resources, such as coal, tar sands, and oil shale, which could offset declining oil and gas supply for years to come. Unfortunately, though, the mining, processing, and burning of these fossil fuels with current technologies remains expensive and is characterized by increasingly unacceptable environmental impacts in light of climate change concerns and intensive land and water utilization.

Already the use of fossil fuels in energy production is contributing to global climate change. Evidence of global warming is nearly incontrovertible, with increasing global surface and air temperatures, receding glaciers and polar ice caps, rising sea levels, and increasingly powerful weather disruptions. The recent Intergovernmental Panel on Climate Change (IPCC) report 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."[17] The IPCC estimates that global average temperatures could eventually increase by 6 degrees Celsius or more if greenhouse gas emissions continue to grow at current rates.[18]

To limit the global average temperature increase to a more manageable 2.4 degrees Celsius, meanwhile, the IPCC estimates that energy-related greenhouse gas emissions would need to decrease by 50 to 85 percent of 2005 levels.[19] Such reductions, in turn, would require the virtual "decarbonization" of the world energy sector, with a massive and widespread shift toward low and zero net greenhouse gas emissions needing to occur throughout the U.S. and global energy system between now and 2050 at an estimated cost of $45 trillion.[20]

Unfortunately, this is not the direction in which the world has been heading in recent years.[21] As developing countries grow their economies, notwithstanding the current world recession, they are consuming increasing amounts of cheap, fossil fuel energy (often coal) and are emitting more (not less) greenhouse gas emissions. Emissions in the developed world have also climbed despite reductions in countries such as Germany. As a result, the Energy Information Administration "reference case" forecast has U.S. energy consumption increasing 19 percent and carbon dioxide emissions by 16 percent by 2030 over current levels given existing policies and expected market trends."[22] This forecast may be adjusted given the current world slow-down, but the fact remains that emissions will grow, and that world-wide, the consumption and emissions growth figures are 55 percent and 57 percent.[23] Altogether, global emissions have grown faster than predicted by the IPCC, accelerating climate change and making the upward emissions trend all the more difficult and urgent to reverse.[24]

In short, the needed decarbonization of the U.S. and global energy system will be a huge undertaking in light of recent trends.[25]

2. *Transformative innovation will be required to address fundamental energy challenges*

To limit global warming, the global energy system must ultimately shift away from fossil fuels as its primary energy source to clean, renewable energy. How will that occur? Immediate progress can be achieved through the adoption of existing technologies and practices that improve the efficiency of energy utilization, such as low energy illumination, high efficiency buildings, fuel-efficient automobiles, and low power computers. Investments in efficiency will bring fuel savings and reduce the net costs of needed infrastructure investments.[26] Past investments in efficiency have helped to improve the nation's energy productivity (i.e., the amount of energy required per dollar GDP) by more than 1 percent per year since 1973.[27] Making global annual efficiency investments of $170 billion through 2020 could cut global energy demand growth by half, generate $900 billion in annual savings by 2020, and make a meaningful contribution to stabilizing carbon emissions at a sustainable level.[28] The United States would need to account for a little over 20 percent of this investment (or $38 billion per year) to achieve the targeted global reductions.[29]

However, large and sustained efficiency investments will not be enough to achieve frequently discussed sustainability goals such as those implied by the IPCC. New technologies and practices will also be needed to mitigate the harmful impact and resource constraints of existing energy sources.[30] Advanced technologies and practices are critical since efficiency gains will likely only slow the growth of global energy demand instead of cutting total emissions as is needed. In technology innovation lies both the potential to reduce the baseline level of greenhouse gas emissions and to reduce the cost of achieving those reductions.[31] Relatively accessible examples of such potential advances include new technologies and practices for reducing carbon emissions from conventional or existing energy sources in the short and medium term. Among such innovations will be 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. Some of this new technology has been developed but has not been deployed yet.[32] Much more of the new technology still needs to be developed, tested, and deployed at a large enough scale to drive down costs.

Of longer term importance will be the deployment and commercialization of affordable, carbon-free renewable energy technologies, such as solar, wind, and biofuels. While renewable energy sources are prominently featured in most "green energy" proposals, a substantial gap remains with current technologies in achieving both the scale and cost structures necessary for major impact.[33] The intermittency inherent in renewable energy sources will require massive development and deployment of central and distributed energy storage technologies.[34] Expansion of renewable energy use will also require investments in a more expansive and efficient electricity grid, such as a new direct-current transmission network.[35]

Investments in efficiency and new energy technologies and work to accelerate their commercialization will have added benefits from creating new jobs across the occupational spectrum. Conservative estimates suggest that the global renewable energy industry may increase to more than 20 million jobs by 2030, with most of these jobs in a handful of countries including the United States.[36] The American Solar Energy Society optimistically projects renewable energy and energy efficiency jobs could grow to 40 million (from 8.5 million today) by 2030.[37]

At any rate, the challenge is clear, and is well summarized by Ted Nordhaus and Michael Shellenberger: With global energy consumption heading for 50 percent or larger growth by 2050 even as we face the challenge of reducing greenhouse gas emissions by 50 percent, the "[needed] transformation will not be accomplished by affixing scrubbers on smokestacks or catalytic converters on tailpipes—technical fixes that required little change to the underlying processes and technologies that they mitigated. Rather, it will require fundamental changes to the underlying technologies and fuel sources that power the global economy."[38]

Or as John Holdren, the new White House science advisor has concluded: "Without an accelerated transition to improved technologies, societies will find it increasingly difficult—and in the end probably impossible—*either* to limit oil imports and oil dependence overall *or* to provide the affordable energy needed for sustainable prosperity everywhere without intolerably disrupting the Earth's climate."[39]

3. Current investments in energy innovation are inadequate

Deployment of clean, efficient, and renewable energy technologies depends in large part, then, on the viability of the innovative process. It also depends on the development of new practices, business models, and social and legal processes to support deployment of new technologies. Unfortunately, current investments in energy technology innovation are inadequate to address the nation's supply, security, and sustainability challenges.

Box 1. A primer on innovation and U.S. R&D

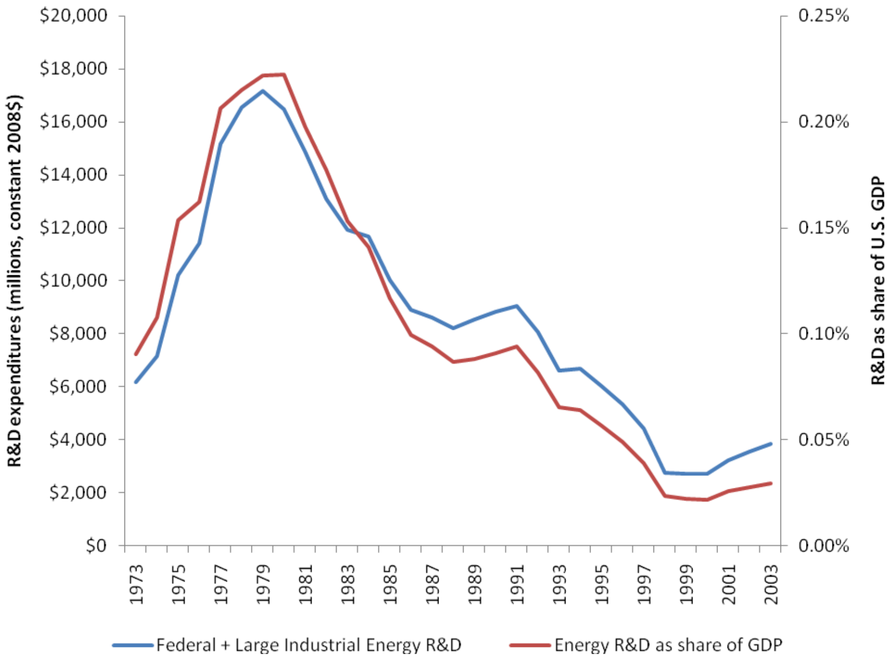
Innovation involves the application of a new idea to processes, products, or organizational design. Three basic activities are often considered as part of the innovation process, including research and development (R&D), commercialization, and deployment. For purposes of tracking R&D investments, the federal government differentiates basic research (building the scientific and technical knowledge base, without clear technological applications), applied research (initial application of basic research findings with potential to address practical applications), and development (early commercialization efforts where new products and processes are developed and demonstrated).

Realistically, innovation is an exceedingly complex and unpredictable phenomenon, extending across multiple actors with differing resources, capacities, and goals. The private sector is largely responsible for the nation's innovative capacity, supporting most commercialization and deployment efforts and a substantial portion (two-thirds) of the nation's R&D. The federal government also plays an important, if secondary, role in U.S. innovation by funding 27 percent of R&D efforts.[40] Three-quarters of federally financed R&D is conducted by industry, universities, or other nonprofit institutions.

Total U.S. investments in R&D have steadily increased since World War II (in real terms) although they have in recent years seemed to plateau.[41] Today's R&D spending of $368 billion annually is approximately 2.7 percent of the nation's gross domestic product (GDP), down from its high of 2.8 percent in 1964.[42] The current U.S. share is higher than spending in many industrialized nations, but lags behind R&D shares of GDP in Sweden, Finland, Japan, South Korea, Switzerland, Iceland, and Israel.

Despite the scale and urgency of the nation's energy challenges, neither large industrial firms nor the federal government have regarded energy research as a high priority for several decades. Today's investments in energy R&D by the federal government and large industrial firms are only one-fifth the level of the early 1980s, and make up just 1.1 percent of the nation's total R&D investment and 0.03 percent of the nation's GDP.[43] Overall, U.S. public and private spending on energy technology research, development, and demonstration comes to no more than $5–6 billion per year, significantly less than 1 percent of what the country spends for electricity and fuels, with less than $3.8 billion going to federal and large-corporation R&D despite the energy industry's annual $1.3 trillion gross output.[44]

National energy R&D grew rapidly in the late 1970s and has since fallen below levels recorded in the early 1970s



Sources: National Science Foundation's Industrial Research and Development Survey (for industrial data) and "Research and Development in Industry" (annual series); National Science Foundation's "Federal R&D Spending by Budget Function" for energy (annual).

These R&D figures do not differ much from those of other industrialized countries (and they are better than those of developing countries) but they remain inadequate in relation to the scale of the challenge and substantially lower than those being recorded by other U.S. sectors. Other U.S. technology-intensive industries spend comparatively more on R&D than the energy sector.[45] Health care, for instance, receives or dedicates the equivalent of nearly 2 percent of its annual sales in federal R&D spending (by a very conservative analysis), while agriculture allots 2.4 percent. By contrast, the energy sector receives from the federal government or dedicates from its own resources just 0.3 percent of gross output to R&D.[46] If the federal government and large industrial firms together were to invest 2 percent of the nation's annual energy sales in R&D (as the health care sector does), it would be investing $25 billion in energy R&D—more than six times current levels. By other measures, sectors like pharmaceuticals and IT are reckoned to spend upwards of 10 percent of their revenue on R&D, which leads to even higher benchmarks for appropriate annual investment in basic and early-stage energy research.

The U.S. health care and agricultural sectors spend substantially more on R&D than the energy and transportation sectors

Industry	Gross Output (billions)	Federal R&D (billions)*	Federal R&D as share of output	Large Industrial R&D (billions)**	Federal + Large Industrial R&D (billions)	Federal + Large Industrial R&D as share of output
Health care	$1,608	$31.3	1.95%	$0.8	$32.1	1.99%
Energy	$1,271	$1.4	0.11%	$2.4	$3.8	0.30%
Transportation	$823	$1.9	0.23%	$0.3	$2.2	0.26%
Agriculture	$347	$2.0	0.59%	$6.1	$8.2	2.35%

* Federal R&D for energy budget function only; does not include expenditures on general science

** Industrial R&D for energy reported for 2003 (latest available data); Private agricultural R&D reported for 1998 (latest available data).

All values reported in constant 2008 dollars.

Sources: Bureau of Economic Analysis' Current Industry Analysis data by NAICS code); National Science Foundation's "Research and Development in Industry"; National Science Foundation's "Federal R&D Spending by Budget Function" for energy; U.S. Department of Agriculture, "Agricultural Research Funding in the Public and Private Sectors" (annual reports).

Today's low level of investment in energy R&D, at any rate, leaves the nation underprepared to meet the energy challenges of the 21st century. For one thing, R&D investment levels closely track with patents, a key indicator of innovative activity. This close association persists at the national level and specifically for energy, as well as for particular energy technologies such as fossil fuels and renewable energy.[47] Thus, with low national spending on energy R&D and commercialization, the economy cannot expect to see the innovative activity necessary to develop new technology, accelerate demonstration and deployment, create new jobs, boost economic growth, and reduce greenhouse gas emissions.

In addition, today's investments in energy R&D are critical given the long lead times needed to research and develop new technology for commercialization and deployment. Development times for energy technologies are difficult to anticipate and may prove longer than for either software or medical technologies, both of which can often be brought to market within five to 10 years.[48] Some energy technologies have been under development for nearly 50 years and are only now seeing widespread improvements, such as with thin-film photovoltaic technology. Other technologies, such as controlled thermonuclear fusion, have been under development for more than 50 years and still remain decades away from possible deployment. The potential benefits of these new technologies are large enough, however, to keep investigation and development going.

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In summary, today's energy challenges stem from the continued dominance of an unsustainable energy infrastructure, largely dependent on fossil fuels, that has clear implications for economic and national security. Stabilizing world and national carbon emissions will require a staggeringly large-scale and broad shift of the current energy system to energy technologies and practices with low to zero net greenhouse gas emissions. Massive investments are needed both to clean up existing energy infrastructure in light of climate change concerns and to meet coming demand. Addressing the sustainability and security challenges posed by the world's energy needs, moreover, will ultimately require substantial investment both to commercialize and scale up the deployment of existing clean and efficient energy technology and to pursue the critical innovation needed to develop and deploy new energy technologies and practices as yet un-invented.[49] Unfortunately, such commitments have yet to be made.

III. MULTIPLE BARRIERS PREVENT SUFFICIENT PRIVATE INVESTMENT IN ENERGY TECHNOLOGY

Past transitions in energy utilization, such as those that took society from wood to coal to oil to electricity, have been driven primarily by the private sector. These transitions have occurred over timescales of generations or even centuries, and involved gradual changes in energy technologies and utilization that allowed producers, consumers, and markets time to adjust. Unfortunately, the consequences of past failures to respond to the sustainability and security impacts of our current carbon-based energy economy now require more immediate and widespread action than the private sector appears prepared to provide. Several market failures and other barriers account for the insufficiency of private engagement in energy technology development and deployment despite the clear societal benefits of such research and innovation.[50]

1. Price signals are not sufficient to ensure adequate development and deployment of sustainable and secure energy technologies

The first substantial market problem that had led to extremely low investment in energy research and innovation is the historically low cost of oil and gas that has prevailed in the absence of pricing and regulatory policies that factor in the full environmental and social costs of using fossil fuels.[51] Firms will naturally invest in energy R&D and technology deployment if they can realize a profit from it. Many already do this, as evidenced by the more than $1 billion spent by large industrial firms on energy R&D each year. However, in the absence of national interventions that price in the environmental "externality" of global climate change and notwithstanding several oil price spikes over the past 40 years, energy prices have remained generally low enough that there has been little incentive for producers or consumers to invest in radically new technology.[52]

To be sure, rising energy prices over the past few years naturally led to an increase in energy R&D by the federal government and large industrial firms. Venture capital (VC) firms, such as Kleiner Perkins Caufield & Byers, are also investing more in "clean tech" or "green tech" development than they have in the past.[53] Venture capital investments for energy and other industrial technologies (including transportation, agricultural, and environmental technologies) have been on the rise lately, with the second quarter of 2008 reaching investment levels almost as high as in the fourth quarter of 1999—the peak quarter for venture capital investment since tracking began in 1995.[54] Before this fall's financial crisis hit and oil prices tumbled below pre-spike levels ($60 per barrel), energy and industrial VC for 2008 looked on track to set new records.

However, with oil prices again low and the nation and the global economy in a recession, prospects for upcoming energy R&D and VC funding are uncertain. While many analysts anticipate prices will rebound and stay higher, today's low prices combined with uncertainty about future prices have already discouraged firms from making the investments needed to seed the nation's energy transformation.[55] And the same goes for much discussed proposals for carbon pricing mechanisms such as a carbon tax or a "cap-and-trade" pricing scheme. At the price thresholds under discussion it is doubtful that price mechanisms by themselves will produce the needed breakthrough technologies or lead to their necessary scaling.[56]

2. Social benefits from R&D and new technology adoption often outweigh private benefits, leading to underinvestment

The second market problem that will continue to depress R&D and innovation investment has to do with the fact that technological innovation remains a public good, the gains of which are broadly shared rather than fully captured by those achieving it.

In this respect, direct emissions policies such as carbon caps and carbon taxes can "price in" the cost of climate-related externalities to society but they cannot deal with firms' inability to capture all of the returns of their R&D and innovation efforts. [57]

The problem is fundamental. Much of the rationale for investment in energy research and new technology lies in the substantial public benefits generated by such activities.[58] Yet the presence of public benefits leads the private sector to conduct less R&D than would be socially desirable. First, social benefits accrue from the knowledge created by innovative activity, which is added to the public domain once created and is hard for firms to control. Other firms may make use of this knowledge and reap the rewards, encouraging free-riding behavior where firms fail to invest and wait for other firms to finance the knowledge base. In addition, the competitive nature of technology often requires a firm to sell its product for less than its total development cost, discouraging expensive investments.[59] Policy mechanisms, such as IP protection (as through the patenting system) and R&D tax credits, have been developed to help with this problem but can only go so far in protecting a firm's investment in R&D.[60] Public benefits also accrue over long periods from improvements in energy efficiency and reductions in pollution and greenhouse gas emissions. These benefits are difficult for firms to capture in any meaningful way due to the lack of market rewards for such investments. Altogether, the social benefits from innovation have been estimated as substantially larger than private benefits.[61]

And there are other issues. To begin with, firms adopting—as opposed to inventing—new technologies create similar social benefits, known as dynamic increasing returns.[62] Early technology adopters generate knowledge and ultimately help the public learn about the feasibility and effectiveness of new technologies in differing environments outside the development laboratory. Innovative firms can make use of this public knowledge to modify technology, thus co-opting some of the knowledge benefits for themselves. The benefits of "learning by doing" efforts also accrue to technology manufacturers, which help to bring down the cost of new technology and benefits society at the expense of technology developers.[63] But in general there will be too little of this effort.

Likewise, a number of "lock in" issues discourage private investment.[64] For one thing, questions are raised by firms regarding the difficulty of delivering alternative energy to the marketplace, which is in many circumstances problematic, most notably because national electricity grids are tailored for large, centralized plants. In this case, energy companies and investors are often reluctant to expend their revenue on risky, innovative, and costly ventures without government regulation or other measures designed to reduce their risks. Such issues are, for example, holding back the delivery of some renewable electricity sources, where rich wind or solar fields may lie far from transmission lines. By contrast, massive existing infrastructure already supports the oil, coal, and gas economy.

A growing body of opinion doubts that carbon pricing responses by themselves will be enough to overcome these barriers and market failures and sufficiently reduce emissions and drive technology change. For example, the watershed U.K. Stern Review concluded: "The presence of a range of market failures and barriers means that carbon pricing alone is not sufficient" to lead businesses and individuals to invest sufficiently in low-carbon alternatives to high-carbon goods and services."[65]

3. Financial considerations encourage the private sector to focus on applied research and technology development

The current corporate financial environment—with its emphasis on shorter-term rates of return—has also served to depress investments in R&D and innovation. Private markets, in this respect, frequently fail to generate sufficient investments in energy innovation when its benefits are poorly known and risks may be high. Such a situation often occurs during the early phases of research into new technologies, and currently affects the search for new technology to address global climate change (such as carbon sequestration).[66]

In years past, large industrial R&D laboratories (such as Bell Laboratories, IBM Research Laboratory, Ford Scientific Laboratory, and DuPont Research Laboratory) were involved with higher-risk, pre-commercialization R&D. However, the ratcheting up in recent decades of investor emphasis on near-term bottom line results has shifted most industrial R&D activity away from basic research and toward technology development, which captures 76 percent of industrial R&D today.[67] The dominance of industrial funding for U.S. R&D combined with its funding priorities help to explain why 60 percent of the nation's total R&D expenditures are spent today on development, with only 22 percent for applied research and 18 percent for basic research.[68] The private sector's funding priorities are also evident in the funding proclivities of venture capital, which favor later-stage development.[69]

These general funding preferences for technology development are also evident in the energy sector. Whereas large industrial firms used to conduct basic energy technology research, industrial energy R&D today tends to focus on "short-term research and technology commercialization," leaving governments to conduct "long-term, higher risk R&D."[70] The possibility of innovation exploitation by competing firms adds to investment risk and encourages the focus on short-term research.[71]

Some of the financing for pre-commercialization research used to be provided by industry contributions to non-profit research consortia, such as the Electric Power Research Institute (EPRI) and the Gas Research Institute. Government used to require contributions from power and gas suppliers as part of the industry's regulatory scheme. Deregulation of electricity markets and subsequent restructuring in the 1990s led to disinvestments in EPRI, with cuts in industrial contributions nearing 50 percent within a few years after deregulation.[72]

Furthermore, industry is less able to address the broader policy issues of technology deployment requiring economic and behavioral sciences, legal and environmental policy, and regional and local impact than are, for example, universities. Universities tend to provide these services, with the majority of their R&D funding from government and nonprofit sources. Their educational mission also provides a highly effective technology transfer mechanism through large-scale deployment of graduates and through faculty involvement via joint research or short-term consulting. However, universities are frequently hindered by complex intellectual property (IP) policies that inhibit the commercialization of campus-based discoveries and constrain the innovation-diffusion process.

4. Uncertainty and a lack of information delay adoption of new energy technology

Uncertainties and ambiguities also hinder the adoption of new energy technologies. Just as investors tend not to invest in basic research and early-stage technology development, consumers tend not to invest in new technology with uncertain features and benefits.[73] This uncertainty helps to account for why consumers lag in adoption of proven energy-efficiency technology that has proven net financial benefits.[74] In this regard, the adoption of energy-efficiency technology often has high upfront costs yet may yield benefits in terms of energy savings over several years. Relatedly, a quantification of the stream of expected future benefits associated with a new technology purchase can be difficult to achieve when the value of future savings varies depending on factors entirely outside the consumer's control (such as future electricity prices). There may also be a lack of information about the availability and features of energy efficient technology, preventing a consumer from even considering it.

Uncertainty can also arise from a lack of sufficient information about future market and policy conditions. Such a situation presently exists for firms considering adoption of new energy technology in light of potential federal climate policy, such as a cap-and-trade system for carbon emissions.[75] A cap-and-trade system that limits carbon emissions and places a price on them would provide a financial incentive for adoption of new technologies that bring down the cost of achieving required reductions. If the effective date for achieving reductions is years away, however, the firm may delay investment even if new technologies could provide some energy-saving benefits today. Firms may also delay adoption until the financial benefits of technology adoption have been demonstrated in the new policy environment, such as when the price of pollution taxes or credits have been set. Such delay is likely when firms are uncertain about the credibility and stringency of future government action.[76]

While delayed adoption may benefit individual consumers in the short term, it prevents the social benefits of dynamic increasing returns that help to bring down production costs. In addition, without the "market-demand pull" of consumers desiring new energy technology, the tendency of the private market to underinvest in energy R&D that addresses sustainability and security goals is further exacerbated.[77]

5. Finally, the benefits of regionally clustering energy research and technology development activities have not been sufficiently realized

And there is one more factor that has kept U.S. energy research, development, and deployment from reaching critical mass. This is the spatially diffuse geography of much U.S. energy research which limits the emergence of dense clusters of interconnected firms and supporting organizations that represent such a potent source of knowledge-transfer and innovation in modern economies.

The current energy R&D enterprise is conducted mostly by isolated research centers throughout the United States. While this geographic diffusion of R&D activity spreads economic development "wealth" around, it frequently fails to generate the benefits of geographically clustered activity. Firms operating in virtually any industry, but especially in knowledge-dependent high-technology sectors, benefit by proximate locations that allow them to utilize a similarly trained workforce, infrastructure, research facilities, educational and training institutions, venture capitalists, and input suppliers.[78] Clusters also accelerate knowledge sharing of all kinds. The Silicon Valley in Northern California is the classic example of a highly productive technology, communications, internet, and computer industry cluster, as are the biotech clusters in Boston and Washington, DC, the financial cluster in New York, and the entertainment clusters in Southern California and Las Vegas.

Clustered activity generates positive externalities by helping to improve productivity and wages for all of the firms and workers within the cluster, which has spillover benefits for the broader regional economy.[79] The benefits of clusters are not guaranteed, however, and some clusters are clearly more productive than other clusters. At any rate, the same dynamics that work to discourage sufficient R&D by the private sector in energy and other industries thwart clustering activity, absent an external coordinating mechanism. That the U.S. alternative energy industry remains nascent, with significant portions of the nation's research having been conducted in secure laboratory settings, has further slowed the emergence of powerful alternative energy clusters in America.

The upshot: Clusters of related firms are not yet as common in the energy field as they are in such other industries as information technology or life sciences.[80] As yet, the cleantech field lacks the emergence of the sort of large, dense regional and virtual industry clusters that can accelerate the knowledge-transfer so necessary to the invention and commercialization of new energy technologies, applications, and processes.

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In sum, a series of significant market problems continue to depress U.S. and world R&D levels, deployment work, and commercialization activity in the energy field. Without aggressive and targeted action, private investment will remain too low.

IV. Government Must Act to Ensure a Sustainable and Secure Energy Infrastructure

Given the lack of incentives for private investment and the sheer magnitude, urgency, and complexity of the energy crisis facing America, public investment in energy innovation will be critical. Without stepped-up public engagement, the transition to a sustainable energy system will not occur fast enough or broadly enough.

As to the nature of the public intervention, several principles—corresponding to the market failures outlined above—should guide policymaking.

First, the government should encourage stronger price signals by placing a price on greenhouse gas emissions, such as through a carbon tax or carbon cap-and-trade. Carbon pricing can help to account for the sustainability and security costs of our current, fossil fuel-dependent energy infrastructure. By increasing the costs of fossil fuel-based energy, it will spur innovation into low-carbon and carbon-free energy alternatives, rather than simply in non-conventional fossil-fuel technologies.[81] Admittedly, the political will appears lacking to impose carbon prices at a high-enough level to spur needed energy transformations, making public investments an important complement to a carbon pricing effort.[82] However, emissions pricing remains even now an important mechanism at minimum for financing future R&D investments and in theory for establishing a demand-driven, profit-based incentive for the private sector to invest in developing new, lower-cost climate-friendly innovations.

A second principle of potential government engagement is that the government should subsidize energy R&D generally, and more specifically, should subsidize particular sorts of research that are currently neglected by private firms: longer-term, higher-risk investigation; strategic basic research inspired by critical needs arising from the goal of developing clean new technology; and in some cases first-of-a-kind technology demonstration projects, so long as the purpose is the generation of substantial new knowledge.[83] The government should also focus on translational research that links scientific and technical R&D with commercial technology development—the stage where many promising innovations fail to receive enough funding to advance, known as the "valley of death."[84] In this regard, the high social rates of return for energy R&D (estimated at around 50 percent compared to private rates of 20 to 30 percent) make energy R&D a good financial investment, and one that will pay off over long periods.[85] The additional public benefits of energy R&D to the nation's sustainability and security are also likely to be quite large, and include the production of new researchers and engineers with the skills necessary to work in the coming clean-energy economy of tomorrow—an important further rationale for public investment.[86] In this way, energy resembles national defense, agriculture, and space research, which all receive public support to augment private investments in pursuit of national goals.

And here it should be said that the government need not and should not rush to fill the entire gap between needed investment and privately provided energy R&D. Government can leverage additional private investment through policy mechanisms such as the R&D tax credit or public-private partnerships. Such policies are not only politically expedient, as they reduce the public financing requirement, but recognize the desirability of coordinated public-private action towards a common public goal. In this case, the goal should be to achieve a sustainable energy infrastructure that dramatically reduces oil imports and environmental impact, thus improving the nation's sustainability and security.

In addition, while the private sector may not be investing sufficiently on its own in energy R&D and technology deployment, it stands ready to participate in an enhanced and publicly funded energy research initiative. For example, the nation's electrical utilities have proposed (through the Edison Electric Institute) that revenue raised from a federal carbon tax or cap-and-trade program be earmarked for energy research by an affiliated industry research organization, such as the Electric Power Research Institute. Similarly, the Gas Research Institute has recommended that industry groups take the lead to conduct the nation's energy R&D, push technology deployment, and develop the infrastructure needed to change the way the United States produces and utilizes energy.

A third desirable priority for government action must be an effort to improve the clarity and accessibility of information on proven energy technologies, especially in light of possible future policy action on climate change. Such information can spur technology learning and bring down adoption costs, providing increasing social benefits over time. By supporting research on proven technologies, government can also provide assurance for the massive financial commitments required in the private sector to deploy these technologies (e.g., nuclear energy).

And fourthly, government should support where it can the clustering of energy research and development activities that speeds knowledge exchange, improves productivity and wages, and fosters regional economic development. A cluster approach is appealing, in this respect, as it promises regional economic uplift in an era of downward pressure on wages due to globalization. But a cluster strategy is also important because clustering fosters innovation, and so has the potential to accelerate the development of clean new energy technologies and processes. Government should seek to catalyze such activity.

As to the specific locus of government engagement to accelerate the needed breakthroughs, all levels of government have some responsibility for affecting the nation's energy transformation.

So far, state and local governments have been taking the leadership role on energy and climate policy, although this situation is less than ideal.

State governments are central players in energy policy due to their responsibilities for regulating energy providers and for implementing federal environmental regulations. In some cases, state governments have made substantial investments in the nation's energy infrastructure and in regulating the development and use of cleaner technologies. Many state governments have made meaningful strides towards a cleaner energy future by passing renewable energy portfolio requirements for electricity production and collaborating in regional energy alliances (e.g., the Northeast's Regional Greenhouse Gas Alliance).

Local governments also play important roles in energy policy by setting land use policies, building codes and energy efficiency standards, and by approving energy infrastructure projects, such as new power stations or transmission lines. Hundreds of city officials have committed—at least in principle—to limit their energy consumption and reduce their greenhouse gas emissions through agreements such as the Climate Protection Agreement of the U.S. Conference of Mayors.

And yet, most state and local governments have limited capacity to expand their efforts. Budgets were already tight before the current economic downturn, forcing energy investments to compete with other policy priorities, such as transportation, education, and health care. The sheer scale of the nation's energy challenges calls for a substantially larger pool of resources than state and local governments can devote to energy.

Consequently, the public responsibility for driving a fundamental energy transformation in America falls largely to the federal government.

Federal leadership on energy policy is appropriate in part given the federal government's historic responsibilities for environmental protection and economic and national security. But the case for federal involvement goes beyond simple tradition and reflects the vast scale and boundary-crossing complexity of the problem. Beyond that, it reflects the fact that only national governments can ensure adequate provision of certain public goods that make the entire nation better off but might not otherwise be adequately produced.[87] Basic and pre-commercial scientific R&D, national security, and environmental protection are all public goods that are not sufficiently provided by the private market and so require public attention. Yet, state and local efforts towards these ends, on their own, will always be thin and uneven. The federal government tried for decades to influence business practices and state policies with financial carrots before it set national standards to ensure environmental quality.[88] Federal responsibility over energy and the environment has therefore grown as business increasingly shifts from the local level to the global level and as the external effects of commerce, including air pollution and greenhouse gas emissions, extend beyond the control of local and state governments.

In short, gaps in pricing and regulatory responses, the insufficiency of private investment, and the inability of most states and local governments to engage at the levels needed all place significant responsibility for investment in energy innovation in the lap of the federal government.

V. The Current Federal Role in Energy Research is Inadequate

The time has come, then, for renewed federal investments in energy that complement and extend the capabilities and responsibilities of the private sector and state and local governments. Research is one important area where the federal government must engage. Yet, both the magnitude and character of today's federal energy R&D programs are inadequate to overcome the market and government failures that hinder problem solving.

1. The magnitude of federal research efforts is inadequate

The scale of current efforts is the first problem with federal energy research. Quite simply, the volume of current federal spending on energy R&D—given market realities—remains far too small to ensure the development of a sustainable energy economy in America. In 2007, the federal government spent $2 billion on non-defense energy technology-related R&D, comprising just 1.7 percent of the federal R&D budget (4.2 percent of the non-defense portion) and 0.014 percent of the nation's GDP.[89] Estimated federal energy technology R&D spending for 2009 is up to $2.37 billion, higher than its 1998 low of $1.27 billion but substantially lower than the $10.5 billion spent at the height of federal spending in 1978 and 1979 (in real terms).[90]

Box 2. The federal energy research enterprise in the United States

The lead agency for federal energy research is the U.S. Department of Energy (DOE).[91] DOE was established as a cabinet-level agency in 1977 to house all federal energy-related activities under one roof, including nuclear weapons development and cleanup. The new agency inherited "muddled, ill-defined missions" of national defense, environmental protection, and domestic energy production and security.[92]

Since 1978, the agency has spent approximately $300 billion on energy R&D, including both defense-related and non-defense projects.[93] Of this $300 billion, 36 percent has been spent on nuclear energy, 28 percent on fossil fuels, 19 percent on renewables, and 15 percent on efficiency, with the remaining for hydrogen and electricity transmission and distribution research.[94] DOE spends approximately $1.4 billion currently on basic energy sciences research with a direct energy technology application.[95]

The bulk of DOE's research is conducted by its national laboratories (NL), which have compiled the backbone of the nation's primary research infrastructure in physical and material sciences, engineering, and increasingly in the life sciences. Since 1962, DOE researchers have won 800 R&D awards issued by *R&D Magazine*, with 30 of the 100 awards made in 2008.[96] Approximately 90 Nobel Prizes have been awarded to researchers at DOE (or its predecessor agencies) since 1934.[97]

DOE's national laboratories are federally funded but administered by industry, universities, or other nonprofit organizations.[98] Industry-administered labs include the Los Alamos and Sandia weapons labs, plus the smaller Idaho and Savannah River NLs. University-administered labs include Ames Lab, Argonne NL, Lawrence Berkeley NL, Lawrence Livermore NL, and several physics labs. Nonprofit-administered labs include Brookhaven NL, Oak Ridge NL, Pacific Northwest NL, and the National Renewable Energy Lab.

Management of the national laboratories is split between the various DOE offices.[99] Three of the NLs are managed through DOE's National Nuclear Security Administration (Los Alamos, Lawrence Livermore, and Sandia National Laboratories) and together control approximately one-third of DOE's research budget. Ten of the NLs are managed through the DOE Office of Science. The Office of Fossil Energy manages the National Energy Technology Laboratory, the Office of Energy Efficiency and Renewable Energy manages the National Renewable Energy Laboratory, and the Office of Environmental Management manages the Savannah River Technology Center.

Many prominent analysts, including members of the National Academies, the President's Council of Advisors on Science and Technology, and the American Association for the Advancement of Science, conclude that today's investments in energy R&D and technology development are insufficient to address the nation's sustainability and security challenges.[100] Commenting mostly on the scale of U.S. energy innovation efforts, Holdren has called U.S. R&D efforts "woefully inadequate."[101] Calls naturally follow for a substantial increase in federal energy R&D efforts. For instance, 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.[102]

Similar calls for a new national energy research initiative are widespread.[103] Conservative estimates call for a doubling of federal energy R&D investments within the next several years.[104] Some have called for ramping up federal energy R&D investments to 10 times current levels, or around $20–30 billion per year. Many call for investments in line with what the nation spent on major initiatives like the Manhattan Project for nuclear weapons development ($21 billion over 5 years) or the Apollo program for space travel ($96 billion over 14 years).[105] The major challenge will be in translating larger funding streams for energy into achieving the sometimes conflicting goals of sustainability and security, while working with the private sector to ensure that new energy technologies pass market tests and can be rapidly deployed.

In short, there is now nearly universal consensus that the nation spends too little on catalyzing new technology approaches to stabilize greenhouse has emissions.

2. The character and format of federal energy research remain inadequate

The character and format of federal energy efforts is also holding back innovation and rapid deployment of clean energy technology. In this connection, today's federal energy research program lacks the mission, capacity, and organizational structure to equip the nation to meet the full run of its challenges.

To begin with, the mission and capacity of the federal energy laboratories—which anchor the nation's present efforts—remain limited in two important ways.

First, the national laboratories do not for the most part have the mission or the capacity to build and maintain the nation's energy infrastructure. This responsibility lies largely with industry. Most of the nation's energy resource extraction, production, and transmission facilities are privately owned and operated. Therefore, new energy technologies and processes developed by the nation's energy research enterprise must pass strict market tests, which discourage adoption except where cost-competitive with existing technologies. This is one reason why the Manhattan Project and Apollo Program pose impractical models for a new energy initiative.[106] In both of these cases, the government was the consumer of new technology and could effectively develop needed technology without needing to subject it to the rigors of market tests.

Second, the national labs do not play a prominent role in producing the human capital necessary to develop, build, and manage the nation's energy infrastructure, which is most properly the role of the nation's universities. Most DOE activities are relatively isolated from education (aside from limited campus-based research programs sponsored by the DOE Office of Science). Furthermore, the nation's complex energy challenges extend beyond science and engineering into the social and behavioral sciences, professional programs in business administration, law, medicine, and public and environmental policy—all areas where national laboratory expertise is limited.

But beyond the inherent mission and capacity of the lab system, today's federal energy research efforts remain in many cases fragmented and insular. As the DOE's SEAB Task Force warns, "The Department of Energy (DOE) 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."[107]

Several problems exist with the current federal energy research paradigm. For one, the DOE R&D offices and programs are organized around fuel sources (e.g., coal, oil, gas, nuclear, and renewable), and are all too often characterized by an "energy technology of the year" approach and internal competition that disrupts longer-term strategic efforts.[108] This fragmentation leads to stovepipe organizations that focus on incremental or discrete technologies as opposed to systems that integrate R&D on the supply, distribution, and end-use needs for the set of energy sources and associated infrastructures required to supply the nation with reliable, affordable, and sustainable energy.[109] This can result in energy policies that seriously underestimate threats and consequences and are all too frequently risk-averse and parochial, tending to seriously misjudge the potential for new high-risk, high-payoff, technologically-enabled opportunities and threats.

Beyond that, the DOE SEAB Task Force raised concerns about the culture of some units of the laboratory enterprise, which it deemed insular given its descent from the security constraints of their earlier and ongoing work in nuclear weapons development. This and other reports concluded that the national energy labs are too far removed from the marketplace and too focused on existing portfolios to support "transformational" research targeted at new energy technologies. Others observe that some DOE programs have been "developed and implemented individually with too little regard for technological and economic reality and too much regard for regional and industry special interests."[110] Along these lines, some early efforts in developing new technologies capable of transforming energy infrastructure by the national laboratories have had limited success in the marketplace (e.g., synfuels, Freedom Car, the hydrogen economy, nuclear power, and FutureGen). Similarly, 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.

Finally, few DOE labs are staffed to conduct the market analysis and public policy research required for large-scale deployment of renewable energy sources, for significant gains in energy efficiency, and for reduction in fossil fuel consumption. Diffusing technology through our social system in a rational and planned way will be as critical to a rapid transformation of our energy systems as the technology itself. 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. With the clock ticking, a major challenge involves developing systematic approaches to technology diffusion that avoid the obvious mistakes. A new approach to technology development and deployment is badly needed to avoid costly false starts that the nation can ill afford.

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In sum, major innovation in research paradigms, policy, and management will be necessary to bring about the needed acceleration of energy technology innovation.

As the DOE SEAB Task Force concluded, "The federal government alone cannot meet the nation's energy related R&D needs. The DOE must collaborate 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."[111]

To address the nation's energy needs adequately, then, the capabilities of DOE mission-focused divisions and national laboratories must be augmented by other research organizations and programs. These augmentations should seek to:

- Provide the scale, continuity, and coordination of effort in energy R&D and demonstration needed to bring an appropriate portfolio of improved options for the timely commercialization of breakthroughs

- 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

- Address adequately the unusually broad spectrum of issues involved in building a sustainable energy infrastructure, including—in addition to science and technology issues—attention to complex social, economic, legal, political, behavioral, consumer, and market issues

- Build strong partnerships among multiple players, including federal agencies; research universities; established industry; entrepreneurs and investors; regional business associations; and federal, state, and local government

- Launch robust efforts capable of producing the human capital and public understanding required by the emerging energy sector at all education levels

VI. Discovery-Innovation Institutes Offer a New Model for Energy Research

So how should America respond? To be sure, a wide continuum of national, state, local, and private-sector responses will be needed to address the full scale and complexity of America's energy challenges, ranging from carbon pricing interventions and regulation to promote clean-energy to the scaling up of smart-energy infrastructure. But for all that, the federal government should place the search for breakthrough technologies and their commercialization at the center of its energy efforts and move to exploit in an integrated way the entire national research enterprise: research universities, corporate R&D laboratories, and federal laboratories.

To that end, the federal government must necessarily augment both the scale of U.S. energy research efforts and the range of formats within which it is pursued.

To begin with, the nation 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).

But that responds only to the scale portion of America's research challenge. Equally important, the nation must experiment with new energy research paradigms, and so a significant fraction of the projected investment increase should be directed toward **a new research paradigm consisting of a national network of regionally-based, commercialization-oriented energy discovery-innovation institutes (e-DIIs) that would serve as hubs in a distributed research network linked through "spoke" relationships to other concentrations of the nation's best scientists, engineers, and facilities.** The DII concept, developed by the National Academy of Engineering (NAE), is characterized by institutional partnerships, interdisciplinary research, technology commercialization, education, and outreach. Such discovery-innovation institutes are designed to link fundamental scientific discoveries with technological innovation through translational research and development to create the products, processes, and services needed by society, working closely with industry and the investment community to demonstrate commercial viability and assist in market deployment. The e-DII concept would also be supportive of and complementary to similar proposals for innovative energy technology programs such as the Advanced Research Projects Agency-Energy (ARPA-E), DOE's Frontier Energy Research Centers, a possible National Energy Research Initiative, or an eventual National Energy Institute. 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.

Along these lines, the DII paradigm represents a contemporary adaptation of the research paradigm created through the sequence of land-grant acts passed by the U.S. Congress in the 19th century. Then, revenue from the sale of federal lands was used to create a network of university-based agricultural and engineering experiment stations on university campuses, augmented with extension services capable of interacting directly with the commercial marketplace. The program was instrumental in developing and deploying the agricultural and industrial technologies necessary to build a modern industrial nation for the 20th century while stimulating local economic growth. Today, the nation needs a similarly bold campaign to enlist America's universities and national laboratories in solving one of the most complex problems the nation has ever encountered.

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

1. Organize around a theme

Today's energy challenges are complex, involving interdependent systems of natural resources, production and distribution facilities, technology development and innovation, capital markets, and environmental systems, such as the global climate. A systems-approach for technology development is needed to deal with this complexity and to transcend the current "siloed" approach common at DOE and its national laboratories. One way to proceed is to organize each e-DII around a particular 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 DII would then be charged with addressing the scientific, technical, economic, policy, business, and social challenges required to diffuse innovative energy technologies of their theme area into society successfully.

2. Foster partnerships to pursue cutting-edge, applications-oriented research among multiple participants and disciplines

The e-DIIs would be profoundly multidisciplinary and collaborative. In this connection, a new research culture is needed to drive the nation's energy transformation, based on the nonlinear flow of knowledge and activity among scientific discovery, technological innovation, entrepreneurial business development, and economic, legal, social, and political imperatives. To this end, e-DIIs should tap the resources and capabilities of multiple players, including companies, entrepreneurs, and investors as well as government agencies (federal, state,and local) and research universities. 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. To keep the focus on commercialization, private-sector and commercialization specialists would be kept in contact with researchers and play lead roles. And because 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.

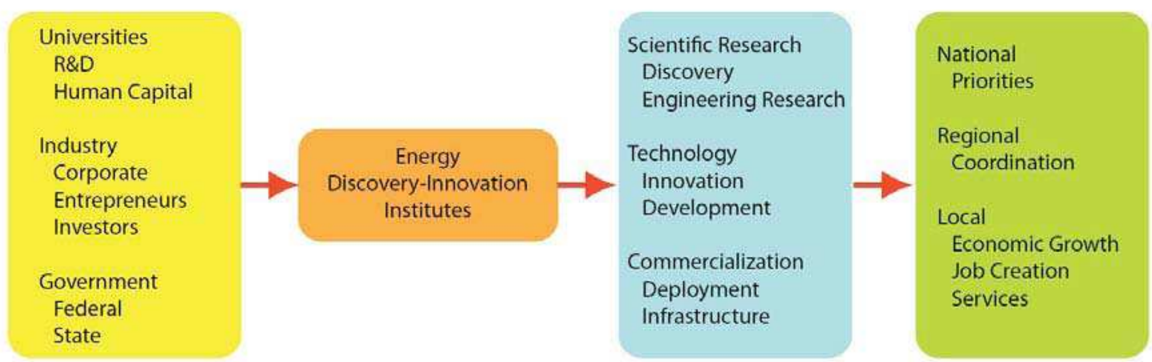
How might this play out? *Federal research organizations* such as the national laboratories could commit talent and infrastructure to fulfill their missions of conducting long-term research to convert basic scientific discoveries into innovative products, processes, services, and systems. *States and localities* could contribute land, capital facilities, and other infrastructure. *Research universities* could commit faculty and staff time and encourage the engagement of students. They could also provide a policy framework (e.g., transparent and efficient IP 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). *Industry*, meanwhile, might lead in providing challenging research problems, technology development, systems integration, and real-life market knowledge, as well as staff who could work with university faculty and students in the institutes. *Entrepreneurs* could facilitate rapid commercialization, new business formation, and job creation. Finally, the *investment community* could provide expertise in licensing and in creating new companies and could provide support for technology commercialization.

The challenge of building a sustainable energy infrastructure also depends as much on socioeconomic, political, and policy issues as upon science and technology. The failure of most current national laboratory and industrial R&D activities to commercialize and deploy new energy technology can be attributed, in part, to their narrow focus on technical and economic issues that fail to address the broader social, behavioral, legal, and political nature of energy challenges. For this reason, the e-DIIs—wherever they are situated—should encompass non-technical as well as technical disciplines, such as the social and behavioral sciences, business administration, law, and environmental and public policy. In all, each discovery institute would serve as a focus of intense interaction among diverse players and between multiple disciplines.

3. *Act as the hubs of a distributed network of campus-based, industry-based, and lab-based scientists and engineers*

Each institute would also serve as a node in a far-reaching network of researchers and inventors working in universities, laboratories, and research centers, consistent with the fundamental purpose of the DII model for coupling 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 core and related basic research group spokes to interact and collaborate among themselves through exchanges of participants, regularly scheduled meetings, and cyberinfrastructure. In this way the direct interaction of the basic research groups would facilitate and greatly intensify collaboration and research progress, creating a basic energy research community greater than the sum of its parts and possessed of sufficient flexibility and robustness to enable the participation of leading scientists and engineers to address the unusual complexity of the nation's energy challenges.

Energy discovery-innovation institutes would draw from a diverse support network, conduct widespread activities, and be oriented towards achieving important social goals



4. *Execute an effective strategy for energy technology development, commercialization, and deployment*

Commercialization, meanwhile, should be the crucial objective of the e-DII network, which would in every instance work closely with industry, entrepreneurs, and the investment community to accelerate the conversion of scientific breakthroughs into commercial deployment. In this connection, each institute would rely heavily on the private sector to help it shape and execute a program of “use-inspired” basic research aimed at developing technologies and processes directly relevant to the goal of reducing the costs of carbon mitigation. “Problem determination” would often flow from the private sector. And then the success of the e-DII should be measured by results, with results rewarded. Suggestive here are the experiences of other successful paradigms for technology transfer, including that of the major academic medical centers (which have played a critical role in commercializing translational biomedical research through business startups). Also relevant are the successes of the agricultural and industrial extension services, and federal initiatives such as the Small Business Innovation Research program (SBIR).

5. Develop and rapidly transfer highly innovative technologies into the marketplace.

To facilitate large-scale commercialization, meanwhile, the rapid transfer of new technologies into the private sector must become a central activity of the e-DIIs.

Such transfer—at wholesale volumes—is crucial if a massive transformation of the nation’s energy infrastructure is to be rapidly achieved, so it is equally essential that publicly funded energy research become easily and quickly available to industry, which will in most cases be the crucial disseminator of new technologies and processes. To that end, the new innovation centers should become major forums for the development of swift, efficient, and predictable practices for the transfer of breakthroughs to the marketplace. In all cases, technology transfer should be structured to maximize the volume, speed, and positive societal impact of commercialization—and the innovation centers should be held accountable for that.

Key here will be the innovative treatment of IP, which in too many cases has become subject to over-management by centralized university technology transfer offices (TTOs) or similar lab-side controls that have at times hindered commercialization.[112] Frequently this over-management has been characterized by a revenue-maximization model that has created incentives for the TTOs and similar bureaucratic units to become gate-keepers and filters rather than facilitators of commercialization as they search (on the university side) for "home-runs."[113] And so the e-DIIs should operate differently. As much as possible, the new centers should provide a safe zone where patenting and licensing rights and other IP issues can be worked out in advance to speed knowledge transfer and facilitate the establishment of the fastest, most appropriate pathways to commercialization.

In this regard, a growing number of successful industry-university, industry-laboratory, and industry-university-laboratory research partnerships—such as those of the Energy Biosciences Institute (EBI), which consists of a partnership among energy giant BP, the University of California at Berkeley (UC), the University of Illinois at Urbana-Champaign (UI), and the Lawrence Berkeley National Laboratory—point the way toward new and effective IP solutions. At that institute, collaborating researchers and industry leaders have piloted several new approaches at the industry-university-laboratory interface that have sought to maximize the social impact of research by facilitating vigorous development by BP or others. In this case, one innovative agreement found the consortium agreeing on governance and IP management in advance and extending to BP not only a non-exclusive, royalty-free license to inventions, but a 90-day option for exclusive, royalty-bearing licenses. This had the effect of making IP predictable at the outset as well as maximizing the likelihood of diligent commercialization as well as maximized social benefits.[114]

And other models exist. Regional alliances or consortia of universities and other organizations (like the Wisconsin Alumni Research Foundation) have in some cases begun to experiment with coming together to standardize their technology transfer activities with an eye to maximizing the volume of transfer.[115] In other instances, commercialization and technology transfer has been sought through the creation of distinct units tightly connected to universities or laboratories but not directly within their governance structure, allowing commercialization work to be more tightly linked to private capital markets and the regional and global business community.[116] Relatedly, web-based approaches show promise of effectively matching those with advances and ideas to those who might want to implement them, and are inherently oriented toward maximizing volume and accelerating transfer.[117] An example of this approach is www.bridgenetwork.com, a web-based platform launched in January 2007 on which participating universities post information about their innovations and nonexclusive licensed technologies directly on the site with an eye to faster dissemination.

6. Stimulate regional economic development

Stimulating regional economic development, particularly in concert with growing local alternative energy industry clusters, should also be a high concern of the e-DII network.

Such a network would be inherently local and metropolitan in its decentralized structure since it would ramp up cutting-edge, applications-oriented research in the universities and federal laboratories within dozens of U.S. metropolitan areas. But the innovation hubs would naturally also augment (by virtue of their profligate transfer activity) the development of local clusters of start-up firms, private research organizations, suppliers, and other players—the true seedbed of innovation.

Yet this desirable natural "spillover" of innovation exchange should not be viewed as simply a happy potential byproduct of the institutes but an important objective. And the possibilities are compelling. With the participation of many scientific disciplines and professions as well as various economic sectors, the e-DIIs will 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. This organizational form, meanwhile, has been successful at generating jobs and stimulating local and regional economic activity, by the nearby location of clusters of start-up firms, private research organizations, suppliers, and other complementary groups and businesses.

As with agricultural stations, the e-DIIs should focus, at least in part, on the unique energy needs and opportunities characterizing their home regions. This regional character would help to stimulate local cluster development and ensure that new technologies respond to local challenges and thus could be rapidly deployed. The regional e-DII focus would also be instrumental in creating in the United States a globally competitive industry in advanced energy technologies with jobs that would be difficult to offshore because of their strong dependence on the local capabilities of the e-DIIs for R&D and workforce development. Once again, the past is prologue: Part of the great success of the land-grant established agricultural and engineering experiment stations in regional economic development was the creation of an affiliated network of agricultural and industrial extension services. This model should be explored as a possible component of the e-DII networks, since such extension activities could play an important role both in achieving the social behavior necessary for energy conservation and efficiency as well as in “green” job creation through small energy business startups.

Box 3. How the e-DIIs’ regional focus might work

The Great Lakes states are home to the nation’s largest concentration of energy-intensive industries—manufacturing, agriculture, and transportation—clustered around large urban populations and heavily dependent upon fossil fuel energy sources. Over one million jobs, directly or indirectly, depend upon energy and related industries in the Great Lakes. Migrating the region’s economy to new, clean technologies while creating a culture of innovation in the region to solve energy challenges in the United States offers a significant economic opportunity.

Two potential themes seem important for e-DIIs in the Great Lakes region to pursue. First, the industries and residents of the Great Lakes region utilize 38 percent 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, the region’s industrial capacity is unlikely to remain competitive in global markets. The e-DIIs in the Great Lakes could focus on carbon sequestration or low-carbon technologies that could be rapidly deployed to replace the region’s coal-fired electricity.

Second, a future new spiking of gasoline prices to Asian and European levels would likely obliterate what remains of the American automobile industry based in the Great Lakes region. Domestic companies are unlikely to shift rapidly to the small, fuel-efficient cars produced by Asian manufacturers or adept enough to exploit hybrid, electric, or hydrogen fuel technologies on a short timescale. The e-DIIs in the Great Lakes region could therefore work with the auto industry to develop new technologies and upgrade existing ones, such as biofuels, advanced battery technology, hydrogen fuel cycles, or other low carbon propulsion systems.

The challenges and opportunities characterizing the Intermountain West states suggest an alternative focus for e-DIIs. The western and intermountain states comprise the nation’s fastest growing region, both demographically and economically. Given its massive projected future development, the region will contend 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. The intermountain states have significant primary energy sources (oil, gas, oil shale, and hydropower) and an unusually strong potential for solar and wind energy. The e-DIIs in this region could take advantage of its national laboratories with research capability in renewable energy technologies, energy distribution, and carbon mitigation and sequestration.

The energy needs and capabilities of the Northeast, Southeast, and Midwest states similarly provide strong rationale for the e-DIIs. 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 e-DIIs. 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.

Finally, the e-DIIs could help better align or nucleate—within metropolitan regions—the multiple, often disparate, energy-related activities of 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. Such regional concentration would surely help 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.

7. Build the knowledge base and human capital necessary to address the nation's energy challenges

The e-DIIs are also 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—amid their other activities—lead the development of educational programs and distributed educational networks that could 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. In this fashion, the e-DIIs would take on a fundamental educational mission through the involvement of their scientists and engineers in sharing educational best practices and developing new educational programs in collaboration with K–12 schools, community colleges, regional universities, and workplace training organizations.

The training of researchers and engineers with the skills necessary to work in either the public or private sectors to produce breakthrough innovations should be viewed as more than an ancillary benefit of the innovation centers and instead seen as a key objective. By supporting science, technology, engineering, and mathematics (STEM) education, graduate and postdoctoral students, and other human capital development, the e-DII network will expand the economy's future capacity to invent and staff the next economy.[118]

8. Expand the scope of possible energy activities

Finally, the e-DIIs would add one more major activity to their repertoire: They would expand the range of possible energy innovation activities. The partnership character of the e-DII network—involving a consortium of universities, national laboratories, industry, investors, and state and federal government—coupled with its regional focus would give the network the capacity to launch projects that are well beyond the capability of the national laboratory system, higher-education, or industry alone. In this connection, the capability of e-DIIs to span all three sectors—federal government, industry, and higher education—could prove to be of immense value. For example, the effort to stimulate a renaissance in the utilization of sustainable nuclear power in the United States will likely involve a coordinated effort among the DOE laboratories that would lead the R&D effort to develop Generation IV nuclear power technologies; industry that would develop the engineering, management, and financial ability to create the necessary infrastructure; and universities, which would be responsible for educating the necessary scientists, engineers, technicians, managers, and other workforce elements. The Apollo program of the 1960s was just such a coordinated effort involving federal laboratories, industry, and universities.

VII. Other Paradigms have been Proposed but Lack the Scale and Comprehensiveness Needed for Transformative Energy Research

It bears noting that a growing perception of need in recent years has led to the exploration of several relevant research and technology development proposals and experiments besides DIIs, including SEMATECH for the electronics industry, the Advanced Technology Program of the National Institute of Standards and Technology, the SBIR grant programs, the Intelligence Advanced Research Projects Activity (IARPA) and In-Q-Tel (IQT) efforts within the intelligence community, and ARPA-E and Energy Frontier Research Centers (EFRCs) for energy research. ARPA-E, IQT, and EFRCs provide important models for energy but individually fall short of responding adequately to the scale, complexity, and urgency of the energy research needs of the nation. Additional models are needed that would complement—not replace—these efforts.

ARPA-E is the DOE's analog to the highly successful Defense Advanced Research Projects Agency (DARPA). DARPA is used for narrowly focused applied technology research to support specific defense priorities. Specifically, DARPA sponsors "revolutionary, high-payoff research that 'bridges the gap between fundamental discoveries and their military use.'"[119] The ARPA-E model would sponsor high-risk energy research with potential technology applications and speed the development of promising technology, which used to be pursued by the Advanced Energy Projects program in DOE, terminated in fiscal year (FY) 2000. The ARPA-E concept was detailed by the National Academies of Sciences in a 2005 report on science and technology R&D and American competitiveness.[120] Congress authorized the formation of a new ARPA-E organization within DOE as part of the America COMPETES Act of 2007 (P.L. 110-69), with initial authorized funding of $300 million for FY 2008. The President's FY 2008 and FY 2009 budgets did not include funding for ARPA-E, and no funds have yet been congressionally appropriated for it.

The ARPA-E model, by itself, lacks the scale and intellectual breadth to address the nation's energy challenges. For one, funding at $300 million per year necessarily limits the scale and effect of the ARPA-E initiative. ARPA-E proponents envision funding at $1 billion per year, closer to DARPA's $3 billion per year budget.[121] In addition, the domain of ARPA-E is by design limited in scope to nimble, high-risk projects that would not otherwise fit into the DOE organizational structure. In this way, fundamental basic research on important energy issues is outside the domain of ARPA-E and must be funded through other mechanisms.

IQT is the venture capital arm of the Central Intelligence Agency to fund technology development with intelligence applications.[122] It is not subject to the bureaucratic constraints most federal agencies face in hiring and funding projects and acquisitions. It also has similar flexibility to commercial venture capital funds in making deals, but focuses more on products or services rather than return on equity or assets. A similar approach could be utilized to fund energy technology development, although critics note that many new energy technologies are not sufficiently developed yet to compete for venture capital (which typically funds late-stage development).[123]

To further develop the knowledge base for transformational innovation in the energy arena, the president and DOE have proposed creating EFRCs.[124] EFRCs would conduct basic energy research in high priority areas identified by the DOE's Basic Energy Sciences Advisory Committee in 2001. EFRCs would be competitively awarded and managed by DOE and be staffed by multiple researchers from firms, universities, national laboratories, or nonprofit organizations. The EFRCs would receive five-year funding of $2 to $5 million per year per center, totaling $100 million for the EFRC initiative. A request for proposals was issued by DOE in 2008 and initial funding for the EFRCs may be appropriated in the final FY 2009 budgets.[125] While basic energy research is critically important, DOE's management of EFRCs would likely make them subject to many of the same problems facing other DOE initiatives, including fragmentation and insularity. New research paradigms are still needed to span all areas of energy R&D, including basic and applied research, and technology development and deployment, with a focus on translational research and commercialization.

In sum, the suggested e-DIIs network would fulfill functions not likely to be fulfilled by other innovative energy research initiatives currently being contemplated even as it complemented them.

VIII. Other Nations are Pursuing DII-Type Partnerships

Other nations, meanwhile, are actively experimenting with new research and innovation paradigms. In fact, the basic DII model of partnership between government, university, and private industry is a popular tool in the innovation strategies and economic competitiveness plans of a number of other countries. Though not always targeted on energy, these other countries' efforts are similar to those projected by the DII concept in that they represent funding and catalyzing initiatives to better connect research to commercialization and deployment to enhance the development of particular regional industry clusters.

One of the most established models of this sort is in Finland. The "triple helix model" of linking government assets, university resources, and business enterprise is at the core of Finland's Centers of Expertise (COE) program—a national network of regional innovation systems that draws in professionals and experts from each of the three different sectors to leverage the strengths of various regions to boost their economic competitiveness. Between 1999 and 2002, 22 centers across Finland (focused on high-tech and low-tech) connected 1,110 experts, 3,075 firms, and 460 research and training units to produce 1,400 innovations (including new products, services, and processes) and 5,700 new jobs.[126] Norway and Sweden have similar Centers of Expertise programs. In Sweden, the country's network of centers is administered through its major universities. By contrast, Finland's centers are often housed in industrial parks.

Science Foundation Ireland (SFI) represents another important antecedent. Founded in 2003, SFI employs a three-pronged strategy aimed at improving the country's science and engineering efforts through the development of human capital, support of research and innovation, and the fostering of partnerships among agencies, research institutions, and industry. Utilizing a competitive, peer-reviewed process, SFI's Centers for Science, Engineering, and Technology (CSET) Campus-Industry Partnership program provides $1.3 to $6.5 million (€1 million to €5 million) annually over five- to 10-years terms to university-based centers that bring together private firms, research institutions, government labs, and other entities to conduct science and engineering research—particularly in fields that support the country's strong biotechnology and information and communications technology industries. One such CSET is underway at Trinity College Dublin. The Center for Research in Adaptive Nanostructures and Nanodevices (CRANN) connects Trinity with Intel, Hewlett-Packard, and other industry partners, creating a powerhouse of cutting-edge material physics and chemistry research at the nanoscale. With 10 "industry researchers-in-residence," CRANN's commercialization efforts are informed by the presence of researchers who possess an intimate knowledge of industry needs. Among the technologies CRANN is working on: materials and devices structures for next-generation semiconductors; transparent electrodes for use in emerging applications like "e-paper;" and new clinical diagnostic tools that utilize magnetic nanowires.[127]

Japan also has a successful national program to drive government-university-industry collaboration focused on technology and knowledge-intensive fields in key economic regions. In Japan's Industrial Cluster Program, government ministries actively work to promote networking among economic actors with complementary technology capacity and needs and advance collaborative R&D. The program connects 5,800 small and medium sized firms to over 200 participating universities and 500 government officials across 19 regional clusters. Between

2001 and 2005, nearly 40 percent of the program's firms started new collaborative projects, 60 percent launched new business lines, and participating universities produced 133 spin-offs.[128]

Other countries are also experimenting with this type of partnership model. In Canada, for example, the government of Quebec recently brought together eminent scientists from the biotechnology industry, university, government laboratory, and hospital circles to launch the Quebec Consortium for Drug Discovery in June 2008. The first of its kind in Canada, the consortium's goal is to maintain and sharpen the Quebec region's competitive edge in pharmaceutical research by fostering synergies between academic, corporate, and institutional research.[129] Similarly, Canada's National Research Council (NRC) developed a cluster initiative in the late 1990s focused on the Vancouver area's strength in the fuel cell and hydrogen industries. About 35 companies, two industry associations, and three universities are involved in the initiative. These entities, along with the recently opened NRC Institute for Fuel Cell Innovation, work together to accelerate the commercialization and deployment of alternative transportation technologies and fuels.[130]

In the United Kingdom, the "Science City" initiative has helped to strengthen and formalize partnerships between universities, government, and industry in the six cities chosen to participate in this program to boost science and technology R&D and job growth.[131] Additionally, the UK recently created a Technology Strategy Board (TSB) to engage in innovation activities that join up R&D and the private sector. Focused on six high-tech domains, including biotech, nanotech, advanced materials, and high value manufacturing, the TSB promotes commercialization of market-demanded breakthroughs through two patallel initiatives. One of these programs—Knowledge Transfer Networks—brings together networks of academic researchers, businesses, and other institutions to collaborate on solving important problems and speeding up market development of technologies in fields such as photonics, digital communications, bioscience, and aerospace. The other program—Knowledge Transfer Partnerships—funds academic researchers and scientists to work in a private firm for a number of years on specific applied research problems with the aim of improving knowledge transfer and innovation among academia and industry.[132]

Developing countries are also looking to the government-university-industry partnership model. The Chinese government, for example, set up four industry-research strategic alliances in June 2007 concerning steel, coal, chemistry, and agricultural equipment. The initiative encompasses 26 leading enterprises, 18 leading universities, and nine key research institutions with the goal of strengthening the technological competency and the diffusion of innovation in these fields.[133]

In short, the experience offered by Finland, Ireland, Japan, and other countries in accelerating commecriailzation through the encouragement of stronger university-government-industry partnerships can and should offer guidance in program design and implementation as American moves to develop an e-DII network.

IX. THE DII CONCEPT HAS ALSO EMERGED AT THE STATE, REGIONAL, AND LOCAL LEVEL

At the same time, states, localities, and disparate individual consortia of interests are experimenting with the development of partnerships among government, universities, and the private sector to spur the commercialization of scientific breakthroughs.

At the state level, New York, Oregon, and Georgia offer helpful models that any new federal effort in the energy area must carefully consider, respect, and complement.

Much like Norway and Sweden's Centers of Expertise programs, New York State has established Centers of Excellence at major state universities to support high-tech research and speed up the commercialization of promising breakthroughs. These centers—focused on technologies from bioinformatics to nanoelectronics—smartly leverage existing innovation assets that cluster within certain regions of the state, providing workspace and capital to foster synergistic relationships between industries, research organizations, and government.[134]

For instance, the Rochester, NY area—known for Kodak and Xerox along with several research universities—is home to the state's Center of Excellence in Photonics and Microsystems. Housed in the Infotonics Technology Center, the Center of Excellence fosters collaboration among New York's universities, dozens of area firms, the Rochester Regional Photonics Cluster, and Brookhaven National Lab in supporting rapid commercialization of microelectronics and miniature systems breakthroughs for communications, biomedical, security, and defense/aerospace applications.[135]

The Center of Excellence in Environmental and Energy Innovations in Syracuse, NY brings together a network of industrial firms, economic development agencies, and research organizations to develop innovative products focused around renewable energy, indoor environmental quality, and water resources.[136] The Hauptman Woodward Medical Research

Institute, the Roswell Park Cancer Institute, and the University of Buffalo's Center for Computational Research provide the anchors for the Bioinformatics and Life Sciences Center of Excellence in Buffalo, NY. The center organizes a network of research institutions and private life science companies all focused on developing tools, interventions, and treatments that improve human health.[137] Other Centers of Excellence include those focused on nanoelectronics (Albany), information technology (Long Island), and small-scale systems integration and packaging (Binghamton).

Oregon is also developing networks of public-private partnerships to accelerate commercialization of high-tech discoveries in the fields of nanoscience, pharmaceuticals, and renewable energy and materials through the state's three Signature Research Centers (SRC). The Oregon Nanoscience and Microtechnologies Institute (ONAMI) is the state's senior SRC, bringing together federal government agencies (including the National Science Foundation (NSF) and the Departments of Commerce, Defense, and Energy), the state, research institutions, and industry to support research and quickly bring innovative breakthroughs to the marketplace. The center benefits from key innovation assets, including the state's three public research universities, the Pacific Northwest National Laboratory, and the deep "Silicon Forest" high-tech industry cluster.[138]

The Oregon Translational Research and Drug Development Institute (OTRADI), run by the Oregon Economic and Community Development Department, supports a network of state universities and biotech companies focused on study and treatment of infectious disease. OTRADI helps Oregon universities and firms further develop their IP prior to partnering with larger firms in hopes of increasing the value of homegrown innovations, leading to more local investment, human capital attraction, and stronger tech-based economic development.[139]

Oregon's newest Signature Research Center—the Built Environment and Sustainable Technologies (BEST) Center—is anchored by Oregon State University, the University of Oregon, and the Oregon Institute of Technology. The center aims to leverage the state's R&D assets in renewable energy, bio-products, and green building in developing innovative solutions that can be marketed through BEST's public-private partnerships. BEST partners include universities, local businesses, and state agencies, with initial funding from the Oregon Board of Higher Education, the state legislatures, and the Meyer Memorial Trust.[140]

For its part, Georgia's Advanced Technology Development Center (ATDC) has for over two decades been strengthening the state's innovation economy by nurturing high-tech companies from the startup stage to success in the marketplace, with ATDC firms producing revenues over $12.7 billion and profits exceeding $100 million since 1987. While the center is headquartered at Georgia Tech, most of its member companies are not affiliated with the university. However, part of ATDC's success in developing profitable companies stems from the access member firms have to Georgia Tech's high quality research facilities and human capital. Development and commercialization of breakthroughs is also facilitated through partnerships with local, state, and national organizations, including the Atlanta CEO Council, the Georgia Research Alliance, and the National Business Incubation Association. These organizations—and several others—provide consulting services, funding assistance, business plan development, and networking opportunities to ATDC member companies.

Other states are getting in the university-government-industry partnership game, including Maryland's Industrial Partnerships program and Oklahoma's Technology Commercialization Center.[141] States are also pushing forward towards sustainability and security goals by passing state policies such as renewable energy portfolios, which are providing some policy certainty to reluctant firms and encouraging investments in advanced energy technologies.[142]

But these are only state-side efforts. So compelling is the underlying logic implicit in the e-DII paradigm and related departures that local metropolitan area leaders—and particular alignments of businesses, universities, and federal labs—are increasingly trying to organize partnerships along the DII line.

For one thing, the constituent elements of the optimal research-commercialization triad—businesses, universities, and the DOE—are already converging in myriad ways to create research hubs, networks, and combinations that foreshadow the projected e-DIIs.

In the energy space alone, numerous universities have already formed formal partnerships with industry and government partners to pursue cross-disciplinary, applications-oriented research to achieve new, commercially-viable breakthroughs in energy technology. For example, cross-institutional, collaborative work related to biofuels is being done by the University of Illinois at Chicago, Iowa State University, the University of Tennessee at Knoxville, and the University of Memphis.[143]

The Energy Biosciences Institute (EBI) is one of the largest of such biofuels-focused collaborative initiatives. Funded by BP at $500 million over 10 years, this partnership between the company, the UC, UI, and the Lawrence Berkeley National Laboratory aims to create a vibrant, interactive, "team science" culture for conducting extraordinarily innovative basic and applied research around alternative fuels and other clean energy concerns. Further, the institute's pre-negotiated licensing protocols help to speed the introduction of any new technological breakthroughs into the marketplace.[144]

Outside of biofuels, the University of Michigan has partnered with DTE Energy and GM through a grant from the Michigan Public Service Commission to assess the impact of widespread plug-in electric vehicle (PGEV) use on the state's electrical system and the state's environment, enhance Michigan's position as a technology leader, and position Michigan to become the center of PHEV-related business and innovation.[145] With a broader portfolio, Florida Solar Energy Center (FSEC) has, for over 30 years, brought together the University of Central Florida, the state of Florida, and federal agencies to create and support the commercialization of new technologies in solar cells, hydrogen energy systems, alternative fuels, and building technologies. With the primary objective of developing new applications for use by industry, FSEC actively licenses its technological breakthroughs to firms across the country.[146] Also geared to pursue a full roster of clean technology RD&D efforts is the Richard C. Lugar Center for Renewable Energy in Indianapolis, a new partnership formed in 2007 between Indiana University at Indianapolis, Purdue University, several energy companies, Argonne National Laboratory, and other federal research centers.[147] Similarly, the Colorado Renewable Energy Collaboratory brings together Colorado State University, the University of Colorado at Boulder, the Colorado School of Mines, and the National Renewable Energy Laboratory to establish joint research ventures between industry, academia, and government to increase the production and use of a full range of renewable energy resources.[148]

Another example of a joint endeavor between universities and a national lab is the Institute for Advanced Energy Solutions established by the National Energy Technology Laboratory (NETL) in partnership with Carnegie Mellon University, the University of Pittsburgh, and West Virginia University. The institute focuses on cleaner, more efficient fossil energy technologies, conducting onsite R&D in those specific areas in which at least two of the universities and NETL already have significant research programs. By expanding interactions between all four institutions, the institute aims to develop regional energy research expertise and promote the growth of a regional energy cluster in Pennsylvania, Ohio, and West Virginia.

For its part, the DOE itself has, indeed, promoted the branching out of its federal labs to do more joint work with different institutional partners. In one signature program, DOE's Office of Science funds three BioEnergy Research Centers in geographically distinct regions of the country that, all told, bring together diverse players from seven DOE national labs, 18 of the nation's leading universities, a range of private companies, and some nonprofit organizations. Each center is an extensive partnership, funded at $25 million dollar per year for at least 5 years and charged with identifying and applying practical solutions to the cost-effective production of renewable, carbon-neutral energy from biofuels.[149] Another DOE effort, the Entrepreneur in Residence program, has teamed up with venture capital firms to place venture-funded entrepreneurs in three of the national labs to directly support and expedite moving promising laboratory technologies to the private sector. Selected entrepreneurs conduct technology assessments, evaluate market opportunities and propose business structures for potential lab spin-offs, which are subject to pre-negotiated licensing agreements.[150]

The private sector, meanwhile, has often played a leading role in establishing new forms of collaboration for promoting innovation, and not just in the energy space. In the communications sector, for example, 12 wireless companies formed a research consortium with the University of California-San Diego Engineering School to conduct applications-oriented research that is relevant to the technical needs of the industry.[151] In manufacturing, the National Center for the Manufacturing Sciences (NCMS) is an extensive research network of approximately 50 large corporations, hundreds of small- and medium-sized firms, four federal agencies, and several universities that uses a collaborative model to rapidly develop and deploy advances in manufacturing technologies and processes.[152] In real estate, Albuquerque's Mesa del Sol project by the developer Forest City Enterprises relies on a very unique partnership between the University of New Mexico, Sandia National Laboratory, state government, and renewable energy firms to showcase environmentally-friendly development practices (e.g., smart grid deployment) and promote regional innovation and economic growth by cultivating clean energy and other knowledge and creative economy industries.[153]

In the energy realm, one new, groundbreaking private-sector initiative is especially noteworthy in its bid to accelerate the development and commercialization of the next generation of aviation fuels. The Sustainable Aviation Fuel Users Group is an alliance that currently includes aircraft manufacturer Boeing, energy technology company UOP-Honeywell, major airlines, key environmental nonprofits, and leading academics in an effort to make commercial aviation the first major global transportation sector to voluntarily drive sustainability practices into its fuel supply chain.[154]

Regional business and industry organizations and economic development alliances, finally, are also testing multi-disciplinary, applications-oriented models for promoting innovation as they seek to transform local economies. NextEnergy in Detroit, for example, catalyzes collaboration between key industry, academic, nonprofit, government, and military stakeholders to expand Michigan's capacity for research, development, and commercialization of promising technologies in alternative fuels and power generation.[155]

Likewise, the Fund for Our Economic Future--an extensive regional philanthropic collaborative—actively provides grants to multi-institutional partnerships to strengthen innovation economy in Northeast Ohio.[156] One of the fund's investments, BioEnterprise, draws on the research and technology licensing activities of local hospital and university systems to create, attract, and accelerate life sciences businesses in the region. Since 2002, BioEnterprise has created more than 70 companies and concluded over 300 technology transfer deals with industry partners.[157] Another fund initiative supports several collaborative technology projects that have been identified by an alliance of technology leaders from state-funded research centers, hospital and university tech transfer offices, and early-stage venture funders as especially promising for rapidly converting research into business development opportunities in fuel cells, nanotechnology, biomedical sciences, and other sectors relevant for Northeast Ohio's economic future.[158]

Similar public, private, and university collaborations are also central to efforts by Science Foundation Arizona (SFAz) to support purpose-driven research and innovation in key sectors of that state's economy. Inspired by Science Foundation Ireland, SFAz committed and invested $33.6 million in FY 2007 and leveraged another $43.8 million from private, nonprofit, and government sources to fund grants advancing research and learning in information technologies, sustainable energy systems, and biomedical research. A portion of these grants went to seeding and accelerating the development of eight start-up companies based on new technologies being developed at the state's public research institutions. In another, more recent effort, SFAz has partnered with the University of Arizona and several mining industry partners to establish a multi-million dollar institute—essentially an e-DII-- devoted to sustainable practices in mineral resource development.[159]

In sum, the nature and urgency of the innovation imperative in myriad fields is impelling multiple players at the state and regional as well as national level to pursue all kinds of diverse collaborations to intensify the search for breakthrough technologies. Now, the time has come for the national government to scale up this bottoms-up ferment through the creation of a vibrant national network of e-DIIs.

X. THE FEDERAL GOVERNMENT SHOULD CREATE A NATIONAL NETWORK OF E-DIIS

And so the federal government should move to accelerate the search for scalable breakthrough technologies that will fundamentally "change the game." Cognizant of the market and governance challenges that discourage sufficient R&D investments, the federal government should place the search for breakthrough technologies and practices at the center of its energy efforts and move to join the unique capabilities of America's research universities to those of corporate R&D and the federal laboratories to drive the needed innovation.

To this end, the federal government should create a highly coordinated national network of regionally based, applications-oriented energy discovery-innovation institutes to serve as the hubs of a distributed energy research network linking the nation's best scientists, engineers, and facilities. Through such an interconnected network, the nation could at once increase its current inadequate energy R&D effort and complement existing resources with a new research paradigm capable of delivering the radical breakthroughs needed to respond adequately to the nation's energy supply, security, and sustainability challenges.

Along these lines, the nation should seek to build a network of several dozen new energy institutes distributed competitively among the nation's research universities and federal laboratories.

Three sorts of institute would anchor the national network:

- *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 a regional or national basis. 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 set 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 capabilities 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 capabilities and opportunities. There might also be the possibility of e-DIIs jointly 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 smaller energy research centers comparable in scale to DOE's Energy Frontier Research Centers or the NSF's Engineering Research Centers, thereby enabling faculty in less centrally located regions or at institutions with limited capacity to manage large e-DII hubs to contribute to the nation's energy R&D as an element of the e-DII network

In terms of its establishment, an interagency process should create the network and competitively award core federal support of up to $200 million per year for each major e-DII operated by university or national laboratory consortia, along with funding for smaller e-DIIs and distributed energy networks connected to the large e-DII "hubs." Federal funding would be augmented with participation by industry, investors, universities, and state governments, for a total federal commitment growing to roughly $6 billion per year (or 25 percent of a recommended total federal energy R&D goal of $20 to $30 billion per year).

In keeping with the DII vision, the national network of e-DIIs should have the following characteristics:

1. The e-DII network should be large enough and be funded at a sufficient level to cultivate the new energy research paradigm

To achieve a critical mass of activities, implementation of the e-DIIs concept should entail the establishment of 20 to 30 e-DIIs. Federal funding for the e-DIIs should vary depending on the scale of planned activities and other resources that could be tapped. Smaller satellite e-DIIs might be funded at $10 million per year. Larger full-scale e-DIIs might be funded at $50–100 million per year. In a few cases, budgets for large, interdisciplinary e-DIIs overseen by university consortia, federal laboratories, or joint university-laboratory-industrial partners may grow, as we have seen, to as much as $200 million per year of core federal funding.

The proposed federal investment in e-DIIs should ideally grow to $5 to $6 billion per year. Although this would represent only about 20 percent of the proposed $20 to $30 billion per year increase in federal energy R&D—most of which would flow to the federal laboratories and industry—it would still represent a doubling of the total amount currently spent on energy R&D by the federal government and large industrial firms. Full funding of the e-DII network would be expected to yield considerable impact, much as NSF's $5 billion annual investment supports the intellectual engine of the nation's scientific, technological, and technical workforce capabilities (outside of the health care and energy fields, which are separately supported by the National Institutes of Health (NIH) and DOE).

While federal funding would provide the core support necessary to sustain the E-DIIs, strong participation from other partners would be expected. For example, states could participate in particular e-DIIs by contributing the necessary land and capital facilities. Industrial partners and investors could contribute financing, equipment, and personnel through joint R&D efforts. Universities could contribute an array of in-kind investments such as personnel, office space, and research infrastructure. They would also be expected to provide the necessary policy environment in areas such as personnel (e.g., relaxing the usual faculty constraints such as tenure requirements) and IP. While such participation by e-DII partners would be expected to become quite significant, they will likely remain modest until the e-DII program builds momentum and capability.

One additional note: The e-DII network is envisioned as one part of a larger commitment to federal energy research, growing to $20–30 billion per year. Most of this new commitment should be directed through existing DOE and industrial laboratories, which have substantial research expertise and infrastructure that could be devoted to new projects. Making a successful commitment to clean energy, however, extends beyond simply pumping more federal dollars into the current energy research enterprise. In this respect, it should be noted that in addition to the specific university- and lab-led components of the e-DII push, additional e-DII-type efforts among the labs could be launched employing some of the large funding increases proposed for the labs' own growth. E-DIIs, in this sense, offer both the lab sector and the university community a transformative new paradigm that should be widely exploited in pursuit of national energy goals.

2. The e-DII network should be an interagency effort

Any new federal energy R&D effort would ideally be established, managed, and funded through an interagency effort rather than as a single federal department's initiative, similar to other federal initiatives such as nanotechnology, high performance computing, and global climate change. Federal agencies that might be involved include Energy, Defense, Commerce, Transportation, Agriculture, the Environmental Protection Agency, NSF, and NIH. If the network was placed within DOE, additional reforms would be needed to free this initiative from some of the constraints that characterize other DOE initiatives. (Some details are provided in the following section.)

3. The e-DII network should complement efforts at the national laboratories, but be organizationally separate

The e-DII network should complement efforts at DOE's national laboratories but be organizationally separate, due to the constraints facing the current lab structure outlined earlier. In this respect, even lab-run e-DIIs should be organizationally distinct. The national laboratories have the unique capacity for large-scale, infrastructure-intensive projects that require substantial technical and management talent. The labs have successfully deployed such capacity towards development of defense systems, for instance. The e-DIIs should not duplicate this expertise and infrastructure, but instead utilize a different research and translation paradigm to collaborate with industry, companies, investors, and governments to speed the movement of breakthroughs into widespread implementation. In this manner, creation of the e-DIIs would provide a clearer mission to the established national lab system, which has been lacking one since the end of the Cold War, even as it committed the nation to a new innovation strategy.

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In terms of its establishment and build-out, the new network would be developed through a competitive award process with gradual phase-in:

- *Award Process:* A competitive award process should be adopted to designate e-DIIs for federal support and inclusion in the network. Proposals should be evaluated by an interagency panel and subjected to the most rigorous peer review. A framework of energy research strategies and priorities should be developed to guide the decision process, perhaps with the assistance of independent advisors such as the National Academies or a new structure such as the proposed National Energy Institute or the advisory board of a possible New Energy Research Initiative program. Because of its long experience and credibility in conducting merit-based competitions for large research centers (such as the Engineering Research Centers and Science and Technology Centers, the NSF should be considered the lead federal agency in managing the e-DII award process. Successful proposals would then receive core funding by individual federal agencies or through interagency agreements to support and anchor the main programs of the e-DII and to provide for infrastructure. To achieve a balanced utilization of all elements of the nation's research triad of federal laboratories, corporate R&D centers, and research universities, the e-DII competitive award process for university-based e-DIIs and federal-laboratory-based e-DIIs should be kept separate and within specified total funding envelopes. For example, consideration of both the relative number of world-class research universities and national laboratories, as well as the fact that the national laboratories would also benefit from very substantial growth of the total federal energy R&D investment (e.g., to $20 to $30 billion per year) suggests that an appropriate target might be $4 billion per year for the university e-DIIs program and $2 billion per year for the federal-laboratory e-DII program (including in both numbers the funding for possible joint e-DII federal laboratory-university partnerships).

- *Award Criteria:* Although the primary award criteria for e-DII awards should be scientific merit and capability, other criteria should be considered such as commitments by participating partners (e.g., industry, investors, and state or local governments); the strength of the management plan; strategies for commercialization (e.g., approaches to technology transfer and IP issues); integration of the e-DII into the regional economy; and plans for connection into the projected hub-and-spoke network that will link up both to the national energy research network and campus- or industry-based scientists. Furthermore, consideration should be given to the ability of the proposed e-DII to leverage investments from other actors in the energy research enterprise, ensuring a larger overall commitment to addressing the nation's energy challenges.

- *Phase in:* The e-DII network should be phased in over time, so it can benefit from ongoing evaluation and assessment. Each e-DII should be subject to rigorous evaluation at regular intervals, together with ongoing assessment of the network's effectiveness in terms of research results, funding matches, commercial spinoffs, and human resource production. In this fashion, five e-DIIs a year could be launched over a five- to 10-year period to create the full network, with the early e-DIIs being viewed as prototypes to refine policy and operational issues (e.g., management, IP, and coordination). While long-term energy research would require sustained funding of the network, it would also be possible to place a sunset of 12 to 15 years on each e-DII so that re-competition for federal support could occur. And indeed, a highly competitive, results-focused accountability system should discipline the operation of the network. In order to promote consistent excellence and high-risk, high-reward research, a component of each e-DII budget (perhaps 10 percent) could be regularly reallocated to promising new ideas and directions at the expense of those that are not showing progress. In this way, the e-DII system would be continually pushing to the forefront on new ideas, weeding out stale projects, and yet allowing good ideas to make progress and continue to move forward. The National Academy of Sciences recommended this approach (at an 8 percent reallocation level) and DOE's Basic Energy Sciences division has since practiced it, with promising results..[160]

As to their operation, the institutes would benefit from a tiered organizational structure and strong network characteristics:

- *Tiered organization:* The e-DIIs would utilize a tiered organization and management structure. Since the proposed network represents a departure from existing research paradigms, it requires an independent institutional and management structure committed to overseeing basic research through rapid deployment of new technologies. Each e-DII should have a strong external advisory board representing the participating partners, including government (federal and state), industry, interested nonprofits, entrepreneurs, and investors. In some cases, partners might play direct management roles with executive authority. The precise organizational and management structure for e-DIIs is not prescribed here, as it should be a component of the evaluation process to award the e-DII funding. This way the proposal process encourages competition, "bottom up" creativity, and innovation and ensures that the e-DIIs have maximum flexibility to achieve meaningful advances in energy research and technology development.

- *Linked external relationships:* The e-DII network should function in a coordinated, integrated manner. To this end, the e-DII network should be undergirded by powerful information and communications technology and overlaid by a network of virtual organizations involving scientists, engineers, industrial management, and federal participants. This way the network would provide a powerful test-bed for the new types of research organizations enabled by rapidly evolving cyberinfrastructure, such as collaboratories and immersive virtual environments, which reduce unnecessary duplication of costly research facilities and cumbersome management bureaucracy. Such coordination would allow separate e-DIIs, focused on different themes, to remain connected and coordinated in pursuit of larger national goals.

XI. ORGANIZING AND FUNDING OPTIONS FOR THE e-DII NETWORK

It will be challenging to develop an organizational and management strategy and generate the necessary funding capable of ramping up a national network of energy discovery-innovation institutes over a short period of time. However, numerous similar initiatives have been launched, as we have seen, so the questions and challenges of implementation can be tackled confidently with the benefit of past experience.

A few comments bear consideration:.

1. The e-DII network could be placed within the Executive Office of the President or within a lead agency

The e-DII network should be organized and funded as an interagency effort. One might consider a strong interagency committee of the Executive Office of the President's Office of

Science and Technology Policy (OSTP) overseeing the program, similar to those for nanotechnology and climate change. In this case, the program management would consist of a project director and representatives from OSTP and the Office of Management and Budget (OMB), with a reporting line to the National Science and Technology Council.

Locating this initiative entirely within DOE could be problematic, due to the limitations of federal energy activities raised earlier in this report. To achieve a balance among intramural and extramural participants (e.g., DOE labs, industry, higher education, and the states), the role of managing the e-DII network would need to be a major assignment for either a senior DOE administrator (e.g., the Under Secretary for Science or Deputy Secretary) or a new senior position such as Level II presidential appointment. The strong role of the e-DIIs in R&D and work with industry to commercialize technology suggests that this position should not be the Under Secretary for Science.

It is also important that this initiative cut across existing DOE programs (e.g., fossil fuels, nuclear, renewables, science, as well as the national laboratories) and have monies appropriated to it that are for pass-through or coordination with other agencies so that a true interagency character can be developed. An alternative arrangement would be to appropriate funds directly to other federal agencies (e.g., Defense, Commerce, Interior, Agriculture) and enable them to also fund the e-DIIs, although this would create the additional complexity of coordinating among multiple appropriations subcommittees—a near impossible task.

2. The e-DII network could be established by Congress

The national e-DII network could be established by a general authorization bill similar to the Hatch Act of 1887 that creates the network as one component of the nation's energy research activities. The bill would designate the administrative home of the network and would include 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 network). Following authorization, specific appropriations requests could then be submitted, as appropriate, to the respective appropriations subcommittees in both chambers of Congress for funding the e-DIIs.

Two Senate bills have already included authorizing language for a handful of national laboratory-based DIIs, including the Protecting America's Competitive Edge through Energy Act of 2006 (S.2197) and the America COMPETES Act of 2007 (S.771). S.2197 proposed funding multiple lab-based DIIs at $50 million per year for FY 2007 through FY 2013. The CBO estimated S.2197 would cost $243 million from 2007–2011.[161] The final version of America COMPETES signed into law (P.L. 110-69) included language for no more than three DIIs each authorized to receive $10 million per year for FY 2008 through FY 2010. No funding has yet been appropriated for the DIIs. The lab-based DIIs in America COMPETES were also limited to developing partnerships with universities and industry, whereas the initial language in S.71 and S.2197 would have allowed partnerships with other actors. A larger and more comprehensive national network of DIIs is necessary than what was authorized in America COMPETES.[162]

The authorizing legislation might also be linked to ongoing efforts, such as the carbon cap-and-trade proposals that are likely to be debated in the current Congress or to other major R&D legislation, such as appropriations for America COMPETES.

3. The e-DII network could be funded using existing revenues, new revenues, or deficit financing

When fully implemented, the proposed e-DII network would receive $5 billion to $6 billion per year to integrate basic science and technology development activities not otherwise undertaken by the nation's energy research enterprise. This would be one component of a larger energy research effort of—ideally—about $20–30 billion per year. While such investments may seem ambitious during difficult economic times and constrained budgets, chronic underfunding of energy research has left the nation underprepared to deal with the scale, urgency, and complexity of the nation's energy supply, security, and sustainability challenges. Difficult choices will need to be made and energy research deserves priority funding in light of these challenges.

Several options exist for funding the core federal support of the national energy research network:

- Funding could be diverted from existing federal subsidies for energy-related activities such as subsidies of energy inefficient technologies (e.g., corn-based ethanol) or unnecessary tax incentives for highly profitable energy industries (depletion allowances for oil and gas production[163]

- Funding could be dedicated from a carbon tax or the auction of carbon cap-and-trade allowances. Revenues from carbon allowances are estimated to yield $100 billion per year once implemented, growing to as much as $500 billion per year over the next several decades[164]

- The e-DII network could be funded out of general revenue, and deficit-financed if necessary. Deficit financing is appropriate given the long-term social benefits of such an investment to the nation's economic competitiveness, national security, and environmental sustainability.

XII. CONCLUSION

The sheer scale of the world's energy challenge combined with the urgent need to commercialize of new and powerful low-carbon technologies in the next 10 to 20 years makes it imperative that nations everywhere—and the U.S. in particular—move aggressively to "change the game."

Today our national energy system—based primarily upon the unsustainable use of fossil fuels and heavy dependence on foreign energy imports—must be remade, and it is increasingly clear that we must not only do much more to accelerate the invention and diffusion of low-carbon technologies, but do it differently.

Current national investments, policies, and programs, however, are inadequate to address these challenges. Too little is being done, and too little of what is being done is employing the newest distributed, "hub-and-spoke" innovation strategies.

Therefore, the nation should embark on a new push to greatly improve both the scale and the format of its efforts to accelerate the invention and commercialization of breakthrough low carbon technologies, practices, and process.

Along these lines, this report urges two major changes in U.S. energy policy. First, it calls for an order-of-magnitude increase in federal investment levels for energy R&D, as a necessary step to matching the enormous scale of the nation's energy problem with massive efforts to develop market-ready technological solutions. Second, it argues that the complexity of the nation's energy challenges require that the nation make use of decentralized, multi-disciplinary, collaboration-oriented 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.

More specifically, the report proposes augmenting expanded energy R&D programs across the nation's range of national laboratories and industrial research centers with a new research paradigm proposed by the National Academy of Engineering: a national network of energy discovery-innovation institutes (e-DIIs). Decentralized, multidisciplinary, and applications oriented, the proposed e-DII network would link together a new regionally grounded, "bottom up" drive to accelerate the commercialization of breakthrough technological advances in many domains. When completed, the new network would consist of 20 to 30 e-DIIs, with interagency federal funding building to a total level of $5 to $6 billion a year.

In all of this, the nation's past responses to earlier crises offers antecedents and grounds of optimism about what can be achieved. In earlier times, the federal government responded to the changing needs of the nation with massive investments in the nation's research capacity during periods of great challenge or opportunity.[165] 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 critical to national security during the Cold War and drove much of America's economic growth during the latter half of the 20th century. And the Apollo Program fulfilled humankind's dream to conquer space by sending men to the moon. These earlier successful efforts demonstrate the nation's recurrent willingness to invest at a scale needed to address pressing national challenges, although the Manhattan and Apollo models are not entirely appropriate to meet today's complex, urgent, and multidisciplinary energy challenges.[166]

Most analogous to what is needed today, in this respect, is 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 e-DIIs 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 governments working together across a broad spectrum of scientific, engineering, economic, behavioral, and policy disciplines to build a sustainable national energy infrastructure for the 21^{st} century, while also stimulating strong regional economic growth.

It is time once again for the federal government to make a major commitment to investing adequately in the R&D necessary to develop breakthrough technologies that will secure prosperity and security for future generations while protecting global environmental sustainability. The proposed e-DII network would represent a critical element of this effort.

NOTES

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[1] See National Academy of Engineering, *Engineering Research and America's Future: Meeting the Challenges of a Global Economy* (Washington: National Academies, 2005)

[2] “E-DIIs” represent an energy-oriented adaptation of the discovery-innovation institute concept developed by the National Academy of Engineering to stimulate applications-oriented R&D across the range of the physical sciences. See National Academy of Engineering, *Engineering Research and America's Future.*

[3] Energy Information Administration, "Annual Energy Review 2007" (Washington, 2008).

[4] Energy Information Administration, "International Energy Outlook 2008" (Washington, 2008).

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[6] Nathan S. Lewis, "Powering the Planet," *Caltech Engineering & Science* 2 (2007): 13.

[7] Energy Information Administration, "Petroleum Basic Statistics," available at www.eia.doe.gov/basics/quickoil.html (October 14 2008).

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[9] Oil dependence here was measured as net imports (total imports minus total exports) divided by total products supplied. Energy Information Administration, "Petroleum Basic Statistics." The United States also imports 16 percent of the natural gas consumed each year, resulting in similar economic and security vulnerabilities as with oil. Energy Information Administration, "Natural Gas Basic Statistics," available at www.eia.doe.gov/basics/quickgas.html (October 13 2008).

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[11] Robert E. Scott, "U.S. Trade Balance Improves for First Time since 2001," Economic Policy Institute, available at www.epi.org/content.cfm/indicators_intlpict_20080215 (October 13 2008).

[12] See Table 3.3a, Energy Information Administration, "Monthly Energy Review (September 2008)" (Washington, 2008).

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[16] Daniel Yergin, "Ensuring Energy Security," *Foreign Affairs* 85 (2) (2006): 69–82; Furman and others, "An Economic Strategy to Address Climate Change and Promote Energy Security."

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[18] International Energy Agency, "Energy Technology Perspectives 2008: Scenarios and Strategies to 2050" (Paris: Organization for Economic Cooperation and Development, 2008).

[19] Intergovernmental Panel on Climate Change, "Climate Change 2007."

[20] International Energy Agency, "Energy Technology Perspectives 2008." See also Richard G. Newell, "A U.S. Innovation Strategy for Climate Change Mitigation" (Washington: Brookings Institution, 2008).

[21] Newell, "A U.S. Innovation Strategy for Climate Change Mitigation."

[22] U.S. Energy Information Administration, "*Annual Energy Outlook 2008* (Washington: U.S. Department of Energy, 2008) in Newell, "A U.S. Innovation Strategy for Climate Change Mitigation."

[23] Ibid.

[24] Ibid.

[25] Ted Nordhaus and Michael Shellenberger, "Scrap Kyoto," *Democracy Journal* 9 (Summer) (2008): 8–19. See also Shellenberger and others, "Fast. Clean, and Cheap: Cutting Global Warming's Gordian Knot," *Harvard Law and Policy Review* 2: 93–118.

[26] International Energy Agency, "Energy Technology Perspectives 2008."

[27] Paul J. Runci and James J. Dooley, "Research and Development Trends for Energy." In Cutler J. Cleveland, ed. *Encyclopedia of Energy* (Oxford, UK: Elsevier, 2004).

[28] Diana Farrell and others, "The Case for Investing in Energy Productivity" (San Francisco: McKinsey&Company, 2008).

[29] Ibid.

[30] International Energy Agency, "Energy Technology Perspectives 2008." See also Lawrence Goulder, "Induced Technological Change and Climate Policy" (Washington: Pew Center on Global Climate Change, 2004); Lewis Milford, "From Here to Stabilization: A Call for Massive Climate Technology Innovation" (Montpelier: Clean Energy Group, 2006) and Nicholas Stern, "The Stern Review: The Economics of Climate Change" (London: HM Treasury, 2006).

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