Cambridge University Press
978-1-107-04371-8 - Transforming U.S. Energy Innovation
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The Need to Transform U.S. Energy Innovation

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1.1. The Need for an Energy Technology Revolution

How will countries provide the reliable, affordable energy needed to fuel a growing world economy and lift billions of people out of poverty without causing catastrophic climate change and other environmental disasters? Answering this question is perhaps the greatest challenge human civilization faces in the 21st century. It cannot be done without a revolution in the technologies of both energy production and use. And for that revolution to arrive in time will require a dramatic acceleration in the pace at which new or improved energy technologies are invented, demonstrated, and adopted in the marketplace.

This book outlines policies the U.S. federal government in particular can adopt to foster such an energy technology revolution. These approaches will help meet the myriad energy challenges of the 21st century – and help ensure that the United States plays a leading role in doing so, capturing its share of the multi-trillion-dollar energy technology markets of the coming decades.

This book seeks to answer four basic questions. First, how much should the U.S. government spend on energy research, development, and demonstration (RD&D), and how should that money be allocated? Second, how can the U.S. government best work with the private sector and encourage it to invest its own funds in researching, developing, demonstrating, and deploying new energy technologies? Third, how can the U.S. government manage its energy RD&D investments and the institutions through which they flow to get the most beneficial energy innovation per dollar invested? Fourth, how can the U.S. government best manage competition and cooperation with other countries in energy technology innovation?

There are no simple answers to any of these questions. But for each of them, we offer new data on the current situation and new analyses that help elucidate the best paths forward. Adopting new approaches in these four areas could transform the picture. With an expanded and effectively targeted federal investment in energy RD&D; effective policies to encourage private sector innovation and deployment; strengthened approaches to managing energy innovation institutions; and strong international cooperation, the United States could radically step up the pace at which it invents and deploys improved energy technologies.

This book draws on a 2011 report, *Transforming U.S. Energy Innovation* (Anadon et al., 2011). In the brief time since then, the U.S. and global energy picture has continued to change, with events ranging from continued expansion of shale gas and oil to conflict with China over trade in solar panels to deep difficulties in Japan over providing energy in the aftermath of the Fukushima nuclear accident. In this book, we have updated our arguments to reflect these events, and added new data, analyses, and case studies. Ours is by no means the first study to call for steps to accelerate U.S. energy technology innovation, including expanded federal investments in energy RD&D (see, e.g., NAS, 2009; Weiss & Bonvillian, 2009; American Energy Innovation Council, 2010, 2011; American Enterprise Institute, Brookings Institution, and Breakthrough Institute, 2010; PCAST, 2010; DOE, 2011b; Henderson & Newell, 2011; Lester & Hart, 2011; Gruebler et al., 2012). But our study provides new insights, through:

- Written surveys of more than 100 experts to explore expert views on how much government investments in RD&D could improve cost and performance of some 25 technologies in seven areas of energy technology[1]
- Extensive economic modeling to explore how such improvements in cost and performance might affect outcomes such as the cost of the U.S. energy system, U.S. carbon emissions, or U.S. oil import dependence
- A broad survey of private-sector energy innovation in the United States, outlining what firms are involved and some of the key drivers of their energy innovation decisions
- An in-depth analysis of DOE's funding for energy RD&D in the private sector
- Detailed case studies of key innovation institutions, to glean lessons on how to increase the effectiveness of DOE's national laboratories and other energy innovation institutions in developing new energy technologies and getting them adopted in the market
- New data on emerging economies' investments in energy technology innovation, and on how international cooperation in energy RD&D is evolving

We integrate these elements in a systems-level approach to energy technology innovation, offering specific recommendations for action to accelerate such innovation in the United States.

[1] Bionergy (12 experts, 5 reviewers), utility scale storage (25 experts, 7 reviewers), fossil energy (12 experts, 3 reviewers), nuclear (30 experts, 2 reviewers), vehicles (9 experts, 1 reviewer), and photovoltaic power (11 experts, 1 reviewer).

Some of the needed steps are already being taken. The Obama administration, the Bush administration before it, and the U.S. Congress have all recognized the pressing need for major improvements in energy technologies, though they have taken different and sometimes conflicting approaches to the problem. As we describe in Chapter 2, billions of dollars in federal investments in energy innovation were a major element of the stimulus bill signed into law in 2009. The new Advanced Research Projects Agency – Energy (ARPA-E) – intended to offer a new focus on high-risk, high-payoff ideas – was authorized in 2007 and funded in 2009. New energy innovation "hubs" have been established to push progress in particular technology areas, from computer simulation of nuclear reactors to making liquid fuels from solar energy, and "Energy Frontier Research Centers" have been created to focus on particular challenges at earlier stages of the innovation chain (DOE, 2013a, 2013b). Loan guarantee programs (established during the Bush administration but invigorated by the Obama administration) have supported construction of new nuclear reactors and new firms in areas such as battery technology and solar power (to some considerable controversy, particularly after the collapse of the solar firm Solyndra). New efficiency standards and incentives, tax credits, and portfolio standards have helped drive deployment of efficiency measures and low-carbon energy technologies, encouraging further private investment in innovation in these areas. Secretary of Energy Steve Chu and his successor Ernie Moniz (chair of the 2010 President's Council of Advisors on Science and Technology [PCAST] study) have both focused intensely on accelerating energy technology innovation. Figure 1.1 shows the main government programs and institutions – old and new – with a primary mandate to spur energy innovation. Whether and how all of these initiatives will gain support and work together remains uncertain.

But deep divisions over political, economic, and technical strategies have prevented the U.S. government from adopting and implementing either a coherent long-term energy strategy in general or an integrated energy innovation strategy in particular (PCAST, 2010; Deutch, 2011). With the current focus on budget cutting in the United States, bipartisan support for energy R&D spending has broken down, with committees in the U.S. Congress proposing substantial reductions in funding. Philosophically, many in the U.S. Congress believe that the government should fund early stage research and then get out of the way and let private markets do the rest – and many are not convinced that human-caused climate change is occurring or is a serious problem (e.g., Inhofe, 2012). These disagreements have led to substantial political fights over issues ranging from loan guarantees to carbon constraints to efficiency standards.

It is important to understand that the incumbent fossil fuel technologies are deeply entrenched, with trillions of dollars in investment already made, decades of cost-reducing innovation already accomplished, a wide range of institutions and infrastructure put in place to support them (both public and private), and ownership

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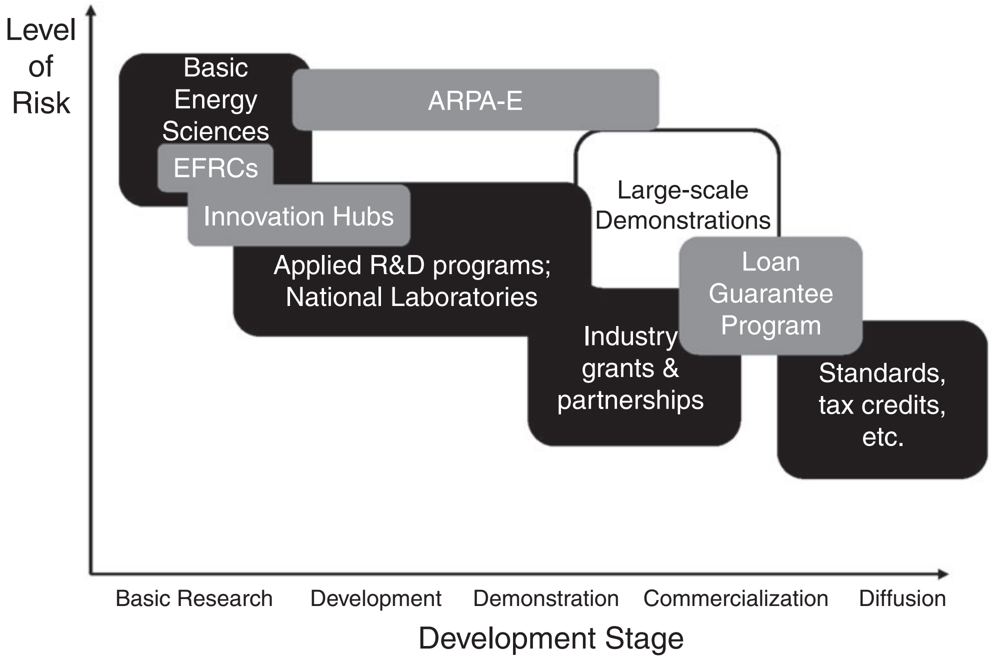

Figure 1.1. Schematic of U.S. government institutions and policies with a primary mandate to accelerate energy innovation. Black boxes denote programs that existed before 2005. The other institutions (with the exception of the "large scale demonstrations," which is an area we have identified as a gap) are more recent: the EFRCs, the Hubs, and ARPA-E were funded in 2009, and the loan guarantee program was instituted in 2005, although the first loan guarantee was issued in 2009. (Adapted from various presentations from the U.S. Department of Energy.)

by some of the world's largest and most powerful firms (Unruh, 2000). Other technologies will not find it easy to compete – and the growth and expansion of other energy technologies is likely to be accompanied by jarring economic shifts and political disagreements. Technology innovation inevitably involves creative destruction, with both winners and losers – and the potential losers are often highly effective in blocking innovations that threaten them (Acemoglu & Robinson, 2012).

In short, although the United States has strengthened its energy technology innovation efforts in recent years, a great deal remains to be done. Filling the remaining gap is likely to require rebuilding bipartisan consensus on the need for action and the roles the federal government should play (though there is a great deal other actors can do in the meantime). We do not have any answers on how this bipartisan consensus can be rebuilt. But we hope that the analysis and evidence presented in this book can help make the case for action and lay out steps the U.S. government could take to accelerate the pace of progress in energy innovation and ensure that these efforts provide the maximum return on the investments made.

1.2. Interlinked Challenges

Today, the United States is enjoying an energy bonanza. Advances in the technologies of hydraulic fracturing ("fracking") and horizontal drilling have enabled huge new production of natural gas and oil, leading to natural gas prices only a fraction of those in Asia or even Europe, and predictions that U.S. oil production may surpass Saudi Arabia's within a decade (IEA, 2012). At the same time, as a result of fuel switching from coal to natural gas and (to a lesser extent) improved efficiency and expanded use of renewables, U.S. carbon emissions are declining (IEA, 2012). Many Americans, if told there was an energy crisis, would respond: "Crisis? What crisis?"

Unfortunately, these developments have, in effect, only lengthened the fuse on the deep and difficult challenges energy will still pose for the United States and globally in the decades to come. In some respects, this progress on fossil fuels has made a more fundamental transformation of energy production and use more difficult: cheap natural gas is making all other energy technologies, from nuclear to renewable to efficiency, less economically attractive than they were before. Yet a more fundamental transformation of energy production and use is still urgently needed, for multiple reasons. The energy problem is simultaneously a security, an economic, a poverty, and an environmental challenge.

1.2.1. A Security Challenge

A wide range of current and former senior national security officials have made it clear that both the U.S. and global addictions to fossil fuels pose severe security challenges (CNA, 2009; Daniel, 2010). Although the increases in U.S. and Canadian production are reducing U.S. reliance on imported oil, prices in global oil markets are tightly linked (as a substantial infrastructure is in place to transport oil from one market to another). Even if the United States did not use a drop of Middle Eastern oil, the U.S. economy would remain vulnerable to sudden price increases in the event of a major disruption in oil supply in the Middle East or elsewhere.

Despite the growth in North American production, it is still the case that much of the world's reserves of oil recoverable at reasonable prices are concentrated in some of the most politically volatile regions of the world. Indeed, the International Energy Agency (IEA) projects that world reliance on the Organization of Petroleum Exporting Countries (OPEC) will increase again through the 2030s (IEA, 2012, pp. 81–124). While the mutual dependence of suppliers and consumers makes it difficult to wield the "oil weapon," chaos in oil-producing countries can scare markets and reduce production, sending prices soaring. High energy prices fill the coffers of some of the world's most hostile governments.

Moreover, military forces around the world are deeply dependent on fossil fuels that compromise operations and raise security concerns – as the casualties from fuel supply trucks in Iraq and the terrorist attacks on fuel shipments in Pakistan to provide fuel to NATO troops in Afghanistan make clear (Defense Science Board, 2008; Simeone, 2009; BBC, 2010).

With most population growth taking place in those regions with limited energy access or low energy use, an energy market that continued to be vulnerable to sharp shifts in oil prices could also lead to civil unrest in some locations and could threaten national and international security. More importantly, it is becoming increasingly clear that the natural disasters, refugee flows, and intensification of poverty that will result in some regions if climate change is not addressed will pose risks to international peace and security (CNA, 2007).

In addition, a global expansion of nuclear power without improvements in technology and strengthened institutional controls could increase the danger of nuclear proliferation and terrorism (as well as the risks of nuclear accidents).

1.2.2. An Economic Challenge

Until recently, the United States sent $700 million dollars a day overseas just to purchase petroleum, an amount representing roughly half the U.S. trade deficit (U.S. Census Bureau, 2010). Volatile oil and gas prices can disrupt investment planning, drive businesses into bankruptcy, and push families into sudden poverty.

At the same time, without an accelerated approach to energy technology innovation, the United States is in danger of losing out on the huge energy technology markets of the coming decades. The IEA projects $37 trillion in global investment in energy supply – not counting technologies of energy end-use – by 2035 (IEA, 2012, p. 49); these markets will drive huge numbers of jobs and large transfers of wealth. Where once the United States was the undisputed world leader in new energy technologies, other countries are now making large investments and rapid progress: China is now the world's largest producer of both solar cells and wind turbines; China and South Korea are able to build nuclear power plants at substantially lower costs than U.S. or European firms are able to do; and China, Europe, Japan, and South Korea, among others, are investing heavily in developing new energy technologies, as described in Chapter 5.

1.2.3. A Poverty Challenge

Today, an estimated 1.3 billion people have no access to electricity. Some 2.6 billion have no access to clean cooking facilities. Providing affordable, reliable, and clean energy for the world's poor is a moral and practical imperative. Lack of energy supplies perpetuates poverty and exacerbates the suffering poverty entails. In particular, the indoor smoke from fires in huts in the developing world is a far larger source of death and disease than all the outdoor pollution in the world's most polluted cities combined (Lim et al., 2012; Rehfuess, Corvalan, & Neira, 2006). Both improved energy technologies and improved institutional approaches to energy supply and use are needed to provide energy for the world's poorest.

1.2.4. An Environmental Challenge

Finally, in a world that remains dependent on fossil fuels for more than 80% of its energy supply, the most profound energy challenge of all is finding ways to provide the energy the world needs without causing catastrophic climate change or imposing other immense environmental burdens. From oil spills in the ocean to air pollution choking many cities around the world to global climate disruption, production and use of energy causes many of the worst environmental problems the world faces, at local, regional, and global scales.

The climate challenge is particularly pressing. The evidence is increasingly clear: the climate is warming, glaciers are melting, the seas are rising, and it appears that extreme weather events – floods, droughts, and heat waves among them – are becoming more frequent and more damaging in some regions (IPCC, 2012). Ecosystems that provide crucial services are changing, and pests and diseases are spreading to new areas as the climate warms. Climate change is already reducing crop yields in some regions, and projections suggest the combination of precipitation changes and heat stress could greatly increase the danger of widespread hunger and malnutrition (World Bank, 2012, 2013; Wheeler & von Braun, 2013; and Easterling et al., 2007). The impacts of climate change are expected to disproportionately affect the world's poor, who are least prepared to cope with them.

Global emissions of greenhouse gases set records in 2011 and 2012 and are projected to continue to grow steadily as energy use continues to expand and continues to rely primarily on fossil fuels (IEA, 2013). With a growing world population and growing economies, the IEA projects that global primary energy consumption may increase to 1.5 to 3 times the current demand by 2050 (IEA, 2010a). Despite projected growth in renewable energy supplies, the IEA projects that unless policies change, use of natural gas and coal will grow more than use of any other energy sources by 2035 (IEA, 2012, p. 51). In that case, CO_2 emissions from the energy sector would increase from the record 31.6 billion metric tons in 2012 to more than 37 billion metric tons by 2035, putting the world on a course more likely to lead to warming of 4°C or more in this century than to meet the goal of holding the temperature increase to 2°C above pre-industrial temperatures. As the president of the World Bank summarized the issue in 2012, such high levels of warming "are devastating: the inundation of coastal cities; increasing risks for food production potentially leading to higher malnutrition rates; many dry regions becoming dryer, wet regions wetter; unprecedented heat waves in many regions, especially in the tropics; substantially exacerbated water scarcity in many regions; increased frequency of high-intensity tropical cyclones; and irreversible loss of biodiversity, including coral reef systems" (World Bank, 2012, p. ix). Moreover, at such levels, the probability of abrupt, severe climate disasters greatly increases. The Bank report warned that these levels of warming "must be avoided." Yet they cannot be avoided without a radical transformation of world energy supply – and that transformation is likely to require dramatic improvements in the cost and performance of low-carbon energy technologies.

The hour is already late: the IEA reports that the last opportunity to meet a 2°C target is slipping away, given the greenhouse gases the energy infrastructure already built will emit during its lifetime (IEA, 2013). The costs of meeting that target or any other will increase the longer the world delays taking substantial climate action, as more expensive high-carbon energy infrastructure gets built every year. Moreover, the greenhouse gases already in the atmosphere will cause continued warming for decades to come, even if further emissions stopped tomorrow. Nevertheless, action that begins soon and continues to ramp up throughout the 21st century can still reduce the risks of the most catastrophic projected effects of climate change.

The other environmental impacts of the current energy technologies are also very serious. China's government has officially estimated that environmental damage – most of it from energy use – cost China $230 billion in 2010, 3.5% of its total gross domestic product (GDP; Wong, 2013). Other countries' economies are also suffering substantial damage. The latest estimates suggest that fine particulates in the air kill some 3.1 million people every year, accounting for some 3.1% of global disability-adjusted life years (DALYs) lost annually (Lim et al., 2012). Indoor smoke from cooking fires in the developing world causes even more disease and death (because the concentrations to which people are exposed are so high), estimated to be in the range of 3.5 million deaths per year and 4.5% of global DALYs (Lim et al., 2012).

1.2.5. Meeting the Challenges

These huge, interlinked challenges must be met, for affordable and reliable energy supplies are the lifeblood of the economy of the United States and of the world. The world's ever-growing reliance on burning fossil fuels simply cannot be sustained – the economic, security, and environmental costs will all prove to be unacceptably high. Indeed, it may simply not be possible to meet growing projected demands for oil and gas at an acceptable cost. While there is debate over when "peak oil" will occur, and production now appears likely to grow for some time, there is little debate that, at some point in the decades to come, oil production will stop growing and eventually decline, even as energy demand continues to grow. Price spikes, supply disruptions, and political tensions over scarce supplies are likely to become increasingly common. The need to develop alternatives to fossil fuels that can be deployed at a massive scale is real and urgent.

As the IEA has put it: "Current global trends in energy supply and use are unsustainable – environmentally, economically, socially.... It is not an exaggeration to claim that the future of human prosperity depends on how successfully we tackle the . . . central energy challenges facing us. . . . What is needed is nothing short of an energy technology revolution" (IEA, 2009a). To meet the challenges, both major innovations in energy technology and new international policies and institutions will be needed. Broad international action and cooperation will be essential: no separate solution implemented within a single country, or even region, will suffice.

The scale of what must be done to meet these challenges is staggering, as the global energy system (the infrastructure of exploration facilities, transmission lines, pipelines, power plants, buildings, vehicles, etc.) is huge. As noted earlier, the IEA estimates that simply maintaining energy supply under already announced policies will require $37 trillion in energy supply investments by 2035 (approximately $1.6 trillion a year); trillions more would be needed to put the energy system on a sustainable track – though much of that additional investment would be recouped in lower fuel costs and reduced environmental damages.

This book includes estimates of the extent to which energy RD&D investments and the resulting improvements in technology can address the interlinked challenges of security, the economy, poverty, and the environment. We deal with the uncertainty in the future outcomes of incremental and radical innovation by representing the costs of meeting a particular demand (gallons of liquid fuel, electric power, and automobile) as a range of possible outcomes.

What is clear from all of the studies conducted over the past 20 years is that today's pace of energy innovation is simply not enough to meet this century's energy challenges. The world's energy infrastructure represents an investment of tens of trillions of dollars, much of it in systems that last for decades. It is like a supertanker that takes miles to change direction, no matter how energetically one turns the wheel. Even the most attractive energy technologies of the past, which offered dramatic new services – from oil to electricity – took decades of growth before they represented a substantial fraction of total energy use. Over the past 60 years, countries around the world have poured tens of billions of dollars into research and development and subsidies for nuclear energy – yet nuclear energy provides only about 6% of primary energy worldwide. Renewable sources, such as solar and wind, have been under development for decades, yet they provide an even smaller portion of the world's energy needs. A dramatic improvement in the pace of energy technology innovation and diffusion is essential. Inventing new energy technologies is not enough – these technologies must be widely deployed if they are to make a difference in meeting security, economic, and environmental energy challenges.

1.3. Expanded RD&D Is Essential – But Will Not Be Enough

Some recent reports have suggested that the world can research its way out of its energy predicament – that with enough R&D dollars, new technologies will be invented that will be so attractive that little further government action will be needed to help them sweep the old technologies aside in the energy marketplace (American Enterprise Institute, Brookings Institution, and Breakthrough Institute, 2010).[2] Our work makes clear that this view is deeply wrong, for two key reasons.

First, the challenges are so great that there will be a need to deploy *both* technologies that can compete on their own with entrenched, incumbent technologies without further government action and technologies that cannot yet overcome the market barriers to widespread deployment without some form of demand-side policies. At any given stage of technological development, there will be some technologies that can compete with fossil fuels already and others that would be competitive if externalities (such as the health effects of fine particulates or the global impacts of carbon) were internalized in the price, or that face other market barriers that require government support to overcome. The world is likely to need large-scale deployment of technologies in both categories to fuel a growing global economy while avoiding climate catastrophes. In the modeling described in Chapter 2, we found that even a dramatic expansion of federal funding for energy RD&D, and the most optimistic expert predictions of the results of that innovation investment, would simply not be enough to achieve the dramatic reductions in U.S. carbon emissions (or the dramatic reductions in U.S. oil use) likely to be needed by 2050 unless this expanded RD&D is coupled with demand-side policies that have the effect of putting a substantial price on carbon emissions. (Indeed, a broader suite of demand-side policies will ultimately be needed, given the different market barriers to deployment of low-carbon technologies that exist in different sectors.) In fact, entire classes of technology that are likely to be crucial to achieving deep reductions in emissions – such as capturing and sequestering carbon from the burning of fossil fuels – are unlikely to ever be economically competitive if the costs to society of dumping carbon into the atmosphere are not taken into account.

Second, in the absence of substantial prices on carbon and other externalities, innovation itself will be slowed, because the private sector will have little incentive to invest in developing low-carbon and low-pollution technologies. The survey of private sector energy innovation described in Chapter 4 makes it clear that expected prices and their effect on potential profits are the dominant factors affecting private sector energy innovation investment decisions. In July 2011, American Electric Power announced that it would abandon its plans to carry out a large-scale demonstration of technology to capture and sequester carbon from an existing coal plant because, in the absence of a carbon price, the concept was simply not economically viable (AEP, 2011; *The New York Times*, July 13, 2011). As this book makes clear, to accelerate the full cycle of

[2] In addition to large RD&D investments, this three-institution report calls for several other steps designed to provide limited support for initial deployments of new energy technologies, including initial military procurements and a reform of deployment subsidies designed to focus on driving down costs. The report holds open the possibility of only a very small carbon price, designed to fund RD&D rather than to give the private sector strong incentives to deploy low-carbon technologies.