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America's Energy Innovation Problem

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America's Energy Innovation Problem (and How to Fix It)

A REPORT FROM THE ENERGY INNOVATION PROJECT

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SUMMARY

The threat of global climate change will require the U.S. to shift rapidly away from its current patterns of energy supply and consumption, in which fossil fuels are dominant, towards low-carbon energy supplies and much more efficient energy use. This transition, which under 'normal' circumstances might have taken a century or more to run its course, must be well on its way to completion in thirty to forty years.

The role of innovation in the energy transition will be crucial. This is because most of the low-carbon energy technologies available today are either too costly or otherwise unable to compete in the marketplace against today's incumbent fossil fuel technologies. The government could simply mandate the use of these more-expensive alternatives, for example by promulgating 'portfolio standards' requiring their adoption in progressively larger amounts. But such policies will impose increasingly heavy costs on energy users and taxpayers, and ultimately America's ability to accelerate the energy transition will hinge on its success in bringing down the costs of low-carbon energy technologies as rapidly as possible. Achieving these cost reductions will require a continuing flow of innovations in many different fields of application over a period of decades. If this is left solely to market forces the pace of innovation will be too slow, because the main impetus for it comes from outside the marketplace. Government actions will be needed to accelerate the process.

The pricing of carbon emissions – whether through a cap-and-trade scheme or more directly as a carbon tax -- is the most efficient way to stimulate demand for low-carbon energy technologies. But as an innovation strategy carbon pricing will not be sufficient, in part because of the many other rigidities and distortions in energy markets, but also because politicians will be reluctant to allow the price to rise high enough to induce innovation at the necessary rate.

Innovation in energy technologies and business processes has the potential to reverse the politically unappealing economic logic of carbon pricing. Instead of relying on a strategy of high prices to induce energy innovation (as well as substitution and conservation) at the required rate, the alternative logic is to promote innovation so as to reduce the costs of low-carbon technologies -- and hence reduce the cost to society of the energy transition.

The federal government is currently preoccupied with the short-term problem of finding ways to spend quickly and responsibly the massive flows of economic stimulus funds that have been directed toward the energy sector. But attention must soon turn to the task

of building an energy innovation system capable of maintaining an accelerated pace of innovation over the long term. The purpose of this paper is to suggest some principles to help guide policy when that occurs. The focus is on the system of institutions within which energy innovation takes place, and the role of government in that system.

To build an effective national energy innovation system, three major obstacles must be overcome. *First*, a more realistic view of the scale of the problem is needed. The innovation challenge is far larger than most people think, and will require a more comprehensive strategy than anything that has gone before. *Second*, a national energy innovation strategy of the necessary size and scope will require a sustainable political coalition to support it. That coalition does not now exist. *Third*, the current organization and structure of government energy innovation institutions is inadequate to the task. While more public support for early-stage research is certainly needed, it will not be enough for existing institutions simply to do more of what they are already doing. New strategies and new institutions will be necessary.

The most challenging problem concerns the intermediate and later (or 'downstream') stages of the energy innovation process. Pressures to accelerate the process, coupled with frustrations over the previous performance of the Department of Energy in these downstream activities, have prompted calls to create new public and quasi-public institutions for technology development, demonstration, commercialization, and diffusion. The need here is for a strategy that strikes a balance between the urgent requirement to step up the pace of these downstream activities, the inability of the private sector to shoulder this burden on its own, and the fundamental limitations and weaknesses of government action in these areas. Specific institutional challenges include the federal government's ability to participate effectively in large-scale energy technology demonstration projects. The government will also need to participate in 'post-demonstration' innovation strategies that bridge the cost gap between newly-introduced low-carbon technologies and lower-cost incumbent energy systems, even while preserving strong incentives for private innovators to reduce the costs of the new technologies as quickly as possible.

No single public or hybrid public-private institution can meet all these requirements. Several attributes of an effective system of innovation institutions can be identified. These include institutional diversity; effective correction mechanisms, including meaningful competition for resources; and organizational specialization. Helpful organizational reforms would include an expanded energy innovation role for Federal agencies beyond the Department of Energy; and a better-defined and upgraded role for regions, states, and local jurisdictions in the national energy innovation system.

Because of the pervasiveness of the energy infrastructure, an innovation strategy designed to accelerate the development and adoption of low-carbon energy technologies implies a broad government presence in the economy. But government innovation policies are just one part of a complex system of market and non-market institutions within which innovative energy products and services are developed and commercialized. In our market economy the government cannot *force* the energy transition to occur; that outcome, if it does occur, will primarily be the result of private decisions and actions. In the end, the success of government intervention in the energy innovation system will hinge on whether it is seen as top-down social engineering, for which there will be very little support, or instead as an intelligent, effective way to augment markets in addressing a fundamental and growing threat to economic security and sustainability.

I. Why Energy Innovation Matters

> *"In no area will innovation be more important than in the development of new technologies to produce, use, and save energy – which is why my administration has made an unprecedented commitment to developing a 21st century clean energy economy."*
>
> President Barack Obama in a speech
> at the National Academy of Sciences, 27 April 2009

When President Obama attends the U.N. Climate Change Conference in Copenhagen next month, he will be acclaimed by other attendees simply for not being George W. Bush. But it will be the President's actions – most importantly his accomplishments on domestic climate change policy during his first year in office – that will be the real harbinger of the success or failure of Copenhagen and the conferences to follow. Without significant progress by the U.S. towards reducing its own carbon emissions, other major emitters like China and India will be less likely to agree to reduce theirs.

President Obama will not repeat the Clinton administration's mistake in Kyoto in 1997, when American negotiators paid scant attention to the domestic politics of committing to reduce carbon emissions and were rewarded with a unanimous rejection of the Kyoto Protocol by the United States Senate. The Obama administration and its allies in Congress have been spending much of this year trying to hammer out the political compromises needed to get domestic climate legislation through. But even though the weight of recent scientific evidence suggests the need for greater urgency, and public awareness of the threat of climate change is certainly greater today, the domestic politics of the issue are at least as challenging now as they were a decade ago.

The President's domestic progress will be judged mainly in two areas: carbon pricing, and more direct support for energy technology innovation. Of the two, the former presents a much greater challenge in the short term. Cap-and-trade, the Administration's preferred approach to carbon pricing and also the main focus of legislative efforts in Congress, is a project of great technical and political complexity. Not only will it impose cost increases on energy consumers -- that, of course, is one of its main purposes -- but it will also create large numbers of winners and losers in different parts of the country, as well as requiring a big new bureaucracy to administer it.[1] None of this would be easy in any circumstances, but the fact that there is not yet a broad political consensus on the gravity of the climate change problem, let alone on how best to solve it, makes the task much more difficult. In June the House of Representatives narrowly passed the Waxman-Markey climate bill featuring a cap-and-trade package, and the Senate is now considering similar legislation. Earlier this year optimistic lawmakers had hoped to have a climate bill enacted before the Copenhagen conference, but that will not happen. Passage next spring is possible, but it is also possible that we will still be awaiting a meaningful carbon pricing scheme at the end of the Administration's first term.

By comparison, progress in energy innovation will be easier to point to. The enormous flow of funds to energy-related projects in the President's economic stimulus package – more than $80 billion altogether, including billions in grants for weatherization, clean coal R&D, and 'smart grid' – will help parry criticisms in Copenhagen and from domestic environmental advocates that not enough is being done. It will also help ease the way to carbon pricing measures. Supporters of cap-and-trade legislation know that public spending on energy innovation, and the 'green jobs' that go with it, can help sweeten what for some parts of the country may turn out to be a bitter carbon pricing pill.

But the real significance of progress on energy innovation lies not in its short-term political benefits, whether in Copenhagen or at home, but rather in the fact that a serious response to the climate change problem will be impossible without it. Achieving President

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[1] A widely-cited study by the Congressional Budget Office estimated that the average cost per household in 2020 that would result from implementing the Waxman-Markey cap-and-trade legislation would be about $175 per year (in 2010 dollars). See Congressional Budget Office, "The Estimated Costs to Households From the Cap-and-Trade Provisions of H.R. 2454", June 19, 2009.

Obama's ambitious goal of reducing U.S. carbon emissions by more than 80% by 2050 will require a rapid shift away from the nation's heavily fossil-fuel-dependent energy infrastructure towards low-carbon alternatives. Nothing less than a fundamental transformation of current patterns of energy production, delivery, and use will be needed. The problem is that the low-carbon technologies available today are variously too expensive, too difficult to scale, or have other negative environmental or economic impacts. Only through innovation can these problems be solved. There will be no single technological solution. Instead, a continuing flow of innovations in many different fields of application will need to be sustained over decades. New technologies for storing, converting, and transporting energy efficiently; new value-added services to help industrial, commercial, and residential users manage their energy use intelligently; new business models to encourage new technology entry into traditional energy monopolies; new technologies to lower the cost of renewable and nuclear electricity; new technologies and systems for capturing and storing carbon dioxide: all of this, and much more, will be needed.

Unfortunately, we are not close to having an innovation system in place that is capable of meeting these needs. That system will be called upon to deliver hundreds of billions of dollars of mostly private investment in cost-competitive, scalable, and environmentally benign new technologies, make thousands of new sites available for the construction of often controversial energy facilities and infrastructure, and every year train tens of thousands of young people, from craft-workers to Ph.D. scientists and engineers. These demands will be far greater than anything yet seen. But government innovation institutions today seem unprepared for the challenge, while the energy industries themselves have been dominated by large, risk-averse corporations with a history of underinvestment in innovation and, often, a strong interest in preserving the status quo.

The energy innovation challenge is different from other kinds of innovation for a very important reason. The major impetus for it comes from outside the marketplace. The actual and potential impacts of climate change are not now factored into the great majority of the millions of decisions made in the marketplace every day by suppliers and consumers of energy. So, while innovation can certainly help ameliorate those impacts, the economic incentives created by the play of market forces alone won't be enough to bring it about. The question is not whether to augment those forces, but how.

Broadly speaking the possibilities are of two kinds: actions designed to induce more private investment in innovation by enlarging the market for it ('market pull'); and measures to promote innovation more directly by supporting the development of new technology ('technology push'). There are many possible ways to do each, and innovation experts often debate the connections among them and the appropriate balance between the two broad strategies.

The threat of climate change is not the only reason to consider such actions. The development of new technologies to mitigate other kinds of environmental impacts, such as mercury and other toxic atmospheric emissions from power plants or the adverse effects of coal mining, cannot be left entirely to market forces either. Nor can innovations designed to respond to the nation's energy security concerns, which in recent years have been aggravated by high and volatile oil prices and the grave security situation in the Middle East. What all these factors have in common is that the costs they impose on society are not fully reflected in energy prices in the marketplace, so a strategy relying solely on market forces to generate incentives for innovation will fall short. The threat of climate change may be the most serious of these problems in the long run, and it is surely the most complex when the scientific, technological, economic and political aspects are considered together, as they must be. But the need to address the other problems, especially energy security, may command more attention. This is significant, since the required responses are not always the same, and indeed may conflict with each other. For example, new technologies for converting abundant domestic coal and oil shale resources into premium liquid fuels would help reduce oil imports, but might also exacerbate carbon emissions as well as local environmental impacts.

Congress and the Obama administration are now gearing up to intervene in support of energy innovation on a large scale. Besides the stimulus spending, President Obama has announced a ten-year plan to spend $150 billion on Federal energy research, development and demonstration activities – a several-fold increase over recent spending rates. The President also recently announced upgraded mileage standards and new greenhouse gas emissions limits for the automobile fleet, even as the White House was negotiating a partial takeover of the U.S. automobile industry. In addition, legislators are working on a mandate for a specified amount of renewable energy production nationwide (the so-called 'renewable portfolio standard'), as well as an efficiency portfolio standard, stronger federal transmission siting authority, and new energy efficiency codes and standards for appliances and buildings.

All of this will be layered on top of a dense network of existing Federal and state mandates, codes, standards, R&D programs, taxes, tax incentives, subsidies, loan guarantees, procurement programs, and rebates designed to promote energy innovation generally, or the development and adoption of particular energy technologies.

Will it all work? Will this patchwork of government initiatives, developed over many years and now about to be boosted by a flood of new federal funds and programs, be sufficient to induce innovation on the scale needed? If not, are there alternative approaches and structures that might work better?

This paper argues that even if all of the Administration's current proposals were to be adopted, the result would fall far short of what is likely to be required. The single most important action is carbon pricing, which will create new incentives for private development and adoption of low-carbon energy technologies and alternative fuels. But carbon pricing alone will not be sufficient, given the urgency and scale of the problem, the inevitable limitations of any politically-negotiated carbon pricing scheme, and the many other rigidities and distortions in energy markets. Yet there is no national strategy for addressing the rest of the energy innovation challenge. Instead, the public debate has been characterized by wishful thinking, with leaders, experts, and others talking up some technologies, talking down others, and claiming variously that if we price it, or if we mandate it, or if we simply say it often and inspiringly enough, the innovations will come.

The first step in developing a serious energy innovation strategy is to move beyond this field-of-dreams thinking. Pricing, mandates, and exhortations will each be part of the solution. So, too, will certain specific technologies, identifiable today. But the task is far bigger and will take much longer than most people realize, and dealing with it effectively will require building an innovation system capable of driving a transformation in patterns of energy supply and use that will unfold over many years. The question is not what can be accomplished in the coming year, or even in the next five years, though progress on this time frame will certainly be important. The critical questions are whether a transition which under 'normal' circumstances might take a century or more to complete can be executed in thirty to forty years at an acceptable cost, and what kind of innovation capability will be needed to accomplish this.

The central issue to consider in building this new national innovation capability is the role of government. Some leaders and commentators have called for a crash program by the federal government – a Manhattan Project or Apollo Project for energy innovation. Such calls are helpful as a rallying cry, but not as metaphors for the task ahead. In both the Manhattan and Apollo Projects there was a single, unambiguous, high-risk technical goal. There was also just one customer – the federal government itself. Success meant achieving just a handful of implementations of the new technology. In both cases this took just a few years. And cost was essentially no object.

Not one of these things applies to the energy innovation problem. In this case there are multiple and sometimes conflicting goals (reduced carbon emissions, but also increased energy security, affordable energy prices, and the development of new industries and the jobs that go with them). There are many different kinds of customers, from individual tenants and homeowners to giant industrial energy users. There are multiple time scales, from a few years to many decades. Success will come not from a few implementations but only if the technology is adopted by large numbers of users. And energy is a commodity, so cost competitiveness is vital.

In this much more complex environment, the questions surrounding the role of government are very different. Should we look to central, national-level public institutions and policies to accelerate the energy transition? Or should we organize the energy innovation system around markets, communities, and other decentralized institutions? If we must look to centralized institutions, should we rely primarily on measures designed to strengthen private incentives to develop and adopt new energy technologies? Or will the government need to engage more directly in 'pushing' innovations into the market?

Finding a balance between public and private action, and between top-down and bottom-up strategies, are familiar themes in the history of American innovation. In recent years these themes have characterized the ongoing digital transformation of the U.S. economy, to which the energy transition can usefully be compared, at least in its scale and pervasiveness. Though sometimes downplayed (especially by entrepreneurs and their solipsistic financiers during the internet boom of the 1990s), government research funds, procurement, standard-setting, finance, and regulation in fact played crucial roles in the information technology revolution. But there is also no doubt as to the central importance of private entrepreneurship, private risk capital, and market mechanisms in that story. The same combination of factors will need to be at work in the coming energy transition. Yet the balance of public and private action is unlikely to be the same.

More government involvement in the energy innovation system seems inevitable, since, as has already been noted (and unlike the digital transformation of the economy), the primary motivations for innovation in this case – increasing energy security and protecting against the threat of global climate change – are societal objectives originating outside the commercial transactions linking private energy providers and users. The greater the risk of climate change, the more urgent the need for government action. Yet the government can't *force* new low-carbon energy technologies to be taken up on a large scale. In our market economy that outcome, if it occurs, will primarily be the result of private decisions and actions. Government innovation policies are just one part of a complex system of market and non-market institutions within which innovative energy products and services are developed, commercialized, and taken up on a large scale. Designing an effective set of innovation policies for an era of more activist government thus requires an understanding of how government policies and institutions interact with private entrepreneurs, with innovative users, and with large, established corporations – in other words an understanding of the energy innovation system *as a whole*.

The role of entrepreneurial innovators in this system is likely to be crucial. It is difficult to imagine a successful energy transition without the risk-taking, relatively fast cycle-time experimentation, and self-correcting characteristics of the entrepreneurial sector. But even in the past the energy sector has not been very hospitable to entrepreneurial innovators. This is partly because of the great scale, large capital requirements, and long cycle times of many energy systems. Partly, too, the pervasive role of government, and the resulting contracting and regulatory risks faced by private firms, have deterred investors in entrepreneurial firms from entering energy markets. The prospect of a government motivated by the threat of climate change to play a more activist role in energy innovation raises new questions about the space for innovation that will then be available for entrepreneurial firms.

Other questions center on the implications of governmental activism for large incumbent energy service providers -- oil companies and electric and gas utilities -- whose relationships with vast numbers of end users, control over the pipeline and grid networks needed to service those users, and access to large pools of capital will surely make them essential players in the coming energy transition. These incumbents are often extensively regulated, and generally enjoy close relations with government, while typically pursuing conservative, risk-averse technology strategies. For their part, government regulators have been known to put their interests in protecting the industries they regulate ahead of innovation goals, acting to inhibit rather than encourage the reallocation of economic resources from the old to the new that always accompanies innovation.

Still other questions concern the organization of the government itself, especially in light of the mixed record of government energy innovation programs since the oil crises of the 1970s. That history is replete with examples of failed or aborted commercial demonstration projects, of interest-group politics and interregional conflicts delaying and constraining Congressional action, of political accommodations to the loudest voices in the energy innovation debate, and of a sometimes-dysfunctional government bureaucracy pushing particular projects, technologies, and subsidies long after their unsuitability has become obvious. A related problem concerns the overlapping jurisdictions of federal and state governments. State regulatory authority is pervasive, especially in the electric power industry, and the complex and fragmented structure of both the industry itself and the states' regulation of it has frequently been a hindrance to energy innovation.

It is timely to consider these questions not least because of the extraordinary reach of recent energy initiatives by both the Obama administration and the Congress. There is a risk that these initiatives, as well as others still under consideration, will result in interventions that are much costlier than they need to be, or that might actually be counterproductive. Some will argue that the risks and costs of climate change are so great that carbon emissions must be reduced regardless of expense. But if the cost of mitigation is too high, or – not quite the same thing – too obviously higher than it needs to be, political support for the government's policies will erode, and in the worst case the mitigation effort will collapse under its own weight. For this reason alone it is important to ask what can be done to increase the likelihood that government actions will be effective.

The question of political support is critical. There is little chance that a major government role in energy innovation will be sustainable over a period of decades without a durable base of political support. The history of innovation in defense technologies since World

War II is instructive. There, the combination of a potent external threat, substantial opportunities for business growth and local job creation, and a politically powerful industrial base, with Congressional allies in every part of the country, fueled sixty years of essentially unbroken political support for advanced defense research and innovation. On a far smaller scale, and with a narrower coalition, government support for agricultural innovation through cooperative extension services has also been sustained for decades. There is no working political coalition to support a national low-carbon energy innovation strategy today. Instead there are disparate and often competing regional advocacies, narrowly defined corporate interests, separate technology and fuel factions, single-issue environmental lobbies, and a public that appears less eager for the government to act on climate policy than in most other societies.[2] In the background stands the federal Department of Energy, still struggling to find a coherent mission more than three decades after its creation at the height of the 1970s energy crisis.

Today the federal government is preoccupied by the immediate problem of finding ways to spend quickly but responsibly the massive flows of economic stimulus funds directed toward the energy sector. But in the relatively near future attention will turn to the task of building a sustainable energy innovation system for the longer term. The purpose of this paper is to suggest some principles to help guide government policy when that occurs. The focus is on the *system of institutions* within which energy innovation will take place, and the role of government in that system. The first step is to develop a clear understanding of the scale and scope of the energy innovation challenge that lies ahead. As we shall see, the magnitude of this task is much greater than is commonly assumed.

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[2] See http://www.worldpublicopinion.org/.

II. Ten (Inconvenient) Truths about America's Energy Innovation Problem

At the heart of the energy innovation challenge facing the world is a productivity problem. The goal is to find new ways to deliver more of the shelter, comfort, mobility, entertainment and other services that energy makes possible *with less* -- less emitted carbon; less use of depletable energy resources; and less cost. For each country the specifics of what needs to be done are somewhat different. For the United States, the nature of the problem is summarized in the following ten points.

1. The critical period for responding to the threat of climate change is the next few decades. Because of the great complexity of the earth's climate system and the many unresolved uncertainties surrounding it, as well as the divergent interests of different stakeholders, there can be no exact answer to the question of what would be an acceptable upper limit on the greenhouse gas (GHG) concentration in the atmosphere. Many climate scientists have concluded that the worst risks of climate change might be avoidable if the atmospheric concentration of CO_2 could be kept below 550 parts per million (ppm), or roughly twice the pre-industrial level. The current CO_2 concentration is about 380 ppm, with smaller amounts of other, more potent greenhouse gases such as methane and nitrous oxide adding another 70 ppm of CO_2-equivalent. Emissions of greenhouse gases continue to rise, and the total GHG concentration is increasing at an accelerating rate – currently somewhere between 2 and 3 ppm per year.[3] In its latest general assessment, published in 2007, the Intergovernmental Panel on Climate Change (IPCC) estimated that a doubling of the atmospheric concentration of GHGs relative to the pre-industrial level would eventually (after a few centuries) cause an increase in the globally-averaged surface temperature that most likely would fall in the 2 to 4.5°C range, with a 50% probability of remaining below 3°C and a small but significant probability of exceeding 5°C. These are

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[3] Other anthropogenic activities such as the release of aerosols have a cooling effect, and the *net* warming effect of anthropogenic releases currently corresponds to the equivalent of about 380 ppm of CO_2. Note that there is often confusion about the form in which GHG concentrations are expressed: for example, as CO2 only; as CO2 plus other GHGs; or as CO2 plus other GHGs plus the (net cooling effect of) aerosols.

globally-averaged figures. Expected temperature changes in large areas of the world would be greater.

Some have concluded that even a 550 ppm ceiling on CO_2 concentration (corresponding to a total GHG concentration of about 670 ppm) would go beyond the bounds of rational risk-taking. The European Union has formally adopted the goal of capping the expected equilibrium global average temperature at 2°C, corresponding to a stabilized GHG concentration of roughly 450 ppm CO_2-equivalent. Since this level has already been reached (although the offsetting effect of aerosol cooling lowers the effective GHG concentration to about 380 ppm) the EU goal is extraordinarily ambitious and almost certainly not achievable. Most policy-level discussions are currently focused on CO_2 stabilization targets in the 450 to 550 ppm range, even though the scientific consensus is that significant ecological and economic damage is very likely at such levels. Yet achieving even the upper end of this range will be extraordinarily difficult. Today the world relies on fossil fuels for more than 80% of its primary energy supplies, and under 'business-as-usual' conditions annual energy-related CO_2 emissions (which account for a large fraction of the world's total GHG emissions) would likely increase three-fold by the end of the century.[4] This would yield atmospheric CO_2 concentrations in the 700-900 ppm range at that time, with the global average temperature rise eventually exceeding 6°C.[5] (As a point of comparison, global temperatures during the coldest part of the last Ice Age were, on average, about 6°C colder than today.)

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[4] L.E.Clarke, J.A. Edmonds, H.D. Jacoby, H.M.Pitcher, J.M.Reilly, R.G.Richels, "Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations", Sub-report 2.1A of Synthesis and Assessment Product 2.1 by the U.S. Climate Change Science Program and the Subcommittee on Climate Change Research, U.S. Department of Energy.

[5] New findings suggest that the warming may be greater than previously thought. A recent study by the Joint Program on the Science and Policy of Global Change at MIT estimates a median result of 5.2°C for the increase in the average global surface temperature in the year 2100 in the absence of policies to restrict GHG emissions (the 'business-as-usual' scenario). (A.P. Sokolov et al, "Probabilistic Forecast for 21st Century Climate Base on Uncertainties in Emissions (without Policy) and Climate Parameters", *Journal of Climate*, Online first, doi: 10.1175/2009JCLI2863.1, 2009.) A 2003 assessment of a similar set of scenarios carried out by the same group had estimated a median result of 2.4°C.

To stabilize the CO_2 concentration in the 450 to 550 ppm range, the transition towards low-carbon fuels and electricity systems would have to begin almost immediately. The longer the delay in getting started, the more difficult it will be to achieve the end goal. Because carbon dioxide molecules released into the atmosphere will stay there for about a century on average, a ton of carbon emitted in any given location today will have roughly the same effect as a ton emitted in any other location at any time over the next several decades. It is therefore appropriate to translate a specific stabilization target into a global, intergenerational 'budget' of carbon emissions. The more of the emissions budget that is used up in the near term, the steeper and more painful the cutbacks in emissions will have to be in later years. This means that what happens during the next few decades is likely to be decisive. If, by mid-century, the link between economic activity and carbon emissions has not been broken and significant progress towards decarbonization of global energy supplies has not been made, the best evidence from the scientific community indicates that the world will have lost almost all chance of avoiding serious and perhaps catastrophic damage from climate change. The fact that the same evidence also holds out the possibility that it might not be as bad as all that, and that -- if we are lucky -- the consequences might be tolerable, makes the calculation a little more complicated. But it does not change the basic conclusion that action on a timescale of a few decades will be needed to avoid a range of dangerous outcomes that at present seem much more likely than the more benign alternatives.[6]

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[6] The great difficulty of achieving decarbonization on this scale is prompting discussion of alternative strategies, including so-called geoengineering schemes to offset or counteract the impact of increases in atmospheric greenhouse gas concentration. Other proposals focus on strategies for adapting to the adverse consequences of climate change. A rational strategy would weigh the expected costs to the global economy of achieving a certain level of reduction in carbon emissions against the expected costs of not doing so. Strictly speaking, mitigation efforts ought to continue until the two sets of costs were equalized at the margin, with proper consideration of the additional possibility that the consequences of failing to act could be much worse than expected.

2. *The magnitude of the energy innovation challenge is not well understood, and is much greater than is often assumed.* Since fossil fuels account for nearly 85% of U.S. energy consumption and more than 80% of total U.S. greenhouse gas emissions, much of the nation's energy-related capital stock will have to be replaced if the goal of reducing U.S. carbon emissions by more than 80% by mid-century is to be achieved. The vast scale of the U.S. energy sector means that this will be an enormous task. Energy goods and services account for more than 6% of all individual expenditures in the U.S. economy.[7] In 2006 (the most recent year for which data are available), energy users purchased almost $1.2 trillion dollars of energy supplies and services.[8] About a quarter of these expenditures were related to electric power, one of the nation's largest industries (larger than air and rail transportation combined). Yet measured by sales electric power is less than half the size of the petroleum industry. The big energy supply sectors -- petroleum, gas, coal, and electric power -- are also among the most capital-intensive of industries, with large-scale production and processing facilities, and massive pipeline, grid and rail transportation systems and fixed distribution networks. Much of this would have to be replaced. The cost of replacing the nation's existing electric generating capacity alone would likely run into many trillions of dollars.

Although recent progress in clean technology has been substantial, with investment in next-generation technologies increasing and new kinds of electrical generating capacity being added at a significant rate, these activities aren't remotely close to the scale of effort that will be required to meet the carbon mitigation goal. It is in fact a straightforward exercise to see what that requirement would be.[9] The key metric is the 'carbon intensity' of the economy -- that is, the amount of carbon emitted per unit of economic output. Over the past 25 years, the carbon intensity of the U.S. economy has

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[7] http://www.bea.gov/national/nipaweb/Index.asp

[8] http://www.eia.doe.gov/emeu/aer/pdf/pages/sec3_10.pdf

[9] For a fuller account of the material in the following paragraphs, see Richard K. Lester and Ashley Finan, "Quantifying the Impact of Proposed Carbon Emission Reductions on the U.S. Energy Infrastructure", Energy Innovation Working Paper 09-006, MIT Industrial Performance Center, October 2009 (available at http://web.mit.edu/ipc/research/energy/papers.html).

declined at an average rate of about 2% per year. This is not nearly fast enough to meet the mid-century greenhouse gas reduction target. How much steeper the decline would need to be depends on the future rate of growth of the economy. The stronger the economic growth rate, the faster the required decline in carbon intensity. A conservative estimate is that the rate of decline would need to accelerate to at least three times the recent trend.

Some uncompromising environmental advocates assert that the risks of climate change are so great that carbon emission reductions must be achieved regardless of what this would mean for economic growth. But that view is not widely shared and as a practical matter national policy is unlikely to privilege the emission reduction goal in this way. If we assume an annual economic growth rate of 2% per capita through 2050 – a fairly modest target by historical standards[10] – and combine this with the goal of reducing U.S. carbon emissions in 2050 by 83% relative to the 2005 level (as called for by President Obama), the implications for the nation's energy system can be stated with mathematical precision. In that case, the rate of decline in the carbon intensity of the economy would have to exceed 7% per year on average every year between now and 2050. The difference between 7% per year and the country's actual recent performance of 2% per year is one measure of the magnitude of the innovation task lying ahead.

To see what this would mean more concretely, the carbon intensity measure can be broken down into two component parts, as shown in the following simple equation:

Rate of change in the carbon intensity of the economy	=	Rate of change in the energy intensity of the economy	+	Rate of decarbonization of the energy supply infrastructure

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[10] A target of 2%/year per capita would be approximately equal to the growth performance achieved by the U.S. economy between 1973 and 2000, and well below the 2.5% growth rate achieved between 1950 and 1973 (and again during the strong expansion years of 1992-2000.)

In other words, reducing the carbon intensity of the economy can be achieved through a combination of reductions in 'energy intensity' (i.e., using fewer energy inputs for each unit of economic output) and reductions in the share of carbon-based fuels in the energy supply mix ('decarbonization'). These two strategies are partly substitutable for each other: the more we do of one, the less we will need of the other. But as discussed below, the need is such that our performance in both areas will have to improve very significantly relative to recent trends.

Over the past twenty-five years, the energy intensity of the U.S. economy declined at an average rate of about 2% per year -- that is, the economy's energy use grew at a rate that was 2% slower than the rate of growth in economic output. This reflects the combination of energy efficiency improvements within individual industries and shifts in the structure of the economy towards less energy-intensive industries. Over the same period, however, the share of carbon-based fuels in the energy supply mix hardly changed at all – in other words, there was essentially no progress towards decarbonization. The combined result of these two trends (2 + 0 = 2%/year) falls far short of what will be needed in the future.

What would it take to increase the combined rate of progress on energy efficiency and decarbonization from 2% per year to 7% per year? Even with an extraordinarily high rate of decarbonization of the energy infrastructure, with adoption rates for every one of the main low-carbon energy supply technologies – solar, wind, geothermal, nuclear, advanced (low-carbon) biofuels, and carbon capture and storage – that are at or even beyond the limit of what most informed observers would today regard as credible, the overall energy efficiency of the economy would still need to improve more rapidly than ever before.[11] In this "all hands on deck" scenario, new low-carbon electrical generating capacity would have to be added at an annual rate of about 120,000 megawatts every year from now until mid-century, requiring a capital investment of 250-500 billion dollars annually. As a point of reference, U.S. developers installed about 8500 megawatts of new wind capacity and 338 megawatts of solar photovoltaic capacity in 2008, a record year for both

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[11] Lester and Finan, op. cit.

technologies. As another point of comparison, during the past decade the highest rate of capacity additions of all kinds occurred in 2001. In that peak year about 67,000 megawatts of new capacity were installed (most of it natural gas fired.) In a more typical year, total capacity additions amounted to 20,000 megawatts or less.

The importance of improving the nation's energy efficiency performance cannot be overstated. For example, even with the extraordinarily high rates of addition of low-carbon energy sources referred to above, if the energy intensity of the economy were to continue to decline at the same rate as during the last two decades (i.e., about 2% per year), the growth rate of the economy would be capped at about 1% per year per capita in order to meet the mid-century emission reduction target. (As a point of reference, in no decade since the 1930s has this broad measure of the nation's economic growth performance been as low as 1% per year per capita.) Achieving the desired emission reductions while simultaneously maintaining a reasonable rate of economic growth will be impossible unless the energy efficiency of the economy improves at a rate significantly above the historical trend.

3. *The energy innovation problem should not be equated with the problem of making scientific breakthroughs.* In order to achieve large-scale decarbonization of the energy supply infrastructure by mid-century, the heavy lifting will have to be done by technologies whose scientific and engineering characteristics are already quite well known. It typically takes many years to move from 'proof of concept' in the laboratory to the first demonstration of a new energy technology at full scale, and many more years or even decades before that technology can achieve significant market penetration. The first modern solar photovoltaic device was developed at Bell Labs in 1954, yet more than half a century later photovoltaic systems – most of them based on the silicon technology demonstrated in that first device -- still only account for one hundredth of one percent of total U.S. electricity generation, despite very generous policy support for market deployment in recent years. Wind power, a technology in use for centuries and similarly the recipient of generous subsidies and other market supports at various times since the

1970s, today accounts for less than 1% of total U.S. electricity generation. Even nuclear energy, the fastest growing new power source of the last 50 years, took nearly four decades following its initial demonstration in 1942 to reach a 10% share of the electricity market – again in spite of a very strong national push to deploy nuclear power during much of that period. Because of these long lead-times, breakthroughs that are today still at the laboratory stage are unlikely to be making a large aggregate contribution to energy supply or use by mid-century, in the U.S. or elsewhere. This is not to say that there is not an important role for breakthrough research (see below). But it does mean that during the next few decades -- the crucial period for combating the threat of climate change -- the major focus of energy innovation efforts will have to be on bringing down the costs, improving the scalability, and reducing the environmental impacts of energy systems that not only are identifiable today but in many cases are already in the marketplace.

Although scientific breakthroughs will probably play a limited role over the next few decades, far-reaching transformations in the *organization* of the energy infrastructure are feasible on this time frame and are likely to be needed. More generally, innovations in business models and political institutions will likely play at least as significant a role as technological innovations and should be regarded as an integral part of the energy innovation challenge.

4. *Scientific and engineering breakthroughs in energy storage, biofuels, solar energy, and other fields may make a much greater contribution in the second half of the century.* Even if emission reduction efforts over the next few decades are successful, the ultimate goal of stabilizing atmospheric greenhouse gas concentrations will take longer to achieve, and will require further deep cuts in emissions. On this longer timescale the potential for continued evolutionary improvements in existing technologies could diminish, while the opportunities for breakthrough technologies to contribute will be much greater. In the best case, longstanding physical limits on the performance of energy transport, storage, and conversion technologies will be overcome. Advances of this type are highly unlikely in the absence of sustained research on fundamental problems in areas such as thermal and

electrical energy transport, new classes of materials, and catalysis. Although the beneficial impacts of such advances may not be observable at scale for decades, the fundamental research on which they will be based must be funded adequately today. These advances may come from a broad range of scientific fields including the life sciences, materials science, and other physical sciences, as well as the energy sciences.

5. *Accelerating the rate of decarbonization of the energy infrastructure necessarily means increasing the role of electricity in the economy.* This is because most low-carbon energy supply technologies are most usefully applied to the generation of electricity. The importance of electricity relative to other forms of delivered energy has been growing for a hundred years, but in order to reduce mid-century carbon emissions to the desired level, the pace of electrification will need to accelerate well beyond the historical trend in every sector of the economy.[12] This includes the transportation sector, where electricity has played a very minor role as an energy source until now. Hopes for lower-carbon advanced biofuels such as cellulosic ethanol do not change that conclusion. Even assuming the early availability of such fuels, it will be impossible to achieve the mid-century carbon emission reduction goal while also maintaining a reasonable economic growth rate without rapid electrification of the automobile fleet.

6. *Removing nuclear power and carbon capture and storage (CCS) from the supply mix would effectively eliminate all plausible pathways to achieving an 80% reduction in emissions by mid-century while also maintaining a reasonable rate of economic growth.* Environmental advocates often exclude both nuclear and coal or natural gas with CCS from the 'clean technology' category. But if these technologies are removed from consideration, it is difficult to see how the carbon emission reduction goal could be achieved except at the cost of unacceptably weak or even negative economic growth. Even with ambitious deployment rates for both nuclear and coal or gas with CCS *and* with much more rapid improvements in energy efficiency, the required rate of installation of new solar, wind, and geothermal capacity will be far greater than anything previously achieved, and will also require

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[12] Richard K. Lester and Ashley Finan, op.cit.

solutions to other problems – such as inexpensive electricity storage, grid reliability, and long-distance transmission – which do not exist today. Both nuclear and CCS face formidable obstacles, but the notion that the nation's economic and environmental goals can be achieved without them does not seem credible.

7. *Public support for policies designed to address the climate change problem, especially policies that raise energy prices, does not currently run deep.* The American public is more aware of the climate change problem than in the past, but still ranks it well below many other policy priorities.[13] Even within the domain of energy policy itself, opinion is divided on how to rank the climate change problem relative to the nation's continuing dependence on the Middle East for energy imports and the impact of high energy prices on jobs and economic growth. These divisions extend even to the most basic question of whether the price of carbon-based energy should be increased so as to promote reduced energy consumption, reduced emissions, and more investment in energy- and carbon-saving technologies, or whether instead the primary goal of energy policy should be – as it has been for decades -- to keep energy prices as low as possible in order to shore up living standards and promote the competitiveness of energy-dependent industries. (The softness of public support for climate change policies may explain why there is no explicit mention of the subject in the titles of either the House or Senate climate change bills.[14])

8. *The promise of job creation from new, low-carbon technologies should not be exaggerated.* In the past, declarations of support for clean energy innovation have been seen by many politicians as a convenient way to demonstrate their commitment to preventing climate change without actually having to support a policy of energy price increases. Now, because of its perceived job-creating potential, energy innovation is increasingly seen as

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[13] The Pew Research Center for People and the Press, January 22, 2009.

[14] The Waxman-Markey bill passed by the House of Representatives earlier this year was titled the "American Clean Energy and Security Act", while the Senate bill, co-sponsored by Senators Kerry and Boxer, is called the "Clean Energy Jobs and American Power Act". According to a recent Rasmussen poll, only 24% of those surveyed correctly identified cap-and-trade as a policy that addresses environmental issues. Nearly 50% thought it addressed health care or financial reform (http://www.rasmussenreports.com/public_content/politics/environment/).

one of the keys to obtaining broad political support for a policy of price increases. The optimism about ‘green jobs’ is only partly justified, however. Certainly there will be large numbers of new jobs associated with renewable and other new energy sources and new energy efficiency and management services. But clean energy innovation is less about the creation of fundamentally new products and services than it is about replacing one set of energy sources and systems based on high-carbon fuels with low-carbon alternatives. Jobs will be added in this process, while other jobs will be lost and foregone. The new jobs will be different in kind, and located in different places. But there may not be any more of them overall. Nor is it clear that they will be ‘better’ jobs than in a high-carbon scenario.

9. *From an innovation perspective, the forthcoming energy transition is more challenging than the ongoing digital transformation of the economy, to which it is sometimes compared.* Unlike many information technology innovations, which involve the creation of fundamentally new products and services, energy is a commodity. And innovation in the energy sector entails competing on cost against highly-optimized energy systems that are typically owned and operated by well-financed, well-established incumbent firms. This imposes stringent, non-negotiable requirements on cost, quality, and reliability performance from the outset -- the toughest kind of innovation environment.

10. *The international dimensions of the energy innovation challenge defy easy stereotyping.* The U.S. has a direct stake in the success of low-carbon energy innovators and manufacturers in other countries, and success there is likelier if effective climate change policies are adopted at home. On the other hand, American firms and their workers in a broad range of manufacturing industries worry that domestic climate change policies will further erode their international competitiveness by raising energy costs. To offset this, they advocate ‘Buy America’ domestic content legislation and tariffs on imports of manufactured goods from countries where carbon emissions will be taxed at a lower rate or not at all. But in the energy sector American manufacturers see a rapidly emerging global market for new low-carbon energy technologies, with more than 80% of global investment in energy infrastructure between now and mid-century expected to occur outside the U.S. They

seek help from the U.S. government in the competition with their international rivals for these markets.

The relationship between the U.S. and China, the world's two largest greenhouse gas emitters, illustrates these complexities. American visitors to China, understandably impressed by the very rapid growth of China's investment in clean energy technologies, often express concern over the likely emergence of Chinese enterprises as increasingly formidable rivals for U.S. energy firms. The energy technology industry, in this view, risks being added to the long list of other domestic industries that have been unable to compete with China-based rivals, at the cost of American manufacturing jobs and profits. These concerns are real, but there are other aspects to consider too. First, and most obviously, the U.S. potentially stands to benefit from the success of China's domestic energy innovation efforts, given the positive consequences for the global climate and for energy security. From this perspective, transferring American clean energy technology to China would serve American interests rather than harm them. Second, as a result of its rapid energy development as well as its more amenable regulatory environment China is increasingly likely to host first-of-a-kind applications of new energy technologies, and as such will become an important source of new technology and market knowledge with value to American firms. Chinese firms are already leading the way in some advanced nuclear technology applications, and may soon do so in carbon capture and storage technologies as well. U.S. firms can benefit from participation in these activities, which often would take much longer or be more costly to carry out in the complex U.S. regulatory environment. Third, U.S. energy firms, following the precedent set by other U.S. manufacturers, are increasingly locating their own R&D, engineering and manufacturing activities in China. The good jobs that go with these activities might otherwise have been located in the U.S. On the other hand, if this relocation results in lower costs, U.S. energy consumers stand to benefit, just as they would benefit from lower-cost energy equipment imports manufactured by Chinese producers, and American politicians and regulators, uneasy about the economic impact on American consumers of higher-cost renewable sources, might be less reluctant to mandate their use.

U.S. and Chinese firms are both participating in global energy technology and manufacturing supply chains, and technology and knowledge is flowing between the two countries in complex ways and in both directions. These flows must be properly valued and paid for by the beneficiaries, whoever and wherever they are. But the rise of competitive clean energy industries in China and elsewhere, while certainly a threat to some American firms, is also essential to the success of global carbon emission reduction efforts, and probably to domestic U.S. mitigation efforts as well.

III. The Government Role in the Energy Transition

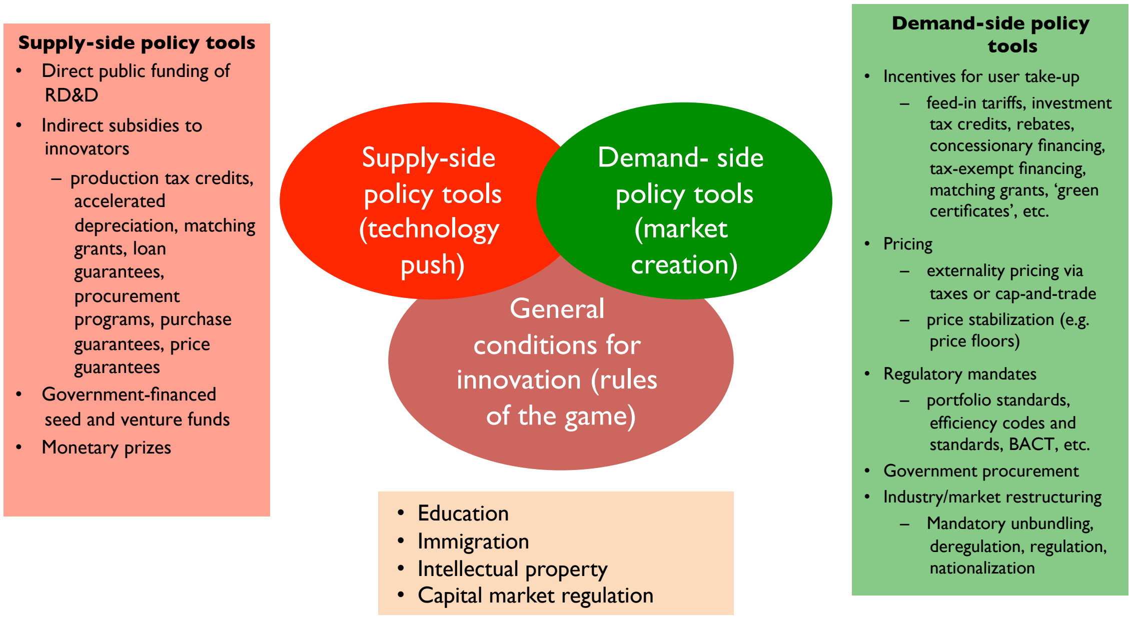
Reducing the rate of carbon emissions to less than 20% of today's level by mid-century will entail a comprehensive turnover of the nation's energy-related capital stock. If left solely to market forces, this transition will not occur fast enough because the costs and risks of climate change are not now priced into energy transactions. To accelerate the transition, government involvement of some kind will be required, and this will likely need to be sustained over several decades. The question is how this can be achieved. Can a set of policies be devised that would have a reasonable chance of bringing about the necessary emission reductions quickly enough, while also meeting the important tests of affordability, efficiency in the use of economic resources, and equity with respect to the distribution of costs and benefits?

The key to accelerating the energy transition is to accelerate the pace of innovation in the energy sector. This is because most of the low-carbon alternatives available today are either too costly or otherwise unable to compete in the marketplace with today's incumbent fossil fuel technologies. In principle, the government could simply mandate the use of the more expensive low-carbon technologies. This is already happening, as the federal and many state governments adopt 'portfolio standards' of various kinds requiring the use of often much costlier low-carbon alternatives. But such policies will impose increasingly heavy costs on energy consumers and taxpayers, and in the end the only sustainable policy for accelerating the energy transition will include, as an integral element, a strategy for bringing down the costs of low-carbon technologies as rapidly as possible.

There are three ways to achieve this goal (see Figure 1). First, the government can work to strengthen energy innovation performance generally by setting and enforcing the rules of the road for private actors in such a way as to reduce or eliminate obstacles to the flow of financial capital, knowledge, and people into and within the innovation system. This is an important responsibility of government in all areas of innovation, not just energy. Second, the government can take a more active hand in the energy innovation process by stimulating the demand for low-carbon technologies. Third, and still more directly, the government can itself share in the risks and costs of energy innovation.

Policies in the first category include measures affecting immigration, intellectual property protection, and capital market regulation, as well as support for education at all levels. The effects of these policies are felt across the economy and may be very significant, but the focus of this paper is primarily on the second and third strategies (‘market pull’ and ‘technology push’.)

Fig.1 The Government Role in Energy Innovation



Supply-side policy tools
- Direct public funding of RD&D
- Indirect subsidies to innovators
  - production tax credits, accelerated depreciation, matching grants, loan guarantees, procurement programs, purchase guarantees, price guarantees
- Government-financed seed and venture funds
- Monetary prizes

Demand-side policy tools
- Incentives for user take-up
  - feed-in tariffs, investment tax credits, rebates, concessionary financing, tax-exempt financing, matching grants, ‘green certificates’, etc.
- Pricing
  - externality pricing via taxes or cap-and-trade
  - price stabilization (e.g. price floors)
- Regulatory mandates
  - portfolio standards, efficiency codes and standards, BACT, etc.
- Government procurement
- Industry/market restructuring
  - Mandatory unbundling, deregulation, regulation, nationalization

- Education
- Immigration
- Intellectual property
- Capital market regulation

Stimulating demand for low-carbon energy technologies. Demand-side policies designed to induce faster take-up of low-carbon technologies, by effectively enlarging the market for them, will in turn stimulate private investment in cost reduction and other innovations and will generally hasten progress down the experience curve. Four types of policy tools are available for this purpose. The first, as already mentioned, is the *pricing of carbon* *emissions*. By attaching a price to carbon – whether through a cap-and-trade mechanism or more directly via a carbon tax – the government can help accelerate the write-off of older, more carbon-intensive technologies and encourage the flow of investment towards low-carbon alternatives.

Second, the government can use its regulatory powers to *mandate* the use of particular new low-carbon technologies, to prohibit or phase out the use of high-carbon incumbents, or to require a certain level of technical performance that all technologies must meet. The government can also mandate information disclosures intended to influence consumer energy choices toward lower carbon emissions. Examples of such policies include the National Renewable Fuel Standard, which mandates the use of 36 billion gallons of biofuels per year in the transportation sector by 2022, and the proposed national renewable electricity portfolio standard, which would similarly require a specified amount of electricity output from renewable sources. Vehicle mileage standards, appliance efficiency standards, product labeling rules, and building codes requiring the use of more-efficient lighting technologies or insulating materials are other examples.

Third, the government can provide *financial incentives* of various kinds – such as targeted tax subsidies, rebates, loans at concessionary rates, loan guarantees, or feed-in tariffs – to encourage private investment in the adoption of low-carbon technologies. (A recent example is the ‘cash for clunkers’ automobile rebate program.)

Finally, the government, as a major owner of energy facilities and the nation’s largest energy user, can use its own very considerable *procurement powers* to target the development of particular new energy technologies and services.

These four approaches – carbon pricing, regulatory mandates, financial incentives, and procurement policies -- are, at least to some degree, substitutes for each other. Each can be applied to induce faster take-up of low-carbon technologies. Compared with the other three, carbon pricing schemes have the virtue of encouraging more efficient technology adoption behavior.[15] A properly adjusted energy price, by equalizing private and social rates of return to investment, will call forth investment in low-carbon energy supplies in the most efficient way. In this case, the government need not be involved in selecting specific energy technologies or fuels to support, a process that is sometimes inefficient and at worst invites abuse or failure. [16] The efficiency advantages of carbon pricing make this the favored tool of many analysts. As the Yale University economist William Nordhaus has noted, "[t]o a first approximation, raising the price of carbon is a necessary and sufficient step for tackling global warming. The rest is at best rhetoric and may actually be harmful in inducing economic inefficiencies."[17]

As a practical matter, however, pricing mechanisms may fall short of their theoretical potential as drivers of low-carbon investment. In market-based schemes such as cap-and-trade, carbon price volatility can be a deterrent to investment.[18] More important, politicians will be reluctant to allow the carbon price to rise high enough to induce a rapid transition to a low-carbon energy infrastructure. If and when Congress eventually adopts a carbon cap-and-trade scheme it will almost certainly have escape ramps, price ceilings, exemptions for critical sectors and for the most heavily affected geographical regions, and other loopholes that will make it fall well short of the ideal of a universal carbon price across the economy which ramps up at the economically optimal rate.[19] As a Carnegie Mellon research team recently noted, 'the effective . . . price under the various cap-and-trade bills that have been introduced or are being discussed is likely to be so low initially, and to rise so slowly over time, that it will not induce the types of investment that will be

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[15] R.G.Newell, A.B. Jaffe, and R. N. Stavins, "The effects of economic and policy incentives on carbon mitigation technologies", *Energy Economics 28* (2006), p. 563-578.

[16] The federal government's corn ethanol program is among the best-known examples of failed subsidy programs, while California's Zero Emission Vehicle mandate of 1990, which called for the deployment of large numbers of battery-powered cars by the year 2000 in order to reduce atmospheric pollution, is a well-known case of a mandate that failed, in this case because of an overestimation of technical potential.

[17] W. Nordhaus, *A Question of Balance: Weighing the Options on Global Warming Policies*, Yale University Press, 2008.

[18] A.D. Ellerman and Paul L. Joskow, *The European Union's Emission Trading System in Perspective*, Pew Center on Global Climate Change, 2008.

[19] As of this writing, the Kerry-Boxer legislation under consideration in the Senate would impose a ceiling price of $28 per ton on emissions allowances.

needed to achieve a 50-80% reduction in CO2 emissions by mid-century.'[20] No surprise, then, that even as Congress is considering a cap-and-trade scheme, it is also moving to enact deployment mandates and subsidies for low-carbon technologies.[21]

Though deployment mandates and subsidies are generally less efficient than pricing mechanisms, their direct economic impacts may be smaller, at least initially. Also, the costs are recovered in different ways; one group of energy users may be subsidized by another, or the costs may be borne by taxpayers rather than by energy users directly. At the outset, moreover, the costs of mandates and subsidies are more likely to be hidden from those who are bearing them. Eventually, though, mandates or subsidies whose cost impacts are initially modest may become unsustainable fiscally or politically as deployments of the targeted energy technologies increase in scale.

In sum, pricing, mandates, procurement policies, and subsidies of various kinds differ in their efficiency properties and also in how the cost burden is allocated, but in every case these costs are likely to act as a practical constraint on the government's ability to accelerate the energy transition, especially as these policies come to be applied on an increasingly large scale.[22]

Direct Support for Energy Innovation. The government can support innovation more directly by itself funding and conducting research, development, and demonstrations (RD&D), by

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[20] Constantine Samaras, Jay Apt, Inez Azevedo, Lester Lave, Granger Morgan, and Edward Rubin, "Cap and Trade is Not Enough", Department of Engineering and Public Policy, Carnegie Mellon University, March 2009.

[21] Although the most-commented-upon part of the Waxman-Markey legislation is the cap-and-trade program, much of the roughly 1000-page bill is devoted to a wide range of regulatory mandates and subsidies.

[22] In practice it is common to find multiple policies simultaneously employed to address the same environmental goal, and this is also true of carbon emission reduction policies. In certain situations – for example, when multiple market failures occur at the same time -- the use of multiple policy instruments may be more efficient than a single policy. However, it is very unlikely that the actual mix of policies in use today approximates the optimal outcome, given the largely uncoordinated way in which these policies have been adopted (see L.S. Bennear and R.N Stavins, "Second Best Theory and the Use of Multiple Policy Instruments", paper prepared for the OECD, October 2006, available at http://ksghome.harvard.edu/~rstavins/Papers/Bennear_&_Stavins_for_ERE_Revisied.pdf)

providing financial and other support for private RD&D activities, or by joint public-private innovation initiatives.

Of course, if these innovations were to succeed in making the new technologies cheaper than today's high-carbon incumbents, there would be no need for carbon pricing or any other kind of government intervention to accelerate the energy transition. But even partial cost reductions would lessen the economic burdens of an accelerated transition. (A stylized description of how investments in innovation would interact with a cap-and-trade scheme to accelerate the transition to a low-carbon energy infrastructure is presented in the Appendix.) So a capable innovation system, effective in bringing down the costs of low-carbon energy technologies and strategies, will deliver a clear public benefit, and a public good argument can be made for government support of energy innovation to supplement the efforts of private innovators.

This argument differs from the position advocated by Nordhaus and others (see above). In that view, as long as the carbon price is set at the correct level, there is no need for additional government support of the innovation process, since private innovators will be adequately incentivized to develop low-carbon alternatives. The argument here is essentially the inverse: government support for innovation, if it successfully augments private efforts to bring down the cost of low-carbon technologies, will lower the carbon price needed to induce the transition to a low-carbon energy infrastructure, thus reducing the economic impact of that transition on energy users and on the economy as a whole. This strategy will have political benefits too, since elected officials, fortified by the lower economic burden on their constituents, will presumably then be more inclined to push forward with policies to accelerate the transition.[23] In other words, government support for innovation will reduce both the economic and the political costs of the

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[23] This argument for government support of innovation is strengthened if (as seems very likely) the government is unwilling to allow the carbon price to rise to the optimal level to induce the transition, since in that case private innovators won't be adequately incentivized to develop low-carbon alternatives, and government support will therefore be needed to compensate for this. But it is important to note that the argument would still hold even if the "right" carbon price were politically attainable.

energy transition compared with a strategy focused solely on inducing faster take-up of low-carbon technologies, in which responsibility for cost-reducing innovation is left to private innovators.

The argument here also differs from the usual rationale for government support of commercially-relevant innovation in industries generally. Both arguments are about the need to compensate for a failure of market mechanisms, but each addresses a different kind of failure. The conventional argument focuses on the 'free rider' problem: private investment in innovation generally falls below the societally optimal level when businesses cannot prevent their competitors from gaining access to the knowledge generated by their innovation activities and cannot force them to pay for it. This is most likely during early-stage research and development, when it is particularly difficult for private firms to capture all of the rewards of their investments. Firms therefore tend to underinvest in these activities -- why pay if you can get it for free? -- and public investment is required to compensate. Energy is no different from other sectors in this regard, and the solution in most cases is the same: direct and indirect financial support from the government for fundamental research and early-stage applied R&D, along with measures such as tax credits for R&D spending that are designed to provide incentives for businesses to invest more of their own funds in R&D activities.

In the case of climate change, however, another kind of market failure occurs on the demand side. Because energy consumers are not paying the full cost of energy services whose use contributes to the risk of climate change, innovators have fewer incentives to develop and deploy new technologies with a lower carbon footprint. So the purpose of the intervention in this case is not to offset the free rider problem at the front-end of the innovation process, but rather to compensate for shortfalls in the take-up of low-carbon technologies in the marketplace. And government support for the early stages of the innovation process is no more likely to be effective in compensating for these shortfalls – and perhaps less so -- than interventions at the later stages of the process, i.e., towards the point of commercialization, or even after commercialization has occurred, when, for many technologies, much of the most important cost-reducing innovation work typically occurs. Moreover, the adoption of new technologies on a large scale often raises new problems that do not occur for more limited application and that may require a series of complementary innovations to overcome them.[24]

The implication of all this is that government will need to participate not only in early-stage research (in order to compensate for market failures in knowledge creation), but also in later-stage development and demonstration activities, in the assumption of commercialization costs and risks, and even in post-commercialization innovation activities. The problem is that government is ill-suited to these latter roles. As technologies approach commercialization, market and business considerations come to the fore. Government decision-makers are less well informed about these issues and less motivated to exploit them, while government administrative procedures are poorly adapted to market-based decision-making. Compared with support for early-stage research, there is a greater risk that government action will be inefficient and politicized and that it will crowd out private investment.

When government has attempted to play this role previously, the record has been mixed. There have been successes, but there have also been disappointments. A significant number of the latter have involved the federal Department of Energy, whose history of participation in large-scale technology demonstrations has been punctuated by several high-profile failures, including the Clinch River Breeder Reactor Project (1972-83), the synthetic fuels demonstration program of the later 1970s and early 1980s, the Yucca Mountain nuclear waste repository project, and the troubled, still unfolding saga of FutureGen, DOE's erstwhile flagship project to demonstrate carbon capture and sequestration.

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[24] For wind and other intermittent renewable resources, for example, achieving scale in deployment will entail solving a number of associated problems involving the grid infrastructure, such as the need for electricity storage technologies, more accurate forecasting tools, load management procedures, simulation and control technologies, and power trading.

Several factors have been implicated in these problematic projects, including[25]:

- a systematic tendency on the part of DOE officials to underestimate project costs (perhaps as a requirement to generate political support);
- a failure to anticipate and plan for the possibility of future variability in fuel prices (e.g., oil price declines in the case of the Synfuels program, and uranium price declines in the case of Clinch River);
- Congressional interference in technology selection and facility siting decisions and personnel appointments, and Congressional pressures limiting the ability of officials to adjust or terminate projects after conditions have changed;
- political cycles in Congress and the Executive Branch and the resulting lack of constancy in policy and funding over the life of the projects;
- funding and management uncertainties generated by the annual budgeting and appropriations process;
- inefficient business practices mandated by restrictive federal procurement regulations and bureaucratic rules governing human resource management, auditing requirements, and the use of federal facilities.
- the absence of a clear institutional mission at the DOE and a culture that has focused more on scientific achievement than the commercial and industrial viability of new technologies.

According to a recent assessment by Ogden, Deutch and Podesta: "[t]he underlying fundamental difficulty is that the DOE, and other government agencies, are not equipped

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[25] See, for example, Linda Cohen and Roger Noll, *The Technology Pork Barrel*, Brookings Institution Press, Washington, D.C., 1991.

with personnel or authorities that permit the agency to pursue a first-of-a-kind project in a manner that convincingly demonstrates the economic prospects of a new technology."[26]

An earlier study of six large federal technology commercialization projects, including the synthetic fuels program, the Clinch River project, the supersonic transport, and the space shuttle, cast the problem in even broader terms: "The overriding lesson from the case studies is that the goal of economic efficiency – to cure market failures in privately sponsored commercial innovation – is so severely constrained by political forces that an effective, coherent national commercial R&D program has never been put in place."[27]

In other circumstances such problems might be automatically disqualifying – serious enough to neutralize any argument for this kind of government role in the future. But the threat of climate change alters the calculus. Now the risk that such government intervention will fail outright or will be costly and inefficient must be weighed against the possibility that success will substantially lower the cost – and increase the political feasibility -- of attempts to accelerate the energy transition. Yet even here the right course of action is not obvious. It is easy to imagine the risk of ecological catastrophe being used to justify even the most ill-advised adventures in government intervention. Against this, though, two facts must be considered: first, a legitimate argument for later-stage government involvement actually can be made in this case; and second, as a practical matter such interventions are already taking place anyway. Recent initiatives include the DOE's Title XVII Loan Guarantee Program, established in 2005, which authorizes federal loan guarantees to commercial low-carbon energy projects using innovative technologies, and ARPA-E, a new research entity established within DOE which will support innovation

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[26] Peter Ogden, John Podesta, and John Deutch, "The United States Energy Innovation Initiative", Center for American Progress, October 2007. An earlier report by a National Research Council committee concluded that "DOE invests little in human resource development for project management compared with the efforts of other federal agencies or private corporations", *Progress in Improving Project Management at the Department of Energy: 2003 Assessment* (National Academy of Sciences, Washington, D.C. 2004.)

[27] Cohen and Noll, op cit.

work spanning the spectrum from basic research to commercialization.[28] Congress and the Administration are now considering several other such measures, including: the Clean Energy Deployment Administration, a federal financing facility designed to accelerate the development and deployment of advanced energy technologies by granting access to various forms of credit that might not otherwise be available, especially for high-risk projects;[29] a special purpose corporation, chartered by statute, to accelerate the demonstration and early deployment of technologies for carbon capture and storage;[30] a quasi-public organization for the sole purpose of financing and executing large-scale energy demonstration projects;[31] and regional energy innovation 'hubs', dedicated to specific areas of technology, with activity spanning fundamental research to commercialization.[32] More initiatives of this type can be expected. The question is under what circumstances are such actions likely to be more or less successful.

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[28] Longer-standing initiatives of this type include DOE's Nuclear Power 2010 program and Next Generation Nuclear Power Plant Program.

[29] Senator Jeff Bingaman of New Mexico recently introduced draft legislation that would create such an entity, and the House is considering similar proposals, all of which would build on the Title XVII Federal Loan Guarantee program.

[30] This proposal, first introduced by Congressman Rick Boucher (D-VA), was subsequently incorporated into the Waxman-Markey climate legislation passed by the House.

[31] Peter Ogden, John Podesta, and John Deutch, "The United States Energy Innovation Initiative", Center for American Progress, October 2007.

[32] For a more detailed discussion of some of these initiatives, see Richard K. Lester, "Reforming the U.S. Energy Innovation System", MIT Industrial Performance Center Working Paper 08-001, September 2008, available at http://web.mit.edu/ipc/research/energy/pdf/EIP_08-001.pdf.

IV. Strengthening Energy Innovation System: The Government Role

The government role at each end of the spectrum of possible participations in the energy innovation process is reasonably clear. At the front end of the process, i.e., in basic energy research, the government pays for most of the work. Decisions regarding the most promising avenues of research are usually delegated to the scientific community (often, though not always, through the peer review mechanism). In most cases the results are made available to all at no cost. The case for government support of this kind of activity has long been recognized, and well-developed institutional arrangements for publicly-funded basic research are already in place.

At the other end of the spectrum, the government can affect prices in energy markets, and pricing changes will in turn affect all participants in the innovation process in ways that again are reasonably well understood. At least conceptually, there is not much disagreement about how a carbon price imposed or enabled by the government would affect incentives and behavior on both the supply and demand sides of energy markets, including the behavior of private innovators. (There is, of course, much less consensus on what level of price would be appropriate.)

Less is known about what kinds of policies would be most effective in targeting the intermediate and later stages of the innovation process, i.e., advanced development, technology demonstration, commercialization, early adoption, and post-commercialization advances. Recognition of the need to accelerate these phases of the innovation process and of the unwillingness of the private sector to shoulder the entire burden conflicts with deep skepticism about the ability of the government to 'pick winners' and the often poor results of its previous forays into this domain. Even conceptually there is no agreement on the appropriate role for government, and no clear understanding of how such a role should be played.[33] At which points in the process should the government intervene, if at all? How to choose the most promising opportunities? What mix of policies should be used? How to share costs and risks with private actors? And how to ensure that unpromising avenues are closed in a timely way?

It is clear that business-as-usual in this important domain of energy innovation will not be adequate. Frustrations over DOE's past performance, coupled with growing pressures to accelerate the energy innovation process, are stimulating calls to create new public and quasi-public institutions in this area.

The case for creating new institutions, as opposed to strengthening and upgrading the Department of Energy, mainly rests on two arguments: (1) the difficulties facing DOE, as an executive branch agency, in recruiting and keeping people with the knowledge – of financial markets and markets for capital goods and energy services – needed for effective decision-making in the downstream stages of the innovation process; and (2) the value of insulating these decisions from the annual Congressional appropriations process and from legislative and executive branch debates about general budget priorities and the deficit.

There are two basic organizational alternatives. One is to create a hybrid organization, involving some mix of government and private sector participation in its key financial, managerial and human resource functions. The other is to use government regulatory authority to create the space (and the source of funds) for a private organization to promote innovation more aggressively. Compared to the former, the latter delegates more of the responsibility for raising and managing funds and for decision-making to representatives of private, for-profit firms. Relative to the private organization option, hybrids run an increased risk of confusion of purpose both because of the broader range of stakeholders and the broader range of goals they would pursue. Although most such hybrids would operate outside the Congressional appropriations process, some would

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[33] When the government itself is the user of the innovation – as in the case of defense technologies – the answers to these questions are much more straightforward: government decisionmakers are the ultimate arbiters, and government involvement at every stage of the innovation process is necessary.

still face a residual risk of political interference because, in the end, they would depend either directly or indirectly on the U.S. Treasury for their financial resources. On the other hand, the private firm option might more susceptible to bias against new technological entrants.

A System of Innovation Institutions

In practice no single institution, whether a government agency, a public-private hybrid, or a purely private entity, will on its own be capable of providing the necessary acceleration in the intermediate and later stages of the innovation process. More likely, multiple institutions will be involved at different stages of the process, with government and private actors each playing a role. Just as it is possible to identify the characteristics of successful individual institutions, so too can desirable attributes be described for the system of innovation institutions as a whole. Some of the most important of these are:

- diversity
- openness/ability to self-correct
- specialization
- capacity to conduct large-scale demonstrations
- capacity to fill the post-demonstration financing gap
- political viability

These criteria are discussed briefly in the following paragraphs.

Diversity. The great variety of ways in which energy is supplied and used in the economy calls for a correspondingly diverse innovation system. Just as no technological ‘silver bullet’ will be found to address all of the different needs, so too will there be no single organizational solution to the innovation problem. Tiny entrepreneurial startups, huge infrastructure providers, venture capitalists, bond markets, pioneering user communities, and many others will all be part of the mix. The innovation process in residential building energy efficiency retrofits bears little resemblance to that in central station power generation, and both are quite different from innovation in the automobile sector. Small-scale product technologies like light bulbs are developed and introduced into the market very differently from complex, large-scale, capital-intensive system technologies like nuclear power plants. Not all of these innovations will require the same degree of involvement on the part of government. Nevertheless, an accelerated transition to a low-carbon, high-efficiency energy system will require innovations in most parts of that system, from large-scale infrastructural technologies to the delivery of energy services to residential energy users, and this will call for a broad range of public roles and capabilities.

Openness/Ability to self-correct. A recurring challenge in the management of innovation is to ensure the openness of the process to new concepts and ideas, while moving expeditiously and in line with resource constraints to down-select the most promising options for further development or deployment. Failures to respond in a timely way to changes in market conditions and technical prospects have marred previous government-funded innovation programs. Technologies have often been supported well past the time when termination should have occurred. In other cases, promising developments have been ignored. Of course, the appropriate standard of performance here, whether in public or private organizations, is not that all technologies should be successful. Indeed, failure is a necessary part of the innovation process.[34] The most important objective with respect to failure is not to avoid it but rather to ensure that it is recognized and dealt with without delay.

All organizations confront the dangers of resistance to new ideas, complacency, and inertia, and a basic objective of organizational governance is to protect against these risks. For private firms operating in competitive markets, the marketplace itself provides an effective, even if not perfect, correction mechanism. Unsuitable technologies and underperforming organizations are weeded out fairly efficiently as competing firms develop different options and test them in the marketplace. Moreover, the prospect of

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[34] Up to half of a typical venture capital portfolio is allocated to company investments that will eventually either lead to a loss or at best break even.

failure in the marketplace – with the ultimate sanction of bankruptcy – is the most efficient way to stem the flow of capital towards unproductive businesses and technologies. This ability of markets to adjust to new information and to self-correct – sometimes referred to as 'dynamic efficiency' – can never be fully replicated in the public sector. But only if there is a reasonably effective mechanism for terminating the flow of funds to unpromising technologies or to underperforming organizations should government institutions be active in the downstream stages of the innovation process.

Organizational specialization. Research that is transformational in its aims – i.e., that seeks to develop an entirely new product or service or a fundamentally different way of producing or delivering an existing product or service -- is typically financed and managed differently from evolutionary or incremental research activities. Similarly, what is involved in exploring, developing, and articulating new technological possibilities is very different from the tasks of choosing among existing, well-defined options and reducing to practice those that have been selected.[35] A well-functioning innovation system supports both types of activity, but because they are so different they cannot usually be carried out within the same organization. It is especially important to preserve organizational space for the discovery, exploration, and articulation of new technological options, since in both governmental and private organizations these activities, and the spaces where they occur, tend to be crowded out by pressures to select a specific way forward and to implement that option as quickly as possible. Transformational R&D is more likely to succeed if it is conducted in a separate organization dedicated to that purpose than if it is grouped with evolutionary R&D in the same organization.

Capacity to conduct large-scale technology demonstrations. The government needs a much better developed capability to undertake large-scale energy technology demonstration projects. As energy technologies move towards commercialization, market forces will almost always outperform government decision-makers at identifying the most promising technical approaches, and as new technologies approach this stage, fewer of the costs and

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[35] Richard Lester and Michael Piore, *Innovation – The Missing Dimension,* Harvard University Press, 2005.

risks of the innovation process should be borne by government. In most industries the task of demonstrating the commercial viability of new technologies is typically the responsibility of private players. But this is unrealistic for capital-intensive infrastructural technologies such as carbon capture and storage and nuclear power. The technical, regulatory, and market risks are simply too great. Controversy over how to allocate costs and risks between private and public players has contributed to the failure of such demonstration projects in the past. There is no standard template for how to do this. Indeed, there are several different objectives for such projects, for example: (a) demonstrating technical viability; (b) generating information that is credible and useful to private investors about the business performance of the new technology in a real-world market and regulatory setting; (c) demonstrating the commercial competitiveness of the technology; or (d) offsetting the risks associated with first-of-a-kind regulatory action. For any given technology it is unlikely that a single project will be capable of achieving all of these goals simultaneously. Different organizational approaches, and different allocations of costs and risks, will be needed in each case.

Capacity to fill the post-demonstration financing gap. Even after the feasibility of a new low-carbon technology has been demonstrated, the residual technology, business and regulatory risks facing innovators in the early stages of technology adoption may still be too great to be accommodated within the project financing structures that are routinely used for mature energy projects. On the other hand, the capital requirements for many of these technologies are much too large to permit early post-demonstration projects to be financed by venture capital.[36] Moreover, the energy produced by these early projects may still cost more than energy from conventional fossil fuel-based sources, even with carbon pricing. And this cost gap may persist for some time. So the government, in addition to sharing in the costs and risks of demonstration projects, will need to participate in *post-demonstration* innovation strategies that bridge the cost gap between these technologies and lower-cost incumbent energy systems, without undermining

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[36] A typical venture investment might be $5-10 million. With syndication, the total infusion of venture capital into a new business opportunity might amount to $50 million. Usually these are pure equity investments, and would only be sufficient to finance, say, a 10-30 MW power project.

incentives for private innovators to bring down the costs of the new technologies as quickly as possible.

Political viability. A strong and active government presence in the energy innovation system will be essential. But the outcome of America's energy innovation challenge is likely to hinge on whether the government response to it is perceived as top-down social engineering, for which there will be very little public support, or instead as an intelligent, effective way to address a fundamental and growing threat to the security and sustainability of the American economy and society.

* * *

Taken together, these criteria suggest several significant changes to the organization of the government's energy innovation activities. These will be discussed in more detail in future Energy Innovation Project papers addressing specific fields of innovation. Here we briefly mention two important structural changes.

1. *Expanding the role of other Federal agencies.* Within the Federal executive branch, the work of agencies beyond the Department of Energy should be expanded. Effective innovation policy, as previously noted, is a combination of 'technology push' and 'market pull'. The capacity of other Federal agencies to contribute to 'pull' in the parts of the economy in which they are active should be exploited more fully. Agencies like the Department of Defense and the General Services Administration, with their vast purchasing power and energy needs, can have great influence over energy innovation. Other federal operating agencies such as the Departments of Housing and Urban Development, Transportation, Veterans Affairs, and Health and Human Services can also do more to encourage the adoption of new low-carbon technologies in their spheres of influence. These agencies have detailed knowledge of the parts of the economy they interact with that is not available to the DOE, and their size and purchasing power will enable them to exert significant influence on technology innovation and take-up in those

areas. A government-wide, multi-agency strategy would also increase the effectiveness of interagency competition in maximizing the impact of federal expenditures on decarbonization.[37] Strengthening the DOE would be an important component of such a strategy. But the creation of a federal 'superagency', in which all roles and responsibilities for energy innovation would be centralized, would quite clearly run counter to this.

2. *Upgrading the roles of the regions and states in the national energy innovation system.* Decisive progress on the energy transition will require decisive action at the Federal level. Stronger federal authority relative to fragmented state policies will be critical in areas such as upgrading the nation's electric transmission system and the implementation of energy efficiency standards for electrical appliances and buildings. On the other hand, there are also essential roles for regions, states and local jurisdictions in the nation's energy innovation system. Many of the relevant authorities – to regulate utilities, to make land-use decisions, to set zoning requirements, to support public education, and to promote economic development – reside at the state and local levels. Entirely new industries are likely to develop in support of the energy transition, and state-level policies promoting the adoption of new technologies and the development of a skilled workforce can have a powerful influence on outcomes. The processes of technology commercialization and new industry formation are in significant part localized phenomena. Geographical proximity enhances interactions between research and educational institutions, investors and entrepreneurs, innovating larger firms, and other important participants in innovation processes. Government policy cannot create these local energy innovation ecosystems, but it can encourage their development. Traditional top-down federal approaches to funding energy RD&D at individual institutions should therefore be augmented by federal support for local and regional energy innovation systems. The

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[37] A similar argument has been made very recently in a draft report published by a team of researchers led by Daniel Sarewitz and Armond Cohen on behalf of the the Clean Air Task Force and the Consortium for Science, Policy and Outcomes of Arizona State University.

partial regionalization of federal energy innovation policy would also provide an opportunity to exploit real differences between regions of the country with respect to resource endowments, economic and business conditions, and public attitudes. It would also create new opportunities for inter-regional competition around important innovation outcomes such as technology take-up.

V. Conclusion

A credible U.S. response to the threat of global climate change will require a rapid shift away from current patterns of energy production, delivery, and use, in which fossil fuels are dominant, towards low-carbon energy systems and much greater end-use efficiency. A major part of this transition will have to be completed over the next few decades. But the low-carbon energy technologies available today are variously too costly, too difficult to scale, or have other negative environmental impacts. Only through innovation can these problems be overcome. No single technical solution will emerge. Instead, a continuing flow of innovations in many different fields of application will need to be sustained over decades. If left solely to market forces, the pace of innovation will be too slow. Government intervention is needed to accelerate the innovation process and the rate of take-up of new low-carbon technologies.

The massive short-term infusion of federal stimulus funds into the energy sector will jumpstart some important lines of innovation, but the need to expend such a large volume of funds so quickly is straining the capabilities of government innovation institutions and risks delaying needed institutional reforms.

Beyond this immediate problem, three major obstacles to an effective national strategy for accelerating the pace of innovation will have to be overcome. *First*, a more realistic view of the scale of the challenge is needed. The task is much bigger than most people think, and it will require a much larger and more comprehensive response. *Second*, a national energy innovation strategy of the necessary scale and scope will require a sustainable political coalition to support it. That coalition does not now exist. *Third*, the current structure and organization of government energy innovation institutions is inadequate to the task ahead. It will not be enough for existing institutions simply to do more of what they are already doing. New strategies and new institutions will be needed. Even if scaled up several-fold, support for early-stage research, the traditional form of government involvement in the energy innovation system, will not be sufficient to induce the required rate of innovation. Similarly, a tax on carbon emissions, whether levied directly or through a cap-and-trade type system, will be necessary but not sufficient. A particularly difficult problem is the lack of a workable approach for government participation in the intermediate and later stages of the innovation process. The need is for a strategy that strikes a balance between the urgent requirement to step up the rate of activity at these stages of the process, the inability of the private sector to shoulder the burden on its own, and the intrinsic weaknesses and limitations of government action of this type. Several broad principles for the development of such a strategy are suggested in this paper. Future papers in this project will elaborate on these principles in specific areas of innovation, including smart grid applications, building energy efficiency retrofits, carbon capture and storage, nuclear power, and small-scale renewable energy technologies. Specific proposals for government institutional reform will also be explored.

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APPENDIX

THE ROLE OF INNOVATION IN ACCELERATING THE ENERGY TRANSITION

Innovations in energy technologies and business models can reduce the costs of deploying low-carbon technologies and so expedite the transition to a low-carbon energy infrastructure. In the best case the cost of the low-carbon technologies would be reduced below that of the high-carbon incumbents. For most technologies this seems unlikely, at least in the near term. But even partial advances would lessen the economic burden of the transition.

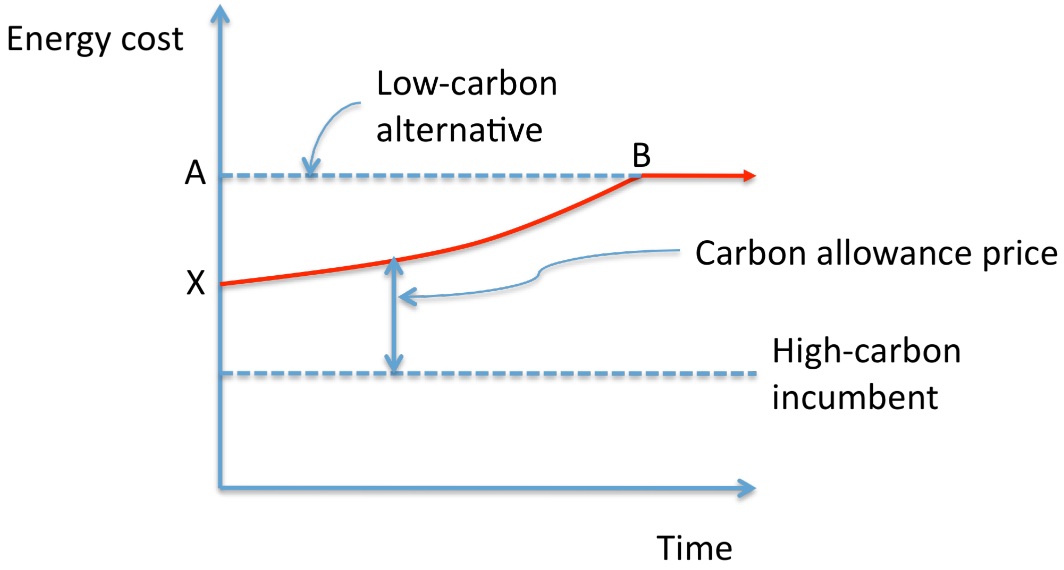
The diagrams in the Figure below show schematically how innovation can achieve this result. The diagrams assume a very simple world in which there are just two energy technologies, a low-cost, high-carbon incumbent and a higher-cost, low-carbon alternative, and the government has adopted a cap-and-trade scheme to reduce carbon emissions. The situation in the absence of innovation is illustrated in panel (a) ("No Innovation"). The effect of progressively tightening the emissions cap is shown by curve XB, which represents the cost of energy from the high-carbon incumbent, adjusted to incorporate the gradually increasing price of the carbon allowances it needs in order to continue to operate. (In this very simple example the fuel cost and other variable costs of the incumbent technology are assumed to remain unchanged over time.) A low-carbon technology is available today but at a cost significantly above that of the incumbent (point A). The low-carbon alternative becomes competitive at point B, when the adjusted cost of the incumbent has risen to its level. The cost of energy is capped at A.

The effect of innovation is shown in panel (b) ("Breakthrough Innovation"). The best outcome occurs when innovation results in a dramatic improvement in the low-carbon technology, which becomes available commercially at a cost below that of the incumbent

(point C). When that occurs, the new technology is the investment of choice and the carbon allowance price falls to zero.
In an alternative scenario (panel (c)), innovation advances the economic performance of the low-carbon technology but its cost is still above the adjusted price of the incumbent at that time (point D). The allowance price continues to rise as the cap is tightened, and the new technology in due course becomes competitive (point E). This occurs earlier than in the no-innovation case, and at a lower energy price.

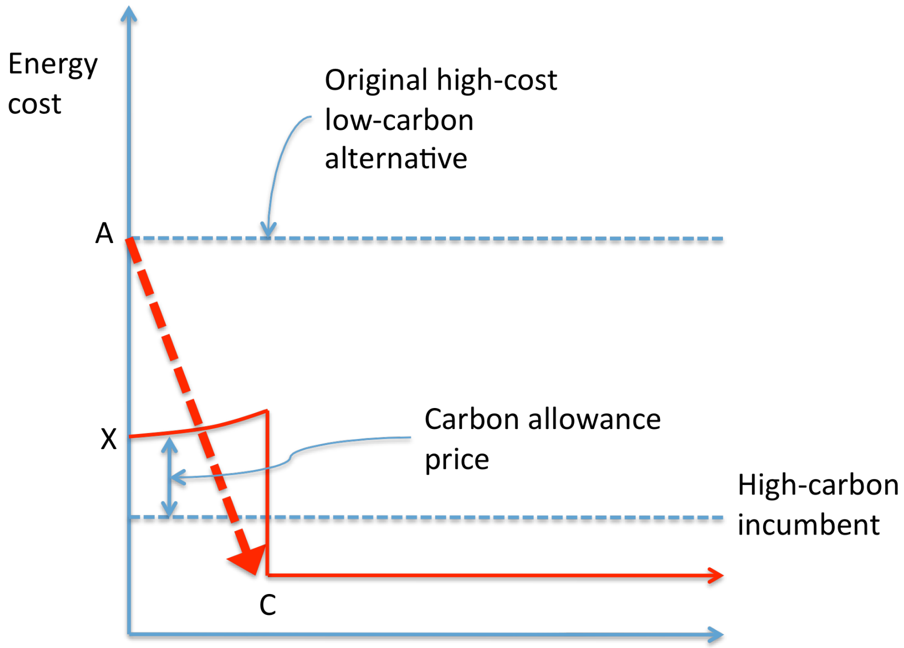
Panel (d) ("Post-commercial Innovation") illustrates the impact of continued cost-reducing innovations after the new technology has already become available. The effect is to bring forward the time at which the new technology becomes competitive (point G), and to reduce further the energy cost. The allowance price falls (point H), as innovation continues to bring down the cost of the new low-carbon technology.

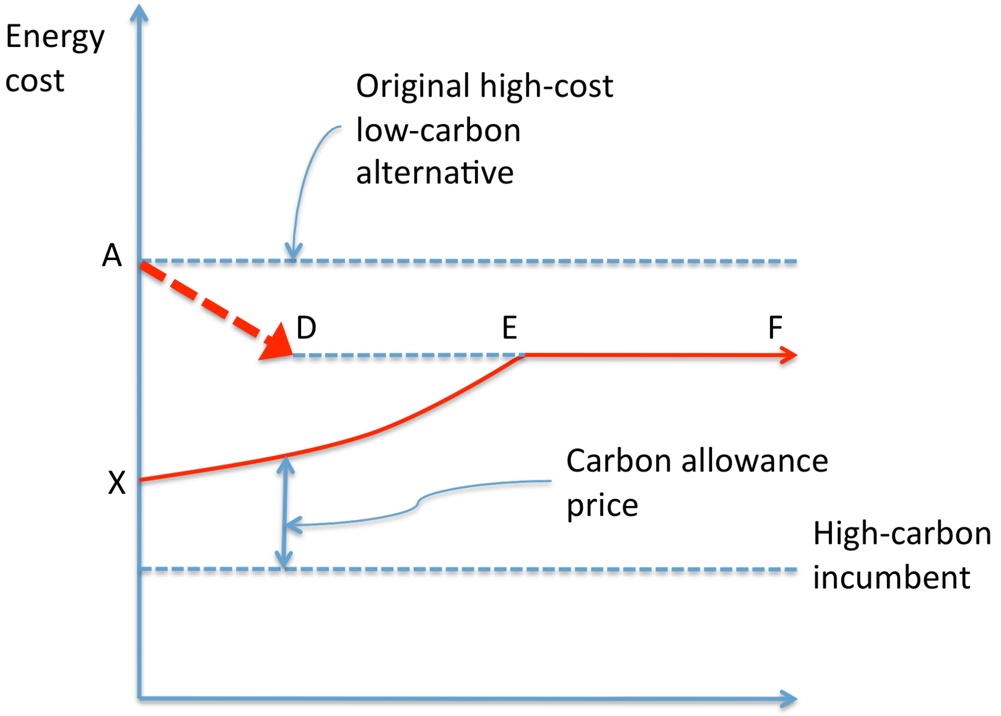
These highly simplified examples make clear that innovation can accelerate the energy transition both directly, by delivering attractive low-carbon technologies to the marketplace, and also indirectly, by making government acceleration strategies less costly and hence more feasible politically. (The effect would be similar if the government were to choose mandates or subsidies instead of cap-and-trade as its acceleration strategies.)



(a) No Innovation

(b) "Breakthrough" Innovation (A ➔C)





(d) "Post-commercial Innovation" (A ➔ D ➔ G ➔H)