Dædalus

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Spring 2012

The Alternative Energy Future, vol. 1

Inside front cover : (foreground) A solar center with 176 solar panels and low-energy lights in Baglan Energy Park, located in Neath, South Glamorgan, Wales, United Kingdom, © Oxford Scientific/Getty Images ; (background) Utility meters installed on the side of a building, © William Whitehurst/Corbis.

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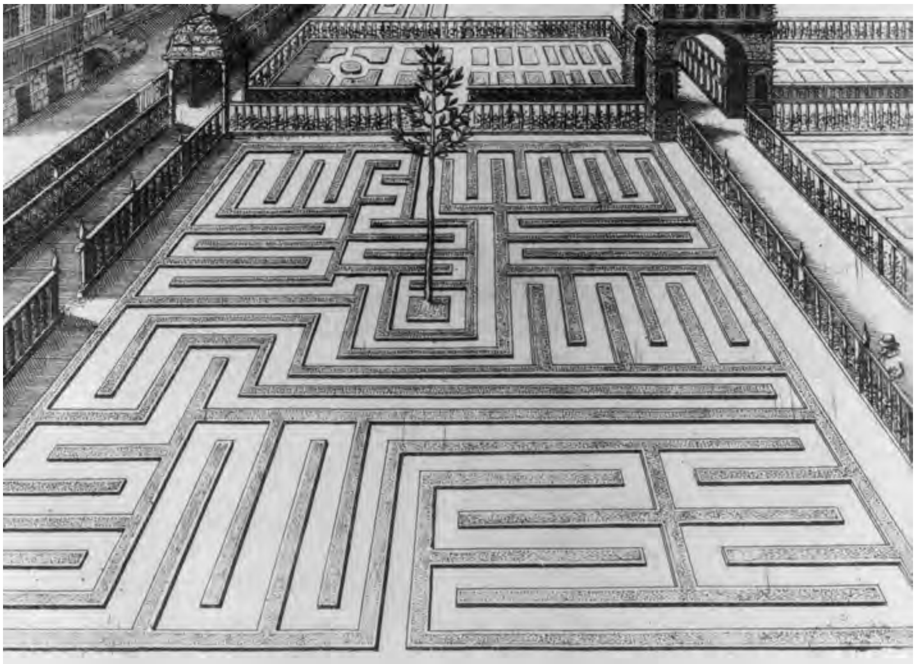

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The Alternative Energy Future: Challenges for Technological Change

Robert W. Fri & Stephen Ansolabehere

Modern life needs energy, and lots of it. During the economic boom following World War II, securing adequate supplies of energy was not a big problem for the United States because we were able to meet our needs with domestic energy sources. But in the early 1970s, two events upset this comfortable situation. Introduced in 1970, the Clean Air Act clamped down on the uncontrolled burning of fossil fuels that had characterized domestic economic development for at least a century. And in 1971, the first oil embargo demonstrated the supply risk inherent in an oil market no longer under U.S. control. Suddenly, the United States had an energy problem.

In the ensuing forty years, eight American presidents proposed policies to solve this problem. Although philosophically different – for instance, President Reagan liked markets to work on their own, but President Carter preferred intervening in them – all had the same immutable goal: to guarantee a reliable, affordable, and clean supply of energy. But despite this common aspiration, the energy policies of all eight presidents shared another crucial attribute: they all failed to make much progress toward meeting their goal.

Today, national energy policy remains in disarray. The proximate cause of the current situation is our failure to adopt a sensible policy to mitigate climate change. Only a few years ago, it seemed that the Copenhagen Climate Change Conference would produce a global agreement on mitigation policy,

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*(*See endnotes for complete contributor biographies.)*

and that in response, the U.S. Congress would pass a strong climate policy. Both Copenhagen and Congress had unraveled by 2010, and we have seen little in the way of national energy policy since.

Against this background, it seems appropriate to ask why creating energy policy is so hard. To provide some insight into this question, the present volume offers views of authors who have recently studied key aspects of energy policy, past and present. Our intention is to examine the lessons learned from decades of disappointment to suggest some directions for the development of a national energy policy that might, in fact, produce a reliable, affordable, and clean energy supply.

The volume's two opening essays frame the central problem of failed energy policy. Michael Greenstone and Adam Looney draw on recent research showing that our energy is woefully mispriced. This research itself is not a new insight, but it is an important up-to-date confirmation of the surprisingly large distortions in energy prices. For example, Greenstone and Looney conclude that coal prices are about half of what they should be to reflect the environmental and human health impacts of mining and burning a fossil fuel that supplies 48 percent of the nation's electricity. Further, if the possible cost of climate change were reflected in coal prices, the price distortion would grow by another third. The distortions are not limited to coal; they pervade the energy system.

Michael Graetz provides a counterpoint to Greenstone and Looney's essay by summarizing the history of energy policy since before the first oil embargo. He documents a record of misdirected policy initiatives that often are more successful in producing subsidies for politically favored industries than in solving energy problems. He notes that the law of unintended consequences is alive and well in energy policy; in this regard, his review of the financial windfall to the paper industry from a regulation designed to increase the use of biofuels is painfully instructive. However, he maintains that the fundamental reason for repeated failures of energy policy is that no president or Congress has ever had the stomach to insist that consumers pay the full price of the energy they use. In fact, the few attempts to correct just the kind of distortions that Greenstone and Looney identify have been beaten back by powerful political forces. For Graetz, the main problem of energy policy is that we refuse to pay a price that reflects the actual and well-known cost of using energy.

So why is it hard to craft a serious energy policy? It's not that we don't understand how to correct for the price distortions in energy. Joseph Aldy and Robert Stavins argue that the only cost-effective and technically feasible solution to this problem is to bring prices into line with the full cost of energy and, importantly, to know how to do so. They examine three policy tools for this purpose – a carbon tax, a cap-and-trade system, and a clean energy standard. All would have a positive effect if correctly designed, although a clean energy standard is less efficient than the other two policies because it does not explicitly price the environmental externality whose cost is not otherwise reflected in the market price. Perhaps this lack of transparency can provide cover for a president and Congress that is willing to go at least some distance toward solving the price problem in a reasonably efficient way.

But price is not the only consideration. Stephen Ansolabehere and David Konisky present new research on how the public views the need for change in the energy system. Three conclusions stand out. First, the connection in the public mind between climate change and the need to transform the energy system is very weak. Second, while people respond to energy prices in a predictable way, they have an overly optimistic opinion of the cost of renewable energy. Third, the major driver of change in the energy system is local pollution. Perhaps these findings suggest that as prices clarify, people will choose the changes needed to deal with climate change; but that for now at least, a focus on the local benefits of cleaner energy is the most effective way to frame the issue. Interestingly, Aldy and Stavins make a similar observation.

Yet there are dangers in being too shortsighted. Daniel Schrag analyzes the role of natural gas in reducing greenhouse gas emissions while we wait for the kind of decisive action needed to tackle coal and oil. Natural gas is attractive because it is cleaner than coal or oil and so produces fewer local pollution problems. And thanks to new technology for accessing unconventional natural gas reserves – think shale gas – there may be enough natural gas available to meet many of our energy demands, improve local air quality, and slow the rate of greenhouse gas production.

Although natural gas seems to have much in its favor, Schrag argues that relying on it is not a good solution to the longer-term problem of climate change. He notes that according to climate science, it is cumulative greenhouse gas emissions over one hundred years or so that change the climate, not the rate at which that cumulative load is emitted. Thus, there is a real possibility that the use of natural gas would delay action to reduce coal and oil use, making it harder to do the job in the long run. Worse, cheap gas could depress prices in a way that discourages the development of the new technology needed to deal with climate change. However, Schrag suggests one optimistic point: if natural gas becomes the fuel of choice, the diminishing power of the incumbent fuels could change the politics of energy.

Regardless of how the price and politics of energy play out, it will be essential to create technology that can grasp the holy grail of affordable, reliable, and clean energy. Developing such technology has long been a mainstay of federal energy policy, and although government has had some success in this area, its record is hardly exemplary. Thus, the companion issue to pricing is innovation. How can government help the private sector develop innovative technology that actually makes it to market, assuming that energy prices are something like right?

Ernest Moniz takes on the innovation issue, building on a recent report of the President's Council of Advisors on Science and Technology (PCAST). He makes the crucial point that innovation involves more than inventing new technology; it also requires that the technology diffuse throughout the economy at sufficient scale to make a difference. Too often, government attempts at innovation have ignored this final but necessary step. Indeed, all ineffective energy policies of the last forty years have fallen into just this trap. Their history is replete with expensive government research programs that produced technology that neither consumers nor industry wanted to buy. Fortunately, we now have a more sophisticated understanding of the innovation process. Moniz, who co-led the PCAST report, summarizes the key lessons, surveys the current (and much improved) state of play, and makes a number of useful recommendations for further progress.

Kassia Yanosek examines the problem of financing the introduction of new energy technologies – one of the key stumbling blocks to innovation and an issue recently in the news. The scale of innovation required to change the energy system is very large, and capital formation is often a challenge. Yanosek identifies a crucial gap in the existing system of capital formation, which she labels the *commercialization gap*. Traditional venture capitalists are willing to invest in high-risk, high-reward innovations, but they are not equipped to finance the large investments needed to deploy the innovation at scale. That, of course, is what large companies in the private sector do, but they are often unwilling to bet large sums on innovations that are not yet proven commercial successes. This is the gap that recent government ventures such as Solyndra have tried to close. Yanosek offers recommendations for doing it right.

Finally, Mohamed El-Ashry lends weight to the need to tackle the innovation system at home by documenting the surprisingly robust initiatives in other countries that are building a world market for new energy technology. He reports that ninety-six countries have renewable power generation policies, and thirty-one have mandates for blending biofuels. El-Ashry focuses on renewable energy, but international activity is accelerating around other energy sources as well. For example, almost half of the sixty-odd nuclear power plants now under construction are in China and India. Of course, all this represents a substantial market in which the United States would like to compete. Perhaps most disturbing, however, is not that we aren't competing successfully now, but that we aren't on a learning curve that would help us compete in the future.

What do we make of energy policy today, given the hard-earned insights of experience? In our view, two main themes emerge from this collection of essays. One is that getting prices right is essential to good energy policy, but that a straightforward solution to this problem – raising energy prices – remains politically infeasible, as it has for forty years. Nevertheless, there may be room for second-best solutions that would at least make a positive contribution to building an affordable, reliable, and clean energy system. For example, well-designed performance standards may be reasonably efficient substitutes for price increases. Focusing public attention on existing environmental insults rather than more global concerns like climate change could also be a useful strategy for taking early action to clean up the energy system. Of course, danger often lurks in second-best solutions, and care must be taken to avoid doing more harm than good. Even so, there is room to do something.

The second theme deals with the need to create the technology to build a new energy system. The nature of the task is well understood, thanks to recent reports by the National Research Council, among others; but it is clear that creating new technology is only the penultimate step in successful innovation. The final step is deployment at a scale that makes a difference. And that means learning to overcome conditions that deflect individual and institutional decisions from presumably rational economic behavior. Physical science and engineering, essential to developing technology, are not the principal tools for addressing these problems. As underscored by a recent report from the American Academy,[1] they are more the province of the social sciences, and greater attention should be given to incorporating social science research into energy-policy development. We will return to that topic in the Winter 2013 issue of this journal.

ENDNOTES

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[1] *Beyond Technology: Strengthening Energy Policy through Social Science* (Cambridge, Mass.: American Academy of Arts and Sciences, 2011).

Paying Too Much for Energy? The True Costs of Our Energy Choices

Michael Greenstone & Adam Looney

Abstract: Energy consumption is critical to economic growth and quality of life. America's energy system, however, is malfunctioning. The status quo is characterized by a tilted playing field, where energy choices are based on the visible costs that appear on utility bills and at gas pumps. This system masks the "external" costs arising from those energy choices, including shorter lives, higher health care expenses, a changing climate, and weakened national security. As a result, we pay unnecessarily high costs for energy. New "rules of the road" could level the energy playing field. Drawing from our work for The Hamilton Project, this paper offers four principles for reforming U.S. energy policies in order to increase Americans' well-being.

Whether by heating our homes in winter, keeping the lights on in our offices, powering factories that manufacture goods, or fueling our automobiles, energy drives our economy and supports our quality of life. Thanks in part to an economic infrastructure heavily dependent on energy use – roads and highways, ports and railways, broadband and computer networks, manufacturing plants and shipping facilities – American workers and businesses are among the most productive in the world and the most globally integrated. A century of innovation, fueled by cheap and plentiful energy largely from coal, oil, and natural gas, has allowed the nation to transition from an agriculture-based economy to one based on high-value-added manufacturing and services aided by computerization. Our standard of living – among the highest on earth – would not be possible without energy and the systems that have been developed to harness it.

Elsewhere in the world, developing economies are trying to catch up – both in terms of economic growth and quality of life – and are expanding their energy production infrastructures accordingly. For example, major rural electrification projects

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are under way in China and India to increase access to energy in villages and to mechanize farming tasks. Furthermore, both countries are rapidly increasing electricity production to feed their sharp industrial growth. Abroad, as at home, rising living standards and robust economic growth require access to plentiful, reliable, and inexpensive energy.

Unfortunately, the sources of energy that we have grown to rely on are more expensive than we once thought. The true cost of energy includes the price we pay at the gas pump or what shows up on the electric bill – known as the "private costs" – and also the less obvious impact of energy use on health, the environment, and national security. Economists refer to these additional damages as negative externalities, or "external costs." A more holistic accounting of the total costs of energy consumption that includes both the private and external costs is known as the social cost of energy use. Recent events like the Deepwater Horizon oil spill, the death of twenty-nine West Virginia coal miners in the worst mining disaster in twenty-five years, and the crisis at Japan's Fukushima Daiichi Nuclear Power Plant are salient examples of the health and environmental costs, and economic risks, of our current energy sources. While these tragic disasters are the most obvious symbols of these costs, they are by no means the largest.

Our primary sources of energy impose significant health costs – particularly on infants and the elderly, our most vulnerable. For instance, even though many air pollutants are regulated under the Clean Air Act, fine particle pollution, or soot, still is estimated to contribute to roughly one out of every twenty premature deaths in the United States.[1] Indeed, soot from coal power plants alone is estimated to cause thousands of premature deaths and hundreds of thousands of cases of illness each year.[2] The resulting damages include costs from days missed at work and school due to illness, increases in emergency room and hospital visits, and other losses associated with premature deaths. In other countries the costs are still greater; recent research suggests that life expectancies in northern China are about five years shorter than in southern China due to the higher pollution levels in the north.[3] The National Academy of Sciences recently estimated total non-climate-change-related damages associated with energy consumption and use to be more than $120 billion in the United States in 2005. Nearly all of these damages resulted from the effects of air pollution on our health and wellness.[4]

The external costs associated with using carbon-intensive fuels also include climate change. If carbon dioxide (CO_2) emissions continue to rise at the current rate, they are likely to drive temperature changes that will have significant environmental and health consequences: rising sea levels, more frequent and more severe storms, increased flooding and drought, and other dramatic changes in weather patterns. These changes in turn could result in an increase in water- and insect-borne diseases, a loss of biodiversity, and the loss of human lives and livelihoods.[5] The U.S. government recently developed a measure to monetize the damages caused by CO_2 emissions: that is, the social cost of carbon. By this metric, carbon emissions in the United States resulted in almost $120 billion in damages globally in 2009.[6] Other environmental costs associated with our current energy sources include the impact of acid rain on vegetation and lakes, the effect of ozone on agricultural productivity, and oil leaks and spills. Further, recent concerns about local damages associated with hydraulic fracturing ("fracking") extraction techniques underscore the land-use issues related to fuel extraction.

There are additional economic, political, and national security risks associated with current domestic energy policies. Oil plays an important role in the American economy: it powers most of the transportation sector and is an important input in many industries. Continuing turmoil in the Middle East has raised the profile of energy security and the geopolitical implications of reliance on oil. In part to protect major oil supplies, the United States has maintained a military presence in the Middle East for more than fifty years. On several occasions, it has become mired in military interventions to prevent oil supply disruptions, among other objectives.

These costs – ranging from increases in lung disease and infant mortality to problems associated with climate change – have been quantified and can be expressed in dollar terms. And these costs can far exceed the price that appears on our utility bills or at the gas pump. For example, we estimate that it costs about 3.2¢ for an existing coal plant to produce a kilowatt hour (kWh) of electricity. But this inexpensive sticker price belies the more significant damages (estimated at roughly 5.6¢ per kWh) of coal-generated electricity to our well-being: shorter lives, higher health care bills, and a changing climate that poses risks to our way of life. The true social cost is almost three times the amount that appears on our utility bills.

Current energy policy tilts the balance in favor of energy sources that appear cheap only because their costs to health, the climate, and national security are obscured or indirect. A better approach to energy policy should encourage fairer competition between energy sources by placing them on equal footing. Based on our work for The Hamilton Project, this paper offers four principles for reforming U.S. energy policies that would move the country in this direction.

The Benefits of Energy Use. The development and exploitation of inexpensive energy sources has been a key driver of economic development and quality of life. The story of the expansion of the U.S. economy, and of the advances and innovations that have made life better for Americans, leaps from one energy-harvesting invention to another: the cotton gin, the steam engine, the lightbulb, the internal combustion engine, the turbine, the mechanized factory, the electrified city, and the computer. The development of coal, oil, natural gas, nuclear power, and other energy sources made all this progress possible and has helped support activity that is integral to our economy and quality of life.

Windmills and watermills, the first modes of generating mechanical energy, were used almost entirely for rudimentary tasks such as grinding grain and pumping water. The development of the steam engine in Britain in the mid-eighteenth century gave birth to industry by powering factories and cotton mills. In the late nineteenth century, the internal combustion engine, which runs the entire modern motor vehicle fleet, was invented. Around the same time, the lightbulb was developed, allowing businesses to keep their doors open even after the sun had set and making it possible for employees to extend their workdays.

Today our economy is heavily reliant on electric power to run businesses and maintain quality of life. Data centers and server farms in the United States require massive amounts of energy. In 2006, they consumed 61 billion kWh of electricity (1.5 percent of total U.S. electricity consumption), more than was consumed by the nation's televisions.[7] Oil fuels more than 90 percent of the nation's motor vehicle fleet and is a critical fuel input for the entire transportation network. The benefits that energy provides, from home heating to facilitation of trade, are integral to our way of life. The United States consumes about one-fifth (21 percent) of the world's energy, despite having less than 5 percent of the world's population.[8]

But U.S. dominance in energy use is about to change. Developing countries – especially China and India – are rapidly increasing the amount of energy they consume as their economies grow and their citizens aspire to better living conditions (Figure 1). While access to plentiful energy is important to maintaining the standard of living in the United States, it has taken on an even more vital role in emerging markets as they transition to a higher standard of living and more energy-intensive economies.

A lack of reliable access to energy has been a major deterrent to economic growth and improved quality of life in most of the developing world. Almost one-fourth of the world's population – most of which lives in sub-Saharan Africa and South Asia – lacks access to electricity.[9] Twice that number – half the world's population – lacks access to clean cooking energy and relies on traditional biomass fuels (wood, dung, coal, and agricultural by-products) that produce smoke and other air pollutants.[10] Indeed, indoor smoke from solid fuels is believed to have been the sixth-leading cause of death and fifth-leading cause of disability in low-income countries in 2004.[11] "Energy poverty" and "fuel poverty" contribute to poverty, health problems that can result in lower life expectancy, diminished access to education and other productive activities, and lower rates of economic growth and productivity.

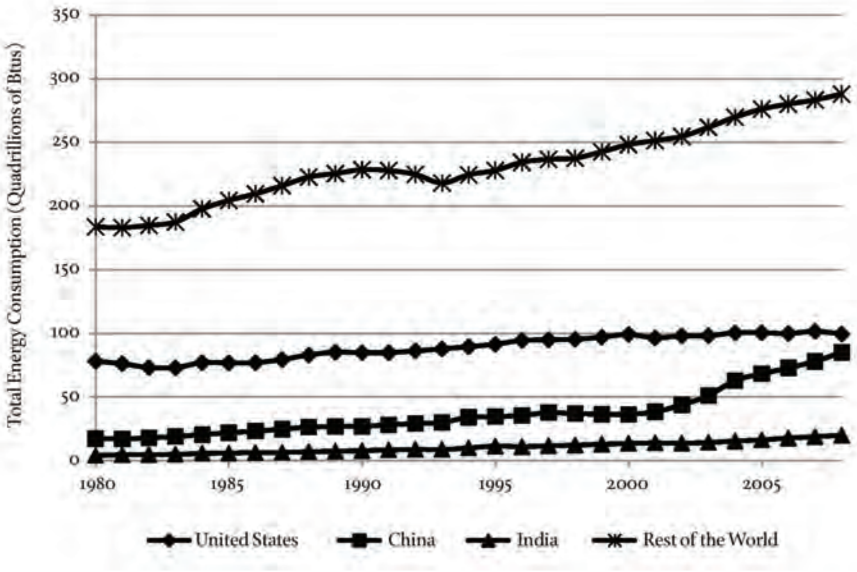
From facilitating trade to raising income and improving health, reliable access to energy could help reduce poverty and improve life expectancy in developing nations around the world. As these nations grow and transition, however, their reliance on fossil fuel–based energy sources will surge, creating another set of global challenges resulting from climate change.

The External Costs of Energy Use. The benefits of the energy sources that we currently rely on are obvious. But it is increasingly clear that the costs of our current sources go well beyond what we pay at the pump or to the utility company. These additional costs of energy use take a variety of forms, from the erosion of living standards to the diversion of taxpayer funds and other critical resources. They include increased health costs, shortened life spans, higher military expenditures and foreign policy constraints, expensive environmental cleanups, and the broad impacts of climate change – all of which are real costs that we impose on ourselves and on future generations.

Health effects of current energy sources. The combustion of fossil fuels results in the release of pollutants that have a significant impact on the health and well-being of American society and the world. Air pollution's greatest costs to society come from health impacts, which make up approximately 94 percent of external non-climate costs.[12] Particulate air pollution, or soot, is associated with elevated mortality rates for adults and infants.[13] In 2010, soot from U.S. coal-fired power plants was estimated to have caused 23,600 premature deaths and more than 500,000 cases of respiratory illness.[14] Soot and other pollutants such as sulfur dioxide (SO_2), carbon monoxide (CO), and nitrogen oxides (NO_x), which lead to ozone, all pose threats to well-being, including higher mortality rates, more hospital admissions, restricted activity days, and increased expenditures on medications for respiratory problems.[15]

The National Academy of Sciences estimates that electricity generation from coal, oil-fueled vehicles and transportation, and electricity production from natural gas caused an estimated $120 billion in non-

Figure 1
World Energy Consumption by Country, 1980 to 2008



Source: Energy Information Administration, International Energy Statistics Database, November 2009, http://www.eia.gov/emeu/international.

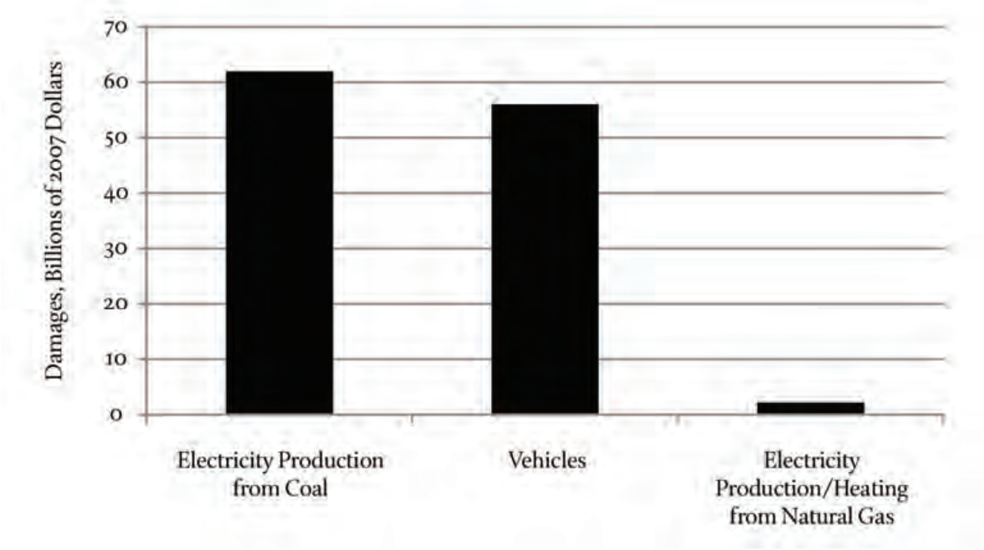
climate-change-related damages in 2005 (Figure 2).[16] Health-related damages account for almost all of these costs.

The health consequences of other energy sources can be severe, as the nuclear crisis in Japan reminds us. Prior experiences with nuclear disasters suggest that they increase the incidence of cancer. Even at doses once thought to be harmless, children born in regions of Sweden that experienced higher radiation fallout from the disaster at Chernobyl have been shown to have reduced cognitive abilities, measured by school performance.[17]

Climate-change impacts. Since the start of the Industrial Revolution, humans have been emitting a growing amount of greenhouse gases such as CO_2, methane, and NO_x into the atmosphere. Figure 3 shows that the concentration of CO_2 in the atmosphere has risen by more than 23 percent over the past fifty years.[18] According to the Intergovernmental Panel on Climate Change, these rising levels of CO_2 and other greenhouse gases will cause rising average global temperatures in the coming years and decades. If current emissions trends continue, global temperatures will increase by an estimated 4.3°F to 11.5°F (2.4°C to 6.4°C) by the end of the century, depending on the climate model and assumptions about economic growth.[19]

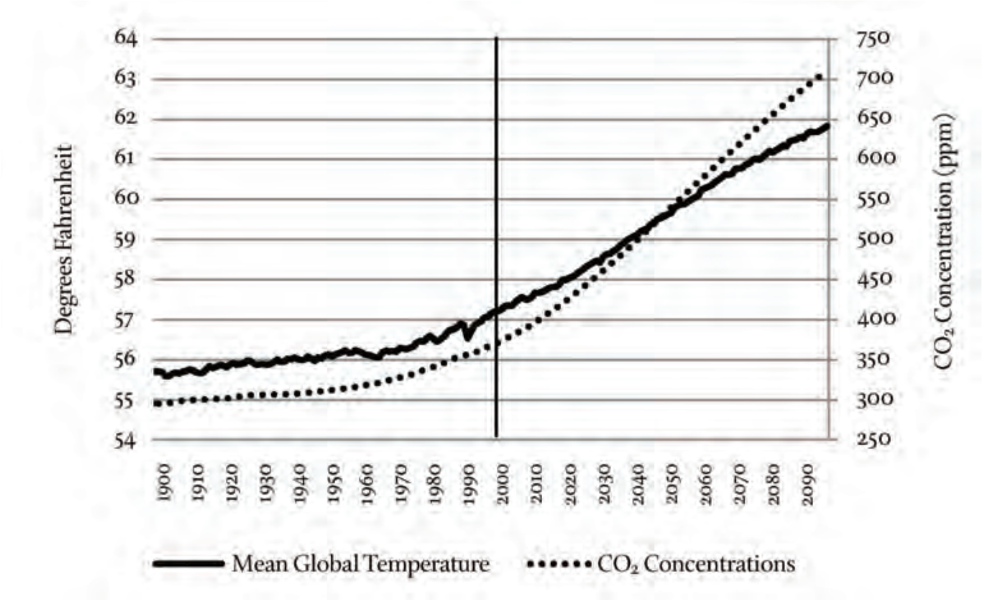
The increase in average temperature is well-documented, but it is less clear how this will affect our lives. One way to illustrate the effect is to look at the incidence of very hot days. Figure 4 reports the current number of days per year when the temperature experienced by the average American falls into certain ranges. In recent history, it has been extremely rare for the average daily temperature (calculated as the average of the daily maximum and minimum) to exceed 90°F; the aver-

Figure 2
Main Sources of Non-Climate-Change-Related Damages, 2005



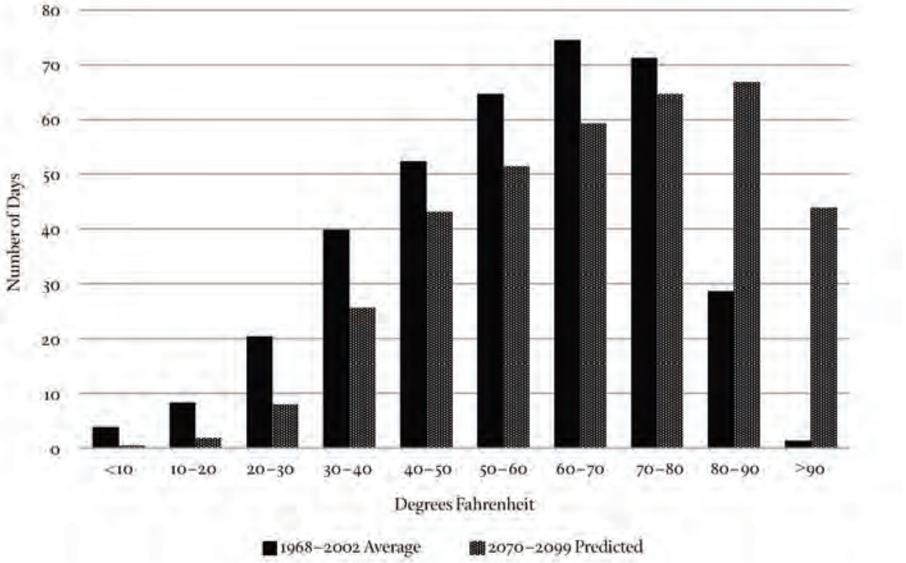
Vehicle costs refer to the total life-cycle costs of producing and operating. Source: National Academy of Sciences, *Hidden Costs of Energy* (Washington, D.C.: National Academies Press, 2010).

Figure 3
Mean Global Temperature and Atmospheric CO_2 Concentrations, 1900 to 2099



Multimodel average temperature; SRES A1B scenario. Source: KNMI Climate Explorer, http://climexp.knmi.nl/.

Figure 4
Current and Predicted End-of-Century Daily Temperatures



Hadley 3-A1Fl predictions, error corrected. Source: Olivier Deschenes and Michael Greenstone, "Climate Change, Mortality, and Adaptation: Evidence from Annual Fluctuations in Weather in the U.S.," *American Economic Journal: Applied Economics* 3 (4) (2011): 152–185.

age American experiences about one such day per year. But in the future, such extremely hot days are projected to become much more regular, occurring about forty times a year. This means the United States will experience roughly four times as many days when the temperature is hotter than 90°F than days when it is below 30°F. This projected change is troubling because the greatest damages from temperature, in terms of elevated rates of mortality and morbidity and reduced agricultural productivity, are concentrated at these high temperatures.[20]

In addition to the increase in temperatures, the higher concentrations of greenhouse gases are expected to lead to other changes on our planet, including changes in precipitation patterns, weather variability, and rising sea levels. Together, these changes in climate are expected to lead to a series of adverse outcomes ranging from reduced agricultural productivity, increased mortality rates, higher flood risks, greater rates of species extinction, compromised ecosystem services, and even increased conflict over scarce natural resources. Furthermore, there is rising concern about the possibility of a catastrophic event, such as a potentially discontinuous "tipping point" in the behavior of earth systems.

In the abstract, it is easy to understand that there is a wide range of risks for the United States and the world population associated with climate change. The challenge of summarizing and monetizing the costs – a necessary next step for informing policy-makers – has only recently been addressed. In 2010, a U.S. government working group estimated the global damages associated with the release of an additional ton of CO_2 into the atmosphere, calling their estimate the social cost of carbon (SCC). The group concluded that the current SCC is roughly $21 per ton of CO_2 emissions.[21] To put that number in context, at a cost of $21 per ton, carbon emissions in the United States last year resulted in roughly $120 billion in global damages. The damages within the United States are projected to be smaller, ranging from about 7 to 23 percent of the total. Of course, the global and domestic damages apply regardless of where on the planet the emissions occur.[22]

With this estimate of the SCC, policymakers now have a bright-line rule to identify effective policies, because they can quantify the benefits of regulations that would reduce carbon emissions. Indeed, the SCC has already become a standard tool in the evaluation of national policy choices. Since the release of the SCC values, the monetized benefits of CO_2 emission reductions have been included in at least seven major regulations (those with costs or benefits above $100 million) across three federal departments and agencies. In Table 1 (discussed below), we use the SCC to quantify the climate-related damages from various energy sources.

Other environmental and economic effects. Other aspects of energy production and consumption also impose external costs. For example, extracting, transporting, and consuming fuels such as coal and petroleum have adverse effects on the environment and impair our quality of life. The methods used to extract fuel, such as coal mining or offshore oil drilling, can be very disruptive to the surrounding ecosystem. Strip-mining, a form of surface mining that peels back layers of soil and rock to expose seams of mineral, destroys vegetation, displaces wildlife, and often permanently changes soil composition. The Deepwater Horizon oil spill in 2010, which damaged both local ecosystems and local economies, is one illustration of the consequences of accidents. Air pollutants, like those that form acid rain or the airborne mercury from burning coal, have negative effects on trees, wildlife, ocean life, and soil quality. The smog that results from air pollutants impairs visibility and interferes with enjoyment of national parks and other scenic vistas.

Pollution also results in economic damages. Ozone can slow plant and crop growth and increase plants' vulnerability to disease.[23] Recent evidence suggests that air pollution has a significant impact on the health and productivity of workers and children's absenteeism rates at school.[24] Ozone, even at levels below Environmental Protection Agency (EPA) standards, has been shown to reduce the productivity of agricultural workers in California.[25]

Even some alternative energy sources, several of which have been heralded as the future of energy use, have significant environmental costs. Biofuels such as ethanol were once considered a promising substitute for carbon-intensive fuels. However, clearing the land, growing, transporting, and processing the crops used for biofuels results in large emissions of CO_2. Examining the entire life cycle of production and consumption of biofuels suggests that at least some of them may be, on balance, worse for the environment than the entire energy cycle for oil.

Macroeconomic stability and international security. Energy security has been a critical concern for U.S. policy-makers since at least the oil shocks of the 1970s. Although U.S. oil intensity – the amount of oil the United States consumes per dollar of economic activity – has been declining by about 2 percent per year since 1980, our economy remains heavily dependent on oil.[26] In the transportation sector, there are almost no substitutes; oil meets more than 90 percent of U.S. fuel needs.[27] Consequently, oil continues to play both a substantive and symbolic role in the economy. The challenges that arise from U.S.

reliance on oil have both economic and geopolitical dimensions.

Dependence on oil imposes macroeconomic risks from oil shocks. Ten of the eleven postwar recessions followed an increase in the price of oil, including the most recent recession.[28] While some research suggests that oil shocks have had steadily smaller effects on economic activity since the 1970s – perhaps because our economy's oil intensity has been diminishing, because policy-makers have learned how to respond better to these shocks, or because the U.S. economy is more flexible today than it was – evidence from the most recent recession suggests that our vulnerability to oil shocks has not disappeared.[29]

Oil consumption also raises geopolitical and national security issues. For more than fifty years, the United States has maintained a military presence in the Persian Gulf. Although it is difficult to disentangle energy security from other national security goals, the need to guard against the possibility of oil disruptions has added urgency to U.S. military action. According to Brent Scowcroft, the national security adviser under Presidents Gerald Ford and George H.W. Bush, "What gave enormous urgency to [the Persian Gulf War] was the issue of oil."[30]

Estimates of Private and External Costs of Various Energy Sources. Smart energy policy must take into account the full social cost of energy production. This includes the private costs of building, maintaining, operating, and fueling electricity generating plants or transportation vehicles, as well as the external costs to health and the environment. Making good energy policy decisions has been especially difficult because the extent of the private and external costs has not always been clear. Indeed, without access to full, transparent information about the true costs of energy sources, policy-makers have not had the tools to make the best choices for the economy and the welfare of the American people. With an "apples to apples" comparison of actual costs, we can help level the playing field among the various energy sources by providing more-accurate information for the public discussion around energy policy.

Table 1 provides new and what we believe are the most complete estimates of the costs of electricity production for several energy-producing technologies, including coal, natural gas, nuclear, wind, solar, and hydroelectric. It reports the full life-cycle costs of creating new electricity-generating capacity using different types of electricity sources; that is, it shows the total social cost per unit of energy of starting up and operating a new plant over the entire lifetime of the plant (sometimes called the "levelized cost") including the health and environmental costs associated with electricity production. These costs are divided into private costs (the cost of building, fueling, operating, and maintaining a plant); non-carbon external costs (primarily the costs to health); and carbon-related external costs due to climate change.[31] The sources for the estimates of the private costs are based on our calculations, described in detail in our paper for The Hamilton Project[32]; estimates for non-carbon costs are from the National Academy of Sciences[33]; and estimates for carbon-related costs are from the Interagency Working Group on the Social Cost of Carbon.[34] We are unaware of any previous effort to pull these cost components together.

Although we attempt to draw on the best available data and research when producing these estimates, there is substantial uncertainty around many of these costs. For some energy sources, estimates of non-carbon external costs are difficult to quantify or are simply not available.

Table 1
The Private, External, and Social Costs of Electricity Generation

Type of Energy	Technology	Capacity Factor[c] (%)	Share of Current Generation[d] (%)	Private Costs[e,f] (¢/kWh)	Non-Carbon External Costs[i] (¢/kWh)	Carbon External Costs[k] (¢/kWh)	Social Costs[m] (¢/kWh)
EXISTING CAPACITY[a]							
Fossil Fuels	Existing Coal	85	45	3.2	3.4	2.2	8.8
	Existing Natural Gas	87	24	4.9	0.2	1.0	6.0
Other Traditional	Existing Nuclear	90	20	2.2	UTQ[j]	~0	2.2
NEW CAPACITY[b]							
Base-Loading Technologies							
Fossil Fuels	Coal (Dual Unit Advanced PC)	85		6.2	3.4	1.9	11.5
	Natural Gas (Conventional Combined Cycle)	87		5.5	0.2	0.8	6.5
Other Traditional	Nuclear (PWR)	90		8.2 – 10.5[g]	UTQ	~0	8.2 – 10.5
	Hydro	52		6.4	UTQ	~0	6.4
Renewables	Geothermal	92		8.3	UTQ	0.1	8.4
	Biomass	83		9.5	UTQ	0.0 – 2.7[l]	9.5 – 12.1
Combined Peaking and Intermittent	Wind (onshore) backed up with Natural Gas Combustion Turbine	85		8.9	0.1	0.8	9.7
	Solar (PV) backed up with Natural Gas Combustion Turbine	85		12.2	0.1	0.9	13.2
Peaking Generating Technologies							
Modified Traditional	Natural Gas (Conventional Combustion Turbine)	30		10.8	0.2	1.3	12.2
Intermittent Generating Technologies							
Renewables	Wind (onshore)	34		8.0[h]	UTQ	~0	8.0
	Wind (offshore)	34		19.1[h]	UTQ	~0	19.1
	Solar (PV)	25		19.5[h]	UTQ	~0	19.5
	Solar (thermal)	18		29.7[h]	UTQ	~0	29.7

Notes and Sources for Table 1

All dollar figures are in 2010 U.S. Dollars (USD). Values not originally reported in 2010 USD are inflated using the Consumer Price Index. A technical appendix (available on request) includes a full description of the methodology and assumptions used to generate these estimates. Cost figures may not sum due to rounding. PC stands for pulverized coal, PV for photovoltaic, PWR for pressurized water reactor, and UTQ for "unable to quantify."

Sources: Authors' calculations; Yangbo Du and John E. Parsons, "Update on the Costs of Nuclear Power," Working Paper 09-004, MIT Center for Energy and Environmental Policy Research, May 2009, http://web.mit.edu/mitei/docs/spotlights/nuclear-fuel-cycle-du.pdf; Energy Information Administration, *Annual Energy Outlook 2011* (Washington, D.C.: Department of Energy, April 2011), http://www.eia.gov/forecasts/aeo/; Energy Information Administration, "Updated Capital Costs for Electricity Generating Plants," November 2010, http://www.eia.gov/oiaf/beck_plantcosts/pdf/updatedplantcosts.pdf; Energy Information Administration, "Consumption Price and Expenditure Estimates, State Energy Data System (SEDS)," June 2010, Table S6a, http://www.eia.gov/states/hf.jsp?incfile=sep_sum/plain_html/sum_pr_eu.html; Energy Information Administration, "Levelized Cost of New Generation Resources in the *Annual Energy Outlook 2011*," 2010, http://www.eia.doe.gov/oiaf/aeo/electricity_generation.html; Energy Information Administration, "Monthly Energy Review," April 2011, Table 7.2a, "Electricity Net Generation: Total (All Sectors)," http://www.eia.doe.gov/totalenergy/data/monthly/query/mer_data.asp?table=T07.02; Energy Information Administration, "Electric Power Annual," April 2011 (rev.), Table 5.3, http://www.eia.doe.gov/cneaf/electricity/epa/epat5p3.html; Energy Information Administration, "Electric Power Monthly," April 2011, Tables 4.10.A and 4.13.A, http://www.eia.doe.gov/electricity/data.cfm#avgcost; Energy Information Administration, "Updates by Energy Source, State Energy Data System (SEDS)," April 2011, Table F23, http://www.eia.gov/states/hf.jsp?incfile=sep_fuel/html/fuel_nu.html; Interagency Working Group on Social Cost of Carbon, "Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866," February 2010, http://www.epa.gov/oms/climate/regulations/scc-tsd.pdf; Internal Revenue Service, "How to Depreciate Property," Publication 946, Cat. No. 13081F, 2011; National Academy of Sciences, *Hidden Costs of Energy* (Washington, D.C.: National Academies Press, 2010).

[a] Estimates for existing coal, natural gas, and nuclear facilities assume the same fuel costs and capacity factors as the new coal dual unit advanced PC, the new natural gas conventional combined cycle, and the new nuclear (PWR) plants, respectively. Existing plants are assumed to have two-thirds the operating, management, and maintenance costs of the corresponding new plants to reflect the fact that existing plants, on average, are subject to less stringent environmental standards and use older technologies. Existing plants are assumed to have fully depreciated all initial capital costs. To account for the fact that existing plants are, on average, less efficient than new plants, we use the estimated heat rates for existing plants in 2009 from Energy Information Administration, "Electric Power Annual," April 2011 (rev.), Table 5.3, http://www.eia.doe.gov/cneaf/electricity/epa/epat5p3.html. The heat rates are 10,461 Btu/kWh for coal, 8,160 Btu/kWh for natural gas, and 10,460 Btu/kWh for nuclear.

[b] These estimates do not include experimental technologies such as plants with carbon capture and sequestration or integrated gasification combined-cycle plants.

[c] Source: Energy Information Administration, "Levelized Cost of New Generation Resources in the *Annual Energy Outlook 2011*," 2011, http://www.eia.doe.gov/oiaf/aeo/electricity_generation.html.

[d] Source: Energy Information Administration, "Monthly Energy Review," April 2011, Table 7.2a, "Electricity Net Generation: Total (All Sectors)," http://www.eia.doe.gov/totalenergy/data/monthly/query/mer_data.asp?table=T07.02.

[e] Private cost estimates for new capacity are levelized costs: they reflect the present discounted value of the total cost of constructing, maintaining, and operating an electricity-generating plant over its entire lifetime and are expressed in terms of real cents per kWh.

[f] Authors' estimates based on a model developed by Yangbo Du and John E. Parsons, "Update on the Costs of Nuclear Power," Working Paper 09-004, MIT Center for Energy and Environmental Policy Research, May 2009, http://web.mit.edu/mitei/docs/spotlights/nuclear-fuel-cycle-du.pdf. Most cost inputs for new capacity, including overnight capital costs, operation and management costs, and heat rates, come from Energy Information Administration, "Updated Capital Costs for Electricity Generating Plants," November 2010, http://www.eia.gov/oiaf/beck_plantcosts/pdf/updatedplantcosts.pdf. Fuel price estimates for coal and natural gas come from Energy Information Administration, "Electric Power Monthly," April 2011, Tables 4.10.A and 4.13.A, http://www.eia.doe.gov/electricity/data.cfm#avgcost; those for nuclear power come from Energy Information Administration, "Updates by Energy Source, State Energy Data System (SEDS)," April 2011, Table F23, http://www.eia.gov/states/hf.jsp?incfile=sep_fuel/html/fuel_nu.html; and those for biomass come from Energy In-

formation Administration, "Consumption Price and Expenditure Estimates, State Energy Data System (SEDS)," June 2010, Table S6a, http://www.eia.gov/states/hf.jsp?incfile=sep_sum/plain_html/sum_pr_eu.html. All plants are assumed to have identical forty-year lifetimes. Estimates for new capacity refer to plants coming online in 2017 to compensate for the significant lead time required to construct many types of new plants.

[g] Range reflects alternative financing costs. The low end of the range assumes a weighted average cost of capital of 7.8 percent (the same assumption for all other technologies), while the high end of the range assumes a weighted average cost of capital of 10 percent. This approach follows *The Future of Nuclear Power: An Interdisciplinary MIT Study* (Cambridge, Mass.: Massachusetts Institute of Technology, 2003), http://web.mit.edu/nuclearpower/; and Du and Parsons, "Update on the Costs of Nuclear Power." The capital cost estimates from Energy Information Administration, "Updated Capital Costs for Electricity Generating Plants" assume that the nuclear plant is built in a brownfield site; greenfield sites may be more expensive.

[h] Estimates for wind and solar are based on current market costs, which have been declining due to advances in technology. Some analysts argue that improved technology will substantially reduce the price of wind and solar power. For example, if overnight capital costs of solar PV were reduced to $2,000/kW, levelized costs for solar PV would drop to 8.6¢/kWh.

[i] Source: National Academy of Sciences, *Hidden Costs of Energy*, 92 (coal) and 118 (natural gas). The NAS estimates the monetized costs resulting from emissions of SO_2, NO_x, and PM2.5 and PM10 (two forms of particulate matter) from existing natural gas and coal power plants, assuming a value of a statistical life of $6 million (in 2000 USD). These estimates do not include external costs other than from those four air pollutants, nor do they include "upstream" costs resulting from mining, drilling, construction, and other activities not directly associated with electricity generation. While it is likely that new plants are more efficient, the assumption that both existing and new plants have the same external costs reflects the fact that both existing and new plants are included under the same SO_2 and NO_x cap-and-trade cap.

[j] Reliable estimates of the non-carbon external costs are unavailable for many electricity-generation technologies, even for technologies like nuclear or hydroelectric, which have demonstrable environmental or health costs. We label non-carbon external costs of these technologies "unable to quantify" (UTQ)

[k] Source: For tons of CO_2/Btu or tons of CO_2/MWh (megawatt hour), see Energy Information Administration, "Updated Capital Costs for Electricity Generating Plants"; for external costs of carbon at $22.5/ton of CO_2 (2010 USD), see the Interagency Working Group on Social Cost of Carbon, "Technical Support Document."

[l] The range of carbon emissions estimates reflects uncertainty regarding the source of biomass fuel materials.

[m] Intermittent energy sources, such as wind and solar, produce power only during periods of sufficient wind and sunlight. The costs in this table do not attempt to monetize the reduction in value that this intermittency imposes on energy users. On an adjusted basis, wind and solar would be more costly. Conversely, peaking generating technologies, such as natural gas combustion turbines, are used only during periods of fluctuating high demand, and thus appear expensive in this comparison. For a more detailed discussion, see Paul Joskow, "Comparing the Costs of Intermittent and Dispatchable Electricity Generating Technologies," CEEPR Working Paper, MIT Center for Energy and Environmental Policy Research, September 2010, http://econ-www.mit.edu/files/6317. In an attempt to define a more appropriate comparison of wind and solar to other base-loading technologies, "Combined Peaking and Intermittent" presents estimates of hybrid wind and solar PV facilities that are backed up by natural gas combustion turbines during periods of intermittency. These hypothetical plants assume that a renewable source is paired with a natural gas combustion turbine of sufficient capacity such that the turbine could fully substitute for the renewable source if it produced no output during some time periods. The average capacity factor of the paired natural gas combustion turbine is chosen such that the average capacity factor for the combined plant is equal to 85 percent (roughly the capacity factor for traditional coal and natural gas combined-cycle plants).

For example, for nuclear and hydroelectric power, the costs from nuclear accidents or from damage to fisheries are very real, but few studies have reliably estimated those costs. Additionally, the prices of fuel sources are determined by market forces, and can rise or fall over time, leading to changes in private costs. Similarly, innovation has reduced the costs of many emerging technologies and may continue to reduce costs in the future.

The fifth column shows estimates of the levelized private costs of generating new electricity from different sources. For baseline power (power that is not subject to interruption), hydroelectric and coal are the least expensive energy sources when measured by private costs.

However, these private costs do not take into account the significant external costs stemming from many electricity sources. The sixth column shows the non-carbon external costs associated with different types of electricity sources, such as negative effects on health and the environment. Coal has high non-carbon external costs of 3.4¢ per kWh – roughly the same size as its private costs for existing capacity and more than 50 percent of its private costs for new capacity. The next column shows the costs associated with carbon emissions, assuming an SCC of $21.4 per ton (the preferred estimate of the Interagency Working Group on Social Cost of Carbon).

The final column shows the social costs, which is the sum of all private and external costs. The costs of several electricity sources increase dramatically when the full costs of production are included. For example, the social cost of existing coal plants is more than double the private cost (8.8¢ compared to 3.2¢); the social cost of new conventional coal plants is roughly 83 percent higher than the private costs (11.5¢ compared to 6.2¢), making coal the most expensive new nonrenewable source of energy. Conversely, for many other electricity-producing technologies, such as hydro, nuclear, wind, and solar, the private costs make up the vast majority of the social costs.

Estimates of the costs of "intermittent" energy sources – wind and solar – must also be adjusted to reflect the fact that they cannot be compared directly to those of base-loading technologies: wind power plants produce power only when there is wind, and solar power plants produce power only when there is sunlight. Sunny and windy times of the day or year do not always correspond to times when demand for power is greatest. Consequently, these types of energy are less valuable even if the cost per kWh is the same as coal, natural gas, or other "dispatching" energy sources (sources that can be turned on and off to produce power when needed most). Similarly, cost estimates for "peaking" generation technologies, such as natural gas combustion turbines, overstate their costs because they are specifically designed to be used in times of very high demand for electricity.

To put these sources on comparable footing, we created hypothetical plants that include intermittent technologies paired with a peaking generation technology (natural gas combustion turbines) that could meet energy needs during periods when solar or wind power is unavailable. These estimates, which we label "Combined Peaking and Intermittent" in Table 1, suggest that some versions of these combined plants could be competitive with many existing technologies if the full social costs of energy production were taken into account. For example, the combined wind/combustion turbine power plant would have social costs almost 2¢ per kWh less than that of new coal capacity. However, this combined wind/combustion turbine technology would still have significantly higher social costs than many other options, including new conventional natural gas power plants and existing coal power plants. Furthermore, the wind and solar estimates are based on siting plants in optimal locations for harvesting these energy sources; the cost estimates would be higher, potentially significantly so, in other locations.

Figure 5 summarizes several of the most important electricity sources from Table 1. These sources are shown in order of their private costs. The private costs are in black, the non-carbon external costs (mostly health costs) are black-and-white checkered, and carbon costs due to climate change are in light gray. The dramatic differences in the private and social costs of different energy sources illustrate how the low-private-cost energy sources we rely on often come with high external costs.

When private costs alone are considered, existing coal power plants appear to be a great deal. These plants account for roughly 45 percent of the electricity in the United States, and they do so at an average price of 3.2¢ per kWh. This appears to be a bargain, but the true costs are much higher – in fact, they are 170 percent higher. Each kWh of coal-generated electricity comes with an additional 5.6¢ per kWh of damages to our well-being, from a combined 3.4¢ per kWh of non-climate-change-related damages (primarily health-related) and 2.2¢ per kWh of climate-change-related damages. Although these costs are not listed on our monthly utility bills, they are nevertheless real. They show up in shorter life spans, higher health care bills, and a changing climate that poses risks to our way of life.

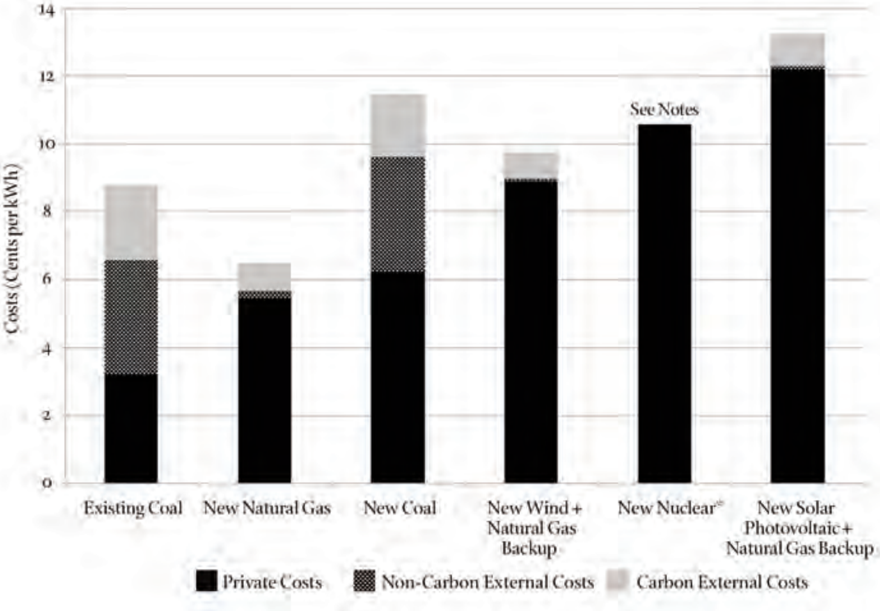
Figure 5 also reports on the costs of other electricity sources. Electricity from new coal plants is more expensive than from existing plants, largely due to the capital costs of building the plant; however, because new plants are slightly cleaner, external costs are modestly lower. Once the full costs of all energy sources are accounted for, natural gas power plants are among the least expensive electricity sources. This outcome reflects the low prices of natural gas due to the recent dramatic increase in reserves and the fact that the health and environmental costs associated with natural gas are lower than for other fossil fuels. (At the time of this writing, the environmental costs associated with the extraction of natural gas through fracking are largely unknown and could increase the social costs of natural gas use.)

For vehicles and transportation, the story is similar. From sticker prices on new cars to the price at the pump, the private costs of transportation are readily apparent to most Americans. The private costs to purchase, maintain, and fuel the average car add up to about $0.51 per vehicle mile traveled over the car's lifetime.[35] But cars, trucks, and other vehicles also impose costs by polluting the air, emitting greenhouse gases, contributing to traffic on busy roads, and through injuries and deaths from car crashes.[36] These external costs amount to more than $0.10 per vehicle mile traveled, or roughly $16,000 for a car that is driven 150,000 miles[37] – which represents more than 20 percent of the car's lifetime private costs.

An additional consequence of the costs in Table 1 is that industry and consumers have little incentive to change their energy preferences based on comparison of direct costs. This is because coal and gasoline are comparatively inexpensive when only their private costs are considered.

In addition to the private and external costs of these energy sources, policies to influence energy production also consume significant fiscal resources. Table 2 details the many subsidies and financial incentives for different types of energy production provided by federal, state, and local governments. The higher cost per kWh for some sources is frequently justified as the result of efforts to jump-start in-

Figure 5
The Private, External, and Social Costs of Electricity Generation



*The non-carbon external costs of nuclear power, including the risk of serious accidents, have not been quantified for this figure. Non-carbon external costs include only damages associated with operating the plant, not "upstream" costs from mining, drilling, and extraction of fuels (including any environmental costs associated with fracking), or from plant construction. Sources: See notes for Table 1.

novations that are necessary to lower costs.

Other government programs also give a boost to preferred energy sources. Liability for nuclear disasters is capped at $12.6 billion, and oil companies' responsibility for spills is capped at $350 million for onshore facilities and $75 million for offshore facilities.[38] Thus, these energy producers are protected from the risks they impose on society, liabilities that other businesses are required to shoulder.[39] Additionally, federal and state legislation has granted a host of subsidies for ethanol production and use, including a tax credit equal to $0.45 per gallon for blending ethanol with other fuels and a variety of other standards that require the use of ethanol.[40] These subsidies impose a substantial fiscal cost on taxpayers while creating market distortions.

Efforts to address the environmental, health, and climate-related effects of our current energy sources are often derided as too costly. But Table 1 emphasizes that many current energy sources are already more costly than perceived; those costs are simply more diffuse and less salient because they indirectly impact health, economic activity, the environment, and national security. Although there are undoubtedly costs associated with moving to energy sources that require higher private outlays, the introduction of policies that cause producers of all energy sources to recognize the full social (that is, private *plus* external) costs will level the playing field and improve our well-being.

Table 2
Federal Energy Subsidies

Type of Energy	FY 2007 Net Generation (billions of kWh)	2007 Federal Subsidy and Support Value (in millions of dollars)
Coal	1,946	854
Refined Coal	72	2,156
Natural Gas and Petroleum Liquids	919	227
Nuclear	794	1,267
Biomass (and biofuels)	40	36
Geothermal	15	14
Hydroelectric	258	174
Solar	1	14
Wind	31	724
Landfill Gas	6	8
Municipal Solid Waste	9	1

Source: Energy Information Administration, "Federal Financial Interventions and Subsidies in Energy Markets: 2007," April 2008, Table 35, http://www.eia.doe.gov/oiaf/servicerpt/subsidy2/.

For example, EPA analyses indicate that the benefits of recently proposed policies to address climate change would have exceeded their costs. The analyses suggest cumulative domestic costs of a cap-and-trade bill at $600 billion to $1 trillion through 2050.[41] But the global cumulative benefits of the emissions reductions produced by enacting a cap-and-trade system would be approximately $1.5 trillion to $1.7 trillion over the same period, indicating that the benefits would have been much larger than the costs. Although a substantial proportion of these benefits would accrue outside the United States, many believe that the adoption of such a carbon policy would lead other countries to implement similar policies to reduce carbon emissions that would produce substantial benefits for the United States.

Reforming Energy Policy. Energy consumption is critical to economic growth and quality of life. America's energy system, however, is malfunctioning. The status quo is characterized by a tilted playing field, where energy choices are based on the visible costs that appear on utility bills and at the gas pump. This system masks the external costs arising from those energy choices, including shorter lives, higher health care expenses, a changing climate, and weakened national security. As a result, society pays unnecessarily high costs for energy.

New "rules of the road" could level the energy playing field. Drawing from our work for The Hamilton Project, we offer the following principles for reforming U.S. energy policies in order to increase Americans' well-being:

1) *Appropriately price the external costs of energy production and use.* Fossil fuels such as coal, oil, and natural gas have costs beyond what users pay to the utility company or at the gas pump. These costs – ranging from increases in lung disease and infant mortality to problems associated with climate change – have been quantified and can be expressed in dollar terms. As argued in the Hamilton Project paper "An Economic Strategy to Address Climate Change and Promote Energy Security"[42] and elsewhere, the best approach is to price these costs directly, through cap and trade or tax policies. If firms and consumers faced the full cost of their energy use, they would have a greater incentive to make more-informed and socially efficient decisions about energy consumption.

2) *Fund basic research development and demonstration.* Many believe that technological innovations are the solution to finding cleaner low-cost energy sources – in other words, that we will innovate our way out of our energy and climate change problems. Unfortunately, there is little incentive for the private sector to undertake either basic research or technology demonstration projects that are good for society because they may not offer the promise of a profitable private return. One impediment is the lack of a clear price signal that provides the right incentive for innovation. A second impediment is the fact that the fruits of basic research and demonstration investments – ideas and methods, as well as information about the commercial viability of these innovations – are hard to capture as they are easily shared among competitors. This impediment would exist even in the presence of cap and trade or a tax based on carbon's social costs. This creates a critical role for government research to provide funding and support for the types of basic research that could help facilitate the creation of low-cost, clean energy sources.

3) *Make regulations more efficient.* Regulation has played, and will continue to play, a significant role in addressing the environmental and health consequences of energy consumption. The current process for promulgating regulations needs to be updated to promote rules that are more efficient and cost-effective. By requiring cost-benefit analysis to evaluate the potential impact of regulations and by assessing the reliability of empirical studies that are used to complete that analysis, we can greatly enhance the effectiveness and reputation of our environmental regulatory system. Furthermore, to ensure their ongoing value, an independent, automatic retrospective review of economically significant regulations is critical. If these reviews find that the costs exceed the benefits, then the regulations should be amended or removed. Finally, genuine reform may involve rethinking and potentially eliminating regulations that become superfluous or counterproductive after energy sources are priced.

4) *Address climate change on a global scale.* Climate change is distinct from many environmental and energy-related issues in that it is global in scope and requires a global effort to address. Although the United States is a leading emitter today, in the future the bulk of emissions growth will come from developing countries. From a pragmatic standpoint, this means that any viable effort to address climate change must involve a coordinated approach by many countries. Negotiations have been complicated, however, and there are smaller steps that can be taken imme-

diately to start down the path toward a global solution. This effort can begin today with a number of measures such as building the capability to monitor total net emissions at the country level (this could be a building block for a trading system) through a combination of satellite- and land-based measurement systems. This would provide evidence of carbon emissions by countries and eliminate issues surrounding the accuracy of reporting, which has been a stumbling block in international negotiations.

A fundamental change in our energy policy will not be easy and will come with costs, with some industries and regions in the U.S. economy being more affected than others. This is because U.S. households and businesses have made decisions based on the expectation of access to energy sources with relatively low private costs. One solution is to offer compensation to those that are harmed. On net, however, the recognition of the full costs of our energy choices would deliver healthier and longer lives, an improved environment, and greater national security.

ENDNOTES

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[1] Environmental Protection Agency, Office of Air and Radiation, "EPA's Transport Rule: What Does It Mean for Environmental Justice Communities?" September 2010, http://www.epa.gov/airtransport/pdfs/WebinarTransportRuleMaterials.pdf.

[2] Abt Associates, "Power Plant Emissions: Particulate Matter-Related Health Damages and the Benefits of Alternative Emission Reduction Scenarios," Report for the Clean Air Task Force, June 2004, http://www.abtassociates.com/reports/Final_Power_Plant_Emissions_June_2004.pdf.

[3] Yuyu Chen, Avraham Ebenstein, Michael Greenstone, and Hongbin Li, "The Long-Run Impact of Air Pollution on Life Expectancy: Evidence from China's Huai River Policy," working paper, 2012.

[4] National Academy of Sciences, *Hidden Costs of Energy* (Washington, D.C.: National Academies Press, 2010), 154.

[5] Intergovernmental Panel on Climate Change, "Summary for Policymakers," in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment*

Report of the Intergovernmental Panel on Climate Change, ed. Susan Solomon, Dahe Qin, Martin Manning, Zhenlin Chen, Melinda Marquis, Kristen Averyt, Melinda M.B. Tignor, and Henry LeRoy Miller, Jr. (Cambridge and New York: Cambridge University Press, 2007).

[6] Interagency Working Group on Social Cost of Carbon, "Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866," February 2010, http://www.epa.gov/oms/climate/regulations/scc-tsd.pdf; Environmental Protection Agency, "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2009," 2011, Table ES-2, http://www.epa.gov/climatechange/emissions/downloads11/US-GHG-Inventory-2011-Executive-Summary.pdf.

[7] Environmental Protection Agency, ENERGY STAR Program, *Report to Congress on Server and Data Center Energy Efficiency Public Law 109-431*, August 2007, 7.

[8] Energy Information Administration, "Shares of World Energy Consumption in the United States, China, and India, 1990 – 2035," in *2010 International Energy Outlook* (Washington, D.C.: Department of Energy, 2010), Figure 14, http://www.eia.doe.gov/oiaf/ieo/world.html.

[9] International Energy Agency, "Energy Poverty: How to Make Modern Energy Access Universal?" in *World Energy Outlook 2010* (Paris: Organisation for Economic Co-operation and Development, September 2010), 7, http://www.worldenergyoutlook.org/docs/weo2010/weo2010_poverty.pdf.

[10] United Nations Development Programme and World Health Organization, "The Energy Access Situation in Developing Countries," November 2009, 1, http://content.undp.org/go/cms-service/stream/asset/?asset_id=2205620.

[11] World Health Organization, "Global Health Risks: Mortality and Burden of Disease Attributable to Selected Major Risks," 2009, 11 – 12, http://www.who.int/healthinfo/global_burden_disease/GlobalHealthRisks_report_full.pdf.

[12] Nicholas Muller and Robert Mendelsohn, "Measuring the Aggregate Damages of Air Pollution in the United States," *Journal of Environmental Economics and Management* 54 (2007): 1 – 14.

[13] Kenneth Chay and Michael Greenstone, "The Impact of Air Pollution on Infant Mortality: Evidence from Geographic Variation in Pollution Shocks Induced by a Recession," *Quarterly Journal of Economics* 118 (3) (August 2003).

[14] Abt Associates, "Power Plant Emissions."

[15] Olivier Deschenes, Michael Greenstone, and Joseph Shapiro, "Defending against Environmental Insults: Drugs, Emergencies, Mortality and the NO_x Budget Program Emissions Market," working paper, 2011.

[16] National Academy of Sciences, *Hidden Costs of Energy*.

[17] Douglas Almond, Lena Edlund, and Marten Palme, "Chernobyl's Subclinical Legacy: Prenatal Exposure to Radioactive Fallout and School Outcomes in Sweden," *Quarterly Journal of Economics* 124 (4) (2009).

[18] KNMI Climate Explorer, http://climexp.knmi.nl/.

[19] Intergovernmental Panel on Climate Change, "Summary for Policymakers," in *Climate Change* 2007, ed. Solomon et al.

[20] Olivier Deschenes and Michael Greenstone, "Climate Change, Mortality, and Adaptation: Evidence from Annual Fluctuations in Weather in the U.S.," *American Economic Journal: Applied Economics* 3 (4) (2011): 152 – 185; Robin Burgess, Olivier Deschenes, Dave Donaldson, and Michael Greenstone, "Weather and Death in India," working paper, 2011, http://dl.dropbox.com/u/2734209/BDDG_Weather_and_Death_paper.pdf.

[21] The $21 figure is the central value, and the U.S. government also recommended conducting sensitivity analyses at $5, $35, and $65. See Interagency Working Group on the Social Cost of Carbon, "Technical Support Document."

[22] For more information on how the SCC values were developed, see Michael Greenstone, Elizabeth Kopits, and Ann Wolverton, "Estimating the Social Cost of Carbon for Use in Federal Rulemakings: A Summary and Interpretation," NBER Working Paper No. 16913, National Bureau of Economic Research, March 2011, http://www.nber.org/papers/w16913.pdf.

[23] Denise L. Mauzerall and Xiaoping Wang, "Protecting Agricultural Crops from the Effects of Tropospheric Ozone Exposure: Reconciling Science and Standard Setting in the United States, Europe and Asia," *Annual Review of Energy and the Environment* 26 (2001): 237–268; John Reilly, Sergey Paltsev, Benjamin Felzer, Xiaoping Wang, David Kicklighter, Jerry Melillo, et al., "Global Economic Effects of Changes in Crops, Pasture, and Forests due to Changing Climate, Carbon Dioxide, and Ozone," *Energy Policy* 35 (11) (2007): 5370–5383.

[24] Rema Hanna and Paulina Oliva, "The Effect of Pollution on Labor Supply: Evidence from a Natural Experiment in Mexico City," NBER Working Paper No. 17302, National Bureau of Economic Research, August 2011; Janet Currie, Eric Hanushek, E. Megan Kahn, Matthew Neidell, and Steven Rivkin, "Does Pollution Increase School Absences?" *The Review of Economics and Statistics* 91 (4) (2009): 682–694.

[25] Joshua S. Graff Zivin and Matthew J. Neidell, "The Impact of Pollution on Worker Productivity," NBER Working Paper No. 17004, National Bureau of Economic Research, April 2011, http://www.columbia.edu/~mn2191/w17004.pdf.

[26] Adam Sieminski, "Energy and the Economy," 2010 EIA-SAIS Energy Conference, Washington, D.C., April 6–7, 2010, http://www.eia.doe.gov/conference/2010/session5/sieminski.pdf.

[27] National Academy of Sciences, *Hidden Costs of Energy*.

[28] James Hamilton, "Oil Prices and the Economic Downturn," Testimony Prepared for the Joint Economic Committee of the U.S. Congress, May 2009; James Hamilton, "Historical Oil Shocks," working paper, Department of Economics, University of California, San Diego, February 2011, Table 1, 33, http://dss.ucsd.edu/~jhamilto/oil_history.pdf.

[29] Olivier Blanchard and Jordi Gali, "The Macroeconomic Effects of Oil Price Shocks: Why are the 2000s So Different from the 1970s?" NBER Working Paper No. 13368, National Bureau of Economic Research, September 2007; James Hamilton, "Causes and Consequences of the Oil Shock of 2007–2008," Department of Economics, University of California, San Diego, April 2009, http://dss.ucsd.edu/~jhamilto/Hamilton_oil_shock_08.pdf.

[30] "Oral History: Brent Scowcroft," interview with PBS *Frontline*, January 1996, http://www.pbs.org/wgbh/pages/frontline/gulf/oral/scowcroft/1.html.

[31] Energy is usually measured in kWh, which is equal to the amount of energy consumed by a 100-watt lightbulb if turned on for ten hours.

[32] Michael Greenstone and Adam Looney, "A Strategy for America's Energy Future: Illuminating Energy's Full Costs," The Hamilton Project strategy paper, Brookings Institution, May 2011, http://www.hamiltonproject.org/files/downloads_and_links/05_energy_greenstone_looney.pdf.

[33] National Academy of Sciences, *Hidden Costs of Energy*.

[34] Interagency Working Group on Social Cost of Carbon, "Technical Support Document."

[35] Internal Revenue Service, "2011 Standard Mileage Rates," Notice 2010-88, 2010.

[36] Ian W.H. Parry and Kenneth A. Small, "Does Britain or the United States Have the Right Gasoline Tax?" *American Economic Review* 95 (4) (2005): 1276–1289.

[37] Ian W.H. Parry, Margaret Walls, and Winston Harrington, "Automobile Externalities and Policies," Discussion Paper 06-26 (rev. ed.), Resources for the Future, January 2007, http://www.rff.org/documents/RFF-DP-06-26-REV.pdf.

[38] Environmental Protection Agency, "Oil Pollution Act Overview," http://www.epa.gov/oem/content/lawsregs/opaover.htm; Nuclear Regulatory Commission, Office of Public

Affairs, "Fact Sheet on Nuclear Insurance and Disaster Relief Funds," August 2010, http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/funds-fs.pdf.

[39] Michael Greenstone, "The Benefits of Cap-and-Trade Would Have Exceeded Its Costs," Up Front blog, The Hamilton Project, Brookings Institution, July 2010, http://www.brookings.edu/opinions/2010/0730_climate_change_greenstone.aspx.

[40] Department of Energy, "Volumetric Ethanol Excise Tax Credit (VEETC)," http://www.afdc.energy.gov/afdc/laws/law/US/399; Environmental Protection Agency, Office of Transportation and Air Quality, "EPA Finalizes 2011 Renewable Fuel Standards," November 2010, http://www.epa.gov/otaq/fuels/renewablefuels/420f10056.pdf; John Collins Rudolf, "End Ethanol Subsidies, Senators Say," *The New York Times*, November 30, 2010, http://green.blogs.nytimes.com/2010/11/30/end-ethanol-subsidies-senators-say/.

[41] Greenstone, "The Benefits of Cap-and-Trade Would Have Exceeded Its Costs."

[42] Jason Furman, Jason Bordoff, Manasi A. Deshpande, and Pascal Noel, "An Economic Strategy to Address Climate Change and Promote Energy Security," The Hamilton Project strategy paper, Brookings Institution, October 2007, http://www.brookings.edu/~/media/Files/rc/papers/2007/10climatechange_furman/10_climatechange_furman.pdf.

Energy Policy: Past or Prologue?

Michael J. Graetz

Abstract: The United States was remarkably complacent about energy policy until the Arab oil embargo of 1973. Since then, we have relied on unnecessarily costly regulations and poorly designed subsidies to mandate or encourage particular forms of energy production and use. Our presidents have quested after an elusive technological "silver bullet." Congress has elevated parochial interests and short-term political advantages over national needs. Despite the thousands of pages of energy legislation enacted over the past four decades, Congress has never demanded that Americans pay a price that reflects the full costs of the energy they consume. Given our nation's economic fragility, our difficult fiscal situation, and the daunting challenges of achieving energy security and limiting climate change, we can no longer afford second- and third-best policies. This essay discusses the failures of the past and how we might avoid repeating them.

We take it for granted that when we come home at night and flip on the light switch, the bulb will illuminate. We also expect the heat to come on when we turn up the thermostat. Although we sometimes flinch at the price, we assume that when we pull up to one of the more than one hundred thousand gas stations in the United States, the fuel will flow from below the asphalt into our cars' gas tanks.

For most of our nation's history, we were able to garner all the energy we used from our own lands: first, wood, then coal and oil. From the end of World War II through the late 1960s, the United States not only produced the bulk of oil consumed domestically, but also served as emergency supplier to the rest of the free world. Large U.S. and British oil companies controlled vast oil reserves in the Middle East. Before the 1970s, our nation's policy struggles over oil had mostly dealt with how to respond to abundance.

We remained remarkably complacent about energy policy until the Arab oil embargo in October 1973 surprised our political leaders and stunned the American public. Complacency had taken hold largely because oil prices had been remarkably sta-

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ble, or even declining, for decades. Oil had been plentiful and cheap. Inflation in energy products had been lower than inflation generally.

The job of U.S. energy regulators – primarily state agencies, such as the Oklahoma Commerce Commission and the Texas Railroad Commission – had predominately been to manage abundant supplies. In effect, they limited output so as not to exceed domestic consumption. In 1969, when he visited the United States to attend President Dwight Eisenhower's funeral, the Shah of Iran offered to sell the United States a million barrels of oil a day for a decade at $1 a barrel; but, in a decision we would come to regret, U.S. policy-makers brushed his offer aside. In May 1971, when Saudi Arabia's King Faisal visited Richard Nixon, oil was not even discussed. Our most conspicuous policy involving oil was an import quota that Eisenhower adopted in the 1950s. The quota kept foreign oil out of the country and raised oil prices high enough to satisfy the oil producers but without making consumers fret. We used up our own oil when it was cheap and plentiful, rather than buying Middle East and Venezuelan oil when it was even cheaper.

But dramatic change was afoot. Principally as a result of strong economic growth and rising incomes, total world energy consumption more than tripled between 1949 and 1972. Worldwide oil demand more than quintupled during this postwar period. However, vast new discoveries and production of oil, especially in the Middle East, had kept prices remarkably stable. The U.S. public viewed abundant, inexpensive oil as a birthright.

Our problems started with Muammar al-Qaddafi. Before he came along, the Organization of Petroleum Exporting Countries (OPEC) had been an ineffectual and unimportant oil cartel. But in 1969, the twenty-seven-year-old Qaddafi led a military coup that overthrew Libya's King Idris. Soon thereafter, Qaddafi expelled all American and British troops from their large Libyan air bases. Then – at a time when Libya was supplying about 30 percent of Europe's oil imports – Qaddafi demanded substantial increases in the price of Libya's oil. Executives of the major oil companies, badly underestimating both Qaddafi's determination and his political skill, essentially ignored him. Qaddafi then went after one of the smaller independent companies, Occidental Petroleum, cutting its production by more than one-third and demanding a substantial price hike. Unlike the major companies, with large sources of oil elsewhere, Occidental depended entirely on Libyan oil to supply its European refineries. Qaddafi knew that. And after Exxon foolishly refused to make up Occidental's shortfall by selling it, at cost, the oil it needed, Occidental capitulated to Qaddafi's price demands. This move gave the majority of profits to Libya, ending the historical 50-50 profit split between the oil companies and the oil-producing nations that had prevailed since the 1950s. It also unmistakably and irrevocably transferred power over Middle East oil away from the oil companies to the oil-producing nations.

Following Qaddafi's lead, Abu Dhabi, Iran, Iraq, Kuwait, Qatar, and Saudi Arabia also sought higher prices for their oil. But the price increases did not satisfy Qaddafi or the other OPEC nations for long: demanding "equity participation" in the oil companies, they established control over the oil in their lands. Soon after this turning point, the 1973 embargo made it unmistakable that control over Middle East oil production had shifted away from U.S. and European oil companies – which for decades had dictated both the level of output and prices – to the countries in whose lands the oil was located.

The structural factors that made OPEC ineffective for its first decade had changed. In March 1971, Texas oil producers announced that they had reached peak oil production and that their output would begin to decline. By 1973, the United States was consuming 6.3 million barrels of oil per day more than it produced; Japan, 5 million more barrels than it produced; and Europe, 13.1 million more than it produced. The Middle East countries were exporting more than 20 million barrels a day. Middle East petroleum reserves were then estimated to exceed 316 billion barrels, while those in every other region of the world were estimated to have fallen to less than 50 billion. With the Middle East governments now in command, the oil companies served primarily as their technicians, sales agents, and managers.

Richard Nixon, the first of eight presidents to confront our nation's new dependence on foreign oil, thought he had a solution in turning to our Cold War allies Saudi Arabia and Iran for support. Washington provided both countries with military aid and encouraged their economic interdependence with the United States, hoping that in exchange they would serve as the Middle East's "two pillars" of anti-Soviet stability and free-flowing oil. Needless to say, that plan failed miserably.

The Iranian pillar collapsed a few years later in an anti-American Islamic revolution. And even though Saudi Arabia and the other Arab states of the Persian Gulf have nominally remained U.S. allies, they, not we, hold the key strings in the relationship. The United States continues to support and aid these regimes despite their authoritarianism. If the sheiks of the Persian Gulf decide to put down popular unrest with the same fervor of Libya and Syria, the hands of U.S. foreign policy will almost certainly be tied.

Our domestic policies also failed us. Notwithstanding all the new laws that Congress has enacted since the oil embargo of 1973, we still have not solved our nation's energy problems. For forty years, we have had no effective response to what all eight presidents from Richard Nixon to Barack Obama have called our "addiction to oil."

When the embargo hit in Fall 1973, both oil and natural gas were subject to domestic price controls that held their prices substantially below market levels. Controls on interstate natural gas prices had been part of our regulatory landscape since the late 1930s. By the mid-1970s, unregulated intrastate natural gas prices were three or four times as great as interstate prices, despite lower transportation costs. In the harsh winters of 1977 and 1978, severe shortages in the Northeast and Midwest led to federal rationing among users.

Oil price controls were a more recent phenomenon, a creature of Richard Nixon's 1971 wage and price freeze, which he had instituted for political advantage – not for the plan's economic soundness. The president and his advisors had expected the freeze to last only ninety days, with a short thawing period to follow. But the plan did not play out as anticipated: a 118-page government report was needed simply to describe the four phases of rules and regulations and some of the effects of petroleum price controls from the August 1971 freeze until the end of 1975 – nearly six years before the controls would be lifted.[1] Price controls produced shortages of home heating oil; lower domestic oil, coal, and natural gas production; hoarding and black market transactions; uncertainty throughout the energy industry and among energy users; and the bestowing of favorable or unfavorable treatment on categories of buyers and sellers unrelated to considerations of fairness or efficiency – to name just a few unfortunate and unintended consequences.

Price controls for oil and gas remained long after other controls had expired. After a period of general controls, a large price explosion followed, ultimately contributing to the combination of high unemployment and high inflation – the dreaded "stagflation" – that would haunt the country in the 1970s. Keeping the prices of oil and natural gas artificially low not only decreased incentives to conserve energy but also diminished the prospects for successfully developing and marketing alternative energy sources.

The political struggle over whether to decontrol the prices of oil and natural gas proved to be the dominant and most contentious energy policy issue of the 1970s, inhibiting policy-makers' ability to respond to a brand-new set of energy conditions. Decontrol of natural gas prices began after 1978, when Congress enacted extraordinarily contentious and complex legislation that slowly allowed prices to rise to market levels over a number of years. On January 28, 1981, eight days after being sworn in as president, Ronald Reagan used the unilateral power that Congress had given the president to lift all federal controls on oil and gasoline prices.

The contradictions of our energy policy in the 1970s had become apparent: Congress endeavored to keep oil and gas prices low to benefit energy consumers, while presidents and environmental organizations exhorted citizens to use less. But why would a homeowner or business make large capital investments in energy-saving windows or insulation, for example, when natural gas and heating oil were cheap? Artificially low prices for oil and gas also hampered the environmentalists' quest for a "soft" energy path. The prices made it much more difficult for energy produced from the sun, wind, or other nonfossil sources to compete with fossil fuels. "For more than nine years," Reagan said, "restrictive price controls have held U.S. oil production below its potential, artificially boosted energy consumption, aggravated our balance of payments problems, and stifled technological breakthroughs."[2] Right on all counts.

After we fulfilled John Kennedy's promise by landing a man on the moon in 1969, presidents viewed committing the nation to a major technological project as proof of their vision and determination. It is therefore not surprising that our presidents sought a technological "silver bullet" to solve our nation's energy problems. For Richard Nixon, the nuclear "breeder reactor" was the solution. Jimmy Carter placed his bets on fueling our cars with "synfuels" made from coal. Both cost billions, and both came to naught.

In Congress, the search for technological solutions to our energy problems presented another opportunity to distribute largesse to constituents and contributors. Congress became deeply involved in the business of picking winners and losers, awarding subsidies – whether in the form of direct spending or tax breaks – in such a way that their costs were often unrelated to the benefits they were intended to produce. Decisions about what to subsidize and by how much were, at best, arbitrary and capricious. At worst, they were wasteful and even nefarious.

The most comprehensive analysis of government energy R&D efforts in the 1970s, a book aptly titled *The Technology Pork Barrel*, concludes that the biggest R&D efforts of that period – the breeder reactor and synfuels projects – were "unambiguous failures" and that our overall energy R&D effort was "hardly a success." Only the efforts to develop better and more economical photovoltaics for solar power garnered even passing marks from the authors.[3]

The greatest problems have been the tendency for Congress to place geographic considerations above technological and economic prospects, along with a pattern of boom-and-bust financing characterized by a debilitating mix of excessive optimism about technological developments, impatience for results, and a process of haste and waste. The synfuels program, for example, favored eastern over western coal for political, not technological, reasons.

Members of Congress frequently have insisted on their own personal priorities, directing funds to individual projects, locations, or institutions by earmarking projects. Between 2003 and 2006, for example, congressional earmarks in Department of Energy programs for energy efficiency, renewable fuels, and electricity production tripled from $46 million to $159 million, with earmarks accounting for about 20 percent of the total 2006 budget.[4] By 2008, congressional earmarks totaled $180 million, with an additional $46 million directed to specific energy projects, including particular biofuel plants and green buildings.[5] Earmarks that year accounted for one-half of the total R&D budget for biomass, one-third for wind, and more than one-quarter for hydrogen projects. The American Association for the Advancement of Science lamented that "earmarks eat up whatever increases there are for most energy programs and cut deeply into core R&D programs."[6] Clearly, many members of Congress have been more concerned with rewarding well-connected constituents and contributors than advancing science or promising technologies.

Federally financed R&D plays an important role in helping identify, develop, and induce the private sector to adopt the kinds of technological improvements that may ultimately enable us to shift from coal and oil to more climate-friendly fuels. But the government's spending priorities have not been set by scientists and engineers. Nor have government subsidies been neutral across products or technologies. Any way you analyze energy subsidies, you will find wide variations in their amounts relative to the fossil fuel savings they yield.

The "black liquor" scandal is the most notorious recent instance of the pitfalls of congressional efforts to pick and subsidize winners. Black liquor, a fuel byproduct from the chemical production of wood pulp used in manufacturing paper, has been used as fuel to power paper mills since the 1930s. In 2007, Congress expanded the definition of alternative fuels eligible for a 50-cents-per-gallon tax credit to include a wide range of petroleum fuels containing biomass products. Paper companies soon discovered that by adding some diesel fuel to their black liquor they could become eligible for billions in tax credits. Instead of reducing the amount of petroleum fuel by substituting a biomass product, they added diesel fuel to the biomass simply to obtain tax credits. The U.S. paper industry garnered about $8 billion from this gambit, having inadvertently become eligible for a tax benefit originally estimated to cost $100 million.

If black liquor is the most scandalous beneficiary of energy subsidies, ethanol has been the most wasteful. In 1978, Congress enacted a 40-cents-per-gallon subsidy for ethanol used in gasoline. Unlike many other subsidies for renewable energy that were allowed to expire in the 1980s, the ethanol benefit has, until December 2011, consistently been extended at a level between 40 and 60 cents a gallon.

When ethanol subsidies were first enacted, the environmental activist Barry Commoner insisted that alcohol fuel could be produced at little or no additional cost and at a commercially feasible price simply as a by-product of farming. Commoner cited a Nebraska test suggesting that a mixture of 10 percent ethanol with 90 percent gasoline would result in 5 percent better gas mileage than gasoline alone.[7] Who could resist the appeal of ethanol? It would help small farmers without increasing their costs and simultaneously produce a cleaner, more efficient automobile fuel as a by-product.

By providing large and ongoing subsidies, we have successfully substituted ethanol for a substantial amount of gasoline. But when one compares the costs of the program to its benefits, applause disappears. Despite Commoner's claims to the contrary, gasohol has a lower fuel economy than gasoline. According to a 1986 report by the U.S. Department of Agriculture, "Each gallon of ethanol contains about two-thirds as much energy as does gasoline."[8] The Department of Energy concluded that gasohol-fueled vehicles average 4.7 percent fewer miles per gallon than gasoline-fueled vehicles. In July 2010, the Congressional Budget Office estimated that in 2009 ethanol subsidies cost taxpayers $1.78 for every gallon of gasoline saved and $750 for every ton of carbon dioxide emissions saved.[9]

Despite their shortcomings, ethanol subsidies, mandates, and tariffs have enjoyed great political support. First, farm states are represented by a substantial, bipartisan, and aggressive cadre of influential senators. Second, the special importance of Iowa as the earliest state to play an important role in our presidential nominating process and the importance of corn to that state's economy have led many a vocal ethanol opponent to reverse that position when running for president. Indeed, every president who has moved into the White House since the 1970s has made campaign commitments to support ethanol subsidies. Finally, key players from corporations that have made the most money from ethanol have been exceptionally generous financiers of political campaigns. Thus, despite the waste caused by ethanol subsidies, and despite their status as a poster child for poor policy, they became very difficult to dislodge.

In the past and today, analysts of energy R&D efforts agree that success will require major institutional changes. Eliminating earmarks is a useful first step; multiyear budgeting for greater funding stability would be a second. Congress's diffuse and overlapping committee structure remains a fundamental problem, perhaps even "dooming the enterprise to failure."[10] That structure, however, is very difficult to change.

Much greater neutrality in the incentives for technological innovations and commercial development is necessary. Trying to pick winners and avoid losers has proved to be a fool's errand.

In theory, if one wanted only to substitute more benign fuels for oil and other carbon-emitting fuels and cared little about curbing overall energy use, a subsidy for the favored fuel substitutes could work as well as a tax on disfavored fuels. Congress, for example, might either increase the gasoline tax by a dollar per gallon or subsidize alternatives by a dollar for every gallon of gasoline they save. Likewise, to combat climate change, Congress might impose a tax of, say, $25 per ton on carbon-emitting fuels or grant a subsidy based on an equivalent amount of carbon dioxide emissions avoided. Either the tax or subsidy approach should decrease the costs of alternatives relative to the prices of oil, coal, and natural gas. In practice, however, taxes and subsidies operate quite differently.

For one, the burdens and benefits of taxes and subsidies are different. A tax imposed on the carbon content of fossil fuels, for example, would burden the producers and consumers of carbon-intensive products. It would raise the price of coal-fired electricity, for example, compared to solar, wind, hydro, or nuclear power, which are carbon free. The tax would reduce demand for carbon-emitting products so that people would consume less, and producers of fossil fuels might also earn smaller profits. Consumers would face higher prices for much of the electricity, gasoline, or home heating fuels they use (although the revenues from the tax could be returned to the public or, for instance, used to reduce payroll taxes so that low- and middle-income consumers would not have less money to spend or save). In contrast, the costs of subsidizing alternative sources of energy would be financed by the public at large; the subsidies would increase the profits of those who produce the favored products and lower costs for those who use them.

Importantly, imposing a tax on disfavored fuels does not create any favorites among cleaner alternatives or among particular technologies. As we have seen when it comes to subsidies, however, our government often plays favorites. In response to a tax on energy, people might change a wide range of behaviors – such as turning off lights, lowering thermostats, driving less or more slowly, properly inflating tires, and maintaining their automobiles more consistently. Congress would have a hard time subsidizing these activities in anything close to an efficient manner. It is also virtually impossible to design a subsidy so that it does not provide an unnecessary benefit for behavior that would have occurred without the subsidy. Some folks, for example, will buy insulation or a more energy-efficient air conditioner or furnace (at least when the old one wears out) without any government subsidy. If half the amount of the favored activity would have occurred without a subsidy, the cost of a subsidy doubles without any additional benefits. Limiting the benefits of a subsidy to generally incremental activity is impractical.

But since the 1970s, U.S. policy has been to subsidize the production and consumption of fuels we want to encourage rather than to tax the use of fuels we want to discourage. Politics explains why. In 1971, Richard Nixon proposed a "sulfur tax" to curb the sulfur dioxide output of coal-fired power plants, which had just reached a new all-time high – the plants having doubled their output of this noxious gas every decade since 1940. Nixon garnered little support for this tax, however. Coal companies obviously opposed it; surprisingly, so did environmental groups, which shortsightedly criticized the level of the tax, claiming that the companies would pay it rather than investing in cheaper technologies.

Other tax proposals hardly fared better. In the 1970s, the Nixon administration announced that it was considering a substantial gasoline tax increase, but it quickly dropped the idea. Gerald Ford rejected any increase in gas taxes, despite support from Alan Greenspan, chairman of his Council of Economic Advisers. President Ford also fired his key energy advisor, John Sawhill, when Sawhill publicly suggested that gasoline taxes be hiked up to 30 cents a gallon. In 1975, the House Ways and Means Committee chairman, Oregon Democrat Al Ullman, proposed a substantial gasoline tax increase, but his plan was soundly defeated on the House floor and never even considered in the Senate. In 1977, Jimmy Carter proposed (as part of his comprehensive energy plan engineered by James Schlesinger) increasing the gasoline tax by a nickel per gallon each year for ten years, up to a 50-cent ceiling, for every percentage point that the nation's gasoline consumption exceeded specified national goals. In March 1980, President Carter exercised the authority he had been given by Congress to impose a fee on oil imports, designed to function similarly to a tax on gasoline; Congress then voted overwhelmingly to stop the import fee from taking effect. As an independent candidate for president in the 1980 election, John Anderson urged an increase in gasoline taxes of 50 cents per gallon, but he garnered only about 7 percent of the popular vote. In 1983, Ronald Reagan signed a gas tax increase of a nickel per gallon to provide additional funds for highway construction and mass transit.

In both 1990 and 1993, Congress came close to imposing a substantial tax on energy consumption, but the motivation then was deficit reduction, not energy policy. In 1990, many observers blamed Congress's failure to enact an energy tax on the fact that oil prices nearly doubled (from $14 a barrel to $24 a barrel between July and September) after Iraq invaded Kuwait. This price spike made it difficult for politicians to pile additional costs onto their constituents. When all was said and done, in 1990, Congress simply increased the federal gasoline tax by another nickel a gallon.

In 1993, when oil prices were again low (having fallen back to about $14 a barrel), President Clinton urged Congress to enact an energy tax – a so-called Btu tax. After much presidential arm-twisting, the House of Representatives barely passed this provision – without garnering a single Republican vote. The Btu tax then died in the Senate. The following year, Republicans won a majority in the House of Representatives for the first time in a generation, defeating many House Democrats who had voted for the Btu tax.

In the Senate, as usual, regional politics inhibited sound policy. Higher energy taxes were opposed by a variety of regional interests, ranging from northeastern liberals worried about low-income constituents who burn home heating oil to western conservatives worried about voters who drive long distances. Midwestern senators were particularly concerned about the potential impact of an energy tax on the international competitiveness of energy-intensive manufactured products, such as steel and chemicals. The Btu tax also foundered on the opposition of key senators from the oil-producing states of Louisiana and Oklahoma.

Following al-Qaeda's attack on the World Trade Center on September 11, 2001, George W. Bush might have rallied public opinion and Congress to support a substantial increase in gasoline taxes, an oil import fee, or perhaps even a broad-based energy tax to fund the military operations he launched in Afghanistan and Iraq. He never even considered such options, however, instead funding those ventures through borrowing.

Nor has President Obama demonstrated any intention of proposing a carbon tax, a gasoline tax, or any other tax to advance his energy policy goals – no matter how strong the merits. On April 16, 2008, debating Hillary Clinton in Philadelphia at a crucial moment in their campaign for the Democratic presidential nomination, Barack Obama pledged not to raise taxes on Americans earning less than $250,000 a year. Hillary Clinton made a similar pledge. Obama repeated this pledge frequently during the 2008 campaign and after he took office: no tax increase for any family making less than $250,000 a year. This promise, of course, seems to rule out a gasoline tax increase, any broader tax on petroleum fuels and products, or a new carbon tax.

Given the failures of energy subsidies and politicians' refusals to impose substantial petroleum taxes, a broad-based energy tax, or a carbon tax, one other major policy option remains: to require specified behavior through regulations or mandates. Before the 1970s, the federal government played only a bit part in regulating energy use. The federal role consisted mostly of the Federal Power Commission's regulation of interstate natural gas; the Atomic Energy Commission's insistent promotion of nuclear power; the building of dams for hydroelectric power; and the leasing of federal lands for exploration of oil and natural gas. But by 1980 – after adding many thousands of pages of new laws and regulations – the national government had entered into every nook and cranny of our nation's energy policy, with federal regulations affecting virtually all aspects of energy production and consumption.

In 1974, for example, Congress required the administration to set specific energy-efficiency standards for thirteen household appliances and heating and cooling equipment. However, the executive branch under Presidents Ford and Carter dithered, and the Reagan administration refused to implement any such rules. Congress responded in 1987 by passing the National Appliance Energy Conservation Act, which not only set national standards for appliances, but also imposed deadlines for the Department of Energy to promulgate specific rules. In 1992, Congress extended energy-efficiency mandates to some lighting products and certain industrial and commercial technologies. More recent legislation further extended and tightened efficiency standards. States also continue to be active in regulation – with California the most aggressive.

Virtually all the federal and state regulations of the 1970s were of the "command and control" sort. Congress, the Department of Energy, the Environmental Protection Agency (EPA), and state authorities told producers and manufacturers exactly what practices were permissible and, frequently, what kind of technology had to be employed to attain regulatory goals. Under the 1970 Clean Air Act, for example, federal regulators set air-quality standards for particular regions of the country, requiring state and local authorities to impose restrictions on individual polluters in order to meet the region's goals. (In some circumstances, the federal regulators told polluters directly what limitations applied to their emissions.)

Throughout that decade, such "command and control" regulations were increasingly criticized as wasteful, expensive, and often ineffective. Complaints about updating delays and ossification became commonplace. Litigation flourished, though with decidedly mixed results. Congress and the EPA frequently loosened and postponed standards they had originally set. For example, the 1970 Clean Air Act mandated that carbon monoxide and nitrous oxide emissions for new cars be reduced by 90 percent of their 1970 levels within five years. Automobile manufacturers soon insisted that achieving this goal was impossible, and by 1977, Congress had lowered the standards to about 50 percent reductions. Even this requirement was subsequently delayed until 1981. EPA enforcement actions frequently resulted in promises by industries to comply "sometime" or "pretty soon."

As energy and environmental regulation came to the fore in the 1970s, economists began urging a regulatory innovation that we now know as "cap and trade." Elsewhere in this volume, Joseph Aldy and Robert Stavins systematically discuss this and related incentives for controlling pollution, but for purposes of our discussion, here is how cap and trade works: Congress (or the EPA) determines the volume of emissions from a particular pollutant that will be permitted. The government then issues transferable allowances to emit a specified quantity of the restricted substance(s). For example, it might issue permits to emit one ton of carbon dioxide in any particular year, with the total number of permits adding up to that year's total permissible emissions. These emissions permits or allowances may either be sold – auctioned – by the government or given away; they can be used by their owners or sold to others. The fundamental idea is that sales (or "trades") of the permits will operate to concentrate their ownership in companies that find it most expensive to curb emissions. Companies that are able to reduce or eliminate their emissions more cheaply than the price of the permits will do so, and then will sell their excess allowances to others who would otherwise have to spend more than the permits' price in order to curb their own emissions. In this way, market transactions allow emissions to be reduced in the least costly manner and avoid the wasteful additional costs that would occur under command-and-control regulations requiring each company to limit its own emissions to a government-specified level.

The most successful use of cap and trade to date, the Clean Air Act of 1990, instituted a pollution permit-trading program to tackle the problem of acid rain caused by coal-fired electric utilities. In applying the market-based cap-and-trade technique, Congress broke a legislative logjam that had prevented it from dealing with the acid rain problem for more than a decade. The Government Accountability Office estimated that cap and trade has saved business more than half the costs (up to $3 billion a year) of command regulations. Recently, however, questions have arisen over whether too many permits have been issued, a common occurrence in cap-and-trade programs.

Even as cap and trade, with its cost-saving advantages over command-and-control regulation, has emerged as the preferred regulatory approach for addressing environmental problems, there has been considerable reluctance to transform preexisting regulatory structures. Take, for instance, the Corporate Average Fuel Economy (CAFE) fuel-efficiency standards enacted in 1975 and phased in during the following decade. Even though the automotive industry took enormous advantage of the "light truck" loophole (read: SUV), which resulted in the number of light trucks growing by two-and-a-half times between 1979 and 1999 – from 22 percent of the nation's motor vehicle fleet to 37 percent – Congress waited three decades before revising the CAFE rules in 2007. The new rules prescribe fuel standards covering both light trucks and automobiles and, beginning in 2011, require average fuel economy to increase to 35 miles per gallon by 2020. In 2009, President Obama accelerated fuel mileage improvements, announcing that a new standard of 35.5 miles per gallon must be reached by 2016. In 2011, he announced that the EPA will issue new regulations requiring automobile manufacturers to double their cars' average fuel consumption from the current 27.5 miles per gallon to 54.5 mpg by 2025.

When the CAFE standards were first enacted in 1975, President Ford, who had long served in Congress as the representative of Grand Rapids, Michigan (a city about 160 miles from Detroit and itself home to an automobile manufacturer early in the twentieth century), had no enthusiasm for mandatory rules of any sort. Furthermore, the automobile industry and its powerful unions had another key ally in Congress: Michigan Congressman John Dingell, who chaired the key House subcommittee. As a result, the mileage requirements enacted in 1975 did little more than ratify changes already under way in the auto industry, with trivial penalties for failing to meet them.

Political journalist Elizabeth Drew of *The New Yorker* described the new standards as "in effect, a product of the Ford Motor Company."[11] Because the mileage requirements were based on the average fuel economy of each manufacturer's fleet, they favored the small cars from Japanese manufacturers, which easily met the requirements and, responding to Americans' taste for larger cars, began to sell larger, less fuel-efficient brands, such as the Lexus and Infiniti. Despite its weaknesses, however, CAFE is regarded by many experts as the most effective conservation measure adopted in response to the OPEC oil embargo and price shocks of the 1970s. That, however, is faint praise. CAFE may rank among our nation's most successful energy policies, but it is a long way from the best we might have had.

Unlike a gasoline tax, the CAFE standards create no incentive for people to reduce how much they drive. Economists have estimated that a gasoline tax of just 25 cents per gallon could have saved as much oil as the fuel efficiency standards at one-third the cost to the economy. Alternatively, a cap-and-trade automobile fuel efficiency regime would permit those manufacturers that are most efficient at increasing gas mileage to sell excess credits to firms that find increasing the mileage of their vehicles more costly. This would substantially bring down the total costs to auto manufacturers of complying with the mileage standards. Given the serious economic challenges that automobile companies now face, lowering the costs of complying with CAFE should be a national priority.

But President Obama is handcuffed. Although he worries about risks from climate change and wants to reduce our dependence on imported oil, persuading Congress to enact policies to reduce the regulatory costs of CAFE seems impossible. Pledges signed by virtually all Republican members of Congress take gasoline taxes off the table. Moreover, despite its conservative Republican pedigree and notable success in reducing emissions from electric power plants that cause acid rain, "cap and trade" has become an epithet in our political process, no matter how cost effective and limited in scope. Cap-and-trade regulations are so poorly understood by the public that political opportunities for mischaracterization and demagoguery abound. Thus, our dysfunctional politics keeps us mired in an inefficient regulatory structure enacted more than thirty-five years ago, while unnecessary costs to our fragile economy multiply. Either a cap-and-trade regime or a gas tax would eliminate more gasoline consumption at a fraction of CAFE's costs. But no politician is now urging us to move in either of those directions.

In Spring 2011, Barack Obama announced his *Blueprint for a Secure Energy Future*.[12] The president said he would use the full force of government power to regulate, bribe, purchase, and cajole in order to transform how we produce and use energy in this country. He promised to open federally controlled property to more oil drilling and to expand production of domestic natural gas. He said he would deploy the might of the federal government's spending power to purchase only hybrid, electric, and alternative fuel cars and trucks as well as to substitute biofuels for petroleum in military jets. President Obama also promised government "incentives" for a litany of oil-saving items and activities, including automobile batteries, electric fueling stations, high-speed rail and mass transit, energy-efficient building materials, and biofuels. Many (if not most) of the incentives the president promised will, unfortunately, take the shape of tax breaks, despite nearly a half-century of compelling evidence –

from ethanol, wind power, black liquor, hybrid vehicles, and energy-saving home improvements, to name just a few – that such incentives are wasteful and inadequate to the task. President Obama also promised to tighten regulatory requirements governing automobile fuel efficiency, to extend such regulations to large trucks, and to adopt new federal requirements for the ways in which the nation's electricity will be produced. Along the way – notwithstanding the then-recent troubles in Japan and subsequent moves away from nuclear power in Europe – he once again embraced nuclear power, and he even gave a thumbs up to that chimera, "clean coal."

No doubt looking ahead to his 2012 reelection campaign, which he kicked off only a few days later, the president said his energy plan would require "tough" choices. But he did not ask the American people to do anything tough. He did not ask us to drive less or more slowly, to turn down our thermostats, or even to turn off the lights when we leave a room. Despite all his bold talk of policy initiatives, the president failed to explain how he planned to pay for his new spending incentives, saying only that this was a "fair" question to ask.

The phrase "cap and trade" was absent from the president's remarks. This, of course, is what distinguished his 2011 energy speech from those he had made during the previous three years. Nor did he venture to suggest that we should tax what we want to reduce – petroleum use and electricity consumption from fossil fuels – and use the revenues that this would produce to reduce taxes on jobs or wages: things we want to increase.

Sherlock Holmes famously instructed us to be alert to a dog that fails to bark. In the large kennel of policies that the United States has deployed to address energy policy, one dog fails to bark – the same dog that never barks. In the thousands of pages of energy legislation and regulations enacted since energy policy came to the fore in the 1970s, Congress has never demanded that Americans pay a price that reflects the true costs of the energy they consume. As I have described, for nearly a decade following the oil embargo of 1973, Congress refused even to allow the price of gas at the pump to rise enough to reflect the worldwide market price of oil. Today, not one of our political leaders urges a requirement that gasoline prices include, for example, the costs of keeping oil moving safely from the Persian Gulf into our gas tanks, or that our electricity prices reflect the costs of coal pollution. None is insisting that the price of fossil fuels should reflect the risks of climate change from greenhouse gas emissions.

The problem, of course, is that reflecting these kinds of costs in the price of energy would require taxing energy consumption, rather than subsidizing its production. And as our nation's massive public debt reminds us, it is far easier for our government to spend than to tax. Despite all the costs our nation has paid in lives and treasure to keep oil moving from the Middle East to our gas tanks, past efforts to tax energy consumption offer no encouragement: Jimmy Carter failed in his effort to tax gasoline; Bill Clinton's Btu energy tax plan suffered a resounding defeat. We should not be surprised that no American politician is now proposing that we tax petroleum use and electricity consumption from fossil fuels.

We will continue our quest for a technological panacea, pretending that such a search is separate from any need to insist that energy prices reflect their true costs. In the absence of a carbon tax or a cap-and-trade system for curbing greenhouse gas emissions, the outlook for carbon-free alternatives does not seem bright. The

Fukushima disaster has made a wary public more fearful of nuclear power, and bets are now off for a "nuclear renaissance" in the United States. Some analysts claim that ongoing improvements in solar technology will drive the costs of solar power below that of coal a decade hence, but we have heard similar hopes before, and they have not been realized.[13] Energy efficiency continues to improve, but the absence of appropriate incentives inhibits progress on that front.

Higher prices and expectations that expanding demand from rapidly developing economies, especially China and India, will keep prices robust have stimulated important technological breakthroughs for natural gas and oil. The ability to extract oil and gas from shale through hydraulic fracturing, or "fracking" – in which a high-pressure mixture of chemicals, sand, and water is used to open cracks in rocks and allow oil and gas to flow into wells miles below the earth's surface – now offers the potential to keep our cars and trucks running without relying on the flow of oil from the Middle East. And we could significantly lower our greenhouse gas emissions by substituting natural gas for coal in generating electricity, if we could only muster the political will to do so.

In the meanwhile, we will continue to rely on second- or third-best policies – government purchases, unnecessarily costly regulations, poorly designed subsidies – even though, given our nation's fragile economy, our difficult fiscal condition, and the daunting challenges of simultaneously limiting climate change and achieving energy security, we have never been more in need of cost-efficient and effective energy policies.

As our failed energy policy story has unfolded – in all its complexity – many villains have come to the fore, including, no doubt, the OPEC cartel and some of its members in particular. At home, we have suffered from poor leadership from both ends of Pennsylvania Avenue, with short-term political expediency trumping sensible long-term policies. Key legislators far too frequently have elevated parochial interests over our national needs and have been led astray by the potential for short-term partisan gains. Our political leaders have also often been seduced by sweet visions of technological silver bullets around the next corner. Environmental organizations have sometimes insisted on unrealistic goals, now and then forged inapt alliances, and been used to further elite, not-in-my-backyard (NIMBY) agendas. Energy companies have frequently underestimated risks and shifted to taxpayers costs that the companies themselves should properly bear.

Amid all the currents and crosscurrents, however, one character plays a particularly central role: price. Although our government has enacted thousands of pages of energy legislation since the 1970s, it has never demanded that Americans pay a price that reflects the full costs of the energy they consume. Nothing that we did or might have done has had as much potential to be efficacious as paying the true price. The contrast with tobacco, for example, in which taxes have been used over time both to reduce its consumption and to help finance some of the costs it imposes on public budgets and society, could hardly be more stark. This failure, alongside quite a few others, accounts for the state of affairs we face today.

Despite all the laws Congress has enacted since 1973, our policies have always been inadequate. The weekend following President Obama's Spring 2011 energy policy speech and the simultaneous release of his *Blueprint for a Secure Energy Future*, many newspapers ran a cartoon by Jeff Stahler depicting the eight presidents from Richard Nixon to Barack Obama, each supplying one word of the refrain: "We must reduce our dependency on Mideast oil." Nearly a year earlier, after President Obama delivered his first Oval Office address to the nation, setting forth his energy policy goals following the BP oil spill in the Gulf of Mexico, Jon Stewart of *The Daily Show* played clips from the same eight presidents – all promising to end our dependence on oil, all offering other energy alternatives, and all setting deadlines for reaching their goals. The problem, of course, is that forty years of energy policy failures is not funny. But our history offers little cause for optimism. Knowing our past failures may not be enough to prevent us from repeating them.

ENDNOTES

[1] U.S. Office of Economic Stabilization, Department of the Treasury, *Historical Working Papers on the Economic Stabilization Program, August 15, 1971 to April 30, 1974* (Washington, D.C.: U.S. Government Printing Office, 1974).

[2] Ronald Reagan, "Oil Decontrol Statement," *The New York Times*, January 28, 1981.

[3] William M. Pegram, "The Photovoltaics Commercialization Program," in *The Technology Pork Barrel*, ed. Linda R. Cohen and Roger Noll, with Jeffrey S. Banks, Susan A. Edelman, and William M. Pegram (Washington, D.C.: Brookings Institution, 1991).

[4] Fred Sissine, *DOE Budget Earmarks: A Selective Look at Energy Efficiency and Renewable Energy R&D Programs*, RL 33294 (Washington, D.C.: Congressional Research Service, March 3, 2006).

[5] Alex R. Broadfoot and Michael E. Webber, "Oil Barrel Politics," *Earth*, April 8, 2009, http://www.earthmagazine.org/earth/article/202-7d9-4-8.

[6] American Association for the Advancement of Science, "R&D Earmarks Hit New Record of $2.4 billion, Up 13 Percent," news release, January 4, 2006, http://www.aaas.org/spp/rd/earm06c.pdf.

[7] Barry Commoner, *The Politics of Energy* (New York: Random House, 1979), 41 – 44.

[8] Earle E. Gavett, Gerald E. Grinnell, and Nancy L. Smith, *Fuel Ethanol and Agriculture: An Economic Assessment*, Agricultural Economic Report No. 562 (Washington, D.C.: U.S. Department of Agriculture, August 1986).

[9] Congressional Budget Office, "Using Biofuel Tax Credits to Achieve Energy and Environmental Policy Goals," July 2010, http://www.cbo.gov/doc.cfm?index=11477&zzz=40959.

[10] Linda R. Cohen and Roger G. Noll, "An Assessment of R&D Commercialization Programs," in *The Technology Pork Barrel*, ed. Cohen and Noll, with Banks, Edelman, and Pegram, 384.

[11] Elizabeth Drew, "The Energy Bazaar," *The New Yorker*, June 21, 1975, 35 – 72.

[12] *Blueprint for a Secure Energy Future* (Washington, D.C.: Executive Office of the President, March 2011), http://www.whitehouse.gov/sites/default/files/blueprint_secure_energy_future.pdf.

[13] Ramez Naem, "Smaller, Cheaper, Faster: Does Moore's Law Apply to Solar Cells?" *Scientific American* blog, March 16, 2011, http://blogs.scientificamerican.com/guest-blog/2011/03/16/smaller-cheaper-faster-does-moores-law-apply-to-solar-cells/.

Using the Market to Address Climate Change: Insights from Theory & Experience

Joseph E. Aldy & Robert N. Stavins

Abstract: Emissions of greenhouse gases linked with global climate change are affected by diverse aspects of economic activity, including individual consumption, business investment, and government spending. An effective climate policy will have to modify the decision calculus for these activities in the direction of more efficient generation and use of energy, lower carbon-intensity of energy, and a more carbon-lean economy. The only technically feasible and cost-effective approach to achieving this goal on a meaningful scale is carbon pricing: that is, market-based climate policies that place a shadow-price on carbon dioxide emissions. We examine alternative designs of three such instruments: carbon taxes, cap and trade, and clean energy standards. We note that the U.S. political response to possible market-based approaches to climate policy has been, and will continue to be, largely a function of issues and structural factors that transcend the scope of environmental and climate policy.

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Virtually all aspects of economic activity – individual consumption, business investment, and government spending – affect greenhouse gas emissions and, hence, the global climate. An effective climate change policy would change the decision calculus for these activities to promote more efficient generation and use of energy, lower carbon-intensity of energy, and a more carbon-lean economy. There are three ways to accomplish this goal: (1) mandate that businesses and individuals change their technology and emissions performance; (2) subsidize business and individual investment in and use of lower-emitting goods and services; or (3) price the greenhouse gas externality commensurate with the harm that such emissions impose on society.

Externality pricing can promote cost-effective abatement, deliver efficient innovation incentives, avoid picking technology winners, and ameliorate, not exacerbate, government fiscal conditions. When all businesses and households face a common price per unit of greenhouse gases embodied in fuels, goods, and services, no additional policies can lower the total cost of achieving a specified climate policy goal. By pricing carbon pollution, the government defers to private firms and individuals to find and exploit the lowest-cost ways to reduce emissions and to invest in the development of new technologies, processes, and ideas that could mitigate future emissions. A variety of policy approaches fall within the concept of externality pricing, including carbon taxes, cap and trade, and clean energy standards.

In contrast, the conventional approach to environmental policy employs uniform mandates to protect environmental quality. Although uniform technology and performance standards have been effective in achieving some established environmental goals and standards, they tend to lead to non-cost-effective outcomes in which some firms use unduly expensive means to control pollution. In addition, conventional technology or performance standards do not provide dynamic incentives for the development, adoption, and diffusion of environmentally and economically superior control technologies. Once a firm satisfies a performance standard, it has little incentive to develop or adopt cleaner technology. Indeed, regulated firms may fear that if they adopt a superior technology, the government may tighten the standard.

Given the ubiquitous nature of greenhouse gas emissions from diverse sources, it is virtually inconceivable that a standards-based approach could form the centerpiece of a meaningful climate policy. The substantially higher cost of a standards-based policy may undermine support for such an approach, and securing political support may require weakening standards and lowering environmental benefits.

Government support for lower-emitting technologies often takes the form of investment or performance subsidies. Providing subsidies for targeting climate-friendly technologies entails revenues raised by taxing other economic activities (either contemporaneously or in the future, with contemporaneous financing via deficit spending). Given the tight fiscal environment throughout the developed world, it is difficult to justify increasing (or even continuing) the subsidies that would be necessary to change significantly the emissions intensity of economic activity.

Furthermore, by lowering the cost of energy, climate-oriented technology subsidies likely result in socially excessive levels of energy supply and consumption. Thus, subsidies can undermine incentives for efficiency and conservation and impose higher costs per ton abated than cost-effective policy alternatives. In practice, subsidies are typically designed to be technology specific. By designating technology winners, such an approach yields a special-interest constituency focused on maintaining subsidies beyond what may be socially desirable. It also provides little incentive for the development of novel, game-changing technologies.

In contrast, real-world experience demonstrates the power of markets to drive changes in the investment and use of emission-intensive technologies. The run-up in gasoline prices in 2008 increased consumer demand for more fuel-efficient new cars and trucks, while also reducing vehicle miles traveled by the existing fleet.[1] Likewise, electric utilities responded to the dramatic decline in natural gas prices (and decline in the relative gas-coal price) in 2009 and 2010 by dispatching more electricity from gas plants, resulting in lower carbon dioxide (CO_2) emissions and the lowest share of U.S. power generation by coal in some four decades.[2] Longer-term evaluations of the impacts of energy prices on markets have found that higher prices have induced more innovation – measured by frequency and importance of patents – and increased the commercial availability of more energy-efficient products, especially among energy-intensive goods such as air conditioners and water heaters.[3]

Real-world experience with policies that price externalities illustrates the effectiveness of market-based instruments. So-called congestion charges in London, Singapore, and Stockholm have reduced traffic congestion in busy urban centers, lowered air pollution, and delivered net social benefits. The British Columbia carbon tax has reduced carbon dioxide emissions since 2008. The U.S. sulfur dioxide (SO_2) cap-and-trade program has cut SO_2 emissions from U.S. power plants by more than 50 percent since 1990, resulting in compliance costs one-half of what they would have been under conventional regulatory mandates.[4] The success of the SO_2 allowance trading program motivated the design and implementation of the European Union's Emissions Trading Scheme (EU ETS), the world's largest cap-and-trade program, focused on cutting CO_2 emissions from power plants and large manufacturing facilities throughout Europe.[5] The 1980s phasedown of lead in gasoline, which reduced the lead content per gallon of fuel, served as an early, effective example of a tradable performance standard.[6] These positive experiences provide motivation to consider market-based instruments – carbon taxes, cap and trade, and clean energy standards – as potential approaches to mitigating greenhouse gas emissions.

In principle, government imposition of a *carbon tax* represents the simplest way to price greenhouse gas emissions.[7] The government could set a tax in terms of dollars per ton of CO_2-equivalent on greenhouse gas emissions from all sources covered by the tax. To be cost effective, such a tax would cover all sources, and to be efficient, the carbon price would be set equal to the marginal benefits of emission reduction: that is, the social cost of carbon.[8] An efficient carbon tax would be expected to increase over time to reflect the fact that as more greenhouse gas emissions accumulate in the atmosphere, the incremental damage from an additional ton of CO_2 becomes greater; such a tax would also include a risk premium to reduce uncertain future damages.[9] Imposing a carbon tax would provide certainty about the marginal cost of compliance, thereby reducing uncertainty about returns to investment decisions, but would leave economy-wide emissions uncertain.

The government could apply the carbon tax "upstream" on fossil fuel suppliers based on the carbon content of fuels or "downstream" on final emitters at the point of combustion, or it could employ a hybrid of the two. In an upstream approach, refineries and importers would pay a tax based on the carbon content of their gasoline, diesel fuel, or heating oil; coal mine operators would pay a tax reflecting the carbon content of extracted coal; and natural gas companies would pay a tax reflecting the carbon content of their gas production and imports. Focusing on the carbon content of fuels would cover about 98 percent of U.S. CO_2 emissions through a relatively small number of firms – two to three thousand – as opposed to the hundreds of millions of smokestacks and tailpipes, for example, that emit CO_2 after fossil fuel combustion. Such a tax approach could also cover other greenhouse gases.

A carbon tax would be administratively simple and straightforward to implement. The tax could incorporate existing methods for fuel-supply monitoring and reporting to the regulatory authority. Given the molecular properties of fossil fuels, monitoring their physical quantities yields a precise estimate of the emissions they release during combustion. Because an emission tax would be similar in form to taxes that many fuel suppliers already pay,[10] firms could easily understand and account for it in their operations.

A crediting system for downstream sequestration could complement the emission tax system. A firm that captures and stores CO_2 through geological sequestration, thereby preventing the gas from entering the atmosphere, could generate CO_2 tax credits. Similar approaches could be undertaken to promote biological sequestration in forestry and agriculture and, potentially, emission-reduction projects ("offsets") in other countries.

Faced with an emission tax, fuel suppliers will increase the cost of the fuels they sell. This will effectively pass down the tax through the energy system, creating incentives for fuel-switching and investments in more energy-efficient technologies. The impact of a carbon tax on emission mitigation and the economy will depend in part on the amount and use of the tax revenue. An economy-wide U.S. carbon tax of $20 per ton of CO_2 would likely raise more than $100 billion per year. The revenue could allow for reductions in existing distortionary taxes on labor and capital, thereby stimulating economic activity and offsetting some of the policy's costs. For example, reducing the payroll tax by 2 percentage points in 2012 could be financed with an economy-wide carbon tax on the order of $15 to $20 per ton of CO_2. Other socially valuable uses of revenue include reducing the federal deficit, funding energy R&D, and compensating low-income households for the burden of higher energy prices.

The implementation of a carbon tax (or cap-and-trade system) will increase the cost of consuming energy and could adversely affect the competitiveness of energy-intensive industries. This competitiveness effect can result in negative economic and environmental outcomes: firms may relocate facilities to countries without meaningful climate change policies, thereby increasing emissions in these new locations and offsetting some of the environmental benefits of the policy. Because a majority of developed countries' emissions occur in non-traded sectors – that is, electricity, transportation, and residential buildings – this so-called emission leakage may, in fact, be relatively modest. However, energy-intensive manufacturing industries that produce goods competing in international markets may face incentives to relocate.

Additional emission leakage may occur through international energy markets. As countries with climate policies reduce their consumption of fossil fuels and drive down fuel prices, those countries without emission mitigation policies may be induced to increase their consumption. The fact that leakage undermines the environmental effectiveness of any unilateral effort to mitigate emissions makes international cooperation and coordination all the more important.

A *cap-and-trade* system constrains the aggregate emissions of regulated sources by creating a limited number of tradable emission allowances – in sum equal to the overall cap – and requiring those sources to surrender allowances to cover their emissions.[11] Faced with the choice of surrendering an allowance or reducing emissions, firms place a value on the allowance reflecting the cost of the emission reductions that can be avoided by surrendering the allowance. Regardless of the initial allowance distribution, trading can lead allowances to be put toward their highest-valued use: covering those emissions that are the most costly to reduce and providing the incentive to undertake the least costly reductions.

In developing a cap-and-trade system, policy-makers must decide on several elements of the system's design. First, they must determine how many allowances to issue (that is, the level of the emission cap) and the scope of the cap's coverage, identifying the types of greenhouse gas emissions and sources covered as well as deciding whether to regulate upstream (based on carbon content of fuels) or downstream (based on monitored emissions). Policy-makers must then determine whether to freely distribute or auction allowances. Free allowance allocation could be "grandfathered," reflecting some historical record such as recent fossil fuel sales. Grandfathering involves a transfer of wealth, equal to the value of the allowances, to existing firms, whereas an auction transfers the same level of wealth to the government. In theory, the government would collect revenue identical to that from a tax producing the same amount of emission abatement. As with tax receipts, auction revenues could be used to reduce distortionary taxes or finance other programs.

In an emission-trading program, cost uncertainty – unexpectedly high or volatile allowance prices – can undermine political support for climate policy and discourage investment in new technologies and R&D. Therefore, attention has turned to incorporating the "cost containment" measures of offsets, allowance banking and borrowing, safety valves, and price collars in cap-and-trade systems.

An offset provision allows regulated entities to offset some of their emissions with credits from emission-reduction measures outside the cap-and-trade system's scope of coverage. Allowance banking and borrowing effectively permits emission trading across time. The flexibility to save an allowance for future use (banking) or to bring a future period allowance forward for current use (borrowing) promotes cost-effective abatement and redefines a series of annual emission caps as a cap on cumulative emissions over a period of years.

A safety valve puts an upper bound on the costs that firms will incur to meet an emission cap by offering the option of purchasing additional allowances at a predetermined price. This effective price ceiling reflects a hybrid approach: a cap-and-trade system that transitions to a tax in the presence of unexpectedly high mitigation costs. When firms exercise a safety valve, their aggregate emissions exceed the emission cap. A price collar combines the ceiling of a safety valve with a price floor created, for example, by a reserve price in allowance auctions.

Increasing certainty about mitigation cost reduces certainty about the quantity of emissions. Smoothing allowance prices over time through banking and borrowing reduces emission certainty in any given year but maintains certainty of aggregate emissions over a longer time period. A cost-effective policy with a mechanism insuring against unexpectedly high costs increases the likelihood that firms will comply with their obligations and can facilitate a country's participation and compliance in a global climate agreement.

As with a carbon tax, cap-and-trade programs could include some variant of a border tax to mitigate the competitiveness impacts of domestic climate policy and encourage trade partners to take on comparable mitigation policies. Border measures under a carbon tax or cap and trade raise policy questions about the application of a trade "stick" to encourage broader and more extensive emission mitigation actions globally, as well as questions about their legality under the World Trade Organization.[12]

The purpose of a *clean energy standard* is to establish a technology-oriented goal for the electricity sector that can be implemented cost effectively.[13] Under such standards, power plants generating power with technologies that satisfy the standard create tradable credits that they can sell to power plants that fail to meet the standard, thereby minimizing the costs of meeting the standard's goal in a manner analogous to cap and trade. An important distinction is that cap and trade establishes the policy goal in terms of the externality (greenhouse gas emissions), while clean energy standards establish the policy goal in terms of a set of technologies with zero- or low-emission characteristics.

For example, state renewable electricity standards, a restricted type of a clean energy standard, typically identify the objective of the standard as a specific renewable share of total power generation (that increases over time).[14] A few states have implemented alternative energy standards that target renewables, new nuclear capacity, and advanced fossil fuel technologies. Proposals for national standards have targeted a combination of all generating technologies except conventional coal.[15]

Clean energy standards that focus on technology targets do not explicitly price the greenhouse gas externality and thus impose a higher cost for a given amount of emission reductions than a carbon tax or cap-and-trade program. A renewable mandate treats coal-fired power, gas-fired power, and nuclear power as equivalent – none of these technologies create credits necessary for compliance – and therefore provides no incentive to switch from emission-intensive coal to emission-lean gas or emission-free nuclear.

A more cost-effective approach to a clean energy standard would employ a technology-neutral performance standard, such as tons of CO_2 per megawatt hour of generation (tCO_2/MWh). Given that all power sources, from fossil fuels to renewables, could be eligible under such a performance standard, this approach would provide better innovation incentives than a renewable portfolio approach and would enable all possible ways of reducing the emission intensity of power generation. The Canadian province of Alberta has employed a tradable carbon performance standard for most large sources of CO_2 emissions, requiring a 12 percent improvement in these sources' emission intensity since 2007.

Power plants would be awarded credits for generating cleaner (less emission-intensive) electricity than the standard, and they could sell these credits to other power plants or save them for future use. Tradable credits promote cost-effectiveness by encouraging the greatest deployment of clean energy from those plants that can lower their emission intensity at lowest cost. Clean power plants could then sell their extra credits to other plants that face higher costs for deploying clean energy. The creation and sale of clean energy credits would provide a revenue stream that could conceivably enable the financing of low- and zero-emission power plant projects.

Eligible technologies for the standard could extend beyond generation technologies, permitting improvements in energy efficiency and emission-offset activities to create tradable credits. Extending the carbon price to a broader set of activities could improve cost-effectiveness, but there are risks in allowing for energy efficiency and other offsets. In both cases, estimating the offset is complex, requires extensive review and monitoring by regulators, and risks undermining the objective of a clean energy standard if some projects do not, in practice, deliver meaningful emission reductions.

Monitoring and enforcement would be relatively straightforward, given that regulators already track electricity generation and CO_2 emissions at U.S. power plants. A power plant could demonstrate compliance through a combination of the following approaches: (1) the plant has lesser or equal emissions per megawatt hour than the standard (or a share of power from clean energy exceeding the standard); (2) the plant purchases clean energy credits from other power plants; or (3) the plant purchases additional clean energy credits from the federal government at a preset price. The last option is similar to "alternative compliance payments" in state electricity portfolio standards (and akin to the hybrid safety-valve approach under a cap-and-trade program) that finance some state energy R&D programs. This approach could provide more certainty about compliance cost under a clean energy standard.

A clean energy standard represents a de facto free allocation of the right to emit greenhouse gases. Suppose that the federal government created a clean energy performance standard of 0.5 tCO_2/MWh (in 2010, U.S. power sector emission intensity was 0.56 tCO_2/MWh). Every power plant implicitly receives the right to emit a half-ton of CO_2 per megawatt hour of generation under such a standard, similar to an output-based allocation of emission allowances under cap and trade.

Market-based policies can support *cost-effective* attainment of policy goals. A carbon tax and cap and trade establish a common price for emitting a ton of CO_2, and the private sector has the flexibility to identify and exploit the least costly ways of reducing emissions. This approach is vastly superior to command-and-control regulatory mandates and can result in lower costs per ton of CO_2 abated than a clean energy standard. Even a clean energy standard designed as a tradable carbon performance standard would be less cost effective than cap and trade or a tax because it does not provide a comparable incentive for efficiency and conservation. The implicit free allocation of the right to emit is functionally an output-based subsidy that will result in more electricity generated and consumed than under cap and trade or a tax.

A renewable electricity standard is even less cost effective because it proscribes some low- and zero-emission technologies from the set of compliance options. In theory, this type of standard could mandate so much renewable power that it spurs a socially excessive amount of total generating capacity, lowers the price of electricity (at least in the short run), and causes a net increase in electricity consumption, contrary to the efficiency and conservation incentives under cost-effective approaches.

Cost-effective implementation is necessary but not sufficient for a climate policy to maximize net social benefits. A socially *efficient* policy, one resulting in marginal costs equal to marginal benefits of emission reduction, would require setting the carbon price equal to the estimated social cost of carbon. Alternatively, policy-makers could set an emission cap that would deliver an expected allowance price equal to the estimated social cost of carbon. Under a clean energy standard, the stringency of the performance standard could be set to yield expected credit prices on par with the social cost of carbon, although the weaker incentive for efficiency and conservation would result in some efficiency losses.

A market-based policy may *raise revenue* to finance reductions in taxes that discourage the supply of labor and capital. Lowering payroll, income, or capital gains tax rates could offset some of the costs of a climate policy. A well-designed market-based policy with a modest carbon price and efficiently targeted reduction in tax rates could – in principle – cause a net increase in GDP, although – in practice – the more likely outcome is some savings in the policy's cost.[16] In general, recycling revenue back into the economy by lowering existing distortionary taxes can allow for a more aggressive greenhouse gas mitigation policy that maximizes net social benefits.

In a world without uncertainty, a carbon tax and a cap-and-trade program could be designed and implemented to yield an identical carbon price and emission reductions. But the choice of policy instrument can affect the net social benefits, given the real-world *uncertainty* that characterizes emission mitigation.[17] The government must implement a climate policy before uncertainty about the cost of emission mitigation can be resolved. If mitigation costs are higher than the government expected, then the climate policy will yield either (a) fewer emission reductions if the government implemented a carbon tax; or (b) higher costs if the government implemented cap and trade. If the foregone economic benefits from fewer emission reductions under the tax are less than the higher costs under the cap-and-trade program, then a tax would be the preferred policy instrument under uncertainty. Otherwise, cap and trade would likely maximize net social benefits relative to a carbon tax.

Uncertainty about the price of carbon inhibits private-sector investment. In recent years, uncertainty about the type, design, and stringency of climate policy has adversely affected new energy and climate-related technology investment. Uncertainty about future modifications to a climate policy may also deter investment, especially for long-lived energy-related capital. For example, a future government could relax policy stringency (with a lower carbon tax or higher emission cap) that would lower the economic return to low- and zero-carbon technology investments. Alternatively, under a cap-and-trade regime, a future government could wipe out the value of an emission allowance bank (the allowances set aside and banked for future use), increasing the stringency of the cap-and-trade program, not unlike recent experience with the effect of regulatory changes on the U.S. SO_2 cap-and-trade program.

While the business community would prefer cost certainty, the environmental community favors certainty over greenhouse gas emission levels. Placing much greater weight on emission reductions reflects the concern of some in the environmental community that business will simply "buy its way out" under a carbon tax and fail to undertake emission mitigation, even though it may be in businesses' interests to do so.

Real-world experience has addressed uncertainty by pursuing hybrid price-quantity approaches, such as state renewable electricity standards that establish quantity renewable goals and include alternative compliance payments that serve as a price ceiling on tradable renewable credits. Such hybrid approaches can provide insurance against policy costs reaching unexpected heights. They may also represent a way of imposing an implicit carbon tax if a cap-and-trade program's safety valve is set at a level that has a very high probability of being triggered.

Although public policies are frequently proposed and analyzed in isolation, they in fact interact with one another in a number of important ways, which can affect a policy's environmental effectiveness and costs. Policies of all kinds – both market-based instruments and conventional policies – act as implicit taxes and interact with preexisting taxes in ways that drive up the policies' costs – the so-called tax-interaction effect.[18] Those policy instruments that produce revenues for government, including carbon taxes and cap and trade with auctioned allowances, can dedicate part or all of their revenue to cutting existing, distortionary taxes, thereby offsetting some or (in principle) all of the tax-interaction effect. These interactions can have profound effects on the costs of a climate policy.[19]

The interaction of flexible, quantity-based policies, such as cap-and-trade systems and tradable clean energy standards, with other climate policies introduces an additional set of issues. In general, allowed trading means that once a flexible, averaging type of policy instrument is in place, any attempt to elicit greater reductions from some specific source or sector under the cap will essentially be undone by some other source or sector covered under the cap. Moreover, when marginal abatement costs at the specific source or sector are increased, the overall flexible (cap and trade) regime is no longer cost effective. This is a major issue for cap-and-trade systems, renewable electricity standards, clean energy standards, and motor-vehicle fuel efficiency standards. Problematic interactions can occur when one policy instrument is nested within another, as with subnational and national policies,[20] or when two policy instruments coexist within the same political jurisdiction.[21] The effects are potentially less severe with a carbon tax than with quantity-based policies because the multiple policies could yield a lower emission level than the carbon tax in isolation, but that benefit would come at the expense of cost effectiveness.

Given that climate change and actions to mitigate it play out in the global commons, it is important that any U.S. policy actions be carefully coordinated with the actions or anticipated actions of other countries. Otherwise, U.S. policies may have no more than trivial environmental impacts (despite their cost) and can increase other countries' emissions through induced leakage of carbon-intensive economic activity.

Cap-and-trade systems seem to have emerged as the preferred national and regional instrument for reducing greenhouse gas emissions throughout much of the industrialized world. The Clean Development Mechanism (CDM), an international emission-reduction credit system, has developed a substantial constituency despite concerns about its performance. Because linkage between tradable permit systems (that is, unilateral or bilateral recognition of allowances from one system for use in another) can reduce compliance costs and improve market liquidity, there is great interest in linking cap-and-trade systems with each other, as well as to the CDM and other credit systems. There are not only benefits but also concerns associated with various types of linkages,[22] but it is safe to say that such linkage may play one of three possible roles: as an independent bottom-up international climate policy architecture; as a step in the evolution of a top-down architecture; or as an ongoing element of a larger climate policy agreement.

A parallel issue arises with respect to national or subnational carbon taxes: namely, they can be linked in productive ways. For purposes of overall cost effectiveness, the various taxes would need to be set at the same level, that is, harmonized.[23] The prospect of harmonization is complicated by equity issues – would developing countries harmonize taxes without some form of side payments? – and related tax issues: how might carbon tax harmonization account for preexisting energy subsidies in developing countries and high preexisting energy taxes in some developed countries?

Considering the variety of policy instruments – both market-based and conventional command-and-control – that countries can employ to reduce their greenhouse gas emissions, it is important to ask whether a diverse set of heterogeneous national, subnational, or regional climate policy instruments can be linked in productive ways. The simple answer is that such a set of instruments can be linked, although coordinating a set of more homogeneous tradable permit systems would be easier.[24] The basic approach behind emission-reduction credit systems such as the CDM can be extended to foster linkage opportunities among diverse policy instruments, including cap and trade, taxes, and certain regulatory systems.[25]

Countries could coordinate effectively through the unilateral use of border adjustments. A national carbon tax, for instance, would take the form of a tax on imports equivalent to the implicit tax on the same goods produced domestically. In the cap-and-trade climate legislation passed by the U.S. House of Representatives in 2009, border adjustments covered only a limited set of energy-intensive, trade-exposed manufactured bulk products.

Political factors are at the heart of policy feasibility. In general, it may be necessary to elicit support from concentrated interests.[26] A key question is whether the process of developing such support reduces a policy's effectiveness (for example, by muting the price signals of a market-based instrument) or increases its cost. Such outcomes are frequently the case. However, a key merit of one of the policy instruments we have considered – namely, cap and trade – is that under many circumstances, the process of developing political support need not impair the policy. An important property of such systems – the independence of the equilibrium allocation of allowances after trading from the initial allocation[27] – permits the legislature to distribute allowances in a way that builds a constituency of political support for enactment without jeopardizing the policy's environmental integrity or its cost effectiveness.[28]

At the same time, it is important to recognize that those market-based policy instruments that raise revenues for government – including taxes and auctioned allowances – can have their own political attraction, particularly at a time of chronic government budgetary deficits.

Any public policy, whether cost effective or not, will inevitably have significant distributional consequences, even if it does no more than reinforce the status quo. In the case of U.S. climate change policy, the near-term distributional impacts will primarily reflect the cost of mitigating emissions. The climate benefits to any single nation from its emission-reduction efforts will be spread globally and over several generations. Any meaningful climate policy will increase energy prices, particularly with regard to energy derived from coal combustion and, to a lesser extent, petroleum and natural gas combustion. Mitigation policies would also benefit firms (and some regions) with zero-carbon technologies, such as wind, solar, and energy efficiency technologies. The economic incidence of energy price increases will make up a considerable share of the distributional impacts, which will vary across sectors of the economy, across regions, and across income groups. These impacts are also likely to have profound political impacts on the feasibility of climate policy and the choice among climate policy instruments.

The political-economy implications of the costs associated with various policy instruments give public officials strong incentive to identify and select policies and instruments with minimal perceived costs. In some cases, policies and/or policy instruments may indeed be low-cost, either because they are essentially unambitious or because they are cost effective.

Another option is for public officials to identify policy instruments that hide or partially obscure their costs. Largely for this reason, ordinary performance and technology standards have long been favored over market-based instruments.[29] A prime example is the apparent political attraction of Corporate Average Fuel Economy standards as a means of increasing the fuel efficiency of American automobiles, in contrast with the political aversion to gasoline taxes, even though the latter would accomplish more at lower cost (but in a highly visible manner).[30]

Public and political interest in a market-based policy instrument may respond positively to the threat of a high-cost regulatory alternative. The business community may prefer a more cost-effective (and hence potentially lower-cost) market-based policy to traditional command-and-control regulation. Some in the environmental community may also support a cost-effective policy if it enables a more ambitious environmental goal than is possible under a conventional regulatory mandate.

During the policy debate over the 1990 Clean Air Act amendments, the prospect of a costly regulatory standard for power plant SO_2 emissions prompted interest in a cap-and-trade regime that became the centerpiece of the law's approach to combat acid rain. Building on the successful experience with SO_2 cap and trade, the Environmental Protection Agency (EPA) worked with Northeastern, Mid-Atlantic, and Midwestern states to design a nitrogen oxide emissions cap-and-trade program to reduce ground-level ozone pollution (smog). While states had the option to implement a conventional command-and-control regulation in lieu of joining the cap-and-trade regime, every state chose to pursue the more cost-effective trading approach.

The threat of a high-cost regulatory alternative for greenhouse gas emissions could influence potential interest in a market-based policy approach. First, the EPA could design regulations under the existing Clean Air Act that include some form of cap and trade or a variant of a clean energy standard. While existing law would circumscribe some potentially appealing attributes of a market-based climate policy (including revenue generation and cost containment through a safety valve) as well as prohibit a carbon tax outright, it could allow for a more cost-effective approach than conventional regulatory mandates. Second, the risk of a politically (and potentially economically) unpalatable regulatory scheme under the Clean Air Act may also mobilize interest in a legislative alternative.

Pursuing a legislative option through Congress could involve a variety of legislative committees that would engage a range of special interests. Consider the example of the Senate: a carbon-tax bill would likely start in the Finance Committee; a cap-and-trade bill in the Environment and Public Works (EPW) Committee; and a clean energy standard bill in the Energy and Natural Resources Committee. If a cap-and-trade or clean energy standard bill raises significant revenue, it would likely be referred to the Finance Committee, while any bill that modifies the Clean Air Act (for example, by substituting a market-based policy for existing statutory authority) would likely be referred to the EPW Committee. The committee that begins drafting a bill will shape that bill in line with its priorities: for example, the Finance Committee will prioritize raising revenue, while the EPW will lay out ambitious environmental goals. The persistence of policy design as a bill moves through the legislative process would result in a final law reflecting those initial efforts.

A successful effort in designing and implementing a market-based policy would also benefit from the positive experiences on other policy fronts related to the gradual increase in policy stringency. In 2008, British Columbia implemented a carbon tax starting at $10 (Canadian dollars) per ton of carbon dioxide and climbing annually until it reaches $30/$tCO_2$ in 2012. To complement this gradual implementation of the policy, in the month before tax collection began, the provincial government provided checks to households representing the revenue expected to be raised by the tax in the first year. As the carbon tax revenue has increased, households and businesses have enjoyed larger reductions in their income taxes.

The SO_2 cap-and-trade program was phased in over two time periods, with the largest power plants covered by the program starting in 1995 and the balance of the covered facilities entering the program in 2000. The EU ETS began with a pilot phase in 2005 that imposed a relatively lax emission cap to enable time for covered facilities and government regulators to gain experience with the trading regime before moving into a more stringent second phase in 2008. State renewable electricity and alternative energy standards have likewise started with relatively modest goals: the average renewable target for the twenty-four operational state programs in 2010 was about 4.7 percent, but will increase by a factor of three by 2020.

The U.S. political response to possible market-based approaches to climate policy has been and will continue to be largely a function of issues and structural factors that transcend the scope of environmental and climate policy. Because a truly meaningful climate policy – whether market-based or conventional in design – will have significant impact on economic activity in a wide variety of sectors (given the pervasiveness of energy use in a modern economy) and in every region of the country, it is not surprising that proposals for such policies bring forth significant opposition, particularly during difficult economic times.

In addition, U.S. political polarization – which began some four decades ago and accelerated during the economic downturn – has decimated what had long been the key political constituency in Congress for environmental (and energy) action: namely, the middle, including both moderate Republicans and moderate Democrats.[31] Whereas congressional debates about environmental and energy policy have long featured regional politics, they are now fully and simply partisan. In this political maelstrom, the failure of cap-and-trade climate policy in the Senate in 2010 was collateral damage in a much larger political war.

Better economic times may reduce the pace – if not the direction – of political polarization. Furthermore, the ongoing challenge of large federal budgetary deficits may at some point increase the political feasibility of new sources of revenue. When and if this happens, consumption taxes (as opposed to traditional taxes on income and investment) could receive heightened attention; primary among these might be energy taxes, which, depending on their design, can be significant climate policy instruments.

Some would argue that a mobilizing event will soon precipitate U.S. climate policy action. But the nature of the climate change problem itself helps explain much of the relative apathy among the

U.S. public and suggests that any such mobilizing event may come "too late." Nearly all our major environmental laws have been passed in the wake of highly publicized environmental events or "disasters," including the spontaneous combustion of the Cuyahoga River in Cleveland, Ohio, in 1969, and the discovery of toxic substances at Love Canal in Niagara Falls, New York, in the mid-1970s. But note that the day after the Cuyahoga River caught on fire, no article in *The Cleveland Plain Dealer* commented that the cause was uncertain, that rivers periodically catch on fire from natural causes. On the contrary, it was immediately apparent that the cause was waste dumped into the river by adjacent industries. A direct consequence of the observed "disaster" was, of course, the Clean Water Act of 1972.

Climate change is distinctly different. Unlike the environmental threats addressed successfully in past U.S. legislation, climate change is essentially unobservable. We observe the weather, not the climate. Until there is an obvious and sudden event – such as a loss of part of the Antarctic ice sheet leading to a dramatic sea-level rise – it is unlikely that public opinion in the United States will provide the bottom-up demand for action that has inspired previous congressional action on the environment over the past forty years.

Despite this somewhat bleak assessment of the politics of climate change policy in the United States, it is much too soon to speculate on what the future will hold for the use of market-based policy instruments, whether for climate change or other environmental problems. On the one hand, it is conceivable that two decades (1988 – 2008) of high receptivity in U.S. politics to cap and trade and offset mechanisms will turn out to be no more than a relatively brief departure from a long-term trend of reliance on conventional means of regulation. On the other hand, it is also possible that the recent tarnishing of cap and trade in national political dialogue will itself turn out to be a temporary departure from a long-term trend of increasing reliance on market-based environmental policy instruments. Perhaps the ongoing interest in these policy mechanisms in California (Assembly Bill 32), the Northeast (Regional Greenhouse Gas Initiative), Europe, and other countries will form a bridge to a changed political climate in Washington.

ENDNOTES

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[1] Valerie A. Ramey and Daniel J. Vine, "Oil, Automobiles, and the U.S. Economy: How Much Have Things Really Changed?" NBER Working Paper No. 16067 (Cambridge, Mass.: National Bureau of Economic Research, 2010).

[2] *Emissions of Greenhouse Gases in the United States* 2009 (Washington, D.C.: U.S. Energy Information Administration, 2011).

[3] See David Popp, "Induced Innovation and Energy Prices," *American Economic Review* 92 (1) (2002): 160 – 180; and Richard G. Newell, Adam B. Jaffe, and Robert N. Stavins, "The Induced Innovation Hypothesis and Energy-Saving Technological Change," *Quarterly Journal of Economics* 114 (3) (1999): 941 – 975.

[4] Curtis Carlson, Dallas Burtraw, Maureen Cropper, and Karen Palmer, "SO_2 Control by Electric Utilities: What Are the Gains from Trade?" *Journal of Political Economy* 108 (2000): 1292 – 1326.

[5] A. Denny Ellerman and Barbara K. Buchner, "The European Union Emissions Trading Scheme: Origins, Allocation, and Early Results," *Review of Environmental Economics and Policy* 1 (1) (Winter 2007): 66 – 87.

[6] Robert N. Stavins, "Experience with Market-Based Environmental Policy Instruments," in *Handbook of Environmental Economics*, vol. 1, ed. Karl-Göran Mäler and Jeffrey Vincent (Amsterdam: Elsevier Science, 2003), chap. 9, 355 – 435.

[7] For an example of a carbon tax proposal, see Gilbert E. Metcalf, "A Proposal for a U.S. Carbon Tax Swap," The Hamilton Project Discussion Paper 2007-12 (Washington, D.C.: Brookings Institution, 2007).

[8] Interagency Working Group on Social Cost of Carbon, "Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866," Washington, D.C., 2010.

[9] If society is highly risk averse and is facing uncertain future catastrophic risks, then the efficient carbon price might be so high initially that it would actually decline over time as uncertainty is resolved. See Robert Litterman, "Pricing Climate Change Risk Appropriately," *Financial Analysts Journal* 67 (5) (2011).

[10] For example, U.S. petroleum refineries pay an 8¢ oil spill liability tax on every barrel of crude oil they refine. A carbon tax could piggyback on this existing tax. The government could collect about $4.30 per barrel for every $10 per ton of CO_2 of carbon tax at refineries. The administrative ease of employing existing tax infrastructure may be more important for the design of developing-country mitigation policies. See Joseph E. Aldy, Eduardo Ley, and Ian

W.H. Parry, "A Tax-Based Approach to Slowing Global Climate Change," *National Tax Journal* 61 (2008): 493 – 517.

[11] For an example of a cap-and-trade proposal, see Robert N. Stavins, "A U.S. Cap-and-Trade System to Address Global Climate Change," The Hamilton Project Discussion Paper 2007-13 (Washington, D.C.: Brookings Institution, 2007).

[12] For a discussion of relevant trade policy and legal questions, see Lael Brainard and Isaac Sorking, eds., *Climate Change, Trade, and Competitiveness: Is a Collision Inevitable?* (Washington, D.C.: Brookings Institution Press, 2009); and Jeffrey Frankel, "Global Environment and Trade Policy," in *Post-Kyoto International Climate Policy: Implementing Architectures for Agreement*, ed. Joseph E. Aldy and Robert N. Stavins (New York: Cambridge University Press, 2010), 493 – 529.

[13] One proposal for a clean energy standard is discussed in Joseph E. Aldy, "Promoting Clean Energy in the American Power Sector," The Hamilton Project Discussion Paper 2011-04 (Washington, D.C.: Brookings Institution, 2011).

[14] See *The Effects of Renewable or Clean Electricity Standards* (Washington, D.C.: U.S. Congressional Budget Office, July 2011).

[15] See American Clean Energy Leadership Act of 2009, S. 1462, 111th Cong., sec. 132; Practical Energy and Climate Plan Act of 2010, S. 3464, 111th Cong., sec. 301; and President Obama's 2011 State of the Union address.

[16] Lawrence H. Goulder and Ian W.H. Parry, "Instrument Choice in Environmental Policy," *Review of Environmental Economics and Policy* 2 (2) (2008): 152 – 174.

[17] See Martin L. Weitzman, "Prices vs. Quantities," *Review of Economic Studies* 41 (1974): 477 – 491.

[18] See Lawrence H. Goulder, "Environmental Taxation and the 'Double Dividend': A Reader's Guide," *International Tax and Public Finance* 2 (2) (August 1995).

[19] See Goulder and Parry, "Instrument Choice in Environmental Policy."

[20] See Lawrence H. Goulder and Robert N. Stavins, "Challenges from State-Federal Interactions in U.S. Climate Change Policy," *American Economic Review Papers and Proceedings* 101 (3) (2011): 253 – 257; and Meghan McGuinness and A. Denny Ellerman, "The Effects of Interactions between Federal and State Climate Policies," Working Paper WP-2008-004, Massachusetts Institute of Technology Center for Energy and Environmental Policy Research, 2008.

[21] See Carolyn Fischer and Louis Preonas, "Combining Policies for Renewable Energy: Is the Whole Less than the Sum of Its Parts?" *International Review of Environmental and Resource Economics* 4 (1) (2010): 51 – 92; Arik Levinson, "Interactions Among Climate Policy Regulations," NBER Working Paper No. 16109 (Cambridge, Mass.: National Bureau of Economic Research, 2010); and Environment Directorate, Organisation for Economic Co-operation and Development, *Interactions Between Emission Trading Systems and Other Overlapping Policy Instruments* (Paris: OECD, 2011).

[22] See Judson Jaffe, Matthew Ranson, and Robert Stavins, "Linking Tradable Permit Systems: A Key Element of Emerging International Climate Policy Architecture," *Ecology Law Quarterly* 36 (2010): 789 – 808.

[23] See Richard N. Cooper, "The Case for Charges on Greenhouse Gas Emissions," in *Post-Kyoto International Climate Policy*, ed. Aldy and Stavins, 151 – 178.

[24] See Robert W. Hahn and Robert N. Stavins, *What Has the Kyoto Protocol Wrought? The Real Architecture of International Tradable Permit Markets* (Washington, D.C.: AEI Press, 1999).

[25] See Gilbert E. Metcalf and David Weisbach, "Linking Policies When Tastes Differ: Global Climate Policy in a Heterogeneous World," Discussion Paper 2010-38, Harvard Project on International Climate Agreements, Belfer Center for Science and International Affairs, Harvard Kennedy School, July 2010.

[26] See Nathaniel Keohane, Richard Revesz, and Robert Stavins, "The Choice of Regulatory Instruments in Environmental Policy," *Harvard Environmental Law Review* 22 (2) (1998): 313 – 367.

[27] See David W. Montgomery, "Markets in Licenses and Efficient Pollution Control Programs," *Journal of Economic Theory* 5 (3) (1972): 395 – 418.

[28] There are, however, certain circumstances in which this independence axiom fails; see Robert W. Hahn and Robert N. Stavins, "The Effect of Allowance Allocations on Cap-and-Trade System Performance," *The Journal of Law and Economics* (forthcoming). In some cases, the tax-interaction and revenue-recycling impacts of the choice of free allowance allocation could significantly undermine cost effectiveness; see Lawrence H. Goulder, Ian W.H. Parry, Roberton C. Williams III, and Dallas Burtraw, "The Cost-Effectiveness of Alternative Instruments for Environmental Protection in a Second-Best Setting," *Journal of Public Economics* 72 (1999): 329 – 360.

[29] See Keohane, Revesz, and Stavins, "The Choice of Regulatory Instruments in Environmental Policy."

[30] See Robert Crandall, "Policy Watch: Corporate Average Fuel Economy Standards," *Journal of Economic Perspectives* 6 (1992): 171 – 180; and Mark R. Jacobsen, "Evaluating U.S. Fuel Economy Standards in a Model with Producer and Household Heterogeneity," working paper, Department of Economics, University of California, San Diego, September 2010.

[31] See Robert N. Stavins, "Polarized Politics Paralyze Policy," *The Environmental Forum* 28 (6) (November/December 2011): 16.

The American Public's Energy Choice

Stephen Ansolabehere & David M. Konisky

Abstract: Public opinion about energy can be understood in a unified framework. First, people evaluate key attributes of energy sources, particularly a fuel's cost and environmental harms. Americans, for example, view coal as relatively inexpensive but harmful, natural gas as less harmful but more expensive, and wind as inexpensive and not harmful. Second, people place different weights on the economic and environmental attributes associated with energy production, which helps explain why some fuels are more popular than others. Americans' attitudes toward energy are driven more by beliefs about environmental harms than by perceived economic costs. In addition, attitudes about energy sources are largely unrelated to views about global warming. These findings suggest that a politically palatable way to reduce greenhouse gas emissions is through regulation of traditional pollutants associated with fossil fuels, rather than a wholly new carbon policy.

Americans do not directly buy the coal, natural gas, or uranium used to generate nearly all the electricity in the United States. Nor do they see, smell, or feel those fuels when they use electricity. In that respect, electricity consumption differs fundamentally from most other consumption goods, including our main transportation fuel, gasoline. Nonetheless, Americans have definite opinions about the best way to generate electricity because the fuels used have immediate effects on their electricity bills, as well as on economic growth, national security, and the local and global environments. Americans want less reliance on coal and oil; they want expanded use of wind and solar power; they want to continue and even expand use of natural gas; and they are deeply torn about nuclear power.[1]

A basic goal of public opinion research on energy is to understand how Americans view their energy choices. Are they content with the existing ways that we generate electricity, or do they want to change significantly the fuels that power the country? If the latter, what drives that preference? How important a factor is global warming, or security, or affordability? The importance of energy as a truly

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public policy matter has never been greater. Challenges of global warming, economic competition, possible oil scarcity, and attendant questions of national security have pushed energy production high on the national policy agenda. In many respects, the environmental movement and public backlash over oil prices in the 1970s were only preludes to the challenges we face today.

Little is known about public attitudes toward electricity generation in general and about the fuels used in particular. Perhaps because of the tumultuous politics surrounding nuclear power and oil prices in the 1970s, there has been much public opinion and psychological research about nuclear power, especially questions of risk, and some research on oil, especially attitudes about gasoline prices and energy companies. There has been almost no research on coal and natural gas, even though those two fuels together account for approximately 70 percent of electricity generation in the United States.[2] And almost no research compares energy sources directly or examines why people prefer one source over another.

The history of nuclear power makes it painfully clear how important public attitudes are to the development of energy policy and to the deployment of any method of generating electricity on a large scale. Nuclear power promised to become a great new energy source for the United States and Europe at the beginning of the 1970s. The United States had invested heavily in this new technology over the previous decade, and numerous plants were planned or under construction. However, rising fears of safety, exacerbated to some degree by Cold War fears of nuclear attack, led to public opposition and protests against siting several prominent facilities. The accident at Three Mile Island legitimated those protests and triggered a three-decade-long "nuclear winter" for the industry, as the development of new facilities came to a virtual standstill. At this time, the National Science Foundation (NSF) also began to include nuclear power as one of its key indicators of public opinion toward engineering and science. By the 1990s, however, attention to the issue had faded. Public attitudes were firmly against building new nuclear power plants, and the numbers had not moved in two decades. NSF stopped asking the public about nuclear power around 2000.

Social scientists today face the task of understanding energy choices and public opinion in a more systematic way because of the twin challenges of economic development and global warming. The prospect of global warming has transformed the debate over energy in American society. How we generate and use electricity and transportation fuel had been viewed as a specific sector of our economy, albeit an important one. A rising threat of global warming has shifted the debate from one that concerns a specific sector to one that touches on most aspects of contemporary society and economy. Further, advances in technology for energy use and consumption will be essential to the transition away from fossil fuels, and that realization has created a strong push in the United States and elsewhere to be in the forefront of the next high-tech boom, this one focused on energy. Global warming and energy innovation have put energy back onto the national political agenda – and in a much broader way than either nuclear risks or gasoline price spikes ever did. What and how the public thinks about energy choices, then, will be critical in making legislative and other policy decisions about energy use.

One troubling finding that has emerged from contemporary survey research is the absence of a connection between global warming and energy use in public opinion. Those willing to pay more on their electricity bills to solve global warming, or who say they are very concerned about global warming, express only slightly higher support for expansion of nuclear power or contraction of coal power – two changes in the U.S. energy portfolio thought to be essential to reduce greenhouse gas emissions from the electricity sector. Even if Americans were to become more concerned about global warming, it is unclear today whether those concerns would translate into support for a realignment of U.S. energy policy. Conventional environmental problems, on the other hand, strongly influence public attitudes about which fuels the United States should use. Accordingly, public policies that reduce conventional pollutants would likely have public support and could be devised so as to reduce use of fuels that emit disproportionate amounts of greenhouse gases.

Public opinion about energy can be understood in a common, unified framework. Such a framework conjectures that people evaluate all fuels in terms of a common set of attributes: affordability, environmental cleanliness, security, and so forth. People evaluate each fuel according to those attributes and use them to formulate preferences about how they would like the United States to generate electricity. Attributes have different weight in people's thinking; cost may be more important than security, for instance. Structuring energy choices in terms of attributes allows us to think of public opinion not as unique to the fuel type, but as driven by a common set of considerations.

In a series of public opinion surveys sponsored by MIT and Harvard beginning in 2002, we have examined the public's energy choice by way of two important attributes: affordability (or economic cost) and cleanliness (or environmental harm).[3] Several key findings emerge. First, people hold beliefs about the economic and environmental consequences for all the main energy sources. Individuals do not all perceive the costs and harms of fuels accurately, but at the aggregate level, public opinion is strongly consistent with elite assessments of the relative cost and environmental harms associated with the major fuels used to generate electricity. Second, nearly all respondents in recent national surveys express a preference about whether they would like the United States to use more or less of the major fuel sources for electricity generation, including coal, natural gas, nuclear power, oil, and hydro, wind, and solar power. Third, people value both affordability and the environment. Individuals express opinions about future energy use that are based on their perceptions of costs and harms. Those who perceive a fuel as less costly and less harmful to the environment express a desire to increase use of that fuel. Importantly, this pattern holds across all fuels. Perceptions of the economics and the environmental harms strongly predict preferences about the use of each energy source.

Thinking about energy choices in this way allows us to characterize public opinion in terms of publicly acceptable alternatives. That is, we can think of energy policy as choices about different attributes of the U.S. electricity generation portfolio. Rather than conceiving of the portfolio as many unique and distinctive fuel sources, we characterize public opinion on energy according to a handful of attributes. Consider the two attributes of affordability to consumers and environmental cleanliness. We can map out how affordable and clean the public perceives each fuel source to be. Then, using the relative weight of cost and environmental harm, we can assess how the public weighs costs and harms relative to each other in evaluating the trade-off between fuels that are relatively inexpensive but environmentally harmful, such as coal, and fuels that are relatively expensive but environmentally less harmful, such as wind and solar power. The public's demand for one or the other of these fuels depends on how strongly costs and environmental harm are valued.

Public opinion, of course, does not mirror the marketplace. In fact, it may reflect what does *not* happen in the private sector. Industrial production of electricity does not fully capture the cost of environmental harms and damages.[4] Public opinion on energy expresses the relatively high value that people place on further reduction of pollution from electricity generation, beyond what is reflected in prices.

Most public opinion research on energy before 2000 was driven by specific concerns or events associated with particular forms of power generation. The gasoline price shocks, the 1969 oil spill off the coast of Santa Barbara, the accident at Three Mile Island, and other events spawned public opinion research about specific crises.[5] The framework presented here builds on such research, but in a way that broadens the picture. While each of those earlier events concerned important aspects of the energy system – whether price or environmental damage – the new wave of survey research on energy attempts to measure the bases of public opinion across the range of energy choices.

A second long-standing avenue of research on the environment concerns tradeoffs. Since the 1970s, survey researchers have asked respondents what they think is more important, "jobs or the environment" (also formulated as "economic development or environment"). This question has been criticized as not being specific enough to inform policy choices, and as not presenting the right choices. Lower energy costs are often viewed as the alternative to environmental regulation. Setting these particular concerns aside, this question attempts to establish how people will trade off one value against another. The question seeks to do explicitly what we do implicitly: that is, assess the degree to which people are willing to trade off higher cost to achieve a cleaner energy system.

Finally, survey research on global warming has greatly expanded. Resources for the Future, the Pew Center on Global Climate Change, and Yale and George Mason Universities, among others, have probed the public's willingness to adopt aggressive climate regulations. Most of this polling asks about climate change directly, and then about conservation, fuel types, and other features of energy use in the context of climate change. We flip this approach on its head, starting with what people know about energy and what it means for designing a publicly acceptable policy to address greenhouse gases.

The traditional framing of survey questions about energy pits jobs versus the environment. This formulation has been criticized because it oversimplifies the true choices and because it presents a tradeoff that need not always be present. Nonetheless, it does capture an essential element about energy and the American public. All fuels can be thought of as having a set of attributes, and perhaps the most important are the economics of providing electricity using that fuel and the environmental externalities produced by that process. There are other important attributes, such as the safety of the production process and national security concerns arising from the supply of different energy sources; however, most public debate and opinion research concerns the economics of providing electricity and the environmental side effects.

A series of surveys conducted through the MIT Energy Initiative gauges how people perceive the economic costs and environmental harms associated with each type of fuel used to generate electricity in the United States today. These surveys, conducted in 2002, 2003, 2006, 2007, 2009, and 2010, were among the first to compare public perceptions of and attitudes about the major fuel sources. The surveys first ask, "How expensive or inexpensive is it to use each of the following fuel sources?" For each fuel source, respondents are provided a range of options, from "very expensive" to "very cheap." The surveys also ask: "Different ways of producing electricity cause pollution, such as air pollution, water pollution, and toxic wastes. How harmful do you think each of the following is to the environment?" Respondents are allowed to evaluate each on a scale from "very harmful" to "not harmful at all."

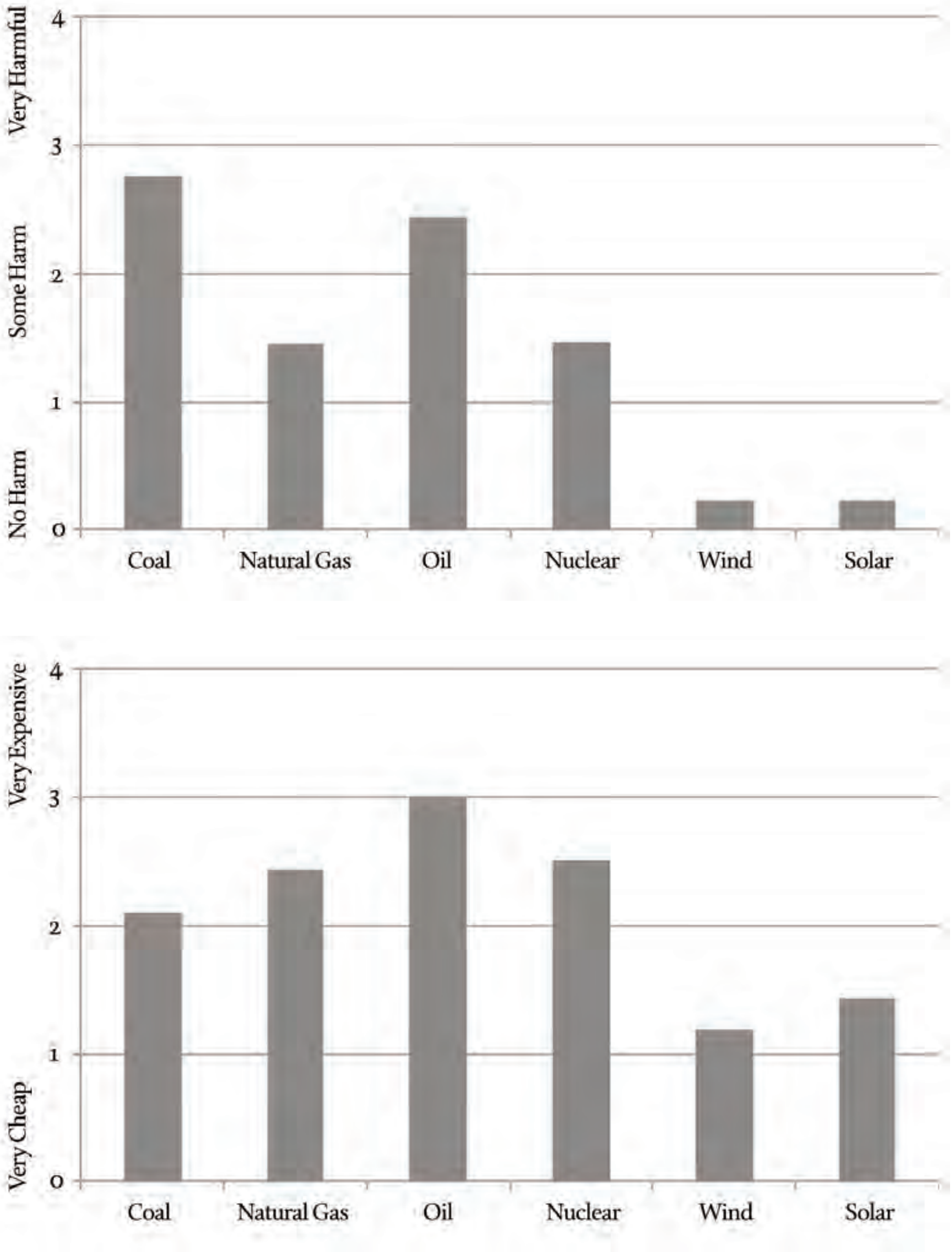
A fairly consistent pattern of responses emerges in all the energy surveys. On the question of environmental harm, Americans see a wide gulf between traditional and "alternative" fuels. Americans, on the whole, think that coal, oil, and nuclear power are harmful to the environment. They think that natural gas is somewhat harmful to the environment, and large majorities view solar, wind, and to a lesser degree hydro, power as not harmful at all.

On the question of economic cost, a similar gap emerges. The average American sees oil and natural gas as somewhat expensive, followed by nuclear power and then coal. Solar and wind power are viewed as somewhat inexpensive. Figure 1 shows the average value of the perceived harm and perceived cost of using each fuel source, as determined by the 2008 MIT Energy Survey. Some of the values move over the course of the last decade. Oil, for example, was perceived to be somewhat less expensive at the beginning of the decade than it was at the end, a change that reflected rising oil prices.

Responses to these two questions allow us to map out how people perceive energy choices according to certain attributes. Wind and solar, for example, are perceived to rate highly on both environmental cleanliness and economic cost. These perceptions are certainly wrong on affordability, which we consider in the final section of this paper. Among the traditional fuel sources, natural gas dominates oil: natural gas is seen as slightly less expensive than oil and somewhat less harmful to the environment. In comparison with natural gas, nuclear power is deemed as just slightly more harmful to the environment and somewhat more expensive. Coal shows an even more dramatic difference with natural gas; it is perceived as noticeably less expensive and substantially more harmful to the environment. (Natural gas is in fact a more costly but cleaner alternative to coal.)

The MIT/Harvard Energy Surveys also ask whether the United States should increase or decrease its use of each fuel to generate electricity. A strong majority (about 75 percent) wants to increase the amount of solar and wind power in the American energy portfolio, while majorities also desire reduced reliance on coal and oil. These broad assessments are consistent with the findings shown in Figure 1, but there is a deeper question: which attribute is more important in explaining preferences? How an elected official or regulator might make decisions that are responsive to public opinion depends not just on how the public perceives different attributes, but on how much weight these attributes have. The relative importance of environment and economics in public thinking can guide how we as a society choose between less expensive but environmentally more harmful fuels and more

Figure 1
Perceived Harm and Perceived Price of Energy Sources as Related to Desired Future Use



Bars represent mean value for each energy source. Source: Energy Survey 2008, MIT/Harvard Energy Surveys.

expensive but environmentally less harmful fuels. In short, how do we decide between coal and natural gas, and, eventually, between fossil fuels and renewable sources?

One can measure the relative weight of attributes in two ways. First, we use perceptions of harm and cost to predict individuals' expressed preferences about whether they think the country should use more or less of each fuel type. We make this prediction by regressing expressed preferences about fuel use on perceived cost, perceived environmental harm, and other factors. Second, we conduct experiments in which some survey respondents are told the actual prices of producing electricity from each source. We can then measure the magnitude of the difference in preferences about which energy source to use between those who are given the correct price information and those who are not. Of particular interest is whether the public becomes less enthusiastic about renewable sources upon learning the relatively high price of those alternatives, and whether the change in preferences is consistent with the first sort of analysis.

Figure 2 shows the relative weight of perceived economic costs and perceived environmental harms associated with each fuel in survey respondents' evaluations of whether the United States should use more or less of a given fuel.[6] The graph shows standardized regression coefficients and their associated 95 percent confidence interval for each perception. In this graph, positive values mean that a given attribute (environmental cleanliness or economic affordability) is valued more highly.[7]

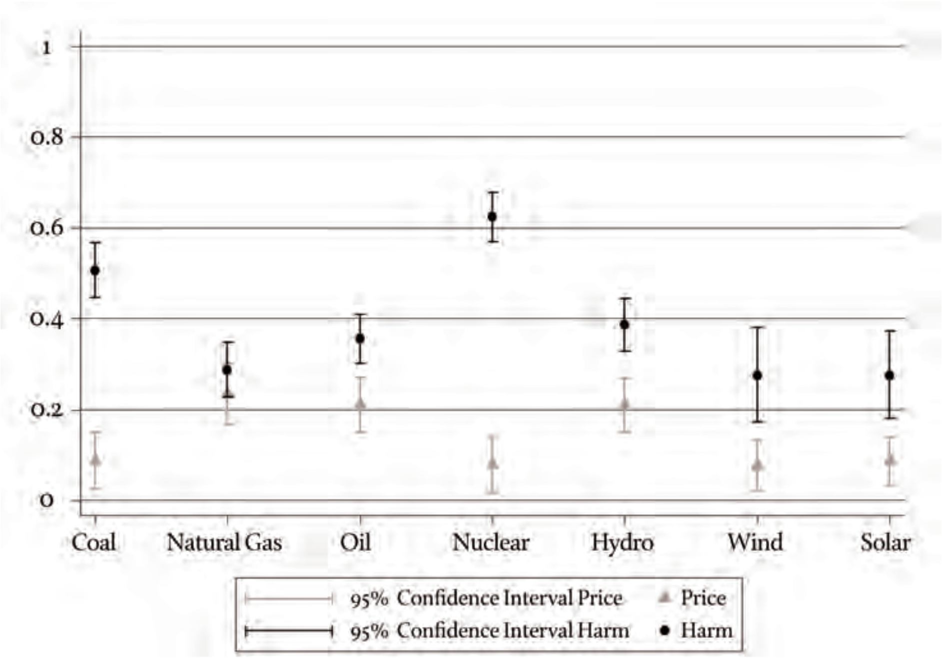
Several qualitative findings stand out. First, Americans value the environment more than affordability. Environmental considerations have a stronger effect than economic considerations in predicting whether people want to increase or decrease use of a given fuel. The difference is particularly large for coal and nuclear power, but it holds for each fuel source.

Second, the weight given to cost is similar (and statistically indistinguishable) across the fuel types. Prices have approximately the same effect on people's thinking about energy use regardless of the fuel. This is an important finding, as it indicates that people respond to prices of each fuel source in the same way. In accord with economic intuitions, people want to substitute more expensive fuels with cheaper fuels regardless of what fuels are involved.

Third, the weights of perceived environmental harms are about the same for most fuels. The weights are indistinguishable for natural gas, oil, solar, and wind. Environmental harms have much greater weight when people think about coal and nuclear power. Considering that coal is seen as the most harmful for the environment, these data suggest a very strong willingness among the American public to move away from coal, even though it is cheaper than alternative fuels.

Fourth, these results reveal that people think about all fuels through a common lens. The weights of perceived prices are approximately the same in public assessments of all fuels, and the weights of perceived environmental harms are approximately the same for natural gas, oil, wind, and solar power. This finding is somewhat surprising because solar and wind are often talked about separately from gas and oil – as if renewable technologies differ fundamentally from fossil fuels. Instead, we find that people think about these fuels using the same attributes and in the same ways, though they have different perceptions of those attributes. Coal and nuclear power differ from the other fuels in the environmental domain; people weigh environmental considerations much more when they think about whether to use

Figure 2
Weight of Perceived Harm and Perceived Price on Desired Future Use of Energy Sources



Source: Energy Survey 2008, MIT/Harvard Energy Surveys.

more of those fuels. This is a serious liability for coal, suggesting that public support for increasing its use is highly dependent on making it into a cleaner fuel (which is quite expensive to do).

A final question is whether people think of environmental harm in local or global terms. The question analyzed so far framed environmental harm in local terms. The surveys also ask respondents how concerned they are about global warming and how willing they are to pay to reduce global warming. In the 2002 MIT Energy Survey, the weight of the measure of concern about global warming was statistically indistinguishable from zero in most of our analyses predicting preferences about future use of fuel source. Only for wind and solar power did concern about global warming matter for people's thinking about the fuel, and even then the effect was small. By the end of the decade, the importance of global warming in thinking about energy had risen, but the effect was still much smaller than the effects of either local pollution or energy prices. Attitudes about global warming have weak or no correlation with attitudes about which fuels we use to generate electricity in the United States. The environmental concerns that people rely on in thinking about energy production and policy, then, are local environmental and health considerations, not global ones.

Experiments provide another way to measure the sensitivity of future energy preferences to perceptions of price and environmental harm. The 2002 MIT Energy Survey included an experiment to measure shifts in attitudes for different energy sources in light of information about changes in costs and harms. The survey sample was randomly divided into five groups. Three groups were provided information about 1) current prices of power generation and projected increases in the costs of fossil fuels relative to other energy sources over the next twenty-five years; 2) current prices of power generation and global warming threats from burning fossil fuels; or 3) current prices of power generation and toxic wastes generated as a by-product of burning fossil fuels. A fourth group was provided all three messages, and a fifth group, serving as a control, was provided with no information. Each group was then asked whether the United States should increase or decrease the use of each energy source of generating electricity.

The effects of the information were modest; that is, people's preferences for increasing or decreasing the use of a particular fuel did not differ much for groups receiving the various messages compared to the group that did not receive any information. One notable exception pertains to the price information. Compared to the control group, individuals provided information about the price of energy were more likely to support the *increased* use of coal, oil, and nuclear power and more likely to support the *reduced* use of wind, solar, and hydro power. These differences were each statistically significant, except for the case of nuclear power. In other words, upon being provided factual information about the relative costs of energy sources, support for traditional fuels increased, while support for the increased use of renewable technologies diminished. There was no similar difference for the groups provided information about global warming or toxic waste; these messages did little to affect preferences for either fossil fuels or renewables. The one deviation from this pattern is that, when provided information about price and environmental harm (particularly toxic wastes), respondents on average were more likely to favor increased use of nuclear power compared to respondents receiving no information. These experimental results show that, similar to the regression analysis, people do not connect global warming to future policies about electricity production.

Additional experiments administered in the 2007 and 2008 MIT Energy Surveys replicated the findings on cost. When informed that solar and wind power are much more expensive than coal and natural gas, support for coal and natural gas rose slightly, and support for solar and wind power dropped substantially.

Public opinion research about energy in the United States points repeatedly to one unfortunate conclusion: concern about global warming is, at best, weakly correlated with attitudes toward particular fuels. That weak correlation suggests that raising the alarm and public education about global warming are unlikely to lead to radical changes in public opinion about energy production and use.

The analyses described above reveal that even if all Americans thought climate change required immediate action, support for coal would decline by only 0.10 on a scale from zero to one, support for solar and wind power would increase by only 0.20, and support for nuclear power would actually decline. That result is consistent with a separate literature on Americans' willingness to pay to reduce greenhouse gas emissions, as well as their support for climate change legislation and international climate agreements. With the exception of recent work by social psychologist Jon Krosnick of Stanford University,[8] nearly all survey research in this area shows that people are willing to approve of only modest carbon taxes or regulatory changes in order to slow greenhouse gas emissions. Climate change, given the current mindset of many elected officials, policy pundits, and environmental advocates, is clearly not going to drive public opinion about energy use and energy policy.

But there is another way to take on the climate problem. The results here reveal that the public is willing to support changes in the mix of fuels used to generate electricity when those changes are based on local environmental problems. Recent analyses by economist Michael Greenstone of MIT and Adam Looney, a senior fellow in economic studies at the Brookings Institution, indicate that much of the increase in the price of coal needed to reduce use of that fuel can be accomplished through stricter regulation of local pollution problems, such as emissions of ozone precursors, particulates, and mercury.[9]

Regulations that tackle these problems will help make a first cut at greenhouse gas emissions from electricity for the simple reason that those problems arise disproportionately with the use of coal. Such a regulatory approach is not a climate policy per se, because it would not regulate coal for the explicit purpose of decreasing carbon emissions. However, regulations aimed at improving local air quality by reducing emissions from coal combustion would have the effect of also reducing greenhouse gas emissions by reducing the use of coal in general. And regulation of pollution from coal-fired power plants would likely receive substantially more public support than similar efforts to reduce coal use through regulation of greenhouse gas emissions.

Perhaps the most intriguing finding is the unity that we see across fuels. For decades, survey research has treated opinion about different power sources as unique. The new wave of survey research suggests that people view all fuels through the same lens. Technological advances that diminish environmental harm or reduce costs will make fuel sources more competitive in the economic marketplace, more acceptable to the public, and more palatable in the political realm.

ENDNOTES

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[1] See, for example, *The Future of Nuclear Power: An Interdisciplinary MIT Study* (Cambridge, Mass.: Massachusetts Institute of Technology, 2003; updated 2009); *The Future of Coal: An Interdisciplinary MIT Study* (Cambridge, Mass.: Massachusetts Institute of Technology, 2007); Toby Bolsen and Fay Lomax Cook, "The Polls – Trends: Public Opinion on Energy Policy: 1974 – 2006," *Public Opinion Quarterly* 72 (2) (2008): 364 – 388; and Eric R.A.N. Smith, *Energy, the Environment, and Public Opinion* (Lanham, Md.: Rowman & Littlefield, 2002).

[2] There has been some effort to understand how Americans weigh energy development and environmental protection, specifically with regard to strip-mining for coal, offshore drilling

for oil and gas, and the opening of the Arctic National Wildlife Refuge to gas and oil exploration.

[3] The surveys were administered through the Internet by Knowledge Networks to a nationally representative group of adult respondents. Knowledge Networks recruits and maintains a panel of individuals who participate in client-based surveys, such as our surveys of energy attitudes.

[4] For a comprehensive report, see National Research Council, *Hidden Costs of Energy* (Washington, D.C.: National Academies Press, 2010).

[5] Paul Slovic, among others, saw a broader framework in which to understand opinion about nuclear power. For more on his risk framework, see Paul Slovic, "Perceptions of Risk," *Science* 236 (1987): 280 – 285.

[6] The regression also includes control variables for various demographic characteristics (age, education, income, race or ethnicity, gender, and marital status), political attitudes, and region of residence. For a similar analysis in the context of not-in-my-backyard (NIMBY) attitudes about different types of power plants, see Stephen Ansolabehere and David M. Konisky, "Public Attitudes toward Construction of New Power Plants," *Public Opinion Quarterly* 73 (3) (2009): 566 – 577.

[7] Standardized regression coefficients allow for more direct comparison of the measures used. One can interpret the expected change in the dependent variable for each standard deviation increase in the measure of interest.

[8] Jon Krosnick, "Large Majority of Americans Support Government Solutions to Address Global Warming," Woods Institute for the Environment, Stanford University, June 2010, http://woods.stanford.edu/research/americans-support-govt-solutions-global-warming.html.

[9] Michael Greenstone and Adam Looney, "A Strategy for America's Energy Future: Illuminating Energy's Full Costs," The Hamilton Project (Washington, D.C.: Brookings Institution, 2011).

Is Shale Gas Good for Climate Change?

Daniel P. Schrag

Abstract: Shale gas is a new energy resource that has shifted the dominant paradigm on U.S. hydrocarbon resources. Some have argued that shale gas will play an important role in reducing greenhouse gas emissions by displacing coal used for electricity, serving as a moderate-carbon "bridge fuel." Others have questioned whether methane emissions from shale gas extraction lead to higher greenhouse gas emissions overall. I argue that the main impact of shale gas on climate change is neither the reduced emissions from fuel substitution nor the greenhouse gas footprint of natural gas itself, but rather the competition between abundant, low-cost gas and low-carbon technologies, including renewables and carbon capture and storage. This might be remedied if the gas industry joins forces with environmental groups, providing a counterbalance to the coal lobby, and ultimately eliminating the conventional use of coal in the United States.

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Over the last ten years, technological innovation has transformed U.S. energy resources. Geologists have long known that organic-rich shales contain large quantities of natural gas, but the technology was not available to recover this gas at a reasonable cost. With the development of cheaper, more efficient horizontal drilling methods combined with improvements in hydraulic fracturing ("fracking") techniques that greatly increase the permeability of the shale, vast reserves of natural gas are now available at relatively low cost. In just five years, shale gas has grown from 4 percent to more than 25 percent of the U.S. supply of natural gas. With the new shale gas reserves, the United States has decades of reserves of a critical energy resource for home heating, electricity generation, and a wide variety of industrial processes.

Environmental groups have had a mixed reaction to shale gas. National environmental organizations focused on climate change, as well as organizations concerned with air-quality issues, have cautiously embraced the new technologies in anticipation that greater availability of low-cost natural gas may displace coal in electricity generation, thereby reducing carbon dioxide emissions and substantially decreasing emission of other pollutants, particularly mercury and sulfur. Indeed, U.S. coal consumption fell 10 percent between 2007 and 2011, while natural gas production rose by 15 percent. On the other hand, many environmental groups have opposed the expansion of natural gas drilling, especially in places that historically have not seen extensive oil and gas activities. Some groups are concerned that the chemicals used in the fracking process will contaminate groundwater aquifers; others are concerned with natural gas leakage into aquifers and even residential houses; others are concerned with the overall footprint of natural gas extraction, including new roads, new pipelines, truck activity, and storage of toxic waste from produced water (a mixture of formation brines and chemicals from the fracking process).[1]

Is the natural gas boom good for climate change mitigation, independent of other environmental concerns? A common view, including that of a recent commission convened by U.S. Secretary of Energy Steven Chu, is that expanded natural gas activities are inherently good for climate change mitigation because natural gas has lower greenhouse gas emissions than coal, which gas will displace for use in electricity generation.[2] A dissenting view is that methane leakage from shale gas extraction leads to greenhouse gas emissions as bad or worse than those produced from coal,[3] although this view is fiercely debated. Considering the timescale of the carbon cycle and the climate system, both of these perspectives are wrong, but for similar reasons. Leakage of methane is not as important as some have argued because its short lifetime limits its impact on anthropogenic climate change, which has a characteristic timescale of roughly one hundred years. But because of this long timescale of climate change, short-term reductions in greenhouse gas emissions – gained from natural gas displacing coal in the U.S. electricity sector – have a relatively small effect on the progression of anthropogenic climate change relative to other impacts of the shale gas boom. The most important of these is how the availability of low-price natural gas affects investment in the research, development, and deployment of truly low-carbon technologies, including renewable energy and carbon sequestration.

The real benefit of shale gas to a responsible climate change policy is a political one, if the economic power of the new industry can break the stranglehold that the coal industry has had on the national discussion around climate policy. The answer to whether shale gas is good or bad for climate change mitigation depends on what policies are used to regulate it; some policy options that encourage natural gas production in the United States are part of a responsible climate policy, but only if they simultaneously encourage other low-carbon technologies as well as disrupt the political power of the coal industry.

Are greenhouse gas emissions from natural gas better than those from coal? The answer would seem obvious. Natural gas has roughly half the carbon content of the average coal per unit energy, thus producing half as much carbon dioxide when combusted for heat or electricity. Moreover, a combined-cycle natural gas plant that generates base-load electricity has a thermal efficiency of roughly 50 percent, which is higher than the newest ultra-super critical coal plants (40 to 45 percent) and much higher than the average coal plant (33 percent) in the United States. Thus, burning natural gas for electricity, when displacing an average U.S. coal plant, results in a reduction in carbon dioxide emissions of nearly a factor of three.

Cornell University scientists Robert Howarth, Renee Santoro, and Anthony Ingraffea question this calculation, focusing on the emissions of methane associated with natural gas production, distribution, and consumption.[4] In their analysis, shale gas production leaks methane at as much as twice the rate of conventional gas wells. Most of this extra leakage, they assert, comes during the well-completion phase, immediately after the fracking, when brine from the formation and water used in the fracking process come out of the well. They argue that this methane leakage, along with leakage during processing, transport, and distribution, results in shale gas having higher greenhouse gas emissions than coal due to the high warming potential of methane relative to carbon dioxide.

Even if one accepts the leakage rates proposed by Howarth and colleagues (and there is considerable uncertainty about their findings), there remains the question of the value of greenhouse gases other than carbon dioxide, particularly those like methane that have short atmospheric lifetimes. To compare the impact of different greenhouse gases, a physical metric called the Global Warming Potential (GWP) was adopted by the Intergovernmental Panel on Climate Change (IPCC) in its *First Assessment Report*.[5] The GWP of a greenhouse gas is defined as the time-integrated global mean radiative forcing of a pulse emission of 1 kg of the gas relative to 1 kg of carbon dioxide over a specified time period, commonly one hundred years. This metric has persisted for the past twenty years despite many economic and technical criticisms.[6] The IPCC established the one hundred–year timescale as a standard for comparison between greenhouse gases, but it is an arbitrary designation. If one chooses a longer timescale – for example, five hundred years – the GWP for methane would be 8 rather than 25. If one chooses a shorter timescale – for example, twenty years – the GWP for methane would be 70.

In the analysis by Howarth and his colleagues, natural gas and coal for electricity are compared for both one hundred–year and twenty-year timescales, but the standard GWP values are amplified by roughly 50 percent based on a model calculation[7] that includes the inhibitory effect of methane emissions on the formation of sulfate aerosols, which cool the climate. Using this calculation raises the twenty-year and one hundred–year GWP values to 33 and 105, respectively. This is a controversial adjustment; sulfate aerosols come primarily from sulfur dioxide emissions associated with coal combustion and are a major contributor to respiratory illness. One might expect sulfur emissions to decrease in the future, even if greenhouse gases do not, and so it is difficult to know how to measure the future impact of methane on emissions of sulfate aerosols. Moreover, the analysis does not use similar accounting to evaluate coal combustion; if one used an identical approach and included coal combustion's impact on sulfate aerosols (as was done for methane), the sulfur emissions associated with coal can substantially offset the warming effects of coal's carbon emissions.[8] Of course, this would be absurd: the longer-term consequences of coal combustion are disastrous. Thus, one can see how Howarth and colleagues reached their conclusion if they value a ton of methane at 105 times the value of a ton of carbon dioxide.

Putting aside the issue of the relationship between methane and sulfate aerosols, the major problem with the comparison between natural gas and coal by Howarth and colleagues is that the GWP does not provide a good indication of the warming caused by different greenhouse gases. Rather, it considers only the time integral of the radiative forcing. A series of studies propose a better metric for comparing different greenhouse gases, the Global Temperature Potential (GTP), defined similarly to the GWP but using the global average temperature response to a pulse emission in a climate model instead of the radiative forcing.[9] The disadvantage of a GTP is that it is model-dependent, although the importance of climate sensitivity of any individual climate model is relatively minor, as one is looking not at the absolute temperature response but the response of the model for one greenhouse gas relative to carbon dioxide. The specific values for GTPs from different climate models are systematically lower for short-lived gases like methane than what are found with GWPs. For example, the GTP for methane for one hundred years is approximately 7.[10] This figure is more than three times lower than the one hundred–year GWP value used by the European Union and the U.S. Environmental Protection Agency (EPA) to compare different greenhouse gases, and is fifteen times lower than the twenty-year GWP used by Howarth and colleagues. Thus, even if shale gas production results in large methane emissions, burning natural gas is still much better for the climate system than burning coal.

The preceding discussion has left unresolved the question of what timescale to adopt for a comparison between greenhouse gases. Howarth and colleagues defend the use of a twenty-year timescale because, they assert, we should care more about climate change over the next few decades. Some have also suggested that the rate of warming is important, especially in terms of the ability of ecological systems to adapt to climate change.[11] Similar arguments are made in a recent UN Environment Programme/World Meteorological Organization report on the climate mitigation value of reducing black carbon and methane through pollution abatement measures.[12] This debate raises a more general question about what timescale is best for evaluating climate mitigation efforts, such as a policy that promotes natural gas consumption relative to coal.

One thing is clear: twenty years is far too short a timescale over which to evaluate climate change policies. This simple fact poses enormous problems for the formulation of climate change policy, as making projections for even the next decade is difficult enough, to say nothing of projecting out over a century. And yet it is the century timescale (at least) that matters. An insightful study by climate scientist Myles Allen and his colleagues[13] showed that the peak warming in response to greenhouse gas emissions depends on cumulative greenhouse gas emissions over a period of roughly one hundred years; moreover, the climate response to any specific emissions scenario is surprisingly insensitive to the emissions pathway.[14] They concluded that climate policy should focus on limiting cumulative emissions rather than setting emissions-rate targets. This result has been replicated by several studies; all find that it is the cumulative emissions over a century, not the rate of emissions, that is most important for the climate response to greenhouse gas emissions.[15] This finding contradicts the argument that the rate of warming warrants attention to shorter timescales. Such assertions are often made without mention of any specific rates or scenarios. In reality, different emissions scenarios with different mixes of methane and carbon dioxide emissions, for example, result in very similar rates of warming over the century. Focusing on reducing methane emissions over the next two decades merely delays warming by a few years by the end of the century – a small benefit relative to efforts to reduce the cumulative emissions of greenhouse gases, which are dominated by carbon dioxide.

Dissecting this result to understand exactly which process is responsible for the one hundred–year timescale is complicated because there are so many different timescales at play. One important factor is the general shape of global emissions scenarios, whose timescale is set largely by the lifetime of new energy infrastructure and the rate of investment in new infrastructure at the global scale. Because carbon dioxide concentrations will continue to rise through much of the century, the impact of any short-term reduction in emissions is offset by future emissions, resulting in only a small delay in eventual warming. Another important timescale is the residence time of carbon dioxide in the atmosphere. Once carbon dioxide is emitted from the combustion of fossil fuel, it is transferred among atmospheric, terrestrial, oceanic, and sedimentary reservoirs by a wide variety of biogeochemical processes that convert carbon dioxide to organic carbon, dissolved bicarbonate ion, or calcium carbonate, and then back again. The rates of these processes determine how long carbon resides in each reservoir, and how long it will take to bring the elevated concentrations of carbon dioxide in the atmosphere back to pre-industrial levels. There are also longer timescales in the carbon cycle. Over the timescale of several thousand years, once ocean equilibration is complete and only 20 to 40 percent of cumulative emissions remain in the atmosphere, dissolution of carbonate rocks on land and on the ocean floor will further reduce the airborne fraction to 10 to 25 percent, over a range of several thousand years to ten thousand years. This remnant of anthropogenic carbon dioxide emissions will stay in the atmosphere for more than one hundred thousand years, slowly drawn down by silicate weathering that converts the carbon dioxide to calcium carbonate, as well as by slow burial of organic carbon on the ocean floor.[16] The size of this "tail" of anthropogenic carbon dioxide depends on the cumulative emissions of carbon dioxide, with higher cumulative emissions resulting in a higher fraction remaining in the atmosphere.

Understanding these long timescales of the carbon cycle shows us that climate change is likely to persist for centuries and millennia. Earth will continue to warm as long as humans continue to emit carbon dioxide from fossil fuel. The long-term goal of a responsible climate policy must be zero emissions – or at least very low emissions. A partial reduction in emissions – especially within just one country – only delays the extent of climate change as the carbon continues to accumulate in the ocean-atmosphere system.

If the climate system is relatively insensitive to shorter timescales of emissions changes, then any methane emissions associated with shale gas extraction are not as important as portrayed by Howarth and his colleagues. So if the shale gas boom in the United States results in lower greenhouse emissions overall because it displaces some use of coal for electricity generation, isn't that a good thing for climate change mitigation? Not necessarily. There are several ways that the shale gas boom's more harmful effects on climate mitigation may outweigh the climate benefit (that is, reduced coal use). For this analysis, I embrace the conclusion of Allen and his colleagues: that effective climate policy should focus on reducing cumulative emissions, not the rate of emissions at a certain point in time. This is not to say that setting targets for the rate of emissions in the near term is a bad idea. First, there will always be some basic connection between rates of emissions and cumulative emissions. Lowering the rate of greenhouse gas emissions is always good for climate change, as lower emissions rates will affect the cumulative emissions. Second, having short-term emissions targets forces our society to invest in the infrastructure and other changes required to reach a low-carbon economy, actions that would be less likely if there were only long-term targets. The problem is that emissions rates are a very imperfect metric for progress toward the long-term goal of near-zero emissions. Indeed, several possible impacts of the shale gas boom in the United States may lead to slightly lower greenhouse gas emissions in the short term, but may actually increase cumulative emissions by delaying the deployment of near-zero emission technologies in the long term.

The argument for the climate benefits of shale gas depends heavily on a comparison between natural gas and coal. But is a direct comparison with coal appropriate? There is no question that natural gas competes with coal in the electricity sector, but only 31 percent of natural gas in the United States is used for electricity generation, compared with 93 percent of coal consumption. Cheap and abundant natural gas may stimulate additional demand in the residential, commercial, or industrial sectors that would negate any displacement in coal combustion. A side effect might also be reduced investments in energy efficiency, for example, that could result in substantial reductions in emissions over the long term. If one designed an energy policy that encouraged shale gas production, with the anticipation that it would lead to lower greenhouse gas emissions by displacing coal, one might discover that emissions reductions in the electricity sector were offset by increased emissions in other sectors that also use natural gas. A quantitative analysis of this issue is difficult to perform because of many other macroeconomic factors that affect natural gas demand, but it is worthy of more attention.

Another serious concern is the impact of low-priced natural gas on the electricity sector for technologies beyond coal – specifically renewable technologies such as wind and solar – and for investment in R&D in renewable and low-carbon energy systems. If the goal is to minimize cumulative emissions and reach near-zero emissions as soon as possible, renewable energy technologies must play a much larger, perhaps even a dominant role in the world energy system. And to do so, the cost of these technologies must compete with fossil fuel systems. Driving down their price will likely come only through wider deployment and through development of new technologies. Both of these actions have been adversely affected by the shale gas boom in the United States, with natural gas prices currently hovering below $3 per thousand cubic feet. The negative impact of low gas prices on renewable energy is not significant if we measure climate progress by looking only at near-term emissions; renewable electricity makes up too small a fraction of the overall electricity sector. But if our goal is to minimize cumulative global emissions over the next century, the delayed investment in renewable technologies may set us back more than the climate benefits achieved from a marginal reduction in U.S. coal consumption. Low gas prices have similarly inhibited investment in nuclear power and carbon capture and storage, both of which are likely to be needed to achieve a near-zero carbon emissions society.[17] Of course, these technologies have faced challenges independent of the competition with low-priced natural gas for electricity generation.

There are enormous benefits in having cheap, abundant natural gas for the United States in terms of the competitiveness of U.S. industry and economic growth in general. But from the climate perspective, the negative impacts on innovation in low-carbon technologies appear to outweigh the benefits of a marginal reduction in emissions from reduced coal consumption.

Ironically, the natural gas industry and the renewable energy industry share a common goal: higher natural gas prices. If the shale gas boom's major negative impact on climate change mitigation is its negative effect on investment in renewable energy and low-carbon technology more generally, then a higher price for natural gas would remedy that situation. And with natural gas prices reaching lower and lower levels in the past two years, the profitability of shale gas has already become more marginal. Some companies are now targeting "wet" shale deposits, which contain a higher fraction of hydrocarbon liquids along with gas, to make the economics of drilling more favorable. A policy that raises the price of natural gas without encouraging increased use of coal would reap the benefits of natural gas, including reduced conventional air pollution; but it would also stimulate investment in renewable energy. This may be the key to reconciling the benefits of the shale gas boom with a responsible strategy for the mitigation of climate change.

Who would be the real winner over the next ten years if a significant price on carbon – for example, $30 per ton of carbon dioxide – were introduced? Renewable energy companies would benefit from a carbon price, although their market share is still quite small. The costs for wind and solar power have come down, but these costs do not include electricity storage or other strategies for dealing with intermittency, which is essential to address as the renewable capacity grows; this would still limit their scale in many places. Nuclear power will also be aided by a price on carbon, although the Energy Information Administration projects that only 9 GW of new nuclear power will be built by 2035 in the United States.[18] Oil is relatively unaffected by a price on carbon simply because oil is already so expensive per ton of carbon. Energy efficiency would be very attractive with a significant carbon price, particularly in states with large amounts of coal-generated electricity. But the major impact of a price on carbon in the United States would be an arbitrage of natural gas for coal in the electricity sector. Even with an increase in natural gas price because of the price on carbon, the natural gas industry would be the winner with regard to climate legislation because it would not be affected as much as the coal industry.

This argument is not based merely on economics. A major obstacle to comprehensive climate legislation in the United States, whether in the form of a carbon tax or a cap-and-trade regime, has been the staunch opposition of the coal lobby, a combination of coal companies and large utilities that own coal-fired power plants. This industrial alliance is notoriously powerful, particularly in the Senate because states with abundant coal resources or numerous coal power plants make up a disproportionate share of the United States relative to their population. Overcoming this political challenge and placing a significant price on carbon (or an equivalent policy that encourages renewables and discourages coal) would represent a major step toward a low-carbon economy, and would achieve many of the goals discussed above, including more deployment of and investment in renewables and carbon capture and storage.

If this analysis is correct, then perhaps there is a path forward on climate change that puts shale gas in a favorable light. Could the economic power of the natural gas industry be pitted against the political power of the coal industry to lobby for climate legislation that puts a price on carbon? Historically, the coal industry has been better organized than the natural gas industry, but natural gas has one important advantage: shale gas has resulted in substantial job growth in the United States, creating far more jobs than would come from an increase in coal production. Consider the case of Pennsylvania, where coal production exceeds gas production on an energy-equivalent basis, but employment by the gas industry now exceeds employment by the coal industry.

A price on carbon would be in the best interests of the natural gas industry; whatever market losses would come with the incentives for renewable and low-carbon technologies would be more than compensated by the decline in coal consumption and the rise in natural gas demand. With a price on carbon, we could see a slight drop in demand for natural gas in the residential, commercial, and industrial sectors, but the elimination of even half the coal from the electricity sector would increase natural gas demand by roughly 25 percent, thus driving up the price (and the profitability) of natural gas.

Building a coalition between the natural gas industry and the environmental community to support a comprehensive climate policy will not be easy. The oil and gas industries have long had a combative and distrustful relationship with the environmental movement. They understand that climate mitigation will ultimately mean an attack on all fossil fuels, not just coal, and so supporting climate legislation may prove folly over the long run, even if there are substantial economic benefits over the next two decades. But if the oil and gas industries will not use their financial and political power to support climate legislation directly, dual attacks on the coal industry by environmental groups and the natural gas industry will still provide substantial benefits in terms of progress toward a low-carbon world. The key is not just to displace some portion of current coal use in the United States, but rather to weaken severely the coal industry's political power by virtually eliminating conventional coal use in the United States. A first step could be for the oil and gas industries to support the new EPA regulations on sulfur and mercury, which would likely force the closure of many older coal plants that were effectively grandfathered under the Clean Air Act and its later amendments.

In the one hundred–year war to build a low-carbon world, it is not necessarily prudent to open up multiple fronts in early battles. By focusing current political efforts on attacking the coal industry and leaving the oil and gas industries out of the initial fight, a path toward a low-carbon economy in the United States can be constructed in a politically pragmatic manner. This does not mean giving the gas industry a free pass on irresponsible practices on drilling or waste disposal. By leveraging the financial self-interest of the natural gas industry to broaden political support for anti-coal policies, environmental groups can simultaneously use a grassroots campaign to pressure existing coal-fired power plants to shut down. The success of this strategy will determine whether shale gas is indeed good for climate change.[19]

ENDNOTES

[1] For a good review of the environmental issues surrounding shale gas, see *The Future of Natural Gas: An Interdisciplinary MIT Study* (Cambridge, Mass.: Massachusetts Institute of Technology, 2011).

[2] Secretary of Energy Advisory Board, "Shale Gas Production Subcommittee Second Ninety Day Report," November 18, 2011, http://www.shalegas.energy.gov/resources/111811_final_report.pdf.

[3] Robert W. Howarth, Renee Santoro, and Anthony Ingraffea, "Methane and the Greenhouse-Gas Imprint of Natural Gas from Shale Formations," *Climatic Change* 106 (4) (2011).

[4] Ibid.

[5] Intergovernmental Panel on Climate Change, *First Assessment Report* (Geneva, Switzerland: UN Environment Programme and World Meteorological Organization, 1990).

[6] For examples, see Keith P. Shine, "The Global Warming Potential – The Need for an Interdisciplinary Retrial," *Climatic Change* 96 (4) (2009): 467 – 472.

[7] Drew T. Shindell, Greg Faluvegi, Dorothy M. Koch, Gavin A. Schmidt, Nadine Unger, and Susanne E. Bauer, "Improved Attribution of Climate Forcing to Emissions," *Science* 326 (5953) (October 30, 2009): 716 – 718.

[8] Tom M.L. Wigley, "Coal to Gas: The Influence of Methane Leakage," *Climatic Change* 108 (2011): 601 – 608.

[9] Keith P. Shine, Jan S. Fuglestvedt, Nicola Stuber, and Kinfe Hailemariam, "Alternatives to the Global Warming Potential for Comparing Climate Impacts of Emissions of Greenhouse Gases," *Climatic Change* 68 (3) (2005): 281 – 302; Jan S. Fuglestvedt, Keith P. Shine, Jolene Cook, Terje Berntsen, David Lee, Andrea Stenke, Ragnhild Bieltvedt Skeie, Guus Velders, and Ian Waitz, "Transport Impacts on Atmosphere and Climate: Metrics," *Atmospheric Environment* 44 (2010).

[10] Andy Reisinger, Malte Meinshausen, Martin Manning, and Greg Bodeker, "Uncertainties of Global Warming Metrics: CO_2 and CH_4," *Geophysical Research Letters* 37 (14707) (2010).

[11] Howarth et al., "Methane and the Greenhouse-Gas Imprint of Natural Gas from Shale Formations."

[12] *Integrated Assessment of Black Carbon and Tropospheric Ozone* (Geneva, Switzerland: UN Environment Programme and World Meteorological Organization, February 2011).

[13] Myles R. Allen, David J. Frame, Chris Huntingford, Chris D. Jones, Jason A. Lowe, Malte Meinshausen, and Nicolai Meinshausen, "Warming Caused by Cumulative Carbon Emissions towards the Trillionth Tonne," *Nature* 458 (7242) (2009): 1163 – 1166.

[14] Ibid.

[15] H. Damon Matthews, Nathan P. Gillett, Peter A. Stott, and Kirsten Zickfeld, "The Proportionality of Global Warming to Cumulative Carbon Emissions," *Nature* 459 (June 11, 2009): 829 – 832.

[16] David Archer and Victor Brovkin, "The Millennial Atmospheric Lifetime of Anthropogenic CO_2," *Climatic Change* 90 (3) (2008): 283 – 297.

[17] Daniel P. Schrag, "Making Carbon Capture and Storage Work," in *Acting in Time on Energy Policy*, ed. Kelly Sims Gallagher (Washington, D.C.: Brookings Institution Press, May 2009).

[18] Energy Information Administration, *Annual Energy Outlook 2010* (Washington, D.C.: Department of Energy, April 2010).

[19] I benefited from conversations with many people, whose comments have improved the argument presented here. They include Graham Allison, David Keith, Henry Lee, Henry Breck, Tim Wirth, Robert Ziff, Steve Pacala, Julie Shoemaker, and Tess Williams. I thank Judith Levi for special encouragement.

Stimulating Energy Technology Innovation

Ernest J. Moniz

Abstract: The innovation system has interrelated components of invention, translation, adoption, and diffusion. Energy technology innovation has lagged that in other domains, and there is a compelling public interest in picking up the pace through appropriate government action. Government and universities are creating new approaches in the invention and translation stages. The Department of Energy (DOE) has implemented novel programs such as ARPA-E. Research universities have moved closer to the marketplace through more diversified industry collaboration models, such as convening research-sponsoring companies both horizontally in a sector and vertically across the innovation chain. Much more needs to be done to expand public-private partnerships and to define a broadly accepted government role in the adoption and diffusion stages. An administration-wide Quadrennial Energy Review process, informed by technical analysis and social science research, offers the best opportunity in this regard.

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The U.S. economy was the engine for twentieth-century global development. The key role of R&D in driving productivity growth has been documented extensively, and American serial innovation was instrumental in producing not just improved products but new technology-based industries. The world's preeminent research university system, a magnet for attracting top talent globally, proved central to these developments. A recent study[1] of the entrepreneurial impact of MIT alone found more than twenty-five thousand alumni-founded companies generating $2 trillion in sales and more than three million jobs worldwide. The local effect is strong, with Massachusetts-based firms producing more than $150 billion in sales and nearly a million jobs worldwide.

Societal features such as a mobile workforce and acceptance of business and investment risk support a culture of innovation. Natural advantages, including a continental scale, an immense natural resource base, the world's third largest population, and the biggest market for new products and services, are also important for U.S. performance. Together, all of these factors facilitate the capture of invention for domestic economic activity and for building an export base.

While this U.S. model remains strong, its very success is changing the game in an age of globalization. Many countries have invested heavily in their research universities, stemming the loss of scientific and engineering talent to other nations and encouraging start-up companies. Further, the fastest-growing markets are in the large emerging economies, which attract not only manufacturing but also global industry R&D. With the largest markets for new energy infrastructure located outside the United States, concerns about the competitiveness of the American economy over time have elevated the importance of retaining an innovation edge.

This brings us to the *innovation system*. My discussion draws on the report of the President's Council of Advisors on Science and Technology (PCAST), *Accelerating the Pace of Change in Energy Technologies through an Integrated Federal Energy Policy*,[2] which adapts a description put forward by Edward Rubin.[3] The report views the development and use of energy technologies as an integrated system, comprised of four interrelated components:

- *Invention*: discovery, creation of knowledge, and generation of prototypes;
- *Translation*: creation of a commercial product or process;
- *Adoption*: deployment and initial use of a new technology; and
- *Diffusion*: increasing adoption and use of a technology.

Importantly, these components cannot be viewed as a linear progression; multiple feedbacks occur all along the chain. That is, while invention is certainly driven by R&D, it is also propelled by the experiences that accompany commercialization, use, and diffusion. Similarly, translation emerges from R&D and may be revisited following adoption. Adoption and diffusion are the stages at which materiality of products and processes are realized (or not). *Innovation, as I use it here, refers to the end-to-end system including market diffusion, not front-end R&D alone.*

Today, clean energy is considered a key area for innovation. The reasons for this view include an anticipated doubling of global energy use and tripling of electricity demand by mid-century, and the attendant major build-out of energy supply, delivery, and use infrastructure. The drivers include economic growth in the developing world, continuing concerns about energy security, and the need to mitigate the risks of climate change. Addressing climate change, in particular, will call for a major transformation of the current fossil fuel–based energy system and inspires a vision of trillion-dollar markets for the leaders in clean-energy technology.

Yet *energy technology was largely passed by in the last decades of innovation* relative to areas such as information and communications technology and biotechnology. Jeff Immelt, the CEO of GE, has observed that during his career with the company, medical technologies have turned over several times while core energy technologies are easily recognized as improved versions of product lines from a quarter-century ago. There was, and is, a great deal of clean-energy activity at the stages of invention and translation to commercial products, often driven by an enhanced participation by venture capital firms. The level of activity at these stages reached unprecedented heights in recent years, boosted somewhat by the stimulus packages put in place in the United States and elsewhere. There have been substantial product improvements to core technologies (for example, increased efficiency of energy supply and end-use technology), but the scale-up of novel technologies across the entire innovation chain, from invention to diffusion with large market share, is modest. Arguably, wind turbines and biofuels are counter-examples; but these technologies have required substantial subsidies and/or mandates to reach their current levels of penetration, raising questions about their further scalability in the marketplace absent a societal willingness to foot a growing bill and/or pricing of externalities such as carbon emissions.

What is it about the energy system that slows innovation? Multiple characteristics should be kept in mind to address this question:

- multitrillion-dollar annual revenues;
- often, large capital needs to reach even the demonstration phase;
- a commodity business, with attendant cost sensitivity;
- well-established efficient supply chains, delivery infrastructure, and customer bases;
- provision of essential services for all activities;
- an emphasis on reliability over innovation;
- a high degree of regulation; and
- complex policy and politics, often driven by regional considerations.

None of these characteristics provides a nimble platform for end-to-end innovation. Rather, they suggest *a business with high barriers to displacement of incumbents*.

Several of the points require elaboration. Energy can be characterized as a *commodity business* in the sense that even novel technologies generally provide the same services as incumbent ones, such as producing electricity (for example, photovoltaics and coal plants) or providing mobility from point A to point B (for example, biofuels and gasoline). Consequently, rather than create novel consumer services, as numerous communication/information technologies have done, *new energy technologies inherently must displace incumbent market share*. This fact diminishes the opportunity for market entry of disruptive technologies unless they meet stringent cost tests early in their deployment. As a result, early adoption of energy technology is highly sensitive to policies and subsidies that help create the initial market.

Conversely, cost reduction must be a principal criterion for new energy technologies, lowering the barriers to new policy introduction. In particular, making zero-carbon technologies more cost competitive would facilitate acceptance of strong policies to limit greenhouse gas emissions. State utility commissions are generally required to provide lowest-cost options for consumers. Alternatively, the technologies may need to address multiple objectives to enhance political palatability. In the case of zero carbon, technologies addressing climate risk mitigation will also strengthen energy security by limiting dependence on fossil fuels, especially oil. However, these considerations generally apply to national policy rather than at the state level, where many energy technology deployment decisions are made.

An exception to the rule is the rapid scale-up of shale gas production in the United States, resulting from the introduction of hydraulic fracturing combined with horizontal drilling. Production has grown remarkably from a very small share of natural gas supply to about one-quarter, propelling the United States back into the global lead for annual natural gas production and driving down domestic prices dramatically. The shale gas "revolution" is the biggest story for U.S. energy in a long time. However, this is a case where incumbent hydrocarbon producers scaled up a business in which they already dominate the supply chains and have the processing and delivery infrastructure. These producers decide on which assets to produce as they have done for decades. It is true that intermediate-sized companies played a central role in scaling the technology before the supermajors, but significant capital availability allowed the latter to move easily into the business.

For new substitutional energy technologies, it remains to be seen how effectively the entrepreneurial culture of the start-up world can scale when incumbent energy producers are not familiar with the technology or with the risk-taking paradigm. "Impedance matching" is needed between risk acceptance (such as venture capital) and capital availability (such as equity investors and large energy companies) and between novel product development at start-ups and management attention and profit-loss reward systems at incumbents.

Another part of the shale gas story frames the innovation challenge.[4] The technology demonstration for unconventional natural gas production (coalbed methane, tight gas, shale gas) was advanced through public-private partnership and diffusion through well-timed synergistic tax incentives. A surcharge on interstate gas transportation, approved and administered by the Federal Energy Regulatory Commission (FERC), and industry cost-sharing funded the Gas Research Institute (GRI). Further, the GRI Board of Directors was required to be composed of industry representatives, from well to burner tip, plus a small number to represent the public interest. The industry thus provided both input to define the research, development, and demonstration (RD&D) portfolio around specific industry challenges and the cost-sharing needed to implement projects. Within the GRI portfolio, a major success was that of unconventional gas, driven by board members representing independent producers.

Equally important, Congress passed time-limited tax incentives for unconventional gas production during the GRI technology demonstration period. The combination of technology development and deployment incentive proved synergistic in establishing an unconventional natural gas industry that is flourishing beyond expiration of the tax credits and producing substantial revenue for the economy and the government. (I shall return to this model of government participation with the private sector in order to advance energy innovation.) Unfortunately, the energy surcharge RD&D financing mechanism that supported the GRI was phased out as a consequence of deregulation.

Highlighting the business challenges to energy technology innovation is not meant to suggest an inability to succeed, but rather to draw attention to the factors that must be addressed to accelerate innovation, which is in the public interest for many reasons. Most of all, climate-change risks grow inexorably with continuing greenhouse gas emissions, and the opportunities to mitigate the consequences of and to adapt to climate change diminish with time and become more difficult to address. In addition, the global markets for clean-energy technology are forming rapidly, and early innovation enhances the probability of capturing market share. Finally, the enormous outflow of funds for imported oil and the vulnerabilities associated with almost complete dependence on oil for transportation fuel places a premium on progress with advanced vehicles and alternative fuels. The question is, what is being done and what more can be done?

The government will necessarily play an important role if clean-energy innovation is to *be accelerated* relative to the pace of the marketplace left to its own devices. The energy system has historically required a multidecade timescale for appreciable change, which is inadequate for the purposes noted above. To accelerate the process, the government, including both the administration and Congress, has at least three distinct roles. One critical, and uncontested, function is to provide the general conditions that stimulate, or at least do not impede, innovation. A clear example is providing a framework for intellectual property (IP) protection that reaches a balance between incentivizing invention and investment without tying up intellectual capital that could stimulate further innovation. Another critical example is passage of the Bayh-Dole Act and its amendments in the 1980s, which allowed universities to move government-sponsored research outcomes to commercialization and profoundly influenced industry-university relations. In a similar vein, the National Technology Transfer Act and the National Cooperative Research Act opened up national lab-industry and industry-industry collaboration, respectively.

A second role is stimulation of technology development and support for the underlying science that enables development. Public support for RD&D is the principal mechanism. R&D financing is generally viewed as an essential government role because the results of early-stage basic research are seldom captured by a single firm, but demonstration is less widely endorsed, both on principle and because of some visible failures over the years. Support for demonstration projects can involve direct funding, such as government cost-sharing, or indirect assistance, such as a long-term purchase agreement for a product.

A third role for government, and the most controversial, is "technology pull" at the adoption and diffusion stages of the innovation cycle. In this function, the government helps create markets using a wide variety of instruments, such as portfolio standards, feed-in tariffs, investment tax credits, consumer rebates, efficiency standards, and federal long-term purchase agreements, among many others. Sometimes multiple instruments are used simultaneously for a particular technology. Viewed optimistically, the large number of approaches has evolved in order to provide options fit to purpose; less optimistically, it may reflect the lack of general support for "picking winners," instances of unintended consequences, and a mixed track record.

Recent government engagement in energy-technology invention and translation has had a positive impact on the early stages of the innovation chain. First, *the Department of Energy (DOE) has introduced three new programs that show great promise for more effectively applying public funds to fill the innovation pipeline*: Energy Frontier Research Centers (EFRCs); ARPA-E (the Advanced Research Projects Agency-Energy); and energy innovation hubs. The EFRC program, originating in the DOE Office of Basic Energy Science, was established through an exemplary process organized over several years to identify the basic science barriers to a host of energy technology breakthroughs. Engaging a wide community of scientists in a series of workshops, the program moved the Office of Basic Energy Science research portfolio more into Pasteur's Quadrant[5] of use-inspired science – an approach fitting to the DOE's mission. Each EFRC is funded at several million dollars per year and focuses on one of the many enabling-science challenges identified in the workshops. As with all these new programs (awards were first distributed in 2009), it is too early to judge outcomes; but the approach deserves praise and should be continued aggressively, at least until the first centers are evaluated on their core mission of opening new technology pathways.

ARPA-E has had the most visibility among the new programs. Established in the 2007 America COMPETES Act, it was initially funded only in early 2009 as part of the economic stimulus bill. The program aims to fund high-risk, high-reward technology development that can then qualify for venture funding within a few years. Many of the awards support university-industry collaborations, and both EFRC and ARPA-E awards generally cluster around major research universities. This highlights the central role of research universities and university-industry partnering in the innovation system, including translation of research into venture investment opportunities for commercial products.

The initial ARPA-E solicitation received well over three thousand concept papers for what was eventually narrowed to just thirty-seven awards. This 1 percent success rate is suggestive of not only an innovative program design but also an enormous capacity at American universities and other research organizations to fill the innovation pipeline. ARPA-E has supported nearly two hundred projects in little more than two years. The program design includes a staff assembled with some relatively young individuals who have experience in the venture world and serve limited terms in the program.

ARPA-E represents a very different way of doing business relative to the established applied-energy programs at the DOE. It has assembled an interesting portfolio targeted at breakthrough technology cost performance. Many of the ARPA-E operational features should be adapted to the applied programs, including streamlined procedures for contract negotiations and colocation of support functions, such as procurement, with program officers.[6] More ambitious reorganization is also necessary. The applied energy offices are organized around fuel: that is, Fossil Energy, Nuclear Energy, and Efficiency and Renewables. For one, grouping Efficiency and Renewables into one office is a relic with little logic to support it. Further, the organization of the offices is backward looking, reflecting a time when the energy marketplace and technology breakthrough opportunities were quite different. Low-carbon technologies are not focused on resource extraction (with the exception of unconventional natural gas as a bridge to a very low-carbon future[7]). The energy marketplace of the future is likely to call for new business models in areas such as electrification of the transportation sector (the lead priority in the recent DOE Quadrennial Technology Review[8]) or the integration of subsurface activity with electricity generation through carbon dioxide capture for storage and enhanced oil recovery.

A complete reorganization of the applied energy offices around key end uses, rather than inputs, would profoundly affect and improve how the RD&D portfolio is shaped. For example, in the last few years of the Clinton administration, the DOE began to utilize a cross-cutting portfolio/road-mapping approach to setting new directions. By organizing programs around strategic objectives rather than fuel, the energy offices identified and addressed major program gaps within a few years. This included both enabling science and technology (a modeling/simulation focus for energy) and applied energy needs that did not fit within the existing stovepipes (electricity grid technologies and reliability). Such an organizational change, combined with use of ARPA-E management approaches, would undoubtedly be disruptive for the applied energy offices and the companies that have become accustomed to doing business with them. Nevertheless, it would likely help these offices become much more effective components of the innovation system. Moreover, while consultation with Congress is essential, much of the reorganization could be accomplished with existing executive authorities.[9]

The third new program element is the energy innovation hub. Three have been established to date, with two more anticipated in 2012. The concept centers on large, multidisciplinary, integrated teams assembled for a multiyear effort, funded at about $25 million per year, and organized to address the basic research and applied engineering needed for a priority technology challenge. In this sense, they could be compared to a "mini-Manhattan Project." Each hub partners with industry to translate its work to commercialization. For example, the first hub was established in May 2010 to develop new predictive simulation tools that can be used by light water reactor (LWR) vendors, researchers, and regulators alike. Based at Oak Ridge National Laboratory (in partnership with the Idaho, Los Alamos, and Sandia Laboratories), it builds on a historic strength of the national labs (advancing the frontier of modeling/simulation of complex engineered systems, such as nuclear weapons), with strong university (MIT, Michigan, North Carolina State), industry (Westinghouse), and user (Tennessee Valley Authority, Electric Power Research Institute) core members. The DOE has adhered to the philosophy of an outcome-oriented oversight approach and a light touch compared to the more intrusive approach that has too often characterized program management in the applied energy offices. The hub has already developed and released an innovative software tool to simulate a virtual LWR.

The organization of the hubs is true to the core mission of the national laboratories but, regrettably, does not reflect how the DOE has in fact interacted with the labs for quite some time. *The DOE should return to a model in which the national laboratories are assigned major mission-aligned challenges that call for significant multidisciplinary teams and sustained efforts that would be difficult to carry out elsewhere.* A focus on outcomes should replace department micromanagement; management authority and responsibility should be left with the operating contractor. Despite their considerable capabilities, the national labs have "punched below their weight" in advancing energy-technology innovation, and "hubification" of the energy R&D program could greatly amplify the effective use of the labs' considerable capabilities.

All told, these new ways of doing business at the DOE are positive initiatives that show sufficient promise to warrant displacement of the management and organizational approaches of the last few decades. They are much better matched to the innovation challenges at hand and the evolving energy marketplace.

Another issue is the scale of the DOE's RD&D program. A number of recent reports, including the PCAST report and one released by American business leaders,[10] have argued for tripling the DOE's RD&D budget to about $15 billion per year. The funding level is somewhat notional, though PCAST provided a crude estimate of the scale: roughly the contribution of energy expenditures to GDP (about 9 percent in the United States) multiplied by the benchmark for public spending on RD&D (1 percent). Among the major economies, only Japan reaches this level of investment.

This budget recommendation raises at least two questions: where is the money, and how should its expenditure be organized? A sustained increment of $10 billion per year for energy RD&D is highly unlikely to occur at a time of budget tightening, and accelerating the pace of innovation calls for making these funds available sooner rather than later. Even if congressionally appropriated funds were available, a better approach might be *generating the revenue through a small charge on energy supply, delivery, and/or use* – a "return to the future" analogous to the surcharge that funded the GRI. A 0.1¢/kWh charge on electricity and a 2¢ per gallon charge on transportation fuel are well within standard variations in consumer price, and each would generate about $4 billion annually. However, while the GRI surcharge was implemented through regulation, the amount of deregulation that has since occurred suggests the need for a statutory approach.

Implementation would follow the general principles used in the GRI model: management by one or more nonprofit organizations fit to purpose; "light touch" oversight by the federal government (the DOE, in this case); a strong industry role in setting the portfolio for technology translation, adoption, and diffusion stages; and a degree of industry cost-sharing. The $5 billion DOE budget should be maintained and reweighted toward R&D, for which it has a much better track record and capability than with demonstration and deployment. The lessons learned with the EFRCs, ARPA-E, and innovation hubs would guide the expanded early-stage portfolio. An explicit mechanism should be set up as an interface between the DOE program and the public-private partnership organizations that manage the additional funds generated by the energy innovation surcharge. This provision would align management of different parts of the innovation portfolio with expertise and knowledge of both the research enterprise and the energy marketplace.

Today, *more than twenty states support efficiency programs and/or research through utility surcharges.*[11] This is just one example of the many ways in which states can take the lead on clean-energy technology and policy, setting a precedent for the federal government to follow. Energy needs and opportunities in the United States are highly variable by region, and the states are naturally more in tune with the best pathways to economic development and job creation for their particular circumstances. At least some of the nonprofit organizations charged with managing the energy innovation surcharge would be best established at the regional level, with coordination to share best practices and different implementation mechanisms that can be experimented within a regional context.

Over the last few decades, universities have moved closer to the marketplace. As noted above, conditions established through legislation such as the Bayh-Dole Act led to dramatic expansion of university-industry cooperation, a domain that previously engaged very few universities at a meaningful scale (MIT and Stanford University were prominent exceptions). Today, novel approaches are being tested at numerous institutions. For example, the MIT Energy Initiative (MITEI)[12] is collaborating with fifteen major companies as research partners. The core of the relationship is a dedicated sponsored research portfolio with customary IP terms, such as IP ownership by the university, a sponsor nonexclusive royalty-free license, and a time-limited sponsor option for a royalty-bearing exclusive license. In practice, sponsors may find ways to exploit project IP using methods other than acquiring licenses: for example, by becoming an equity investor in a start-up when the technology is adjacent to current core business. Certainly, all work is publishable after appropriate steps are taken to manage the IP.

The MITEI partnership includes a number of additional elements. Significantly, the initial five-year commitment stipulates a consultation mechanism that allows the portfolio to evolve in alignment with faculty interests and company strategic planning. Extensive exchange between university and company researchers is common. Indeed, companies with the largest portfolios place a senior research manager at the university to stay engaged with projects, maintain the back-and-forth flow of information, and identify new university researchers and opportunities.

MITEI's most interesting feature may be a set of *mechanisms that allow all the companies to come together in a commons*. The Initiative has formed a governing board that helps guide overall MITEI directions. A jointly supported seed fund provides crucial support for early-stage ideas generated by faculty across the full spectrum of energy-related activity, including, specifically, social science and management research as well as science, engineering, architecture, and planning. The companies, which span the oil, equipment, and infrastructure sectors, have seen nearly three hundred proposals over four years. Once the proposals are distributed and evaluated throughout the companies, all the companies in the partnership come together with MITEI leadership to perform an intensive selection review; this is not unlike a panel review that one might see at the National Science Foundation (NSF) or the National Institutes of Health. The discussion itself, drawing on the different interests and outlooks of companies across the energy space, is instructive. The companies have no IP capture from the funded projects but can track the projects and support extensions as part of their individual sponsored research portfolios. More than eighty such projects have been funded, and the program has served the important purpose of stimulating both new collaborative ideas with the companies and drawing in faculty who had not previously engaged in energy-related research.

As company representatives get to know one another, they begin to form small "consortia of the willing." Typically, these are cross-cutting analytical projects useful to an industry sector, although some consortia now support science and engineering with IP implications. This is one manifestation of the role of the *university as a convening place for companies, even direct competitors in the marketplace*. Another is the conferences and symposia in which the companies participate along with others in the innovation chain, such as venture capitalists and energy law firms. In other words, a space is provided for convening energy-system players both horizontally in a specific sector (for example, petroleum) and vertically along the entire innovation chain, from inventors to the largest energy incumbents.

The MITEI example highlights the growing intimacy of the university-industry relationship. This phenomenon is driven by the university commitment to engage with the marketplace (in some sense, reweighting the research portfolio to emphasize Pasteur's Quadrant rather than Bohr's[13]) and the increasing trend in industry toward open innovation models. This convergence augurs well for stimulating early-stage innovation.

Another recent development at MIT has been a series of multidisciplinary analytical studies of key clean-energy pathways that provide a sound engineering-economic base as a platform for policy recommendations grounded in facts. MIT's interdisciplinary study on *The Future of Natural Gas*, cited above, is an example. These studies do not fit the mold of traditional academic research aimed at peer-reviewed journals, although they do produce priority research agendas and graduate student theses that lead to such publication. The work requires close collaboration between natural scientists, engineers, and social scientists, particularly economists and political scientists engaged in public attitudes research. Universities have much to offer in providing policy-motivated technical analysis. Such policy, which includes that for publicly supported RD&D, can in turn have significant consequences for shaping the government role in the innovation system.

As recommended in the PCAST report, the *DOE should incorporate a multidisciplinary social science research program into its energy programs as an important component of the innovation system*. Social science research will help inform the pathway for clean-energy technologies through the entire innovation chain, exploring questions such as: How and why do such technologies satisfy consumer choice? What are barriers to adoption? How can public policy best enable technology push and pull? What economic and cultural factors may influence take-up of new technologies internationally? Would reengineering of American products help their export potential? How can start-up companies and the largest incumbents in the energy sector interface their different cultures and resources to stimulate innovation effectively? These are some of the many questions relevant to innovation that are amenable to rigorous social science research. In addition to providing sufficient in-house capacity to guide its research program, the DOE, perhaps in cooperation with the NSF, should support such research at universities and nongovernmental research organizations. An institution analogous to the National Bureau of Economic Research (or possibly even a supplement to it) would provide an interesting model.

While there are many promising new approaches to filling the energy-technology innovation pipeline at the invention and translation stages, *acceleration in the adoption and diffusion stages continues to be more challenging, especially with respect to the government role*. The public-private model discussed above can be an important contributor, especially at the adoption stage, but the prospect of implementing an energy innovation surcharge in the near future is bleak. A recent congressional initiative to introduce a "line charge" on coal-generated electricity – the proceeds of which would have established carbon capture and sequestration to enable continued coal use – did not get very far, even though the measure had a fair degree of support in the industry.

The most obvious and conceptually simple approach to accelerate low-carbon deployment at scale is the imposition of a substantial economy-wide price on carbon dioxide emissions. Alternatively, a regulatory cap on emissions that tightens over time could be put in place. In either approach, a high degree of confidence that the policy will stay in place over a considerable period of time – rather than be subject to dramatic shifts in Congress and the administration – will be important for generating private investments at scale in a timely fashion. Similar mechanisms could address the externality of energy security and oil dependence. The prospects for carbon pricing continue to be inauspicious. At best, a continuation of proxy policies such as renewable portfolio standards and tax credits, often at the state level, can be anticipated. These policies tend to be inefficient for the overarching purpose of stringent carbon dioxide emissions reductions and, by observation, have too often been subject to starts and stops. Such policy realities highlight the importance of clean-energy technology cost reduction as a more assured path to deployment and, then, to appropriate policy by lowering implementation costs. Furthermore, it is not clear that pricing externalities would accelerate innovation at the needed pace without additional energy-technology policy steps.

It should come as no surprise that I do not have the answers for how the government should intersect the latter stages of the innovation process in a general sense. However, PCAST recommended a pragmatic approach to an integrated federal energy policy that would employ all the tools available to the government in a coherent way. Termed the Quadrennial Energy Review (QER), the process is necessarily complex, but history suggests that anything short of a full multiagency effort is unlikely to provide a robust plan that accounts for the many threads of an energy policy. Furthermore, a degree of analysis is required that has not been present in previous efforts.

Energy policy is derivative of many policies: environment, technology and competitiveness, diplomacy and security, natural resources, and land and food, among many others. Indeed, multiple agencies that are not labeled "energy" have major equities and long-held perspectives on key elements of energy policy. Often, the preferred policies for different agencies' agendas conflict. Further, states and local governments play a strong role, for example with building codes, and their approaches can vary dramatically in different parts of the country; certainly, California's energy policies have influenced the national market. The tools available to support innovation are also diverse, ranging from direct support of RD&D to a variety of economic incentives, regulation, standards, and federal procurement, among other instruments. Congress is equally fragmented: in the House of Representatives and Senate, many committees beyond those tasked with energy policy have equities that mirror those of the different executive agencies. To overcome this fragmentation of responsibilities and perspectives, and especially if the goal is a plan that has staying power in advancing adoption and diffusion, PCAST recommended a

> QER process to provide a multiyear roadmap that:
>
> - lays out an integrated view of short-, intermediate-, and long-term objectives for Federal energy policy in the context of economic, environmental, and security priorities;
> - outlines legislative proposals to Congress;
> - puts forward anticipated Executive actions (programmatic, regulatory, fiscal, and so on) coordinated across multiple agencies;
> - identifies resource requirements for the RD&D programs and for innovation incentive programs; and, most important,
> - provides a strong analytical base.[14]

This is a tall order intellectually and organizationally. Several process elements are essential to fostering a chance for success. First, the Executive Office of the President (EOP) must use its convening power to ensure effective cooperation among the myriad relevant agencies. However, the capacity to carry out such an exercise and to sustain it does not (and should not) reside in the EOP. The DOE is the logical home for a substantial Executive Secretariat supporting the EOP interagency process that would present decision recommendations to the president. However, the scope of the analytical capability needed does not currently reside at the DOE or any other agency. The DOE needs to build this capability, presumably supplemented by contractor support to gather data, develop and run models, and carry out analysis, such as independent energy-system engineering and economic analysis. Market trends and prices would be part of the analysis, including international markets and robust analyses of uncertainty. The Energy Information Administration can help with some data gathering and models, but its independence from the policy function needs to be preserved. The national laboratories also lack this range of functions, and tasking them with providing the analytical support to the policy process would be regarded as a conflict of interest; their focus is best directed at research, invention, and technology transfer. Building this analysis capacity is a large job that will take time.

For the QER to succeed, the government must seek substantial input from many quarters in a transparent way; certainly, ongoing dialogue with Congress and the energy industry are essential. The good news is that members of Congress have supported the development of the QER[15] as a way to present a coherent starting point for congressional action across many committees. A hope is that *Congress could then use the QER as a basis for a four- or five-year authorization that would provide the private sector with the increased confidence needed to make sound clean energy investment decisions*.

Given the magnitude of the task, PCAST recommended in 2011 that the DOE carry out a Quadrennial Technology Review (QTR) – a first step centered in a single department and focused on technology. The QTR resulted in a rebalancing of the R&D portfolio toward the oil dependence challenge through advanced vehicle development, particularly transportation electrification. The key now will be to extend the processes developed for the QTR to the multiagency QER, involving the EOP in a leadership role. Taking the next steps in 2012 will maintain momentum and establish the capabilities needed for the QER by early 2015, the time frame recommended by PCAST.

While some may view 2015 as a frustratingly long time away, the alternative is to rely on wishes rather than analysis while failing to gain multiple perspectives in a fair and open manner. Rushing the process will result in a poorly done job that will not accomplish any of the key QER goals. Certainly, it will not bring together succeeding administrations and Congresses around a reasonably shared vision and set of objectives that can accelerate innovation in service of national competitiveness and environmental and security goals. Continuing with fragmented and economically inefficient policies, technologies "du jour," and frequent shifts will complicate private-sector decisions rather than facilitate innovation. The government unavoidably plays a strong role in the innovation process, even when this is unacknowledged in policy and political debates. The issue now is to present both a set of principles and fact-based analyses supporting coordinated government-wide actions that earn decent buy-in from major stakeholders.

ENDNOTES

[1] Edward B. Roberts and Charles Eesley, *Entrepreneurial Impact: The Role of MIT* (Kansas City, Mo.: Kauffman Foundation, 2009).

[2] President's Council of Advisors on Science and Technology (PCAST), *Report to the President on Accelerating the Pace of Change in Energy Technologies through an Integrated Federal Energy Policy* (Washington, D.C.: Executive Office of the President, November 2010), http://www.whitehouse.gov/ostp/pcast.

[3] Edward S. Rubin, "The Government Role in Technology Innovation: Lessons for the Climate Change Policy Agenda," *Proceedings of the 10th Biennial Conference on Transportation Energy and Environmental Policy*, Pacific Grove, California, 2005.

[4] *The Future of Natural Gas: An Interdisciplinary MIT Study* (Cambridge, Mass.: Massachusetts Institute of Technology, 2011).

[5] Donald Stokes, *Pasteur's Quadrant: Basic Science and Technological Innovation* (Washington, D.C.: Brookings Institution Press, 1997).

[6] PCAST, *Accelerating the Pace of Change in Energy Technologies*.

[7] *The Future of Natural Gas*.

[8] *Report on the First Quadrennial Technology Review* (Washington, D.C.: Department of Energy, 2011).

[9] PCAST, *Accelerating the Pace of Change in Energy Technologies*.

[10] American Energy Innovation Council, "A Business Plan for America's Energy Future," 2010.

[11] Lewis Milford, Mark Muro, Jessica Morey, Devashree Saha, and Mark Sinclair, "Leveraging State Clean Energy Funds for Economic Development," Brookings-Rockefeller Project on State and Metropolitan Innovation, 2012.

[12] See http://web.mit.edu/mitei.

[13] Stokes, *Pasteur's Quadrant*.

[14] PCAST, *Accelerating the Pace of Change in Energy Technologies*, 8.

[15] Senate Energy and Natural Resources Committee, Hearing on the Quadrennial Energy and Technology Reviews, November 2011; S.1703, "The Quadrennial Energy Review Act of 2011."

Policies for Financing the Energy Transition

Kassia Yanosek

Abstract: Historically, energy transitions have occurred gradually over the span of several decades, marked by incremental improvements in technologies. In recent years, public interest in accelerating the next energy transition has fueled a clean-energy policy agenda intended to underpin the development of a decarbonized energy economy. However, policies to date have encouraged investors to fund renewable energy projects utilizing proven technologies that are not competitive without the help of government subsidies. A true transition of the energy mix requires innovations that can compete with conventional energy over the long term. Investments in innovative technology projects are scarce because of the "commercialization gap," which affects projects that are too capital-intensive for venture capital yet too risky for private equity, project, or corporate debt financing. Accelerating innovation through the commercialization gap will require governments to allocate public dollars to, and encourage private investment in, these riskier projects. Policy-makers will face a trade-off between prioritizing policies for accelerating the energy transition and accounting for the risks associated with innovation funding in a tight budgetary environment.

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In recent years, concerns over energy security, climate change, and maintaining U.S. competitiveness have made the next energy transition a prominent topic in public debate. These concerns have led to calls to reduce dependence on foreign oil, decarbonize our energy supply, and create new "green" industries. Many believe that these goals can be addressed through a single solution: the creation of a robust clean energy industry. If successful at scale, this new market would accelerate the next energy transition to a low- or zero-carbon economy.[1] On the surface, it appears that the transition may be under way. In 2010, investment in clean energy technologies and projects reached a record $268 billion globally and $30 billion in the United States.[2] Annual growth rates have exceeded 25 percent over the past five years. Despite this boom in investment, clean energy still has far to go to make a dent in the energy mix: in the United States, renewable energy (excluding hydropower)

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made up 5 percent of the energy supply in 2009.[3] Furthermore, most renewable energy assets operating today can attract private investment only with significant public subsidies. In the short term, maintaining strong growth rates will depend on whether governments continue to provide sizable supports for the industry. In today's tight fiscal environment, robust government aid and the health of the current industry are questionable.

To make this next energy transition in an accelerated time frame, the United States and other economies must scale clean-energy technologies beyond the limitations of government funding and the boom/bust cycles that have characterized the industry to date. A true energy transition to a low-carbon economy will require innovations and new technologies that can compete with conventional energy on both cost and scale, without the crutch of government.[4] This essay addresses financing – the key challenge to accelerating the commercial adoption of new energy innovations – and what can be done about it.

Energy transitions permeate all sectors of the economy and have catalyzed major periods of economic growth, most notably the industrial revolutions in Western Europe and the United States in the eighteenth and nineteenth centuries. Energy transitions also provide noneconomic benefits including improved air quality (as in the case of cleaner-burning fuels) and improved geopolitical positioning, as energy supplies become more diverse and less reliant on foreign imports. These important effects explain why energy transitions are viewed favorably by society and have warranted R&D efforts in both the public and private sectors.

Large-scale energy transitions from one primary energy supply to another have characteristically been gradual, spanning several decades. Examples include the major transitions from biomass to coal and from coal to oil as the dominant energy supply. Improvements in the steam engine stimulated the transition from biomass to coal in eighteenth-century Europe. The steam engine, originally designed to pump water out of coal mines, had been used for this purpose as early as the late 1600s. But not until 1769 – more than a half-century later – did James Watt's more compact, portable design lead to the widespread commercial use of the coal-powered steam engine for railroad and steamboat transportation.

The U.S. transition from biomass to coal dominance occurred over the course of the nineteenth century. In 1800, wood and animal feed[5] supplied 95 percent of U.S. energy use; by 1880, wood comprised 20 percent of U.S. energy supplies, while coal made up 70 percent.[6] The Industrial Revolution played a major role in expanding the use of coal. In addition to railroad transportation, coal was used to fire iron blast furnaces for industrial steel production, beginning with weapons production during the Civil War.

Technology innovations, such as the steam engine, are often incremental improvements over old technologies or are borrowed from other applications. A more modern example of incremental, borrowed innovation in power generation is the combined cycle gas turbine (CCGT). CCGT owes its existence to military-backed R&D on jet engines in the 1950s. Major manufacturers such as Westinghouse and GE recognized that the jet engine expertise they were developing could be transferred to gas turbines.[7] Today, CCGT is one of the most prevalent technologies in new-build power generation.

The sheer capital intensity needed for developing and deploying new technologies is a major reason why innovation happens incrementally. Moving energy technology innovations from niche markets to market diffusion is challenging in large part because energy systems are complex value chains requiring major infrastructure investments – such as new power plants or storage infrastructure – to shift to new resources. Liquefied natural gas (LNG) – methane that has been temporarily converted to liquid form for storage or transport – is an example of an energy source that has great potential yet has taken decades to develop into a viable industry, given the large infrastructure challenges of building a global LNG value chain. Infrastructure investments in the hundreds of millions of dollars are necessary, for example, for building import capacity to receive and re-gasify LNG.[8]

In short, energy transitions occur over long time periods, are often marked by gradual improvements in technology, and require massive infrastructure investments. Transitions, and the investments that support them, typically ensue only when new innovations have superior cost advantages over the status quo.[9] Thus, history suggests that the next energy transition will be a multidecade process. Can the transition to a decarbonized energy economy buck historical trends? Politicians on both sides of the aisle have voiced a desire to see this happen. Clean-energy goals have been prominent features of presidential energy agendas since the turn of the twenty-first century, with calls for rapid change on ten- and twenty-year time frames. While in office, President George W. Bush announced goals to replace 75 percent of U.S. oil imports from the Middle East by 2025, and in 2007 called for a reduction in gasoline demand by 25 percent over ten years. President Obama's election agenda for energy included goals of putting 1 million plug-in hybrid cars on the road by 2015 and generating 25 percent of electricity from renewable sources by 2025.[10] More recently, in his 2011 State of the Union address, Obama announced a goal to generate 80 percent of electricity from clean-energy sources by 2035.

The bold goals and policies of the Bush and Obama administrations have played a part in growing the clean-energy market over the past several years. But the majority of investment activity over the course of these administrations has been concentrated in projects that cannot compete in the marketplace without government supports – an expensive path to an energy transition. In 2010, conventional clean-energy projects, which are quick to build and easy to commission – such as large-scale wind farms, solar parks, and corn ethanol plants – made up 61 percent of total new U.S. clean-energy investments. Corporate and government R&D accounted for less than 4 percent.[11]

Tax credits and accelerated depreciation benefits attract private-sector financial investors to conventional projects. Currently, these subsidies account for more than half the after-tax returns on investments in conventional wind farms and two-thirds of the after-tax returns on solar farm investments.[12] These rich supports have created an industry dependent on their existence in the short term, resulting in boom/bust cycles characterized by investment patterns that are highly correlated with the expiration and reinstatement of tax credits.

The 2008 financial crisis demonstrated the critical importance of tax credits to the sector's viability. Investors in clean energy lost much of their taxable earnings, crushing demand for tax credits and, therefore, investment in the sector. The 2009 American Recovery and Reinvestment Act (ARRA), signed by Obama, instated the emergency scheme Section 1603, which offered cash grants designed to "temporarily fill the gap created by the diminished investor demand for tax credits."[13] Section 1603 deployed $2.7 billion into the U.S. renewable-energy project market in 2010, covering 30 percent of the up-front capital costs of shovel-ready wind and solar projects. While one can justify these funds by viewing them as true stimulus dollars, developers using the cash grants had few incentives to cut costs in order to make these technologies more competitive over the long term.

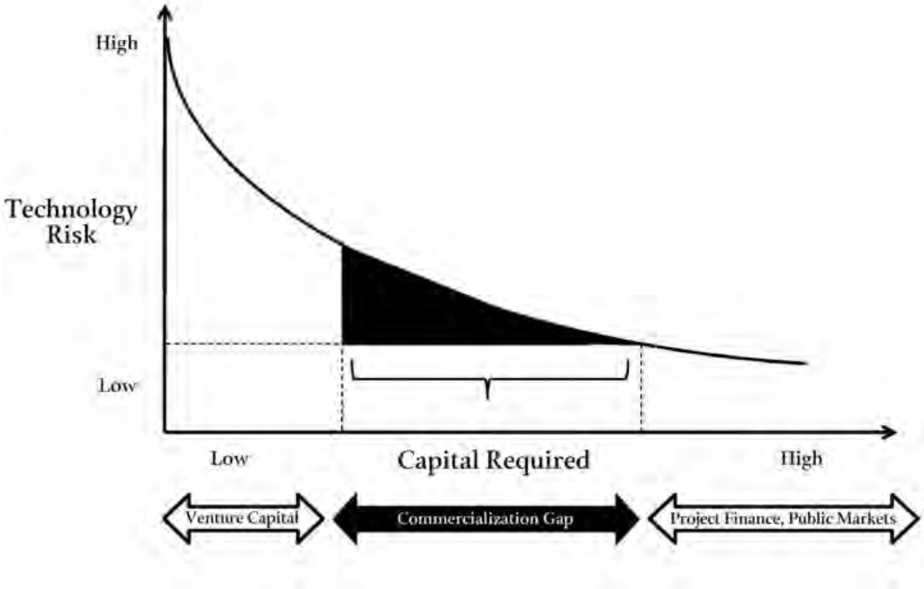
As stimulus dollars taper off over the next few years and government subsidies fall victim to budgetary cuts, the economic sustainability of a clean-energy industry that relies so heavily on short-term government supports is improbable. If government officials wish to accelerate the next energy transition, they will need a different strategy to develop an industry that can survive without major subsidies, one that prioritizes funding to develop decarbonized energy technologies that can compete dollar-for-dollar against carbon-based energy. Such technologies do not exist today, in part because of persistent financing challenges, or *financing gaps*, that impede their mass diffusion.

In the energy sector, financing gaps occur when the private sector does not get the investment returns it seeks. A *technology gap* occurs when university and government lab innovations lack financing for the next phase of development into potential commercial applications. This gap precedes funding by venture capital. In 2008, the government took steps to address the energy technology gap by establishing the U.S. Department of Energy Advanced Research Projects Agency-Energy (ARPA-E). Filling the technology gap is not a new role for government (the Department of Defense has funded similar programs with undisclosed budgets), but whether such a program will perform well within the Department of Energy (DOE) has yet to be determined, given that DOE programs are more subject to political winds and bureaucratic challenges.

The greater challenge is the *commercialization gap*. Technologies in this gap require massive investment to move beyond pilot and demonstration testing to commercial viability, at which point the private sector will take over full funding. Attracting private investment to these technologies is difficult. They are often too capital-intensive for venture capital yet too risky for private equity, project, or corporate debt financing (see Figure 1). Next-generation nuclear, clean coal, and large-scale solar technologies fall into the commercialization gap as a result of the sheer size of investment needed for proving their capability. To help close the gap, the government ideally would lower the financial risks for private-sector investors backing first-commercial technologies and projects. While the government role is critical in the commercialization gap, the risks and costs for taxpayers are high. Government funding in the form of financial guarantees or direct subsidies can add up to hundreds of millions, even billions, of dollars awarded to one company.

Nonetheless, the U.S. government has a history of supporting commercialization programs, beginning with nuclear energy programs in the 1950s and 1960s. The Atomic Energy Commission's Nuclear Light-Water Reactor Development Program contributed significantly to the commercialization of light-water reactors installed by electric utilities in the 1960s. In the aftermath of the 1973 oil embargo, federal investments in energy R&D grew dramatically – from $2.4 billion in 1974 to $7.4 billion in 1980 – causing a surge in commercialization activities. These programs included the $4 billion

Figure 1
Technology Risk versus Capital Required, showing the Commercialization Gap



Source: Tana Energy Capital LLC.

Synthetic Fuels Program and the $2 billion large-scale Solar Demonstrations Program.[14] Urgent concerns over U.S. dependence on foreign oil motivated the majority of these expenditures; 73 percent of funding from 1978 to 1981 was used to produce liquid and gas fuels from coal and oil shales.[15]

The government's track record in these and other commercialization programs has been mixed at best. Funding commercialization is thorny: it entails taking venture capital–like risk but also requires substantial capital commitments in the hundreds of millions of dollars for commercial-scale development – a difficult proposition to explain to taxpayers when such projects fail. Failures are often highly publicized; the recent case of solar company Solyndra is one example. Another much criticized government-funded failure, the Synthetic Fuels Corporation, was established in 1980 to finance the development of synthetic fuels plants, which were predicted to produce two million barrels of liquid fuel per day. Amid collapsing oil prices, the program was canceled within five years, having reached a production rate of only ten thousand barrels per day and incurring costs of $5 billion. Since the 1980s, the overall trend has been to support basic science instead of applied energy-technology development programs, with notable exceptions such as clean coal projects.[16]

Yet presidential administrations persist in supporting policies designed to accelerate the next energy transition, which requires closing the commercialization gap. In an era of depleted government budgets, policy-makers must ask: is funding the commercialization gap worth it?[17]

The risks of using scarce taxpayer dollars to accelerate new technology deployment must be weighed against potential benefits of creating competitive innovation industries over the long run.

The role of private-sector capital in technology funding has grown in recent years with the advent of venture capital and private equity funds. Venture capital, which was traditionally focused on the information-technology sector, has of late been invested in the clean-energy industry: venture investment in the energy sector increased from $0.4 billion in 2004 to $2.4 billion in 2010, a 35 percent annualized growth rate. Meanwhile, private equity investment, which is primarily concentrated in companies with proven technologies, grew from $0.3 billion to $3.1 billion, a 47 percent annualized growth rate.[18]

Despite the introduction of new types of capital into the funding picture for energy innovation, the commercialization gap remains. The risk/return profiles of commercialization do not fit the venture or private equity investment fund models, which seek returns exceeding 25 percent and paybacks within a five-year time horizon (see Table 1).[19] Capital-intensive commercialization companies rarely fit this profile. Projects have longer timelines and, in the case of project-based power generation investments, have limits on their investment returns due to the regulated nature of the power sector.

Corporate investment has also increasingly played a role alongside private funds. Given their strategic interests, long-term investment horizons, and cheaper cost of capital, corporations are ideally suited for funding commercialization in the private sector, as long as these risky investments are limited to a small portion of their capital budgets. Google, BP, Exxon, Chevron, GE, and Siemens are just a few of the large companies that in the past decade have launched energy-technology investment arms or bolstered their investment groups to focus on energy technologies and commercialization. U.S. power utilities – while not incentivized by their regulated business model to do so – have also of late invested in innovation. Utilities have started internal investment arms, developed commercialization projects, and made direct investments in funds or joint venture funds for strategic reasons.[20]

Aside from a handful of coal gasification and carbon sequestration projects, few DOE dollars were allocated to commercialization efforts in recent years. Section 1703 of the 2005 Energy Policy Act, which established the Loan Guarantee Program (LGP), changed this status quo. The LGP was designed to support a portfolio of new and improved technologies not yet available in the commercial marketplace with loan guarantees backed by the U.S. government. The purpose of these credit supports was to improve the risk/return profile for first-commercial, capital-intensive technologies, thereby motivating investment of private-sector capital in projects including nuclear, large-scale solar, geothermal, and energy storage. Although the program was authorized in 2005, Congress did not appropriate funding to implement it effectively; as a result, Section 1703 did not make any loan guarantees under the Bush administration.

The LGP was revitalized by 2009 ARRA stimulus funding, which amended the policy to also guarantee loans for commercial projects facing funding challenges as a result of dislocations in the credit markets. The revision was a significant departure from the original mandate of the LGP, as awards were not limited to commercialization gap projects and

Table 1
Energy Technology Financing: Investment Stage and Financing Participants

Stage of Development	Definition of Stage	Financial Characteristics	Financing Instruments/ Participants	Typical Investment Required/Target Return Profile*
R&D	Basic research	N/A	DOE/national labs; some corporate strategic investors	$0 – 2m (N/A)
Proof of Concept	Prove a concept/ qualify for start-up capital	N/A	Bootstrapping; angel funding	$2 – 5m (N/A)
Prototype and Pilot Scale Production	Complete product development	Losses Minimal assets Negative cash flow	Early-stage venture capital	$5 – 15m (10 – 15x, 40 – 50+%)
Prototype System Development	Initiate manufacturing; advance projects through pilot scale	Losses Minimal assets Negative cash flow	Venture capital; occasionally debt	$15 – 30m (10x, 40%)
Pre-Commercial Scale-Up	Scale up projects and manufacturing processes for technologies not yet proven at commercial scale	Losses Minimal assets Negative cash flow	**Commercialization gap**	$30 – 50m (5 – 10x, 35 – 40%)
Growth/ Commercial Scale-Up	Growth stage for expansion/capital used for working capital; expansion for commercial scale-up	Break-even to profitable Rapidly growing assets Negative or modestly positive cash flow	Corporate debt; leases (equipment); private equity	$50 – 200m (> cost of capital)
Commercial Replication (Maturity)	Mature, stable-growth businesses	Profitable Stable asset levels Positive cash flow	Self-sustaining; public debt and equity; markets; infra funds	+$200m (> cost of capital)

*Multiple of money or internal rate of return. Estimates assume a five-year hold for venture capital/private equity investments. Source: Table created by author.

applicants were judged on stimulus-related goals including short-term job creation. ARRA provided $4 billion for funding credit subsidy costs supporting $32.4 billion in loans.[21] As of July 2011, the DOE had issued conditional commitments for $35 billion in loans or loan guarantees to thirty-two projects. The projects span technologies related to wind, solar, advanced biofuel, geothermal, and nuclear energy as well as transmission and battery storage.

Despite the program's progress in deploying funds, the LGP has been fraught with an ambiguous mission, structural challenges, and front-page scrutiny of its first award recipient – Solyndra – which declared bankruptcy in September 2011. Evaluating the LGP program in detail – including the laborious interagency process that industry participants and the DOE itself have criticized – is beyond the scope of this essay.[22] However, it is important to consider whether the LGP, as the sole active U.S. government program designed to address the energy technology commercialization gap, is effective. It is also worth considering the extent to which the failure of Solyndra demonstrates the inadequacy of the program to identify high-potential technologies, or whether failures like Solyndra are simply "par for the course" in the difficult enterprise of funding the commercialization gap.

It is likely too early to tell if any company in the LGP portfolio will help accelerate a low-carbon energy transition through funding the commercialization gap. However, the LGP offers lessons that can help position future programs for success.

Commercialization programs ideally should focus on the persistent financing challenges of innovation acceleration – not short-term job creation goals. The LGP ultimately was amended to include commercial technologies and was funded by a stimulus program requiring the DOE to select companies that could facilitate the short-term goal of stimulating job creation. Thus, the DOE was incentivized to select companies with the greatest job-generation potential, such as large-scale project deployments or manufacturing operations. By contrast, commercialization gap manufacturing companies or projects without proven technologies or steady revenues are less likely to scale up headcount overheads before their business models can support them. Riskier commercialization companies that employ high headcounts – Solyndra being an example – do so risking failure, which can result in lost jobs. Critics of Solyndra's high-profile bankruptcy highlighted the 1,100 jobs lost when the company shut its doors, citing the failure of the LGP as a stimulus program. If the LGP had been laser-focused on the goal of promoting commercial innovation – rather than trying to be a climate change mitigant, job creator, and technology accelerator all at the same time – the program would have more appropriately been judged by the public as a tool for technology advancement.

Loans and loan guarantees are limiting and may not be the most appropriate mechanism for funding commercialization technologies. The LGP is limited to providing loans and loan guarantees, financial tools most suited to projects and companies that are commercially viable and have a contracted revenue stream in place, such as a long-term power purchase agreement (PPA). As a debt provider with a fixed return, the government has little incentive to take on projects that offer neither PPAs nor any monetary upside. Consequently, the majority of LGP awards funded projects using existing technologies.[23] However, higher risk projects (for example, first-commercial projects using a new coal gasification technology) may represent significant technological breakthroughs. If a government funding program could provide equity or quasi-equity instruments to projects, it could not only help these projects advance, it could also benefit alongside the private sponsor at an appropriate rate of risk/return and build a revenue stream to finance future program funding costs.[24]

Funding efforts would benefit from private-sector expertise and an arms-length relationship with the DOE. The LGP's multiagency review process suffers from long delays and funding awards that are easily politicized. The "check" on the DOE is understandable, given the difficultly in choosing the best portfolio of projects for government support. However, putting the investment decision-making function at arm's length from agencies and hiring private-sector technical and financial skill sets to award funds would remove bureaucratic and political agendas from the funding process, reduce conflicts of interest, and provide greater autonomy to investment decisions. Public information on the Solyndra investment process shows that this funding award – and potentially others – benefited from political involvement. While this sort of activity is nothing new in Washington, inside political tracks reduce the rigor and transparency of an investment decision-making process.

Another way to augment decision-making rigor is to align monetary compensation for investment managers with the performance of the portfolio – a common approach in the private sector. Linking pay to performance would better serve the goal of successful commercialization. A current plan to improve the commercialization funding process and the rigor of investment decision-making calls for a Clean Energy Deployment Authority (CEDA). This proposed (but still not approved or funded) administration could, among other things, partner with private-sector funds investing in the commercialization gap and would sit as an independent agency under the DOE.

The challenges of implementing commercialization programs offer a number of lessons about how difficult it is to speed a naturally incremental process, particularly amid competing agendas (such as short-term job creation) and the political nature of disbursing government dollars for high-cost, high-profile projects. The following are principles and recommendations to guide future policy-makers in funding energy technology commercialization.

- *Go big or go home: the massive scale of investment needed should not be underestimated.* Commercialization is risky; funding it entails a number of venture capital–like "bets." It is also capital-intensive: for example, demonstrating an advanced nuclear technology or utility-scale solar thermal facility requires hundreds of millions, or even billions, of dollars. If policy-makers want to accelerate innovation through the commercialization gap, they must be serious about taking on the sheer scale of effort needed to fill the gap that, given the risk/return imbalance, the private sector cannot. Programs must be well funded (unlike the 2005 loan program), placing investments across a range of technologies to provide multiple opportunities for success. Furthermore, additional investments in ancillary infrastructure (such as new transmission lines or electric car charging stations) are necessary to support commercial deployment of new innovations.

- *Stress the incremental benefits – and embrace the failures.* Inevitably, technologies demonstrated in pilot projects or pilot deployments will fail to reach commercial diffusion. This does not mean all is lost; historically, technological innovations are incremental and appropriated for other uses. An example of this phenomenon is the infamous Synthetic Fuels Corporation, which, although viewed as an expensive failure, laid the groundwork for coal gasification technology utilized today.

- *Leverage global investment dollars to encourage investment in commercialization.* Given the sheer investment needs and risks associated with commercialization, as well as the fact that energy is a global market, the United States is unlikely to create the next energy transition on its own. One solution could be the creation of a global commercialization fund that would pool the capital of ten countries instead of one, allowing for a large portfolio of multimillion-dollar demonstration and first-commercial projects. Putting aside complexities that could thwart this effort, such as intellectual property assignments and domestic industry development goals, a global innovation fund would pool risk among various participants, leveraging foreign dollars and limiting taxpayer exposure to risky government investments.

ENDNOTES

[1] I define a *low-* or *zero-carbon economy* as an economy with a minimal output of greenhouse gas emissions, achieved through low-carbon energy use and improved energy efficiency.

[2] The total includes mergers and acquisitions and equity reinvestment. New investments in 2010 represent $211 billion. See Bloomberg New Energy Finance and United Nations Environment Programme, *Global Trends in Renewable Energy Investment 2011 : Analysis of Trends and Issues in the Financing of Renewable Energy*, July 2011.

[3] U.S. Energy Information Administration, *Annual Energy Review* 2009 (Washington, D.C.: Department of Energy, August 2010).

[4] For a discussion of how innovation is necessary to meet goals to limit climate change, see David Victor, "Promoting Technological Change," in *Global Warming Gridlock : Creating More Effective Strategies for Protecting the Planet* (Cambridge: Cambridge University Press, 2011), chap. 5.

[5] In this case, animal feed was the "input" for horse-drawn transport.

[6] Vaclav Smil, *Energy Transitions : History, Requirements, Prospects* (Santa Barbara, Calif.: Praeger, 2010).

[7] Diffusion of CCGT technology was also driven by policy and regulatory influences, such as the collapse of natural gas prices in the 1980s and the advent of the Public Utility Regulatory Policies Act in 1978 ; ibid.

[8] The LNG value chain consists of natural gas production, liquefaction capacity, transport, shipping, and storage. While global capacity grew robustly between 2000 and 2008, the recent growth in shale gas production in North America and the dampening of natural gas prices have significantly slowed the industry's development.

[9] Robert Fri has succinctly summarized technology innovation in the energy sector: "the process of innovation is typically incremental, cumulative, and assimilative"; Robert W. Fri, "The Role of Knowledge: Technological Innovation in the Energy System," *The Energy Journal* 24 (4) (2003): 51 – 73.

[10] For the Obama energy plan as he articulated it while a candidate and as president-elect, see http://change.gov/agenda/energy_and_environment_agenda/.

[11] Bloomberg New Energy Finance and United Nations Environment Programme, *Global Trends in Renewable Energy Investment 2011*.

[12] Author's calculations ; data are from Morgan Stanley.

[13] See U.S. Department of Treasury, http://eetd.lbl.gov/ea/emp/reports/lbnl-3188e.pdf.

[14] James J. Dooley, "U.S. Federal Investment in Energy R&D: 1961 – 2008," Pacific Northwest Laboratory, October 2008. It is interesting to note that 24 percent of all federal R&D investments made during the half-century from 1961 to 2008 were made between 1974 and 1980.

[15] Committee on Benefits of DOE R&D on Energy Efficiency and Fossil Energy, Board on Energy and Environmental Systems, Division on Engineering and Physical Sciences, National

Research Council, *Energy Research at DOE: Was it Worth it? Energy Efficiency and Fossil Fuel Research 1978 – 2000* (Washington, D.C.: National Academies Press, 2001).

[16] Dooley, "U.S. Federal Investment in Energy R&D," 13.

[17] See Committee on Benefits of DOE R&D on Energy Efficiency and Fossil Energy, *Energy Research at DOE*. The committee found that return on investment related to federal government support for energy R&D was positive.

[18] Bloomberg New Energy Finance and United Nations Environment Programme, *Global Trends in Renewable Energy Investment 2011*.

[19] Venture capital funds typically seek returns of 30 to 40 percent over five to eight years; private equity funds typically seek returns of 25 to 30 percent over that time frame.

[20] Examples include Duke Energy and DTE Energy, which have invested in innovation companies and participated as investors in energy-focused venture funds. Duke and American Electric Power have been active in clean-coal demonstration projects in partnership with the DOE. California-based utilities, including Pacific Gas & Electric Company, have invested in solar-focused funds for residential rooftop solar projects.

[21] The Congressional Budget Office forecast a 12 percent probability of default.

[22] For critiques of the LGP, see Government Accountability Office, "Department of Energy: Further Actions are Needed to Improve DOE's Ability to Evaluate and Implement the Loan Guarantee Program," GAO Report 10-627, July 2010; and U.S. Partnership for Renewable Energy Finance, "The Clean Energy Deployment Administration (CEDA): Key Aspects and Improvements to the Department of Energy (DOE) Loan Guarantee Programs," July 2011.

[23] Loan Guarantee Program Projects, https://lpo.energy.gov/?page_id=45.

[24] Currently, the Federal Credit Reform Act (FCRA) limits the government to participating in project investments through debt instruments. FCRA was enacted in 1990 to improve the measurement of the budgetary costs of federal credit programs. The legislation requires federal credit subsidy costs to be calculated and accounted for on a net present value basis over the life of a loan.

National Policies to Promote Renewable Energy

Mohamed T. El-Ashry

Abstract: The world is entering a new energy era marked by concerns over energy security, climate change, and access by the poor to modern energy services. Yet the current energy path is not compatible with sustainable development objectives. Global demand for energy will continue to grow; so will CO_2 *emissions. Achieving a low-carbon energy world will require an unprecedented technological transformation in the way energy is produced and used. That transformation has begun, as renewables capacity continues to grow, prices continue to fall, and shares of global energy from renewables continue to increase. Government policies are the main driver behind renewable energy's meteoric growth. Still, the world is tapping only a small amount of the vast supply of renewable energy resources. There is broad consensus that the role of these resources should be expanded significantly in order to meaningfully address energy security, energy access, and climate change.*

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The main driver of sustainable economic development is sustainable energy. Yet there is broad consensus that the current path of global energy development is not sustainable in economic, environmental, or social terms. Moving to a more sustainable development path is the central global challenge for energy policy. The world's energy needs will be almost 60 percent higher in 2030 than they are now, and CO_2 emissions will increase at about the same rate.[1] In 2009, fossil fuels accounted for 81 percent of total global primary energy supply, which doubled between 1971 and 2009. Rising global demand for fossil fuels plays a key role in the continued growth of CO_2 emissions. In fact, CO_2 from energy production and use represents about 65 percent of global emissions. In 2009, the BRICS countries (Brazil, Russia, India, China, South Africa) accounted for 33 percent of global energy use and 37 percent of CO_2 emissions from fossil fuels; and energy consumption in these countries is expected to grow in coming years as a result of their strong economic performance.[2] According to McKinsey &

Company, more than 75 percent of the world's energy infrastructure needed by 2030 has not yet been constructed, and most of it will be built in developing countries.

To meet this infrastructure goal in the context of heightened concern over energy security and climate change, greater global attention is being given to clean and renewable sources of energy. Recognizing "with a sense of urgency" that decisions taken now will be decisive for a transition toward a sustainable energy future, world leaders gathered in Johannesburg, South Africa, at the World Summit on Sustainable Development (WSSD) in 2002 to call for a substantial increase in the global share of renewable energy.

In Copenhagen in 2009 and Cancun in 2010, the international community agreed to limit the rise in worldwide temperatures to no more than 2 degrees Celsius above preindustrial levels, which scientists regard as the threshold for avoiding the most serious effects of global warming. Given that global demand for energy could more than double by 2050, reducing global emissions by at least 50 percent from 1990 levels will require an unprecedented technological transformation of how energy is produced and used. Widespread deployment of currently available clean-energy technologies and development of new, cheaper, and more efficient technologies are needed to achieve this goal.

Continuing along the current path of energy development is not only incompatible with sustainable development objectives, it also makes the world more vulnerable to supply disruptions and price shocks as international trade and economic growth expand, especially in developing countries. The continued rise in oil prices reflects concerns about meeting the fast-growing demand for energy and the risks of dependency on fossil fuels. The high price of oil is taking its toll on the economies of less developed countries. In little more than a decade, the cost of these countries' oil imports has quadrupled to an estimated $100 billion in 2011, or 5.5 percent of their GDP.[3]

In a 1931 meeting with Henry Ford, Thomas Edison told the inventor of the gasoline-powered car: "I'd put my money on the sun and solar energy. What a source of power! I hope we don't have to wait until oil runs out before we tackle that." Eighty years later, in 2010, global investment in renewable energy grew 32 percent to a record $211 billion.[4] Renewable energy supplied an estimated 16 percent of global final energy consumption and delivered close to 20 percent of global electricity production. Including hydropower (about 30 GW added in 2010), renewable energy accounted for approximately 50 percent of total added power generation capacity in 2010.[5] Table 1 and Figure 1 show, respectively, regional and worldwide trends in the consumption of new renewable energy from 2000 to 2010.

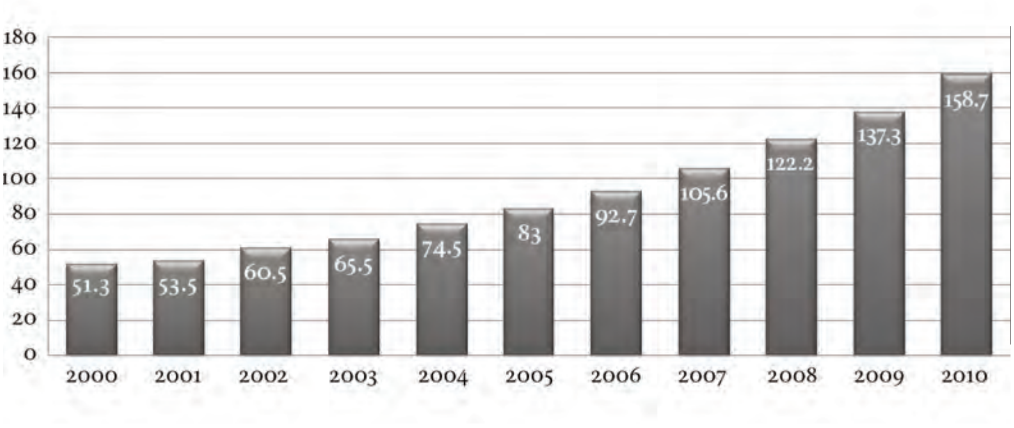
Wind power grew by 23.6 percent in 2010 and, at $95 billion, continued to be the favored technology for investors. Asia deployed the largest share of new wind installations – 54.6 percent – with China ranking number one in total installed capacity, accounting for 50 percent of the world market for new wind turbines. The solar sector experienced the strongest growth, with investments climbing 53 percent to a record $79 billion, helped by declining prices and key government support. In 2010, 18 GW of photovoltaic (PV) power were installed globally – the first time more than 10 GW were installed and connected to electric grids in a single year. Today, more people than ever before derive energy from renewables.

Table 1
Consumption of New Renewable Energy by Region, in Million Tonnes of Oil Equivalent (Mtoe)

	North America	Central & South America	Europe & Eurasia	Middle East	Africa	Asia Pacific	Total
2000	21.1	3.9	14.8	0.0	0.3	11.2	51.3
2001	20.2	4.5	16.8	0.0	0.3	11.7	53.5
2002	22.2	5.0	20.5	0.0	0.4	12.4	60.5
2003	22.6	5.4	24.0	0.0	0.4	13.1	65.5
2004	23.5	5.7	30.1	0.0	0.6	14.6	74.5
2005	24.9	6.2	35.3	0.0	0.6	16.0	83.0
2006	27.0	6.4	40.9	0.0	0.6	17.8	92.7
2007	29.3	7.6	48.4	0.0	0.6	19.7	105.6
2008	34.1	8.5	56.0	0.0	0.7	22.9	122.2
2009	38.7	9.3	61.6	0.1	0.9	26.7	137.3
2010	44.2	11.1	69.6	0.1	1.1	32.6	158.7

New renewables include wind, geothermal, solar, biomass, and waste. Source: REN21, *Renewables Global Status Report 2011*.

Figure 1
Worldwide Consumption of New Renewable Energy, in Million Tonnes of Oil Equivalent (Mtoe)



New renewables include wind, geothermal, solar, biomass, and waste. Source: BP Renewable Statistical Review 2011.

National Policies to Promote Renewable Energy

Renewable energy policies and capacity targets are the main drivers of renewable energy growth. By early 2011, at least 118 countries had some type of policy target or renewables-support policy at the national level, compared to 55 countries in early 2005. Public policies have had a major impact on driving renewable energy markets, investments, industry development, and social benefits. In developing countries, such policies have caused a remarkable change in the geographic spread of renewable energy as of 2010. Adoption of renewable energy technologies is no longer confined to the industrialized world. More than half of the existing renewable power capacity is in the developing world, especially in Asia. Significant advances have also occurred in many Latin American countries, and at least twenty countries in the Middle East, North Africa, and sub-Saharan Africa have active renewable energy markets.

Thanks to its pioneering Renewable Energy Law, China now leads in several indicators of market growth. In 2010, China was the top installer of wind turbines and solar thermal systems and the leading hydropower producer. India is fifth worldwide in total existing wind power capacity and is rapidly expanding many forms of rural renewables, such as biogas and solar PV. Brazil produces virtually all of the world's sugar-derived ethanol and has been adding new hydropower, biomass, and wind power plants, as well as solar heating systems.

One force propelling renewable energy policies and development is the potential to create new industries and generate new jobs. Jobs from renewables number in the hundreds of thousands in several countries. Globally, there are more than 3.5 million direct jobs in renewable energy industries, about half of them in the biofuels industry, with additional indirect jobs well beyond this figure.

Momentum is building. But business, investors, activists, and scientists alone cannot change the way we produce and use energy. These groups can anticipate change, facilitate it, and profit from it, but they cannot drive it. Public policies that create markets, remove barriers, level the playing field, and establish clear objectives and targets for renewable energy and energy efficiency help shape the future. Energy policies affect the price, availability, and advancement of new technology; therefore, they determine how quickly we reach the point at which consumers can choose electricity generated by wind and sun or purchase more efficient lighting, appliances, and cars.

Policies to support renewable energy investments vary from country to country. Experience shows that no one policy or instrument has been the sole driving force in the growth of renewable energy investments. Countries choose a combination of policies and regulations that fit their circumstances. Key among the successful policies and regulations adopted by many countries are: (1) clear goals and targets as well as strategies and implementation plans; (2) a level playing field and fiscal incentives to reduce up-front costs, including tax credits, loans, and guarantees; (3) regulatory instruments such as portfolio standards or quota systems, feed-in laws and tariffs, and green certificates; (4) rural energy provisions and electrification policies; (5) capacity development to ensure the necessary capabilities and skills; and (6) strong public institutions at the national level for setting priorities and establishing policy and regulatory agendas. These policies and regulatory frameworks must be stable and long lasting to ensure investor confidence.

At least ninety-six countries, more than half of which are developing countries, have established national targets for expanding renewable energy use. These targets represent commitments to shares of electricity production (typically 10 to 30 percent from renewables), total primary or final energy, heat supply, installed capacities of specific technologies, and shares of biofuels in road transport fuels. Many targets also exist at the state, provincial, and local levels. Although some were not met or were scaled back, many countries achieved or exceeded their targets set for 2010; Sweden has already surpassed its goal for 2020. Existing targets were raised in a number of countries, including Finland, Germany, Spain, and Taiwan, and entirely new targets were adopted in South Africa, Guatemala, and India, among others.

Ninety-six countries have implemented renewable power generation policies. The feed-in tariff (FIT) remains the most widely employed policy, in place in at least sixty-one countries and twenty-six states or provinces worldwide. FIT schemes have effectively promoted renewable power generation with long-term fixed-price premium payments, network connections, and guaranteed purchase of all generated electricity. Most FIT-related activity in 2010 focused on revisions to existing policies in response to strong markets that exceeded expectations, particularly in the case of PV. Several developing and transition countries introduced new FIT policies in 2010 and early 2011. In addition, ten countries have enacted renewable portfolio standards (RPS) or quota policies at the national level. At least fifty other jurisdictions have such policies, including thirty U.S. states (plus Washington, D.C.) and the Canadian province British Columbia, which requires that 93 percent of new power capacity be renewable. Quota policies have been effective when designed to reduce risk, for example, in case of long-term contracts.

Many additional types of policies are being implemented to support renewable power generation, including direct capital investment subsidies, grants, or rebates; tax incentives; energy production payments or credits; and public financing. Net metering, or net billing, policies exist in at least fourteen countries, including Italy, Japan, Jordan, and Mexico, and in almost all U.S. states. Green energy purchasing and labeling programs are growing, with more than six million green power consumers in Europe, the United States, Australia, Japan, and Canada.

Mandates for blending biofuels exist in thirty-one countries at the national level and in twenty-nine states or provinces. Subsidies and tax exemptions are also used to promote biofuels. Finland, Ethiopia, Thailand, and Spain all revised existing biofuels policy legislation in 2010, and South Korea and Jamaica implemented new blending mandates.

City and local governments continue to become increasingly important players in promoting the local generation and use of renewable energy. Local support policies include renewable energy targets; urban planning that incorporates renewable energy; building codes that mandate or promote renewable energy; tax credits and exemptions; investment in renewable energy for municipal buildings and transit; subsidies, grants, or loans; and a variety of informal, voluntary actions to promote renewable energy at the community level.

Even with this progress, new renewable energy (excluding traditional biomass) accounted for just 7 percent of total primary energy demand in 2010.[6] Absent further progress, it will expand to only 14 percent by 2035, according to International Energy Agency projections. The world is tapping only a small amount of the vast supply of renewable energy resources worldwide, with the technical potential of renewable energy several times greater than global energy demand. This is particularly true for electricity generation. Solar energy, for example, can be harnessed almost everywhere, and its potential alone is many times higher than global electricity consumption. A new report released by the Intergovernmental Panel on Climate Change notes that renewable energy could provide as much as 77 percent of the world's energy needs by 2050.[7]

Critical to securing a sustainable, affordable, and climate-friendly future for this generation and many to come is the ability of individuals and institutions to effect change in the way we generate and use energy. Only by significant scaling-up of renewable energy will we enter the virtuous cycle of cost-reductions followed by more significant scaling-up. To accomplish that goal, we must:

- Connect the dots, bringing knowledge and experience together in partnerships – at all levels – so that cleaner, more efficient energy systems are available at scale;
- Establish renewable energy targets for individual energy markets as shares of projected demand in the electricity, heat, and transport sectors;
- Phase out fossil fuel subsidies and use taxes and regulations to promote market conditions in which renewable energy can compete – but without shifting a disproportionate share of additional burden to the poor;
- Encourage the expansion of renewable energy technologies for decentralized applications that are already cost-competitive with conventional fuels, such as diesel generators, once the up-front costs are bought down for low-income users;
- Utilize public funds to leverage and incentivize large-scale private investment in developing countries; and
- Invest in research, development, and deployment of cheaper and more efficient clean-energy technologies and adapt them for use in developing countries.

And most important, with the planet's population heading for nine billion within our children's lifetime, we need to act fast.

ENDNOTES

[1] *Energy & Sustainable Development* (Paris: International Energy Agency, 2007).

[2] *CO_2 Emissions from Fuel Combustion* (Paris: International Energy Agency, 2011).

[3] *World Energy Outlook 2011* (Paris: International Energy Agency, 2011).

[4] Bloomberg New Energy Finance and United Nations Environment Programme, *Global Trends in Renewable Energy Investment 2011: Analysis of Trends and Issues in the Financing of Renewable Energy*, July 2011.

[5] REN21, *Renewables Global Status Report 2011*, http://www.ren21.net. *GSR 2011* provides a comprehensive view of the global renewable energy policy landscape, including country-by-country listings of renewable energy targets and renewable energy promotional policies. The bulk of my discussion of specific countries' government policies is based on information and analysis from *GSR 2011*.

[6] Including traditional biomass, renewable energy supplied 16 percent of world energy consumption in 2010.

[7] *Special Report on Renewable Energy Sources and Climate Change Mitigation* (Geneva, Switzerland: Intergovernmental Panel on Climate Change, 2011).

Inside back cover: (foreground) A plug-in hybrid electric vehicle at a charging station on "Electric Avenue" near Portland State University in Portland, Oregon, © iStockphoto.com/andipantz; (background) Overview of a congested multilane highway, © Ocean/Corbis.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