

policy

Proceedings Overview

technology

The Challenge of a Low-Carbon Future

Addressing the challenge of global climate change will require a significant reduction in annual greenhouse gas (GHG) emissions in the United States and throughout the world by 2050. A commonly stated goal is to stabilize atmospheric concentration of carbon dioxide (CO₂) at twice its pre-industrial level.¹ To meet such a goal in the context of increasing global demand for energy, an increase of roughly 100 to 300 percent of present-day worldwide “primary power” consumption would need to come from non-CO₂-emitting sources such as renewables, nuclear, and the use of fossil fuels with carbon capture and sequestration.² In addition to low-carbon primary energy sources, a future low-carbon economy will require widespread use of lower-carbon fuels and energy carriers such as hydrogen, and significant improvements in the efficiencies of energy production, distribution, and end-use technologies.³ The transition to a low-carbon economy could have other benefits, including increased energy security, improved public health, and increased economic development, but it will take several decades and will not be easy. Achieving this transition will require near-term and long-term actions. In the near term, it will be necessary to take advantage of current technologies and opportunities, and to make substantial investments in the technologies of the future.

It will be especially difficult to meet the technological challenges inherent in developing and deploying a suite of low-carbon energy technologies while achieving the traditional goals of U.S. energy policy (i.e., providing extensive energy services at low cost and through secure supply to a growing population and economy). Furthermore, low-carbon energy technologies that compete with entrenched conventional (and usually high-GHG-emitting) technologies are likely to encounter market, political, and societal barriers to deployment.

Accordingly, there is a clear need to initiate and sustain policies to push and pull low-carbon technologies into the market. Without such policies, businesses, consumers, and citizens are missing opportunities for cost-effective GHG reductions and investment for the future. Too often, the debate over GHG emission reductions pits near-term actions against long-term investments in technology, when both are necessary. A variety of policies, public and private leadership, and broad societal engagement will be needed to bring low-carbon technologies into the market. Characteristics of the energy sector—long capital cycles,⁴ a high degree of system inertia, and susceptibility to path-dependency⁵—highlight the need to begin now to promote technological change and enable far-reaching deployment over the next 50 years.

Background on the “10-50 Solution”

Considering the long-term nature of the climate change challenge, the Pew Center on Global Climate Change and the National Commission on Energy Policy (NCEP) hosted a workshop entitled “The 10-50 Solution: Technologies and Policies for a Low-Carbon Future” in March 2004.⁶ The overall goal was to articulate a long-term vision of the

technologies and industrial process changes that would have to be in place 50 years from now to effectively address climate change, as well as the policies that would have to be initiated in the short, medium, and long term to achieve this vision. More specifically, the workshop aimed to achieve three goals:

- ❑ Analyze the strengths, weaknesses, barriers, and opportunities for technological options that could enable a low-carbon future;
- ❑ Develop plausible time frames for when various low-GHG technologies and strategies might start to generate significant GHG reductions; and
- ❑ Identify steps (particularly policies) that could facilitate the development and deployment of these technologies.

In preparation for the workshop, the Pew Center and NCEP commissioned new analyses in five key technology areas with the potential to play a significant role in a low-carbon economy: efficiency, hydrogen, carbon sequestration/coal gasification, advanced nuclear technologies, and renewables. This is not an exhaustive list of future low-carbon energy technologies. Although many other technologies and solutions such as the use of biofuels, terrestrial sequestration, and land use changes⁷ will likely play a role in the transition to a low-carbon future, the workshop restricted its focus to only five of the critical low-carbon technology options due to resource constraints. In addition, lessons drawn from analyses of these technologies should inform policy-making that could promote other low-carbon energy technologies as well. One overview paper and two to four contributing pieces were commissioned in each of these technological areas to provide alternative views of the likely technological path forward in the short, medium, and long term; these papers also examined relevant challenges and policy considerations for each technology area. Overview authors were asked to present their papers as part of panel discussions at the workshop.

In addition to panels discussing the technologies identified above, the workshop featured several other panels and presentations. One panel explored opportunities in industry for reducing GHG emissions and policy options for encouraging further reductions. The role of natural gas in the transition to a low-carbon future was discussed through a brief presentation, and it was a topic of discussion throughout all of the workshop sessions. Finally, keynote speakers shared their perspectives on relevant topics including an update on the implementation of the United Kingdom's plan to reduce GHG emissions by 60 percent over the next 50 years,⁸ opportunities for addressing climate change and energy security concerns simultaneously, and examples of how forward-thinking states and businesses are taking action on the issue of climate change and energy policy in the absence of federal leadership.

More than 100 policy-makers, business leaders, NGO representatives, and leading experts participated in the workshop.⁹ Starting with the background papers and presentations, participants worked to identify options for promoting low-carbon energy technologies and industrial processes in the near, medium, and long term. Technological

uncertainty, policy uncertainty, and uncertainty regarding the degree of success of policy-induced technological change prevented many participants from offering many policy recommendations beyond the near term. Thus, most workshop discussions focused on the policies needed within the next decade or two to enable these technologies to be widely deployed over the next 50 years and beyond. This overview summarizes the papers and identifies key points brought out in the conference.¹⁰

Status, Potential, and Options for Promoting Development of Five Low-Carbon Energy Sources and Technologies

A portfolio of new technologies and policies will be needed to enable the transition to a low-carbon future by 2050. Workshop participants voiced widespread support for a broad national policy that establishes a carbon price through market-based tools such as cap-and-trade or taxes. Revenues from such measures could be used, in part, to support research, development and deployment (RD&D)—another key component of a comprehensive program to achieve significant emission reductions. Various policy approaches to stimulating specific technologies as well as economy-wide reductions are discussed below.

In the pull-out at the front of this proceedings, Figure 1 summarizes the technological status and expected deployment of the five areas of focus in the 10-50 Workshop. This figure shows the significant potential to reduce energy-related GHG emissions by 2050 through a portfolio of technology options. However, many of the assessments and predictions of technological potential shown here are based on the assumption that policies enacted in the near term would enable increased development and mid- and long-term market deployment of the indicated technologies.

The pull-out at the back of this proceedings, Figure 2, describes various policy proposals put forth by workshop participants. A mix of these policies, plus others yet to be defined, will probably be necessary to enable the development and deployment over time of the technologies described in Figure 1. As Figure 2 indicates, numerous policy proposals suggested in workshop papers and discussions focused on the next 10 to 15 years, and very few aimed beyond the 2015–2020 time frame. This more limited focus can be attributed partly to a hesitancy to make policy prescriptions in the face of technological (and other) uncertainties, but it also reflects the widespread sentiment of the 10-50 Workshop participants: that it is imperative to start now to develop technologies that will enable a low-carbon economy by 2050.

Whereas Figure 2 emphasizes the need for near-term policy actions, Figure 1 shows the significant and continued potential to reduce GHG emissions by deploying these low-carbon technologies throughout the next five decades.¹¹ The integration of Figures 1 and 2 shows that a suite of policies must be enacted in the near term to enable continuous incremental reductions in GHG emissions through deployment of these technologies and to better position society to select among low-carbon options in the future.

Figures 1 and 2 also show that enabling a low-carbon future will likely entail the utilization of a variety of low-carbon technologies and policies, and that both broad and technology-specific policies will be required. Below is a discussion of the current and future technological potential of each of the five areas studied, as well as policies to create incentives for deployment of each of these technologies over the long term.

Energy Efficiency

Broadly speaking, energy efficiency has saved the U.S. economy billions of dollars in energy expenditures since the middle of the 20th century. Energy consumption per dollar of real GDP has fallen by more than 50 percent since 1949,¹² and energy price changes as well as specific policies—including corporate average fuel economy (CAFE) standards,¹³ mandated appliance energy efficiency standards, and building codes—have resulted in billions of dollars of savings from reduced energy imports and electric energy expenditures, as well as hundreds of millions of tons of CO₂ emission reductions.

The technological potential for energy efficiency improvements in the next 10 to 20 years, and potentially throughout the next 50 years, remains large. However, the degree to which these potential savings are realized will depend on increases in the cost of energy, adoption of policies, public and private investments spurred by incentives and pricing, as well as continued improvements in energy-efficient technologies. Nonetheless, even with present-day technologies, the potential energy savings and CO₂ emissions reductions from energy efficiency are significant and critical. A few examples illustrate this point:

- Adoption of four pending appliance standards (clothes washers, fluorescent light ballasts, water heaters, and central air conditioners) could result in significant energy savings for U.S. consumers, possibly saving as much as \$10 billion in energy costs by 2010¹⁴
- Replacement of four building technologies (ballasts, lamps, windows, and refrigerators/freezers) with high-performance alternatives during the natural building stock replacement cycle could save 190 billion kilowatt hours (kWh) by 2010 and an additional 130 billion kWh by 2050¹⁵
- Creation of “cool communities”—which entails using more reflective roofing materials and better use of landscaping for solar absorption and shading—could reduce annual cooling loads by 10 percent and thereby reduce total U.S. annual energy use by 0.5 percent¹⁶
- Widespread adoption of “daylighting”¹⁷ technologies in U.S. buildings could reduce 3–6 percent of total U.S. energy use (or 30–60 percent of lighting-related energy)¹⁸
- Widespread adoption of better air conditioning technologies compatible with natural ventilation and night or high mass cooling¹⁹ could reduce total U.S. energy consumption by 5 percent²⁰

- Use of distributed wind, solar, and geothermal resources located on site of many buildings in the United States by 2050 could make them net energy exporters²¹

The technological opportunity in the industrial and transportation sectors is also large. Estimates of the long-term potential for energy-efficiency increases in the industrial sector range from 30 to 65 percent,²² and fuel economy of automobiles and light trucks could increase by 50 to 100 percent by 2030.²³

Policy Options

Some near-term policy options are likely to increase adoption of energy-efficient technologies:

- Mandatory reporting of GHG emissions. As seen with reporting of the Toxics Release Inventory²⁴ and individual firm GHG targets, entities conducting inventories find opportunities for cost-effective efficiency improvements and other GHG emission reductions²⁵
- Adoption and promotion of building codes focused on maximizing GHG reductions—examples might include “cool” roofs, daylighting, and ventilation
- Federal mandatory appliance standards—attractive candidates include air conditioners, clothes washers, fluorescent light ballasts, and water heaters
- Increases in public RD&D in innovative energy efficiency technologies and integrated systems, including publicly funded demonstration programs that recognize major building type and climate specific opportunities
- Increased CAFE standards
- Incentives for the private and public procurement of highly efficient technologies in areas from buildings to vehicles such as hybrid-electric and advanced diesel vehicles

Hydrogen in Transportation

If produced from low- or zero-carbon energy sources, hydrogen can be used as a transport fuel with nearly zero “well-to-wheels”²⁶ GHG emissions.²⁷ Hydrogen also has the potential to achieve other societal benefits such as reduced local air pollution and increased energy security. Presently, hydrogen is predominantly produced for use in the worldwide petrochemical industry, and its use in transportation applications is insignificant.²⁸ Continued R&D on hydrogen technologies is likely to continue for the next 10 to 15 years, with limited fleet and demonstration-project testing. Many analysts think that a societal decision on hydrogen’s long-term viability as an energy carrier will be needed in the 2015–2020 time frame. Assuming technological and cost progress, hydrogen vehicles could start significantly penetrating the market after 2025.²⁹

Significant technical challenges face the widespread use of hydrogen as a transportation fuel, including difficulties associated with on-board hydrogen storage and the durability

and cost of hydrogen conversion devices (specifically fuel cells). In addition to overcoming these many technical challenges, a reduction in economy-wide GHG emissions from the use of hydrogen as a transportation fuel depends on the cost and technical feasibility of producing hydrogen from low-carbon energy sources, including renewables and fossil fuels with carbon sequestration. Despite these significant challenges, hydrogen offers perhaps the best hope for solving multiple societal challenges facing current and future transportation energy use, and thus it deserves serious consideration.³⁰ However, the political will to address the external impacts of energy use through policy and technological progress will determine whether hydrogen plays a major role as a future energy carrier.³¹

In light of the challenges facing the use of hydrogen as an energy carrier, it is important to continue to explore other options for reducing GHG emissions from the transportation sector, including biofuels and, most importantly, highly efficient vehicles such as hybrid-electric vehicles. In addition to offering the potential for significant near- and medium-term GHG reductions, continued commercial experience with many technologies used in hybrids (e.g., electric drive trains, advanced batteries, and sophisticated electronic control systems) will be beneficial for any eventual hydrogen internal combustion engines or fuel cell vehicles. In addition, policies that promote the use of highly efficient vehicles are likely to also encourage the use of hydrogen vehicles.

Policy Options

The near-term policy options listed below will be needed to enable hydrogen to make a significant contribution to a low-carbon economy by 2050:

- Development of a national energy policy that addresses the external costs of energy use, including security, climate change, and traditional air pollutants
- Continued and increased federal support for hydrogen-related R&D, including special emphasis on low-carbon hydrogen production, hydrogen storage, and fuel cells
- National and international harmonization of hydrogen codes and standards
- Continued federal and state government support for, and participation in, public/private partnerships and demonstration programs (e.g., California Fuel Cell Partnership, FreedomCAR, and international cooperative efforts)
- Incentives to increase the development and deployment of hybrid technology and vehicles and other low-carbon transportation technologies—many of which are part of an evolutionary path toward the use of hydrogen and fuel cells
- Education of consumers and the public regarding the societal costs of transportation energy use and options for reducing such impacts, specifically including hydrogen

Carbon Sequestration/Coal Gasification

The use of coal gasification technologies coupled with carbon capture and sequestration in geologic formations has the potential to allow the United States (and the world) to use its significant coal resources without releasing substantial GHG emissions to the atmosphere. Although coal is mostly used for electricity generation, it is also possible to make hydrogen from coal using gasification technologies. Thus, production of electricity and hydrogen from coal, combined with carbon capture and sequestration (CCS), could enable significant CO₂ emission reductions from both the electricity and transportation sectors, which currently account for more than two-thirds of U.S. GHG emissions.

Injection of CO₂ into geological formations has been practiced for decades in the United States in “enhanced oil recovery” (EOR) projects in oil and gas wells.³² In addition to EOR projects, there are six CCS projects underway worldwide. However, none of the six currently operating projects nor any other planned projects sequester as much CO₂ per year as would be needed to offset emissions from an average U.S. coal plant.³³

Although estimates of total carbon storage capacity vary widely, the global geologic capacity of depleted oil and gas reserves, coalbed methane reserves, and salt-water filled formations is significant—most likely enough to enable sequestration of significant percentages of global GHG emissions from the use of fossil fuels. One estimate of the “known” resource places U.S. storage capacity at about 50 years’ worth of CO₂ emissions from U.S. electric power plants in depleted oil and gas reserves alone.³⁴ Further work is needed to determine the capacity of salt-water filled formations that are suitable for carbon storage (potentially the largest resource for carbon sequestration).

Despite the potentially large storage capacity, significant barriers remain before widespread use of coal gasification with CCS would be feasible, including

- validation of the geologic integrity of storage;
- cost of the carbon capture and separation technologies;
- integration of gasification, CCS, and electricity generation technologies; and
- public acceptance of geologic storage of CO₂.

Policy Options

If these issues are properly addressed within the next decade, coal gasification with CCS could enter the commercial market around 2020–2025. Many experts conclude that conducting a mix of domestic and international public/private partnership demonstration projects is the best way to overcome some of these barriers. Accordingly, the main policy recommendation regarding CCS is a significantly ramped up demonstration and validation program for CCS technology and the integrity of geologic storage, starting immediately. These recommendations, as well as other near-term policy options are identified below:

- International coordination to plan, fund, and deploy coal gasification with CCS trial projects that focus on remaining technical issues and with publicly shared results (e.g., adequately addressing remaining uncertainties will likely require four to six projects, at an estimated cost of approximately \$5 billion, and an estimated project lifetime of 10 years)
- Establishment of carbon sequestration trial projects in the United States to validate the integrity of geologic storage (e.g., such validation will likely require four such projects at an estimated cost of approximately \$1 billion, and an estimated project lifetime of 10 years)
- Removal of policy disincentives to shutting down old coal plants
- Initial establishment of a regulatory framework for underground CO₂ storage
- Promotion of R&D to reduce the cost of separation and capture technologies
- Increase in consumer and citizen education efforts regarding the scientific and social costs and benefits of continued use of fossil fuels with geologic carbon sequestration

Advanced Nuclear Generation

Nuclear power currently provides approximately 20 percent of U.S. electricity supply from 104 operating reactors. Conventional nuclear power is considered by most to be a “mature” technology. Despite its significant role in the U.S. electricity mix, the last new nuclear plant was ordered in 1979,³⁵ and there are no current plans to build more in the United States.³⁶ Furthermore, approximately 10 percent of U.S. nuclear plant licenses will expire at the end of 2010, and more than 40 percent will expire by 2015.³⁷ Any significant ramp-up of nuclear capacity would likely be a lengthy process, due in large part to the significant time required to license and build a new nuclear plant. Thus, the ability of nuclear power to contribute to avoiding significant GHG emissions by 2050 will likely be determined by whether a major deployment of nuclear power in the United States starts in the next 10 to 15 years.

Such a deployment highly depends on the degree to which the nuclear industry can overcome serious barriers, including

- cost;
- technical, political, and social concerns about nuclear waste disposal;
- increased proliferation risk; and
- public concern about the continued and expanded use of nuclear power.³⁸

Policy Options

Listed below are some of the near-term policy options that could address the barriers to nuclear generation and that could increase the likelihood of a large-scale deployment scenario. However, even with the adoption of a comprehensive suite of policies to promote nuclear power, the role of nuclear power in the future will ultimately be

determined by the willingness and ability of the electric industry to increase deployment of nuclear plants.

- Electricity production tax credits for “first mover” nuclear plants up to 10 gigawatts electric (Gwe) at a level similar to the wind production tax credit (currently 1.8 cents/kWh)
- Significant expansion in size and scope of the U.S. DOE’s nuclear waste management R&D
- Strengthening and reorientation of the current international safeguards regime to meet the non-proliferation challenges of globally expanded nuclear power
- Re-ordering of the priorities of the U.S. DOE nuclear fuel cycle R&D to focus on the “once-through”³⁹ fuel cycle
- Public dialogue and education on the costs and benefits of nuclear power, especially in the context of climate change

Renewables

Some experts estimate that renewable sources of energy, including wind, solar, geothermal, oceans, and biomass, could provide between 20 and 50 percent of U.S. electricity by 2050.⁴⁰ Despite this potential for growth, these sources currently provide a small fraction of commercial energy in the United States and around the world. For instance, in 2000, wind, solar, and geothermal energy (in combination with combustible renewables, and the burning of garbage and other wastes) collectively provided just 1.6 percent of electricity production worldwide.⁴¹ In 2002, these sources provided 2.2 percent of electricity generation in the United States.⁴²

Despite their low levels of deployment relative to other electricity-generating technologies, renewables such as wind and solar continue to sustain impressive annual growth rates. The wind industry grew by 30 percent annually worldwide over the past five years, and annual global growth in the production of photovoltaic cells holds steady at roughly 20 percent.⁴³ Nevertheless, closing the gap between the current low level of renewables deployment and their high potential will likely require significant and sustained policies and programs.⁴⁴

Policy Options

Listed below are policy options to motivate and support a massive ramp-up of renewables. Each of these policy proposals focuses on one or more of the commonly cited market or technical barriers facing widespread deployment of renewables: cost, intermittency,⁴⁵ the remote nature of many renewable resources,⁴⁶ and the number of generation sources that would be required.⁴⁷

- A national renewable portfolio standard with set-asides for specific generation technologies⁴⁸ and with tradable renewable energy credits

- A massive “third stream”⁴⁹ of R&D by the U.S. DOE focused on renewables; such a program should be on the order of an “Apollo” project and should include three characteristics:
 - A focus (at the National Renewable Energy Laboratory and other national labs) on making renewables commercially competitive beyond niche markets
 - Reduced uncertainty in funding for renewables—possibly “forward-funding”⁵⁰ of renewables R&D to reduce the year-to-year variability of the annual appropriations process
 - Revamping of the U.S. DOE’s renewables R&D portfolio to include more high-risk R&D (i.e., away from strictly risk-averse R&D portfolios)
- National test beds for new electricity grid systems followed by an extensive modernization of the grid, including intermittent and distributed energy and combined heat and power
- Increased research on expanding energy storage options
- Pollution fees for polluting energy sources
- Continued support to help renewables become competitive with fossil fuels for electricity generation (e.g., through tax credits)

Common Themes and Policy Recommendations

In addition to the technology-specific insights above, a number of common themes and policy recommendations emerged from the workshop. Broadly speaking, these can be grouped into four over-arching points: (1) clear and consistent policy signals are urgently needed; (2) a portfolio of technologies and policies will be needed to drive the absolute reduction of GHG emissions necessary to address climate change; (3) a low-carbon technology revolution will require both leadership and broad engagement throughout society; and (4) it is essential to start now. These common themes and policy recommendations are explained in more detail below.

Clear and Consistent Policy Signals Are Urgently Needed

Policy is needed to set the framework for a low-carbon future, and businesses and markets need to believe in the legitimacy of the policy framework. For instance, the United Kingdom is implementing a goal of reducing GHG emissions by 60 percent by 2050. Such a commitment sends a very powerful signal to markets that the UK government is serious about addressing climate change, and it helps to reduce the level of uncertainty in the investment decision-making process of private and public entities. It also aligns the government’s various efforts toward the same goal of reducing GHG emissions through advancing the RD&D agenda, transportation policy, energy policy, environmental policy, and other areas. In addition, the UK government’s willingness to revise policies after input from businesses (specifically establishing an interim target for the year 2015 as part of its “renewables obligation”) can be key to establishing legitimacy and to further strengthening market confidence.⁵¹

Additional policies that send clear economy-wide signals of a shift towards a low-carbon future include mandatory reporting of GHG emissions, and imposing a price on GHG emissions such as would be established through enacting an emission cap-and-trade system. However, such “signal” policies should be supplemented where appropriate with technology-specific policies as well as policies that broadly promote the significant development and deployment of low-carbon energy technologies. The UK plan includes such necessary supportive policies. It is particularly important to implement climate policies now, because the current policy uncertainty is costly for firms that must make investment decisions without a clear idea of what future climate policies will govern them. For example, the long lifetime of capital stock that firms invest in today may slow the rate at which the United States can obtain significant GHG emission reductions in the future.⁵²

Mandatory Reporting of GHG Emissions. Past experience shows that emission tracking and reporting by companies can be extremely effective at motivating GHG reductions and innovation—companies find that “what gets measured gets managed.” One important first step in any domestic program could be developing a reliable and credible system for tracking and reporting GHG emissions. Similar to the federal Toxics Release Inventory (TRI) program, a mandatory GHG reporting program would apply to all major sources of GHG emissions and would require disclosure of the reports in a publicly accessible Internet-based database. Between 1989 and 1999, manufacturers’ release of 340 chemicals covered under the TRI program dropped by 45.5 percent.⁵³

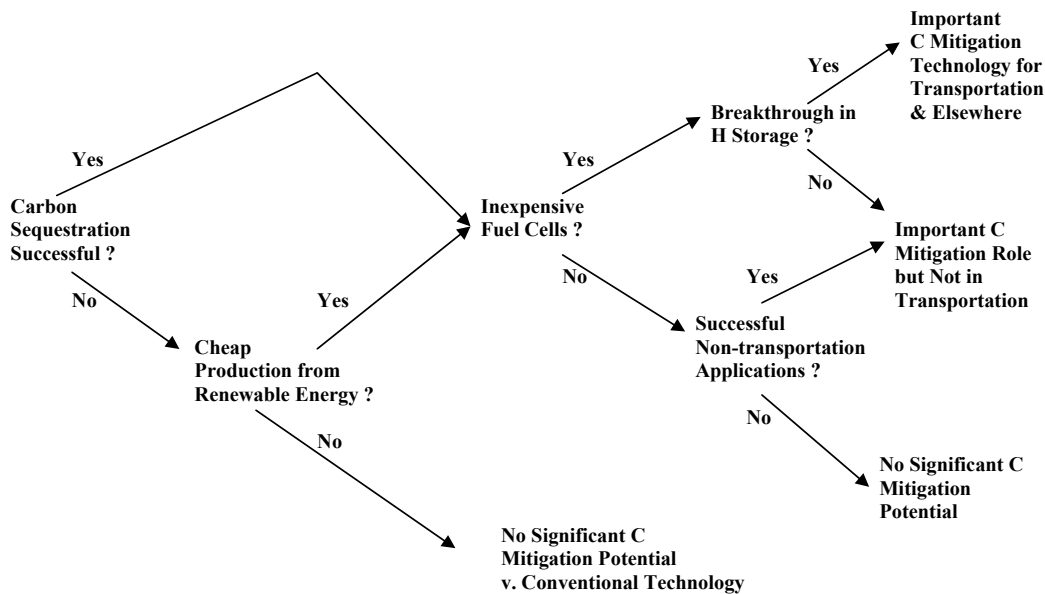
GHG cap-and-trade. Emission trading has emerged as a popular and cost-effective policy tool for controlling air pollution, perhaps most notably in the reduction of sulfur dioxide (SO₂) emissions under the U.S. Acid Rain program. A properly designed program provides a framework to meet emission reduction goals at the lowest possible cost. It does so by giving emission sources the flexibility to find and apply the lowest-cost methods for reducing pollution. Emission trading is especially well suited for controlling GHG emissions because the effects of GHGs are the same regardless of where the source is located and when the emissions occur.⁵⁴ A conventional cap-and-trade program establishes an economy-wide or sectoral cap on emissions (in terms of tons per year or other compliance period) and allocates or auctions tradable allowances (the right to emit a ton of GHGs) to GHG emission sources or fuel distributors. The total number of allowances is equal to the cap.⁵⁵

Policy Flexibility Should be Balanced With Reasonable Policy Certainty

Early policies should not be too prescriptive in picking one technology while significant technological and market uncertainty remains. On the other hand, uncertainty regarding future technology options cannot be used as an excuse for near-term inaction. Developing

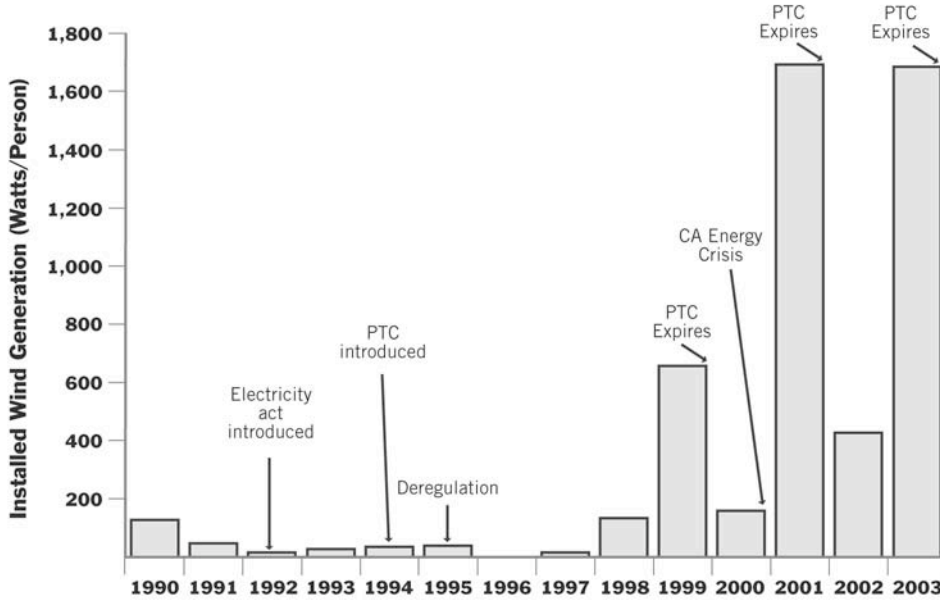
an effective strategy for addressing the low-carbon energy challenge will require ongoing evaluation and course corrections as technologies evolve. Therefore, policies need to be structured to ensure the flexibility to allow them to take advantage of near-term options, while keeping the door open to other long-term options. Mistakes will be made, and precautions must be taken to reduce their frequency and magnitude, but the likelihood of mistakes happening should not stop aggressive experimentation with new technologies and policies. The challenge of designing policies under technological uncertainty and the possible need for societal choices at some point in the future are highlighted in Figure 3.⁵⁶ This chart shows many of the potential technology breakthroughs involved in a transition to hydrogen over the next few decades, and it highlights the need for policy flexibility.

Figure 3: “Decision Analysis” of Hydrogen Energy as a Carbon Dioxide Mitigation Strategy for Transportation



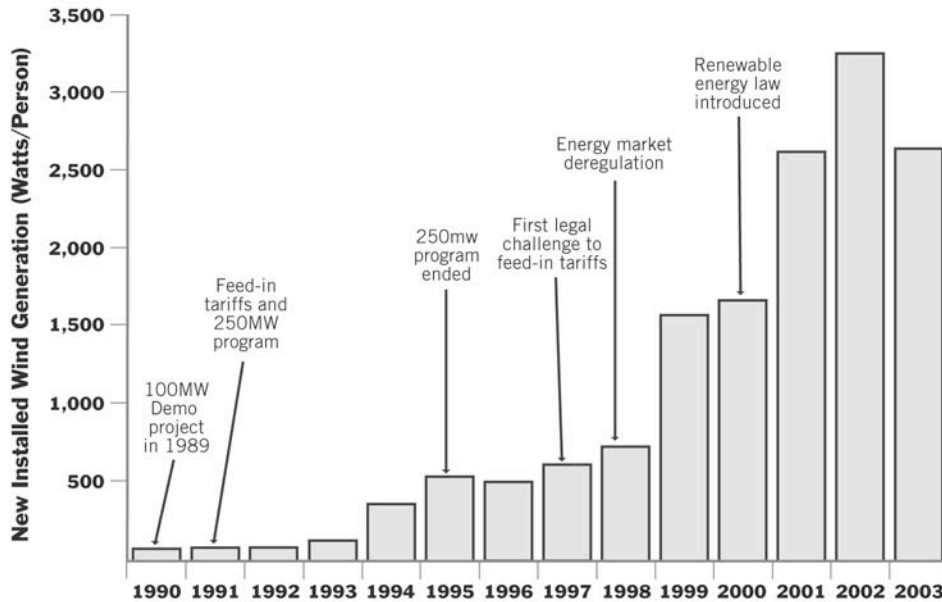
At the same time, any suite of policies must balance the need to allow for iterative policy development with the need for policy certainty over a reasonable time period to foster sustained research and market development. The effect of inconsistent policy support for low-carbon energy technologies is graphically demonstrated in Figures 4 and 5. Figure 4 shows the “boom and bust” effect of the existence and expiration of the wind production tax credit (PTC) in the United States, while Figure 5 depicts the steady wind industry growth in Germany given steady regulatory support.

Figure 4: The effect on the U.S. wind industry of the expiration of the PTC⁵⁷



Source: BTM Consult ApS and Vestas Wind Systems

Figure 5: The effect of consistent policy support for wind in Germany⁵⁸



Source: BTM Consult ApS and Vestas Wind Systems

The figures demonstrate that policies to promote low-carbon technologies must be in place long enough to foster market confidence and sustain market growth over a reasonable period of time.

A Portfolio of Technologies and Policies Will Be Needed to Address Climate Change

There was general consensus that no single technology or policy will be sufficient to enable a low-carbon future by 2050. Many low-carbon energy technologies and fuels are currently available or offer great promise for the future (including many not addressed in the workshop), and such a portfolio will be needed to satisfy the world's current and future energy needs in a climate-friendly manner. Similarly, a suite of policy options will likely be needed to push and pull these technologies into the market. Although many past governmental attempts to “pick winners” have been unsuccessful, a comprehensive strategy to enable a low-carbon future will likely require the development and enactment of both general and technology-specific policies, because, over time, investment will likely center on specific viable low-carbon technologies. The government will likely have to engage in some form of technology husbandry with its limited R&D resources. For example, if hydrogen is to become a significant transportation fuel, development of hydrogen infrastructure must begin at some point—a process that is unlikely to occur in the absence of specific policies. The challenge is to design policies that are neutral enough to promote the development and deployment of a suite of low-carbon technologies, yet also tailored enough to push and pull some specific low-carbon technologies that might not enter the market under a broad policy mechanism. Both types of policies are needed.

Efficiency Will be Key in Both the Near and Long Term

Efficiency will be key to achieving a low-carbon future in 2050. For example, the United Kingdom expects efficiency gains to account for nearly half of its targeted 60 percent CO₂ reductions over the next 50 years,⁵⁹ and in 1997, the U.S. President's Council of Advisers on Science and Technology (PCAST) found that cumulative efficiency gains of 2 percent per year (in terms of energy use per GDP) could reduce the need for low-carbon energy sources by two-thirds by 2050.⁶⁰ There are also many opportunities for significant efficiency gains in the near term, especially in the building and transportation sectors, but some degree of regulation and/or standards will probably be necessary to realize these gains in the market.

Buildings are a big variable over the next 50 years. The potential for significant reductions in building energy use over the next 50 years is huge, yet the degree to which this potential will be realized remains uncertain. New and enhanced policies and initiatives will likely be needed to realize the potential for GHG reductions from the building sector, possibly including enhanced use of building codes and standards (e.g., LEED – Leadership in Energy and

Environmental Design standards⁶¹). U.S. DOE-sponsored design competitions might help to inform buildings codes and standards development. Increased product standards (e.g., appliance efficiency standards) also could facilitate emission reductions.

Hybrids are also key to a “10-50” strategy. The increased use of hybrid vehicles may enable significant GHG emission reductions in the near, medium, and possibly long term. Encouraging the deployment of hybrids, or other lower-GHG vehicles such as advanced diesels or cars powered by biofuels, is consistent and complementary with policies that may promote a transition to a hydrogen-based transportation system. Increased “hybridization” and/or “electrification” of the drive train is likely to be critical to future hydrogen-based vehicles that may be deployed in significant numbers (most likely after around 2030), and hybridization will likely be key to any future options for light duty vehicles.⁶²

Natural Gas Could Play a Key Role in the Transition

Natural gas will play an important role in any transition to a low-carbon future, but the extent of this role will be determined by the degree of success of efforts to address supply and price concerns in the United States and the global market. During the 1990s, natural gas emerged as the fuel of choice for new electricity-generating capacity in the United States because prices were low, new gas plants are relatively quicker and cheaper to build, and natural gas is cleaner than other fossil fuels. For example, until cost-effective CCS technologies are developed and employed, combustion of one Btu of natural gas will produce 40 percent less CO₂ than combustion of one Btu of coal.⁶³

Recently, however, U.S. natural gas prices have increased dramatically, depletion rates of domestic conventional natural gas resources have risen rapidly, and many known reserves are in areas that are restricted or that tend to be difficult and expensive to produce.⁶⁴ As a result, several energy companies have announced plans to build new coal-fired units, and the United States has seen significant natural gas demand destruction,⁶⁵ particularly in natural-gas intensive industries such as fertilizer manufacturing. Nonetheless, aggregate demand for natural gas in the United States is expected to increase from 22.8 trillion cubic feet (TCF) in 2002 to 31.4 TCF by 2025.⁶⁶ A combination of efficiency improvements to reduce demand and measures to increase supply will be necessary for natural gas to facilitate the transition to a low-carbon future. A suite of technologies and investments will be needed to address the following key natural gas challenges:

- More efficient use of natural gas resources (this is particularly critical for taking pressure off supply in the near term);
- Support for research and development of conventional and unconventional gas resources;
- Addressing of domestic supply constraints (e.g., development of new reserves, siting of liquefied natural gas (LNG) terminals);
- Access to stranded gas resources; and
- Extension of the resource base through alternative fuels.⁶⁷

Increased and Revamped RD&D is Necessary

Effective research, innovation, development, and deployment strategies will be critical to enabling a low-carbon energy future. Current levels of federal RD&D need to be significantly increased to reflect parity with other sectors in the U.S. economy (on an RD&D dollars spent per GDP-generated basis) and with the magnitude of the challenge of enabling a low-carbon energy future. Equally as important, strategies for managing these funds need to be revamped. Current RD&D efforts on low-carbon technologies suffer from a cultural focus on niche markets, inter- and intra-agency “stove-piping,” uncertainty caused by the annual appropriations process and cycle, and detrimental Congressional earmarks on scarce funds. The federal government needs a more integrated approach to RD&D—to focus the appropriate agencies and resources on critical RD&D needs at appropriate times within a long-term R&D framework. “DARPA-like”⁶⁸ management is needed to instill a culture focused on development and commercialization of these technologies, and forward funding would help reduce the level of uncertainty and detrimental earmarks. Public/private partnerships and government procurement have a key role to play as developers and incubators of technology and to foster “learning by doing”—a critical step in bringing down the cost of low-carbon technologies and increasing deployment. While support for breakthrough technologies is often appealing, experts point out that what often appears to be a breakthrough is indeed the result of years of incremental investment and work. Public/private partnerships are an effective vehicle for enabling sustained incremental improvements in the performance and cost of low-carbon technologies.

International Efforts are Needed

Domestic RD&D and policy efforts need to be conducted in concert with international efforts, while considering the energy needs of the international community. Some RD&D efforts (e.g., those focused on coal gasification/carbon sequestration) would benefit greatly from collaboration and/or coordination with those in other countries. International efforts are needed to harmonize codes and standards for lower-emission vehicles, especially those relating to hydrogen vehicles and infrastructure.⁶⁹ Basic energy-service needs and desires will dominate the energy development trajectories of much of the developing world over the next 50 years. RD&D efforts between developed and developing countries, although sometimes politically unpopular, can be mutually beneficial, and they will be necessary to enable a worldwide low-carbon energy future in 2050.

A Low-Carbon Technology Revolution Will Require Both Leadership and Broad Engagement Throughout Society

The Need for Leadership

Enabling a low-carbon future will require strong leadership from public- and private-sector decision-makers including federal and state lawmakers, business executives, and other public leaders. Like sending a “signal” to a market through a cap-and-trade program, high-profile leaders’ acknowledgement of the collective need to address climate change can profoundly affect the behavior of consumers, investors, employees, and citizens. Such impacts have been demonstrated when CEOs of large corporations have made reducing GHG emissions within company operations a high priority. Experience has shown that when employees are told to look for opportunities to reduce GHG emissions they have done so very effectively. Such leadership is also being demonstrated by many state governors who have recognized the need to address the significant risks that climate change poses to their states, and who have decided to fill the leadership void left by the federal government.

The Need for “Bundling,” Non-traditional Alliances, and Public/Private Partnerships

Many workshop participants stressed that effective use of “bundling,” alliances, and public/private partnerships will be necessary to enable a low-carbon future. Policy initiatives that promote low-carbon energy technologies will be most effective if they are bundled with efforts that address multiple societal concerns such as increasing energy and national security, reducing conventional air pollution, and promoting local economic development. Enactment of such bundled policies may benefit from alliances of stakeholder groups that have not traditionally worked together, including national security experts and environmentalists, and proponents of nuclear power and proponents of renewables. Similarly, bundling of individual GHG reduction measures will also be important to increasing the deployment of low-carbon technologies. For example, maximizing the deployment of multiple small building efficiency measures may be best achieved through building codes or similar policy tools, and the deployment of renewables could be significantly increased through cost reductions enabled by bundling renewables projects with efficiency measures. Finally, public/private partnerships will be important in accelerating the development and deployment of low-carbon technologies. Such collaborations draw on the specific expertise of government, business, and academia, combining scarce resources and sharing insights for effective research, development, and deployment outcomes.

The Role of Consumers and Citizens

The need to involve consumers and citizens in the development of markets for low-carbon energy technologies and fuels is obvious to many, but strategies for doing so are not as readily apparent. Public education is needed to explain the benefits of addressing climate change, the risks of inaction, and the options for reducing GHG emissions. Better

labeling of fuels (e.g., at the pump) and energy-consuming products (e.g., appliance energy-use labels), and increased availability of relevant information on energy generation and use could be effective in raising consumer awareness. Product standards and increased availability of “green” power also would affect the markets for low-carbon technologies. In addition, increased consumer information in the building and electricity sectors might play an important role (e.g., required disclosure of building energy use during sales transactions of the existing residential capital stock, and disclosure of sources and emissions to electricity consumers). Furthermore, policies that address mixed incentives (e.g., between landlords and tenants) may help to increase consumer interest in reducing energy use.

The Need for Greater Engagement from the Research Community

The financial resources and creative ingenuity of universities and private-sector research institutions need to be more focused on the critical challenge of providing for a future low-carbon energy system. Such increased engagement would likely include better funding for relevant graduate-level research, more attention to these issues in undergraduate and graduate education, and an institutional and collective focus on addressing the critical research issues related to low-carbon energy sources and technologies throughout the public and private research communities.

It Is Essential to Start Now

Finally, a recurring theme of the workshop was the need to immediately start developing technologies and policies to address climate change. Already some governments and businesses have begun taking steps to reduce emissions, but as the workshop papers make clear, more can and should be done in the near term. While climate change is a long-term problem and some solutions might take years to play out, many actions can be taken now to reduce emissions and to lay the groundwork for future technological development and associated GHG reductions.

Conclusions

Using a portfolio of energy technologies and policies, the United States can be well into a transition to a low-carbon future by 2050. However, achieving such a future necessitates a significant, explicit, and comprehensive effort, including policy signals to markets that indicate a long-term policy commitment to such a future. Clear GHG reduction targets for both the near and long term are needed to encourage consumers, citizens, and companies to look for ways to reduce GHG gas emissions; to spur private investment in low-carbon technologies; and to set the broader framework for policies that will enable a long-term GHG reduction target to be realized.

However, such economy-wide signals, although necessary, will not be sufficient to enable a low-carbon energy future. Significantly reducing energy-related GHG emissions

by 2050 will require continued improvements in energy-related technologies, and it will require policies that push and pull a wide variety of low-carbon energy technologies into the market. To that end, increased and refocused RD&D covering a broad suite of critical low-carbon energy technologies is needed, including a restructuring of RD&D portfolios to reflect the need for massive deployment of low-carbon energy technologies. Meaningful technology deployment will also require investments in critical energy-related infrastructure and robust market development policies. Dissemination of such technologies will also benefit from policies such as new efficiency standards and consumer labeling. In addition, public and private leadership, consumer and citizen involvement, engagement of the research community, and international cooperation will be key to developing and significantly deploying a suite of low-carbon technologies.

Analogous to an energy RD&D portfolio, the United States needs a flexible and evolutionary policy portfolio that consists of sound climate policies to promote GHG reductions, creates and promotes the use of new low-carbon technologies and fuels, and ultimately provides for the decoupling of economic growth and CO₂ emissions. Most importantly, it is critical to start now to spur the critical investments necessary to provide for a low-carbon future by 2050.

¹ 550 parts per million (ppm) or less.

² Global primary energy consumption is currently approximately 12 terawatts (TW). See Hoffert, Martin I. 2004. Renewable Energy Options—An Overview. Paper prepared for the Pew/NCEP “10-50 Solution” Workshop. Washington, D.C., March 25–26, 2004; and Hoffert, M.I., K. Caldeira, G. Benford, et al. 2002. Advanced Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet. *Science* 298: 981–987.

³ Although the largest potential for reducing GHG emissions lies in the reduction of CO₂ associated with fossil-fuel energy production and consumption, carbon sequestration and the reduction of non-CO₂ GHGs also offer opportunities for reducing GHG concentrations in the atmosphere. See Reilly, J.M., H.D. Jacoby, and R.G. Prinn. 2003. *Multi-gas Contributors to Global Climate Change: Climate Impacts and Mitigation Costs of Non-CO₂ Gases*. Pew Center on Global Climate Change, Arlington, VA.

⁴ See Lempert, Robert J., Steven W. Popper, Susan A. Resetar, and Stuart L. Hart. 2002. *Capital Cycles and the Timing of Climate Change Policy*, Pew Center on Global Climate Change, Arlington, VA. See also Mintzer, Irving M., J. Amber Leonard, and Peter Schwarz. 2003. *U.S. Energy Scenarios for the 21st Century*. Pew Center on Global Climate Change, Arlington, VA.

⁵ Path dependency refers to the concept that technological change and development are strongly influenced by past changes and choices.

⁶ The 10-50 Solution: Technologies and Policies for a Low-Carbon Future, a workshop co-sponsored by the Pew Center on Global Climate Change and National Commission on Energy Policy (NCEP), Washington, D.C., March 25–26, 2004.

⁷ Other important components of a GHG-friendly energy future that were not explicitly examined during the workshop may include coalbed methane, geothermal energy, nanotechnology, ocean wave energy, information technologies, sensors, materials, and biotechnology.

⁸ See Department of Trade and Industry. 2003. *Energy White Paper: Our energy future—creating a low carbon economy*. The Stationary Office, London, UK (February). See <http://www.dti.gov.uk/energy/whitepaper/index.shtml>.

⁹ A complete list of workshop attendees is available at the front of this proceedings.

¹⁰ This overview by the staffs of the Pew Center and NCEP aims to summarize the main points and common themes from the workshop papers and the discussions at the workshop. It may not represent the

views of all the authors of 10-50 Workshop background papers or of all of the 10-50 Workshop participants.

¹¹ That is, the boxes indicating significant GHG emissions reduction potential are more spread out along the timeline and are not as concentrated in the 2005–2015 time frame or the 2045–2055 time frame.

¹² Metcalf, Gilbert E. 2004. Energy Efficiency Overview Paper. Paper prepared for the Pew/NCEP “10-50 Solution” Workshop. Washington, D.C., March 25–26, 2004.

¹³ CAFE standards were established in 1975 by Congress. They required new passenger car fuel economy to increase from 18.0 mpg in 1978 to 27.5 mpg in 1985, where the standard remains to this day. Congress also required NHTSA to set standards for light trucks, and the standards were recently raised to 22.2 mpg by 2008. See Greene, David L., and Andreas Schafer. 2003. *Reducing Greenhouse Gas Emissions from U.S. Transportation*. Pew Center on Global Climate Change, Arlington, VA.

¹⁴ Loftness, Vivian. 2004. Improving Building Energy Efficiency in the U.S.: Technologies and Policies for 2010 to 2050. Paper prepared for the Pew/NCEP “10-50 Solution” workshop. Washington, D.C., March 25–26, 2004, p. 2.

¹⁵ Ibid.

¹⁶ 6 percent of all U.S. energy is used in cooling residential and commercial buildings. Loftness, 2004, p. 2.

¹⁷ Daylighting is the use of natural light to supplement or replace interior artificial lighting. See http://www.nrel.gov/clean_energy/passivesolar.html.

¹⁸ 10 percent of all U.S. energy is used for lighting buildings. Loftness projects that adoption of daylighting technologies could reduce annual lighting energy consumption 30–60 percent. Loftness, 2004, p. 2.

¹⁹ High-mass cooling utilizes material that absorbs heat or coolness and stores it for a long time (e.g. concrete) to keep a structure cool by extracting heat from indoor air during the day and releasing it at night. See <http://hem.dis.anl.gov/eehem/99/990515.html#99051504>.

²⁰ Loftness, 2004, pp. 2–3, based on the “effective use of natural conditioning with well-designed windows, window controls, and mechanical and lighting system interfaces, promises to yield major energy efficiency gains of up to 5 percent of all U.S. energy use.”

²¹ Loftness, 2004, p. 3.

²² Price, Lynn, and Ernst Worrell. 2004. Improving Industrial Energy Efficiency in the U.S.: Technologies and Policies for 2010 to 2050. Paper prepared for the Pew/NCEP “10-50 Solution” Workshop. Washington, D.C., March 25–26, 2004, p. 2.

²³ Greene and Schafer, 2003.

²⁴ See *Greenhouse Gas Reporting and Disclosure: Key Elements of a Prospective Program*. In Brief, Number 3. Pew Center on Global Climate Change, Arlington, VA.

²⁵ Workshop participants asserted that companies can only “manage what they measure.” In addition, programs such as state-level mandatory waste audits have been linked to reductions in waste generation at the company level through improved information.

²⁶ Well to wheels or “full fuel cycle” emissions refer to all the emissions involved in producing and using a fuel including: primary feedstock extraction, transport of the feedstock to a fuel production plant, fuel production, storage and distribution of fuel, and use of the fuel (for example, in a vehicle). See Ogden, Joan M. 2004. Hydrogen as an Energy Carrier: Outlook for 2010, 2030, and 2050. Paper prepared for the Pew/NCEP “10-50 Solution” workshop. Washington, D.C., March 25–26, 2004, p. 3.

²⁷ Although hydrogen can be used in stationary applications, the focus of the hydrogen-related analysis commissioned for the 10-50 Workshop was hydrogen in transportation applications.

²⁸ Raman, Venki. 2004. “Today there are many tens of hydrogen fuel stations in the U.S., Europe, and Japan serving very small numbers of hydrogen demonstration vehicles,” quoted in Hydrogen Production and Supply Infrastructure for Transportation. Paper prepared for the Pew/NCEP “10-50 Solution” Workshop. Washington, D.C., March 25–26, 2004.

²⁹ See Ogden, 2004.

³⁰ Hydrogen can be made from a number of widely available primary energy sources, including natural gas, renewables, coal, and nuclear power. It also can be used in fuel cells and internal combustion engines with high conversion efficiency and essentially zero emissions of GHGs and conventional air pollutants. Therefore, if hydrogen is made from a zero-emission sources like renewables or fossil fuels with carbon capture and sequestration, it would be possible to produce and use fuels on a global scale with almost zero full fuel cycle emissions of GHGs and greatly reduced emissions of air pollutants. See Ogden, 2004, p. 1.

³¹ Ogden, 2004, p. 11.

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- ³² It is important to note that the EOR process does not necessarily involve long-term storage of CO₂. Studies are under way to determine what happens to the CO₂ after it is injected into geological formations in the EOR process.
- ³³ Each 1,000 MW plant emits and would need to sequester approximately 7–8 million tons of CO₂ per year (mtons/yr). Currently, the largest CCS project in the world (in Weyburn, Canada) sequesters 1.7 mtons/yr, and the largest planned project (in Gorgon, Australia) plans to sequester 4 mtons/yr starting in 2006.
- ³⁴ Burruss, Robert C. 2004. *Geologic Sequestration of Carbon Dioxide in the Next 10 to 50 Years: An Energy Resource Perspective*. Paper prepared for the Pew/NCEP “10-50 Solution” Workshop. Washington, D.C., March 25–26, 2004, p. 4.
- ³⁵ Deutch, John, Ernest J. Moniz, et al. 2003. *The Future of Nuclear Power—An Interdisciplinary MIT Report*. Massachusetts Institute of Technology. See <http://web.mit.edu/nuclearpower/>, p. 21.
- ³⁶ Three power companies are currently pursuing Early Site Permits for existing nuclear sites, with the intent to “bank” these sites for possible use in the future. The U.S. DOE is funding the three site banking projects on a 50/50 cost share basis. See Kray, Marilyn C. 2004. *Long-Term Strategy for Nuclear Power*. Paper prepared for the Pew/NCEP “10-50 Solution” Workshop. Washington, D.C., March 25–26, 2004, p. 5.
- ³⁷ Kray, 2004, p. 3.
- ³⁸ Moniz, Ernest J. 2004. *Nuclear Power and Climate Change*. Paper prepared for the Pew/NCEP “10-50 Solution” Workshop. Washington, D.C., March 25–26, 2004, p. 1.
- ³⁹ The once-through mode means removing the spent nuclear fuel for geological disposal. Closed fuel cycles are those in which the irradiated fuel is chemically processed to separate and recycle in the reactor components that have energy value, principally plutonium. See Moniz, 2004, p. 1.
- ⁴⁰ Hoffert, 2004, p. 16. See also Kammen, Daniel M. 2004. *Renewable Energy Options for the Emerging Economy: Advances, Opportunities and Obstacles*. Paper prepared for the Pew/NCEP “10-50 Solution” workshop. Washington, D.C., March 25–26, 2004, p. 1.
- ⁴¹ Hoffert, 2004, p. 2.
- ⁴² U.S. DOE, EIA. 2004. *Annual Energy Outlook 2004*. See <http://www.eia.doe.gov/oiaf/aeo/electricity.html#elerene>.
- ⁴³ Kammen, 2004, pp. 1-2.
- ⁴⁴ Hoffert, 2004, p.2; Kammen, 2004, p. 1.
- ⁴⁵ Most renewable resources are intermittent generation sources, i.e. their generation capacity is not constant and is subject to natural variability of such factors as wind speed and solar insolation.
- ⁴⁶ i.e., distance from areas of major electrical demand and lack of adequate transmission infrastructure.
- ⁴⁷ Hoffert, 2004, p. 3.
- ⁴⁸ Of the total percentage of electricity that would have to come from renewables under an RPS, a certain amount, or “set-aside,” could be required from one source or technology (e.g., solar). Kammen, 2004, p. 4: “At present, wind is the cheapest form of renewable energy in many locations, and care needs to be exercised to open markets to a range of renewables such as in the Nevada RPS, where a specific set-aside exists for solar energy. Allowing regional differentiation could also be a significant benefit, so that biomass-rich regions such as the Southeast and Midwest, could adopt initial set-asides for biomass-based renewable fuels.” Such a standard could be phased in over a period of years to take advantage of cost reductions as technologies develop. For example, an RPS could start at 3 percent initially, ramping to 5 percent a set number of years later, and so on with a relatively high number (e.g., 20 percent) established as the standard 20 years out. This could help minimize the costs of such a standard by avoiding significant investments in certain technologies before they are more cost competitive.
- ⁴⁹ Currently, the U.S. DOE’s two primary areas of focus are (1) centralized coal electricity and hydrogen production with carbon sequestration, and (2) next generation nuclear reactors (Hoffert, 2004, p. 2).
- ⁵⁰ Forward funding is “a type of multiyear appropriation that is made available in the middle or toward the end of a fiscal year and remains available through the next fiscal year: for example, from July 1 of one year through September 30 of the next” (see http://www.house.gov/rules/glossary_fbp.htm). Forward funding removes some of the uncertainty, delay, and earmarking associated with the standard congressional appropriations process.
- ⁵¹ MacNaughton, Joan. 2004. *UK’s 50 year energy strategy*. Presentation to the Pew/NCEP 10-50 Workshop. See also Performance and Innovation Unit. 2002. *The Energy Review: A Performance and*

Innovation Unit Report—February 2002. Cabinet Office, London, UK. See <http://www.number-10.gov.uk/su/energy/1.html>.

⁵² See Lempert, Robert J., Steven W. Popper, Susan A. Resetar, and Stuart L. Hart. 2002. *Capital Cycles and the Timing of Climate Change Policy*. Pew Center on Global Climate Change, Arlington, VA.

⁵³ See *Greenhouse Gas Reporting and Disclosure: Key Elements of a Prospective Program*. In Brief, Number 3. Pew Center on Global Climate Change, Arlington, VA.

⁵⁴ For more information about emissions trading, see Ellerman, A. Denny, Paul L. Joskow, and David Harrison Jr. 2003. *Emissions Trading in the U.S.: Experience, Lessons, and Considerations for Greenhouse Gases*. Pew Center on Global Climate Change, Arlington, VA.

⁵⁵ See Nordhaus, Robert R., and Kyle W. Danish. 2003. *Designing a Mandatory Greenhouse Gas Reduction Program for the U.S.* Pew Center on Global Climate Change, Arlington, VA.

⁵⁶ The figure is drawn from Greene, David L. 2004. *Climate Change Policy for Transportation While Waiting for Hydrogen*. Paper prepared for the Pew/NCEP “10-50 Solution” workshop. Washington, D.C., March 25–26, 2004.

⁵⁷ The explanatory arrows on this graph refer to policy actions that occurred during one year (bar) on the graph, but which had an effect on the next year (bar). For example, the PTC expired in 1999 during a capacity “boom” in the industry, which was subsequently followed by a “bust” in 2000. The California energy crises (and renewal of the PTC in 2000) was followed by another “boom” in 2001. Source: BTM Consult ApS (2004) International Wind Power Development World Market Update 2003: Forecast 2004–2008. BTM Consult ApS, Ringkøbing, Denmark, and Vestas Wind Systems. “International Context.” Presentation at the Ontario Wind Policy Summit. Canadian Wind Energy Association. February 24, 2004. See http://www.canwea.ca/downloads/en/PDFS/Context_-_Session_1.pdf.

⁵⁸ Feed-in laws guarantee independent power producers (e.g., wind generators) a certain price for the electricity they provide to the grid. These prices are set by statute, and rate-payers pay the difference between the “feed-in” price and the average cost of electricity. See http://www.windworks.org/articles/fl_ElectricityFeedLaws.html. Source BTM Consult ApS (2004) and Vestas Wind Systems.

⁵⁹ MacNaughton, Joan. 2004. “UK’s 50 year energy strategy.” Presentation to the Pew/NCEP 10-50 Workshop. See also Performance and Innovation Unit. 2002.

⁶⁰ Holdren, John P. 2004. “Integrating Common Themes: Some Observations for the Workshop on Technologies and Policies for a Low-Carbon Future.” 2004. Presentation to the Pew/NCEP 10-50 Workshop.

⁶¹ See U.S. Green Building Council, http://www.usgbc.org/leed/leed_main.asp.

⁶² Wimmer, Robert (Toyota Motor North America). 2004. “De-Coupling Business Growth Coupling Business Growth from Carbon Emissions from Carbon Emissions.” Presentation to the Pew/NCEP 10-50 Workshop.

⁶³ See Smith, Douglas W., Robert R. Nordhaus, Thomas C. Roberts, et al. 2002. *Designing a Climate-friendly Energy Policy: Options for the Near Term*. Pew Center on Global Climate Change, Arlington, VA.

⁶⁴ Kenderdine, Melanie. 2004. “High Natural Gas Prices Could Impact Environmental Imperatives.” Presentation to the Pew/NCEP 10-50 Workshop.

⁶⁵ Demand destruction refers to the temporary or permanent reduction in demand for natural gas usually caused by rising natural gas prices and usually referring to industrial sector demand for natural gas.

⁶⁶ U.S. DOE, EIA. 2004. *Annual Energy Outlook 2004*. See <http://www.eia.doe.gov/oiaf/aeo/>.

⁶⁷ Kenderdine, Melanie. 2002. Prepared Remarks of Melanie Kenderdine—6th Annual World Energy Experts Conference, Abu Dhabi, UAE, January 28–29, 2002.

⁶⁸ DARPA (the Defense Advanced Research Projects Agency) was established by the U.S. Department of Defense in 1958. Its initial mission was to coordinate the military’s competing missile, space, and missile-defense programs. Its role has evolved to focus on three main areas: computers and information technologies, sensors and surveillance, and directed energy weapons. “Cloning” DARPA would require the replication of its clearly defined, well-accepted mission, autonomy, flexibility, and links with the best non-government research groups. See Alic, John A., David C. Mowery, and Edward S. Rubin. 2003. *U.S. Technology and Innovation Policies: Lessons for Climate Change*. Pew Center on Global Climate Change, Arlington, VA.

⁶⁹ Wimmer, 2004, slide 7, and Ogden, 2004, p. 13.