The Balancing Act:
Climate Change, Energy Security and the U.S. Economy

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DEAR BUSINESS LEADERS AND STAKEHOLDERS:

On behalf of Business Roundtable's Sustainable Growth Initiative, I am pleased to present *The Balancing Act* — a thoughtful, forward-looking study designed to inform policymakers about the choices and consequences associated with addressing the risks of global climate change.

Business Roundtable believes that leadership on global climate change is not just a job for government. We believe the business community has a special obligation to step forward as well because of our central role in producing, distributing and consuming energy, and because of our role in building an environmentally and economically sustainable future through our contributions to the development and deployment of new, efficient, low-carbon technologies.

Consistent with this role, *The Balancing Act* represents a vision for advancing America's long-term economic, environmental and energy security interests through the development and deployment of advanced technologies. Leveraging the extensive technological, economic and policy expertise of Business Roundtable member companies, the study identifies key barriers to technology development and deployment, presents sensible policy recommendations for removing these barriers, and quantifies the potential economic and environmental impact of adopting those recommendations.

The study is the culmination of a year-long effort, and the economic and political environment has evolved rapidly since we began. The global community is now engulfed in a serious recession, investment has retrenched worldwide and a number of key industries are in a fragile state. Meanwhile, America has elected a new president, Congress has passed the largest stimulus package in the nation's history, and energy and environmental legislation has moved to the top of the agenda. Although not all of these developments are fully reflected in the study, we believe that the central messages remain true. America's long-term economic, environmental and energy security challenges remain unchanged. Forging solutions that simultaneously address all of these long-term challenges will be essential to placing the nation on a pathway toward truly sustainable growth. We believe that the development and deployment of advanced technologies holds the key.

Global climate change is an exceedingly complex issue, and there is a wide range of views about the balance of risks to society and the appropriate response by government. Business Roundtable membership reflects this diversity of opinion, and the Sustainable Growth Initiative has focused on finding points of consensus within the business community. *The Balancing Act* represents an ambitious effort to forge such a consensus. Although not all Roundtable members agree with every statement or each policy recommendation, we all agree with the central conclusion: that a balanced portfolio of advanced technologies will be critical to forging a climate change policy that is sustainable from an environmental, economic and energy security perspective.

America cannot afford narrow approaches to climate change that threaten to simply exchange one unsustainable pathway for another. The challenge is too great, the future too uncertain, the stakes too high. America needs a sustainable climate change policy that unleashes technological innovation; encourages new investment; and leverages domestic resources to bring our environmental, economic and energy security interests into balance.

Michael G. Morris

Michael G. Morris
Chairman, President and CEO
American Electric Power Company, Inc.
Chairman, Sustainable Growth Initiative
Business Roundtable

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Executive Summary

According to leading scientists, there is increasing evidence that the Earth's climate has been warming over the last century and that increases in temperature are affecting many global ecosystems. At the same time that warming has been occurring, greenhouse gas (GHG) concentrations in the atmosphere have increased due to rising worldwide GHG emissions. Major sources of these emissions include the combustion of fossil fuels, tropical deforestation and other land-use changes. Because the consequences of climate change for society and ecosystems are potentially serious and far-reaching, steps to address the risks of such climate change are prudent now, even while the science continues to evolve.[1]

Business Roundtable supports collective actions that will lead to the reduction of GHG emissions on a global basis with the goal of slowing increases in atmospheric concentrations and eventually stabilizing them at levels that will reduce the risks of climate change. While the Roundtable supports actions to address climate change, its members have a range of views and preferences about the policy tools that will best achieve this objective. Recognizing that legislation and regulation are currently under consideration, the Roundtable supports an open and constructive dialogue about the principles that should shape climate policy and the pros and cons of various strategies.[2]

Leadership in addressing climate change is not just a job for government. The business community has a special obligation to step forward because of its central role as a major producer, distributor and consumer of energy. The business community's importance to forging an environmentally and economically sustainable future is heightened by its critical contributions to the development and deployment of new, efficient, low-carbon technologies.

Consistent with this role and the desire to contribute to an open and constructive dialogue, Business Roundtable undertook a collaborative effort among member companies to develop, evaluate and recommend technology-based solutions to meet the "sustainable growth challenge" — that is, the challenge of achieving large-scale reductions in GHG emissions while also maintaining robust economic growth and enhancing energy security. During a six-month process, experts from more than 30 Roundtable member companies regularly convened to evaluate the potential of various technologies; identify key barriers to realizing each technology's full potential; develop recommendations for removing those barriers; and quantify the economic, environmental and energy impacts of implementing those recommendations.

The point of departure for this effort was an assessment of the nation's key economic, environmental and security challenges. Based on this evaluation, Business Roundtable identified three strategies that are likely to form the foundation of a successful sustainable growth agenda:

(1) More efficiently consume electricity and heating fuels in homes and businesses;
(2) Leverage domestic resources to produce cost-effective, low-carbon electricity; and
(3) Modernize the transportation fleet and diversify the transportation fuel mix.

Business Roundtable then identified a portfolio of six "technology pathways" that are critical to implementing these strategies, as well as two "enabling pathways" that are essential to realizing the full potential of the entire portfolio. The six technology pathways include building efficiency improvements, renewable power generation, advanced nuclear power generation, carbon capture and storage, advanced vehicle technologies, and advanced biofuels — all of which demonstrate great promise as contributors to a more sustainable future. The two enabling pathways include grid modernization and enhanced domestic supply of oil and natural gas — the former being a technical prerequisite for implementing many efficiency and low-carbon electric power technologies, and the latter being vital to creating the stable economic conditions necessary to support large-scale investments in the nation's energy system.

To determine the potential economic, environmental and energy impacts associated with Business Roundtable's policy package, each pathway was rigorously evaluated by a team of Roundtable member company engineers, economists and public policy experts. Each team's inputs were then modeled by the University of Maryland's Inforum Modeling Project and Keybridge Research LLC. Modeling simulations were conducted with Inforum's highly respected Long-term Interindustry Forecasting Tool (LIFT), a dynamic general equilibrium model of the U.S. economy that uses a unique "bottom-up" technique to simulate economic, environmental and energy impacts.

The modeling framework assumes that a carbon price is established in 2012 and compares simulations in which Business Roundtable's recommendations for removing barriers to technology development and deployment are adopted to simulations in which they are not. In addition, each scenario is conducted under both "low" and "high" carbon price trajectory assumptions, which helps to bound the analysis and explore key sensitivities. Importantly, the study remains agnostic as to the type of instrument that is used to establish the carbon price (e.g., a cap-and-trade system or a carbon tax) and instead focuses on the larger policy, market and technological context into which the carbon pricing instrument might be inserted.

The purpose of the modeling exercise is to compare and evaluate policy recommendations that have the potential to reduce barriers to technology development and deployment and thereby improve outcomes for American households and businesses. The simulations are not forecasts of what Business Roundtable or its member companies believe will happen. Rather, they are illustrative scenarios of how carbon prices, technologies and policies may interact in the coming decades to influence key economic, environmental and energy variables.

The modeling results demonstrate that an approach that leverages a balanced portfolio of technologies, including all pathways identified above, combined with strong policy leadership that eliminates critical barriers to technology development and deployment, will dramatically increase the nation's prospects for meeting the sustainable growth challenge.[3] Furthermore, given the uncertainties associated with long-term technological progress and energy price trends, other pathways will likely be necessary to reach ambitious GHG reduction targets in an economically sustainable manner. These other pathways may include some that are readily available today (e.g., enhanced domestic production of natural gas coupled with increased natural gas use in the electric power industry), some that are currently under development (e.g., the application of advanced vehicle technologies to the heavy-duty vehicle fleet) and still others yet to be imagined.

In general, the modeling analysis finds that the imposition of a carbon price is likely to have a significant negative impact on the economy. In the short term, the imposition of a carbon price will likely result in significant dislocations throughout the economy that are likely to be borne unequally across regions and industries. Policymakers must endeavor to make this transition as smooth as possible. The modeling results also suggest, however, that a balanced portfolio of technologies coupled with strong policy leadership can mitigate the long-term economic costs associated with a sharp reduction of GHG emissions and help the nation reach a sustainable equilibrium.

Specifically, the study finds that:

- **In the absence of policies that remove barriers to technology development and deployment, imposing a price on carbon is likely to result in significantly lower U.S. economic growth in coming decades.**

In scenarios in which a carbon price is established but Business Roundtable's policy recommendations are not adopted, real gross domestic product (GDP) declines by approximately 2 percent by 2050, while CO_2 emissions are reduced by 19 to 44 percent.[4] Furthermore, under such assumptions, efforts to mandate a higher level of GHG mitigation — either directly by establishing a more ambitious GHG emissions cap or indirectly by imposing a more aggressive carbon tax — are likely to result in significantly lower rates of economic growth than those envisioned in this study.

- **In contrast, a balanced portfolio of technologies coupled with policy leadership can significantly mitigate the negative effects on U.S. economic growth while achieving greater reductions in GHG emissions.**

In scenarios in which a carbon price is established and Business Roundtable's recommendations are adopted, real GDP declines by less than 1 percent by 2050, while CO_2 emissions are reduced 45 to 62 percent. In short, the Roundtable's policy recommendations for removing barriers to technology development and deployment are estimated to deliver almost twice the GHG mitigation at roughly half the economic cost.[5]

- **A balanced portfolio approach is likely to be the only approach that has the potential to achieve the large-scale reductions in GHG emissions advocated by many policymakers.**

In scenarios in which both a carbon price is established and Business Roundtable's policies are adopted, CO_2 emissions decrease by an average of 5.1 gigatons in 2050, an impressive reduction given that additional reductions are likely from activities not explicitly modeled in this analysis. Nevertheless, the fact that many policymakers support even more ambitious emissions targets suggests that a portfolio approach that leverages *all* six technology pathways (and others not examined in this study) is likely to be the only approach that has the potential to meet many policymakers' goals. Ultimately, a strategy that relies on anything less than a balanced portfolio of technologies will likely require significantly higher carbon prices and incur substantially greater economic costs to achieve a given level of mitigation.

- **A balanced portfolio of technologies combined with policy leadership can reduce energy consumption, diversify the transportation fuel mix and enhance energy security.**

In scenarios in which both a carbon price is established and Business Roundtable's recommendations are adopted, the electrification of the transportation sector combined with the deployment of hydrogen fuel cell vehicles, increased penetration of advanced biofuels and continued advancement in internal combustion engine technology reduces energy consumption and greatly diversifies the transportation fuel supply. At the same time, the analysis suggests that the increased deployment of some advanced vehicles is likely to enhance consumers' capacity to alternate among fuels and respond to evolving market conditions. This combination of fuel supply diversity and fuel choice flexibility is likely to reduce the nation's vulnerability to instability in any one energy market and improve the economy's resiliency in the face of fuel price volatility.

- **Policy leadership can provide relief to American households from the costs associated with reducing GHG emissions.**

In scenarios in which a carbon price is established but Business Roundtable's recommendations are not adopted, average annual household consumption — a common measure of household welfare — decreases by $800 to $1,500 (2008$) per year relative to the Business as Usual baseline, or 0.7 to 1.2 percent of average annual household consumption, over the 2010–50 period. This decrease represents the cost to U.S. households of transitioning to a low-carbon economy.

This study finds, however, that this cost can be cut in half through policy leadership that accelerates technology development and deployment. In this case, average annual household consumption is reduced by $400 to $800 (2008$) per year, or 0.3 to 0.7 percent of average annual household consumption over the 2010–50 period. In short, the cumulative benefits associated with Business Roundtable's policy package could substantially reduce the transitional costs to American households.

- **Policy instruments that are transparent, consistent and gradual will be more effective and more likely to minimize the economic impact of climate change policies.**

Model simulations conducted for this study indicate that, especially in the initial years of the policy, the imposition of a carbon price will result in significant dislocations within the economy. This is likely to reduce real GDP growth, household consumption and other indicators associated with economic welfare, particularly if the nation is expected to adapt abruptly to the carbon constraint. On the other hand, transparent and steady policy instruments introduced gradually and incrementally are likely to enable businesses, investors, workers and consumers to better prepare and take appropriate action to minimize costs.

- **The economic and environmental impacts of U.S. climate change policies are highly dependent on the policies adopted by major trading partners.**

This study assumes that America's major trading partners adopt climate change policies that, on average, result in less substantial price increases than those experienced in the United States. Specifically, it is assumed that a policy-induced price increase of $1 for goods and services produced in the United States is matched by a price increase of 80 cents for goods and services produced by U.S. trading partners. This price increase differential reflects a loss in U.S. competitiveness that registers as a small but significant decrease in net exports, which reduces real GDP. If foreign prices were set to reflect even less reciprocal action by trading partners, the additional loss of U.S. competitiveness would likely further reduce GDP.

This underscores the importance of insuring that U.S. actions on climate change are both cost-effective and matched with credible commitments by other countries. Although not explicitly examined in this study, the loss of competitiveness that results from sharply asymmetric climate change policies could potentially shift production and investment to less regulated jurisdictions. In addition to the economic damages such a shift in production and investment would cause the U.S. economy, it also could result in so-called "emissions leakage" — an offsetting increase in emissions in other, less heavily regulated countries. Consequently, policymakers must remain sensitive to the prospect of emissions leakage in energy intensive and globally competitive industries and design policy frameworks that have the potential to level the carbon playing field for these uniquely challenged sectors.

- **The economic costs required to achieve large-scale reductions in GHG emissions will not be shared equally by all industries or all regions.**

It is important to note that the economic costs required to achieve large-scale reductions in GHG emissions will not be shared equally by all industries or all regions of the country. The current study focuses on the macroeconomic impacts of climate change policies, but the reported aggregate impacts mask the significant dislocation and adjustment process that would accompany any climate change policy and do not reveal the hardships and challenges that businesses, investors, workers and consumers in particular sectors of the economy will experience in adapting to a carbon-constrained world. Policymakers must endeavor to make this transition as smooth as possible.

Conclusion

The modeling results suggest that addressing the issue of climate change by either directly or indirectly placing a price on carbon is likely to place a significant strain on the U.S. economy. The results also suggest, however, that strong policy leadership can significantly mitigate these negative economic impacts by accelerating the development and deployment of advanced technologies. These technologies have the potential to cost-effectively reduce GHG emissions in the residential and commercial buildings, electric power, and transportation sectors of the economy, which are responsible for the bulk of GHG emissions. Meeting the sustainable growth challenge will not be easy, however, and policy leadership will require practical solutions, political compromise and bipartisan cooperation.

In addition, the results illustrate that there is no single technological solution to the sustainable growth challenge. Any policy that fails to leverage the full potential of a balanced portfolio of technologies is likely to either fail to achieve a desired level of emissions reductions or achieve a mandated level of emissions reductions by imposing unacceptable costs on the economy — thereby simply exchanging one unsustainable pathway for another.

The key lesson for policymakers is that any sustainable climate change policy must be based on a robust approach to technology development and deployment. Climate change policy must not only reflect current technological expectations but also must acknowledge the likelihood that some promising technologies may underperform expectations while other technologies that are less visible today may emerge as cost-effective solutions. Given the long-term nature of climate change policies and the uncertainties associated with technological progress, a balanced portfolio approach coupled with strong policy leadership is likely to be the only approach that can simultaneously and sustainably advance the nation's economic, environmental and security objectives.

Chapter 1
Introduction and Background

The Sustainable Growth Challenge

According to leading scientists, there is increasing evidence that the Earth's climate has been warming over the last century and that increases in temperature are affecting many global ecosystems. At the same time that warming has been occurring, greenhouse gas (GHG) concentrations in the atmosphere have increased due to rising worldwide GHG emissions. Major sources of these emissions include the combustion of fossil fuels, tropical deforestation and other land-use changes. Because the consequences of climate change for society and ecosystems are potentially serious and far-reaching, steps to address the risks of such climate change are prudent now, even while the science continues to evolve.[6]

Business Roundtable supports collective actions that will lead to the reduction of GHG emissions on a global basis with the goal of slowing increases in atmospheric concentrations and eventually stabilizing them at levels that will reduce the risks of climate change. Given this ambitious but achievable goal, the global community's challenge is to identify and implement strategies that have the potential to generate significant emissions reductions while also maintaining robust economic growth and enhancing security — that is, the sustainable growth challenge.[7]

While Business Roundtable supports actions to address climate change, its members have a range of views and preferences about the policy tools that will best achieve this objective. Recognizing that legislation and regulation are currently under consideration, the Roundtable supports an open and constructive dialogue about the principles that should shape climate policy and the pros and cons of various strategies.[8]

To contribute to that dialogue, Business Roundtable launched a collaborative effort among member companies to develop, evaluate and recommend sensible solutions to the sustainable growth challenge. Drawing on the extensive technical expertise of more than 30 member companies, this effort builds on the Roundtable's comprehensive policy blueprint, *More Diverse, More Domestic, More Efficient*, and extends that framework to more explicitly encompass the economic, environmental and security challenges associated with addressing global climate change.

Unfinished Business

Since Business Roundtable began this study in mid-2008, Congress passed and President Obama signed into law the American Recovery and Reinvestment Act (ARRA) of 2009. ARRA contained funding and tax incentives for a variety of energy initiatives, particularly those related to energy efficiency, renewable power, advanced vehicle technology, worker training and grid modernization. Carbon capture and storage technologies also received funding in ARRA. As a result of Congress' action, some of the Roundtable's policy leadership recommendations contained in this study have been partially addressed. However, our economic modeling has demonstrated that it will take a portfolio of options, involving every sector of our economy, to meaningfully reduce GHG emissions in a cost-effective way. While some of these options, such as greater building efficiency and increased use of renewables, can make important contributions to meeting our energy and environmental goals, they are insufficient alone to sharply reduce GHG emissions or adequately diversify our sources of energy.

Accordingly, Congress and the administration have much more to do to develop a comprehensive energy and environmental policy. In particular, Business Roundtable's recommendations regarding nuclear electricity generation, carbon capture and sequestration, expanded access to domestic fossil fuel resources, and developing policies to allow the construction of a national high-voltage transmission system to provide greater access to renewables must be addressed satisfactorily to materially reduce GHG emissions in an economically sustainable manner. In short, while the policy measures adopted in ARRA represent an important down payment and a step in the right direction, more will be required to facilitate a smooth and efficient transition to a low-carbon economy.

While traditional paradigms frequently place the pursuit of our economic, environmental and security interests in competition, Business Roundtable believes that innovative technologies, efficient markets and strong policy leadership have the capacity to transcend such limitations.[9] Viewed through this lens, the sustainable growth challenge is reframed as the need to identify a portfolio of technologies with the greatest potential to simultaneously advance all three pillars of a sustainable growth agenda and leverage efficient markets and targeted policies to unlock their full potential.

In pursuit of this objective, policymakers have a wide range of instruments at their disposal. Many of the legislative frameworks under consideration in the U.S. Congress rely primarily on market-based mechanisms, such as carbon taxes or cap-and-trade programs. By establishing a price of carbon, market-based mechanisms seek to correct a ubiquitous market failure — the negative externality associated with GHG emissions — and send price signals to energy producers and consumers that encourage behavioral changes and technology innovation.

However, while economic theory and experience teach us that market prices are the most efficient mechanism for allocating scarce resources, reducing GHG emissions solely through the imposition of a carbon price poses a unique set of challenges. Virtually all advanced technologies suffer from noneconomic barriers that prevent them from reaching their full market potential, including technological barriers (e.g., underinvestment in basic and applied research), market barriers (e.g., split incentives) and institutional barriers (e.g., regulatory, legal and policy constraints). If left unabated, such barriers may hamper market efficiency, frustrate policies and drive up costs, regardless of the type of carbon pricing instrument chosen.

Business Roundtable believes that without efforts to remove or reduce barriers to technology deployment, unsustainably and unnecessarily high carbon prices would be required to significantly reduce GHG emissions — effectively exchanging one unsustainable pathway for another. Strong policy leadership that aggressively and systematically eliminates critical barriers to deployment, however, can unlock the full potential of a portfolio of key technologies that will allow the United States to reduce emissions in a shorter timeframe and at a lower cost while maintaining a robust economy and diversifying the nation's energy sources. Anything less is, simply put, unsustainable.

About This Study

Business Roundtable believes that leadership in addressing the sustainable growth challenge is not just a job for government. The business community has a special obligation to step forward because of its central role in producing, distributing and consuming energy. Recognizing this obligation, the Roundtable merged its energy and environmental task forces to form the Sustainable Growth Initiative. Chaired by Mike Morris, CEO of American Electric Power, the Sustainable Growth Initiative was charged with uniting competing interests in the business community and forging a detailed policy roadmap that could simultaneously advance our nation's economic, environmental and security objectives.

With this goal in mind, the Sustainable Growth Initiative launched an extensive collaborative effort to bring together leading energy technology producers, consumers and innovators to forge a comprehensive strategy for transitioning the United States to a low-carbon economy. During a six-month process, Business Roundtable regularly convened experts from member companies to evaluate the potential of various technology pathways; identify key barriers to achieving each technology's full potential; develop recommendations for removing those barriers; and quantify the economic, environmental and energy impacts of implementing the recommendations via an economic modeling exercise.

Scope

The point of departure for this effort was an assessment of the nation's key economic, environmental and security interests. Based on this evaluation, Business Roundtable identified three strategies of a sustainable growth agenda in which the policy approaches must be carefully assessed for their intended costs and benefits:

(1) More efficiently consume electricity and heating fuels in homes and businesses;
(2) Leverage domestic resources to produce cost-effective, low-carbon electricity; and
(3) Modernize the transportation fleet and diversify the transportation fuel mix.

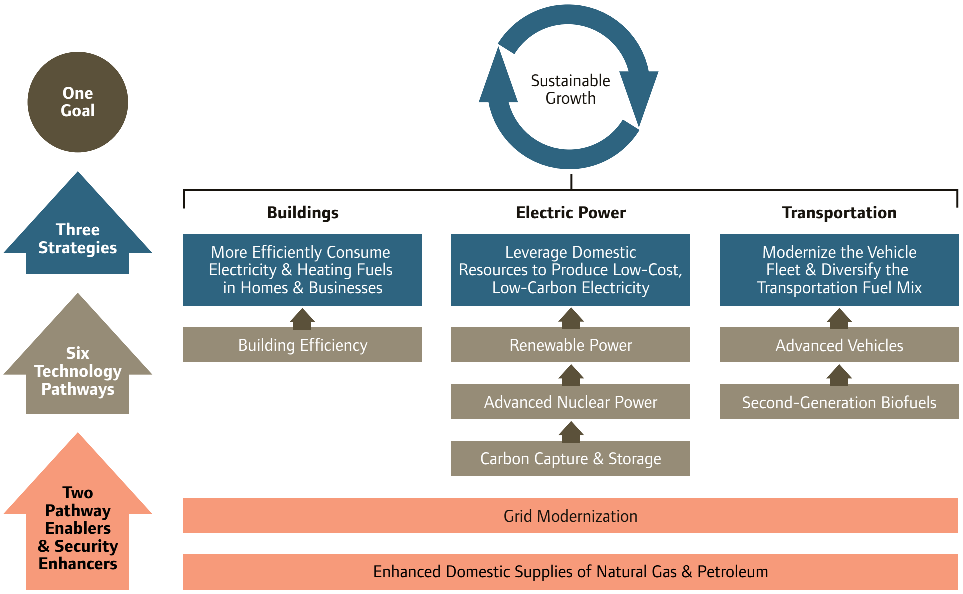
Business Roundtable then identified six "technology pathways" that are critical to implementing these strategies and achieving sustainable growth:

(1) Building efficiency improvements;
(2) Renewable power generation;
(3) Advanced nuclear power generation;
(4) Carbon capture and storage;
(5) Advanced vehicle technologies; and
(6) Advanced biofuels.

Business Roundtable also identified two "enabling pathways" that are essential to realizing the full potential of the entire portfolio: grid modernization and enhanced domestic supply of oil and natural gas.

The six technology pathways and two enabling pathways examined in this study were chosen in part to expand upon the framework presented in the 2007 Business Roundtable report *More Diverse, More Domestic, More Efficient*. The six technology pathways also were chosen because they are among the most promising pathways needed to meet the sustainable growth challenge, although they are not the only pathways that will be needed.[10] The two enabling pathways were chosen because they are essential to supporting a long-term shift to a low-carbon economy, with grid modernization being a technical prerequisite for implementing many efficiency and low-carbon electric power technologies, and enhanced domestic supplies being vital to creating the stable economic conditions necessary to support large-scale investments in the nation's energy system.

Figure 1.1: Meeting the Sustainable Growth Challenge



Process

To leverage the expertise of its member companies, Business Roundtable established eight technology working groups and charged each with evaluating the current status and future potential of a given technology; identifying the technical, market and institutional barriers associated with that technology; and developing policy recommendations to overcome those barriers and realize the technology's full potential. In addition, each working group was presented with a range of policy assumptions and asked to develop detailed scenarios and quantify characteristics (e.g., cost, deployment, GHG emissions) associated with each technology pathway. These scenarios were then modeled to evaluate the economic, environmental and energy impacts.

The economic modeling component of the study was conducted by the University of Maryland's Inforum Modeling Project and Keybridge Research LLC. Modeling simulations were performed using Inforum's highly respected Long-term Interindustry Forecasting Tool (LIFT) — a dynamic general equilibrium model of the U.S. economy that uses a unique "bottom-up" technique to simulate economic, environmental and energy impacts. These simulations were conducted under a range of carbon price and public policy scenarios that were developed through an extensive collaborative process between the technology working groups and the modeling team.

For each scenario, the technology working groups were charged with developing detailed "technology templates" to serve as primary inputs to the model. Estimates for technology cost, performance and penetration were developed through the combination of expert judgments of engineers, economists and public policy experts from Business Roundtable member companies and well-respected public sources. The Inforum-Keybridge modeling team then integrated these technology templates into the LIFT model individually to simulate the economic, environmental and energy impacts associated with each pathway. The templates were then collectively integrated as input to the model to simulate the impacts associated with pursuing a comprehensive portfolio of strategies. This process culminated in detailed simulation results for more than 30 scenarios — yielding a wealth of quantitative data and analysis that should serve as a valuable resource for business leaders and policymakers.

Study Organization

This study is divided into two sections. The first section, consisting of Chapters 2–9, offers qualitative assessments of the six technology pathways and the two enabling pathways discussed above. The second section of the study includes Chapters 10, 11 and 12. Chapter 10 describes the modeling framework. Chapter 11 discusses the modeling inputs that were provided by the technology working groups. Chapter 12 presents the modeling results of implementing a balanced portfolio of technologies and offers key findings.

Chapter 2

Residential and Commercial Building Efficiency

Often characterized as the "first fuel," energy efficiency is unique in its potential to substantially advance all three pillars of a sustainable growth strategy. Energy efficiency can improve our economy by increasing productivity, competitiveness and consumer purchasing power; it can improve our environment by decreasing greenhouse gas (GHG) emissions intensity and the nation's carbon footprint; and it can improve our security by decreasing overall energy demand and reducing the nation's overall exposure to energy price volatility.

Although opportunities to improve energy efficiency exist throughout the economy, evidence suggests that a concentration of attractive opportunities exists in the residential and commercial buildings sectors. For example, a 2007 McKinsey & Company report highlighted the potential for low-cost GHG abatement via improvements in energy efficiency in new and existing buildings.[11] In fact, many energy efficiency improvements in the residential and commercial sectors offer negative costs — that is, the estimated net present value of savings in energy costs over the lifetime of the project exceed the investment costs. In such instances, the deployment of energy efficient technology can both curb GHG emissions and boost economic growth.[12]

Despite the potential for net savings, many opportunities to improve energy efficiency in the residential and commercial buildings sectors remain untapped. Decisionmakers in these sectors are frequently presented with misaligned and muted incentives that prevent or discourage cost-effective technology choices. In some instances, for example, the individual choosing the energy technology (e.g., the homebuilder) is not the individual who will bear the ongoing costs of operating that technology (e.g., the homeowner). In other instances, consumers may not be able to afford the initial investment in energy efficient technology, despite the prospect of relatively short payback periods and long-term net savings. Consumers also may simply lack the information or awareness required to evaluate, compare and choose among technologies with various energy efficiency profiles.

Targeted public policies have the potential to properly align and clarify natural incentives. By removing critical barriers to technology deployment in the residential and commercial buildings sectors, strong policy leadership can unlock the full potential of the building efficiency pathway — thereby mitigating the adverse economic impact of climate change regulation, reducing the nation's GHG emissions and enhancing its security.

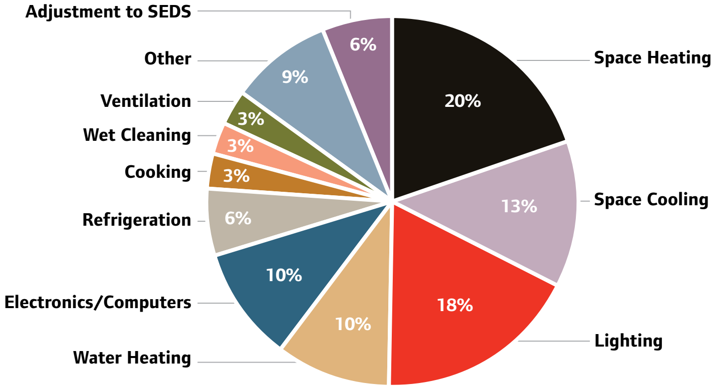
Technology Pathway Overview

The importance of improving energy efficiency in the commercial and residential buildings sectors is underscored by their dominant and pervasive influence on the U.S. energy equation:

- U.S. commercial and residential buildings are responsible for about 39 percent of the nation's primary energy use.[13]
- Approximately 20 percent of the nation's natural gas and 72 percent of the nation's electricity are consumed in commercial and residential buildings.[14]
- Commercial building electricity consumption is the fastest growing sector, and by 2030 it is expected to surpass the residential sector as the leading source of electricity demand.[15]

Nearly three-fourths of all energy consumed within residential and commercial buildings is directed to six end-use activities: space heating (20 percent), lighting (18 percent), space cooling (13 percent), electronics/computers (10 percent), water heating (10 percent) and refrigeration (6 percent).[16] Improving energy efficiency in these areas requires actions on four fronts: (1) increasing the energy efficiency of appliances; (2) increasing the energy efficiency of new and existing structures; (3) streamlining energy intensive activities through greater use of information and communication technology; and (4) reducing end-user energy use through conservation, time-of-use metering, education and awareness.

Figure 2.1: Buildings Sector Energy Consumption by End-Use Activity



Source: U.S. Department of Energy (DOE), Energy Efficiency and Renewable Energy (EERE) (September 2008), *2006 Buildings Energy Data Book*, Table 1.1.4

Some individual strategies and technologies can be cost-effectively implemented in most buildings over a relatively short period, including replacing incandescent light bulbs with more efficient bulbs or enhancing building standards for new buildings. Other strategies, such as installing more or better insulation in existing structures, may not be cost-effective in some buildings until other major renovations are undertaken. Those strategies may take much longer to fully implement.

Importantly, technologies to make residential and commercial buildings significantly more energy efficient are available now. Weatherization; insulation; energy efficient windows; and more efficient appliances, lighting, and heating, ventilating and air conditioning (HVAC), can all be applied to existing buildings today. For new construction, "zero energy" and "near-zero energy" residential and commercial buildings are achievable through the integration of innovative design and efficient materials, appliances and HVAC operating systems. While continued development of new building efficiency technology is essential, accelerating the deployment of available technologies is critical to reducing GHG emissions in a cost-effective manner in the near term and placing the United States on a trajectory toward sustainable growth in the long term.

Technology Pathway Barriers

Despite readily available, cost-effective technology that can be bought off-the-shelf today, significant barriers often prevent energy efficiency investments:

Principal-Agent Barriers

Also known as "split incentives," principal-agent barriers limit homebuilders' and commercial developers' motivation to invest in energy efficiency for new buildings because they do not pay the ongoing energy bills. For instance, homebuilders and building owners who pass through utility costs to renters want to minimize first sale cost, whereas added efficiency investments at the front end usually benefit the homebuyer, apartment renter or commercial lessee only over the longer term. The principal-agent barrier affects half or more of the energy use in the most common residential and commercial end-use markets.[17]

Transaction Cost Barriers

Transaction cost barriers affect individual consumers and small business decisionmakers faced with potentially dozens of small efficiency investment options. Collectively, these opportunities could result in substantial savings. Individually, however, such opportunities may be too small to justify the in-depth analysis or research required to take advantage of them. In a June 2008 report, the National Governors Association identified the transaction cost barrier as one of the more significant barriers.[18]

Customer Barriers

Customer barriers can arise when individuals and small businesses lack information on energy savings opportunities, awareness of how energy efficiency programs make investments easier or funding to invest in energy efficiency. Also, in some instances, there is a reluctance to deviate from the regional norms based on climate, available materials and skills. Further, new energy efficient materials can be seen as risky until the builder gains experience with them, as new materials require additional time to train workers.[19]

Policy Barriers

Some public policies can disincentivize utility support and utility investment in energy efficiency. For example, while demand reduction investments may be significantly cheaper than building new generating capacity or purchasing new supplies of electricity or natural gas, energy efficiency projects may be disincentivized by state and utility resource planning processes that do not consider efficiency and demand reduction a resource.[20] Investments in distributed generation and cogeneration technologies also may be disincentivized by existing policies.

Summary of Technology Pathway Barriers

Even though investments in energy efficiency can often be characterized as high return and low risk, various barriers hinder efforts to maximize potential efficiency benefits. Technology, however, is not one of these barriers. Energy efficiency is one of the few resources available that can reduce GHG emissions in a cost-effective manner without significant technology improvements. Simply put, energy efficiency technologies have not penetrated the market to the extent possible because of market and policy barriers. While the federal government has created programs to address many of these barriers, more needs to be done at the local, state and national levels to increase awareness of these technologies and provide incentives for their implementation.

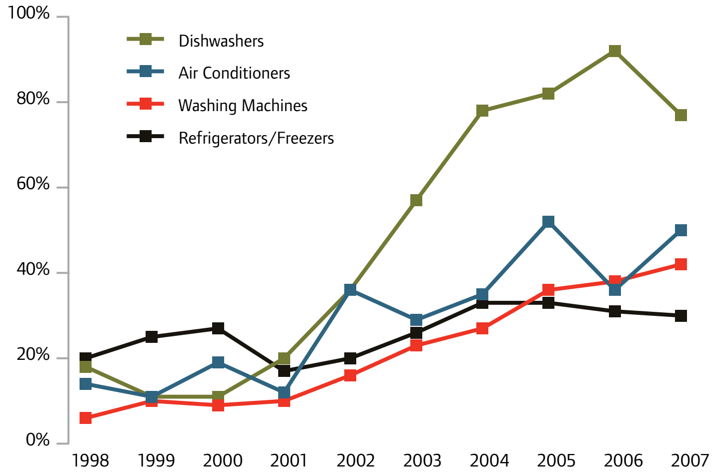
Policy Considerations

Appliances

The U.S. federal government establishes energy efficiency standards for most major appliances, including refrigerators, hot water heaters, dishwashers, washers, dryers, air conditioners, furnaces and ovens. Pursuant to law, the U.S. Department of Energy (DOE) is required to set appliance efficiency standards at levels that achieve the maximum improvement in energy efficiency that is technologically feasible and economically justified. The Energy Independence and Security Act of 2007 (EISA) updated certain standards, established timelines for the promulgation of standards for certain products, and now requires periodic review and updating of existing standards when appropriate.

In addition to its standards-setting responsibilities, the federal government promotes energy efficient residential and commercial appliances, electronics, office equipment and other equipment through the ENERGY STAR program, introduced in 1992. The ENERGY STAR program, funded by DOE and the Environmental Protection Agency (EPA), evaluates various products and rates them based on their energy efficiency. This has been an important mechanism for making energy efficiency increasingly marketable and accelerating the deployment of energy efficient equipment. In 2004 alone, DOE estimates that ENERGY STAR appliances saved enough energy to power 24 million homes.[21]

Figure 2.2: U.S. Market Share of ENERGY STAR Appliances



Source: ENERGY STAR, National Appliance Sales Data, 1998–2007

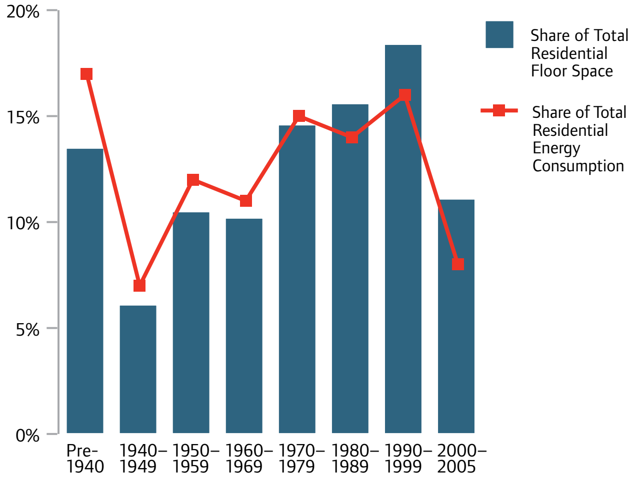
Nevertheless, many consumers do not buy energy efficient appliances or update their older appliances. Appliance distributors often bundle energy efficiency features with other special and expensive features, causing some consumers to choose lower initial cost appliances without realizing the long-term efficiency savings they are foregoing. Furthermore, customers frequently lack the time necessary to conduct proper research before purchasing a replacement appliance — resulting in "panic purchases" of appliances that are initially cheaper but less energy efficient.

Building Design and Envelopes

Currently, the U.S. building stock is estimated at 330 billion square feet.[22] Between now and 2035, it is estimated that 52 billion square feet of U.S. building stock will be demolished, 150 billion square feet will be remodeled and another 150 billion square feet will be newly constructed.[23] Consequently, strengthened building codes for new and remodeled buildings can have a major long-term effect on energy usage. In particular, building codes can be effective in overcoming the principal-agent problem.

Building codes are set at the state and local level, although national standards-setting organizations, such as International Energy Conservation Code (for residential buildings), American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE, for commercial buildings) and equipment manufacturer trade associations, play an important role in their development. In addition to mandatory building codes, many states and localities use voluntary programs that go beyond codes, including the EPA's ENERGY STAR program, DOE's Building America program, the Green Building Initiative's Green Globes program, the National Association of Home Builders' NAHBGreen program and the U.S. Green Building Council's Leadership in Energy and Environmental Design program.[24]

Figure 2.3: Residential Floor Space and Energy Consumption by Vintage



Source: Energy Information Administration (EIA), *2005 Residential Energy Consumption Survey,* Tables HC 1.1.1, US 1

While building codes have become more stringent in recent years and appliances have become more efficient, the increasing size of U.S. homes, additions to commercial floor space and the proliferation of electronics within homes and commercial facilities have tended to offset energy savings from newer homes and appliances. Also, while energy usage per square foot is much lower in new buildings, the existing stock of structures and appliances turns over slowly. For example, about three-quarters of homes are more than 15 years old.[25] Accordingly, policies focused solely on strengthening new building codes, although necessary, will miss substantial savings opportunities. Policies also are needed to encourage existing homeowners and commercial building owners to make cost-effective energy efficiency investments when retrofitting existing structures.

Information and Communication Technologies

Information and communication technologies (ICT) play a critical role in reducing energy waste throughout the economy. For example, advances in teleworking and teleconferencing can reduce the number of people traveling to work and business meetings. As e-commerce and e-billing costs decline and the number of people shopping and paying bills online increases, there will be lower transportation costs and less paper used. As ICT technologies become more integral to the products and services people use, the energy savings continue to grow.

There are several ways to improve ICT productivity gains. First, reducing the energy needed to design, manufacture and distribute the ICT equipment to consumers would improve energy productivity. Second, there must be an increase in the operating efficiency of ICT technologies once they are installed. The Climate Savers Computing Initiative believes that desktop computers waste nearly half the power delivered to them, and the industry has since committed to a 50 percent reduction in the power consumption of computers by 2010.[26] Finally, ICT technologies could have an enormous impact on the efficiency of electricity transmission and use by facilitating smart grid technologies such as time-of-use metering, as discussed at greater length in Chapter 6.

Summary of Policy Considerations

Business Roundtable members believe that federal guidance and policies are in place to make a significant contribution to improving energy efficiency in residential and commercial buildings. Appliance efficiency standards, the ENERGY STAR labeling program, new lighting efficiency requirements, federal energy efficiency initiatives and favorable tax policies for efficiency investments will all make a significant contribution to meeting building efficiency potential. Initiatives contained in EISA require state regulators to consider mandating that utilities employ integrated resource planning and establish rates for supply-side resources that put energy efficiency expenditures on par with utility investments — thereby helping to resolve existing policy barriers. Diligent leadership at the state and local levels, however, will be essential to ensure that these policies are fully implemented.

Many experts believe that improved performance levels can realistically achieve energy use reductions of more than 50 percent per square foot by 2050 for new buildings and more than 35 percent per square foot for existing buildings. To encourage these changes, however, strong policy leadership is needed on multiple fronts. Building codes and efficiency standards, whether at the regional or national level, must be enforced and strengthened to drive and reward efficiency. Policies resulting in greater government incentives and private-sector investment are imperative to promoting the deployment of energy efficient appliances. Additionally, policies assisting market "aggregators" may be required to overcome the transaction cost barrier and more efficiently harness individually minor, but collectively significant, savings opportunities. Furthermore, policies that address the need for consumer education and provide assistance with the upfront costs of newer, better technology also will be critical, while homebuyers and mortgage providers must be encouraged to focus on the long-term costs of occupancy rather than the initial costs of purchase. Finally, many efficiency technologies can be implemented in a more cost-effective way in new buildings than in existing buildings. Accordingly, many technology adoption incentives and policy changes will need to differentiate between new builds and retrofits.

Policy Recommendations

- Congress should provide full and stable funding for energy efficiency programs authorized in the Energy Policy Act of 2005 and EISA. These acts contain a plethora of energy efficiency programs, ranging from updated appliance efficiency standards, green building research and demonstration, new lighting requirements, federal building efficiency standards, and authorization for a variety of research programs.
- Lenders and builders are encouraged to promote "green mortgages," which recognize the lower monthly expenses associated with energy efficient homes and provide consumers with a greater awareness that improved efficiency can provide long-term financial savings.
- States and local governments should consider requiring that a home energy audit be done on homes offered for sale and that audit results be disclosed to prospective homebuyers.
- State regulatory authorities should adopt policies to make the delivery of energy efficiency a core part of utilities' businesses, including adoption of policies that put energy efficiency on an equal footing with energy supply.
- State and local governments should continuously update and enforce modern building codes, including standards that will potentially accommodate future energy efficiency devices (e.g., time-of-use metering, occupancy controls, etc.).
- All levels of government should continue to educate consumers regarding the difference between one-time, out-of-pocket and lifetime costs of various efficiency investments.
- Business Roundtable members and others are encouraged to be active participants in the National Action Plan's process and proceedings and in other energy efficiency efforts being led by conservation and efficiency organizations, standards-setting organizations, and trade associations focusing on efficiency.

Chapter 3

Renewable Power

Successfully transitioning the United States to a low-carbon economy will require measures to improve both the demand and supply sides of the U.S. energy equation. Improvements in energy efficiency can dramatically reduce electricity demand and curb greenhouse gas (GHG) emissions. However, new sources of electricity supply will still be necessary to meet the needs of a growing economy and to replace older plants as they approach the end of their useful lives. Satisfying these needs in a sustainable manner will require the deployment of advanced power generation technologies that leverage the nation's domestic resources to produce low-cost, low-carbon electricity.

Accelerating the deployment of renewable power technologies will be particularly important to the goal of decarbonizing the U.S. electric power mix. Many regions of the United States are endowed with excellent renewable resources, including abundant supplies of wind, solar, biomass, geothermal and other sources. Efficiently integrating these resources into the U.S. electricity supply is a key component of a sustainable growth agenda. With virtually zero fuel costs or GHG emissions, renewable power can be an attractive source of affordable and clean electricity, especially in the context of volatile fossil fuel prices and potential carbon restrictions. Equally important, renewable power technologies can simultaneously leverage the nation's domestic resources and diversify its energy mix — thereby enhancing U.S. economic and national security.

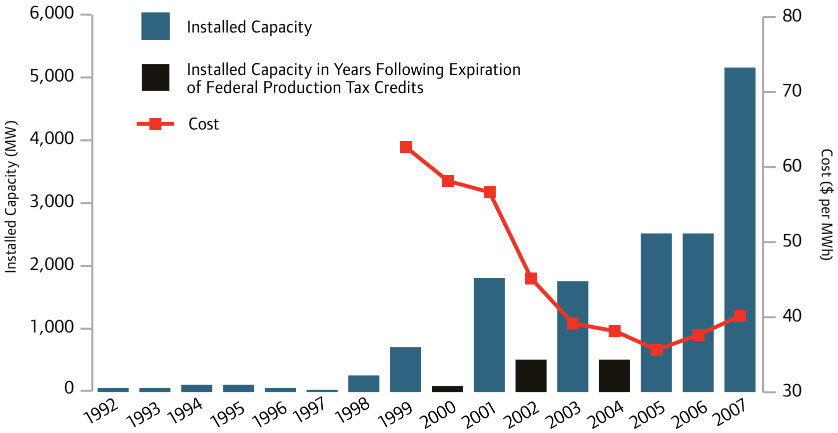
Technology Pathway Overview

Wind Power

Wind power holds significant promise as a cost competitive and environmentally friendly source of energy. Recent technological advances — including taller towers, larger turbines and lighter weight materials — are rapidly increasing economies of scale and improving the competitiveness of wind power in locations with suboptimal conditions. In locations with optimal resources, wind power is already a commercially viable and economically competitive technology. Nevertheless, in most instances, production tax credits (PTCs) and other financial incentives are still necessary to keep wind power competitive with the lowest cost alternatives.

Investment in the deployment of wind power has increased rapidly in recent years. Over the past eight years, for example, cumulative wind capacity in the United States has grown an average of 27 percent per year.[27] In 2007 alone, more than 5,000 megawatts

Figure 3.1: Installed Wind Capacity and Cost



Source: American Wind Energy Association (2008), *Annual Wind Power Outlook;* DOE, ERRE (2008), *Annual Report on U.S. Wind Power Installation, Cost, and Performance Trends: 2007,* p. 24, Figure 27

(MW) of new capacity were added and $9 billion invested, almost twice the amount installed in 2006.[28] As of September 2008, the United States is the world's leader in wind-generated power with more than 20,000 MW of installed capacity.[29]

Despite these promising developments, wind power currently represents a small fraction of the U.S. electric power market. Total installed wind capacity generated slightly more than 1 percent of U.S. net electricity in 2008.[30] Estimates suggest, however, that wind power has the potential to make a substantial contribution to the U.S. electric power mix in future decades. For example, the U.S. Department of Energy (DOE) estimates that, under favorable policy conditions and with large investments, it is possible for the United States to produce as much as 20 percent of its electricity with wind by 2030.[31]

Solar Power

Solar-generated electricity also is a rapidly expanding sector. There are two primary methods of solar power electricity generation:

- Photovoltaic (PV) technologies use purified silicon or thin film modules to convert sunlight directly into electrical energy. Although still relatively expensive, PV power generation is well suited for niche applications (e.g., traffic lights) and remote off-grid systems. Large-scale PV systems also are being deployed for commercial buildings, factories and the electric grid in the United States and Europe.
- Concentrated solar power (CSP) technologies convert the energy from concentrated solar rays into heat, which is used to produce steam that drives conventional steam power cycles. Prior to the production of steam, some of the thermal energy can be temporarily stored for future use, addressing the inherent issue of solar power intermittency. This unique characteristic of CSP technology makes it easier and more efficient to integrate into existing electrical grids and thereby provide solar-powered electricity on a commercial scale.

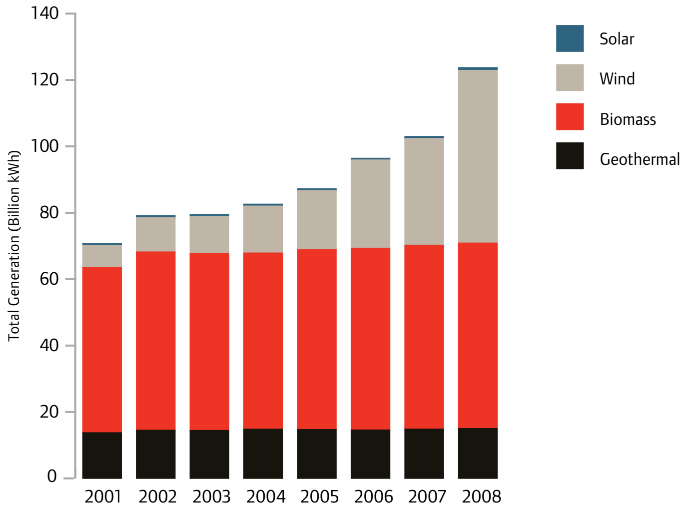
PV is the fastest growing type of alternative energy in the United States, with installed grid-tied generating capacity increasing by nearly 60 percent in 2008.[32] Installations are projected to continue to expand, boosted by falling costs of panels and by an investment tax credit (ITC) of 30 percent for residential, commercial and utility applications. CSP is second only to wind as the fastest growing utility-scale renewable energy market, with up to $20 billion in expected investment over the next five years.[33] Between 2007 and 2008, solar electricity generation increased by 221 gigawatt hours (GWh), bringing cumulative solar electricity generation to 833 GWh, accounting for .02 percent of total U.S. electric power generation.[34]

Biomass Power

Biomass-generated electricity is attractive in its ability to harness the otherwise untapped energy potential of large amounts of biodegradable waste materials produced by different industries. Electricity from biomass can be generated by one of four technologies: (1) combustion, (2) co-firing, (3) gasification and (4) anaerobic digestion. Co-firing, a process that substitutes biomass stock for fossil fuels in existing coal-fired power plants, is currently the most economical technology with the shortest pay-off period on investment. Biomass gasification technology holds the greatest long-term potential for efficient biomass-based electricity generation.

Biomass electricity generation is currently used by the forest industry and utility sector. In fact, the U.S. pulp and paper industry is one of the nation's leading users of biomass fuels — meeting 60 percent of its power needs through the use of renewable biomass for self-generation.[35] Including all energy applications, biomass represented about 3 percent of the nation's energy supply in 2007.[36] Of that, more than 55 billion kilowatt hours (kWh) of electricity was generated from biomass, approximately 1.3 percent of total electricity generated.[37]

Figure 3.2: Renewable Power Electricity Generation



Source: EIA (June 2008), Annual Energy Review (AER), Table 8.2a

Geothermal and Other Renewable Power Sources

Geothermal energy relies on clean and sustainable heat from the Earth. Resources of geothermal energy range from the shallow ground to hot water and hot rock found a few miles beneath the Earth's surface. Wells are drilled into underground reservoirs to tap steam and extremely hot water, which drive turbines and associated electrical generators. Enhanced geothermal systems are engineered hydrothermal reservoirs created to commercially exploit the Earth's naturally occurring heat. Unlike solar and wind resources, geothermal energy resources are continuously available. Currently, the installed domestic capacity of geothermal power plants is approximately 3,000 MW in five western states. Wave and tidal power and additional hydro resources are other potential sources of renewable electricity generation.

Technology Pathway Barriers

The majority of wind and solar resources in the United States remain untapped and will continue to be so until the significant barriers preventing these resources from reaching their full potential are removed. For instance, optimal wind and solar resources are often located in remote areas, far from urban load centers. Unfortunately, the nation's electric transmission system was not designed to transmit large quantities of electricity from remote areas rich in wind and solar resources to urban centers. Building new transmission capacity, however, poses difficult siting and cost allocation issues, and the intermittent nature of wind and solar generation might make it more difficult to economically justify the building of new, high-voltage transmission capacity solely for renewable energy. Finally, although conventional wind power is well advanced, additional technological progress in the areas of solar, offshore wind and energy storage will be necessary if renewable power is to become sufficiently cost-effective to play a large-scale role in producing the nation's energy.

Transmission Barriers

While fossil fuel resources are not uniformly distributed over geographic regions, they can often be transported over large distances at a relatively modest cost — enabling generating plants to be located close to load centers.[38] Optimal wind and solar resources are not transportable and, for the most part, are located far from load centers. The only way to deliver those wind and solar resources to load centers is by transmitting the electricity that they produce over long distances. The existing transmission system, however, was built to deliver locally or regionally produced electricity over relatively short distances. Also, the existing transmission system frequently faces capacity constraints. Investments in new transmission technologies will therefore be essential to transport wind- and solar-generated electricity from resource-rich locations to the centers of heaviest demand, a necessary step before wind and solar power can become economically competitive on a large scale.

The grid investments required to realize the full potential of wind and solar power are likely to be significant. For instance, American Electric Power and the American Wind Energy Association recently collaborated on a study analyzing transmission needs associated with allowing wind energy to supply 20 percent of the nation's electricity needs by 2030. According to the study, approximately 19,000 miles of extra-high-voltage (765 kilovolt [kV]) lines would provide a robust interstate overlay grid to accomplish this goal at a cost of about $60 billion in today's dollars.[39] To put this into perspective, current estimates suggest that the utility industry will invest about $31.5 billion in transmission facilities from 2007 to 2010.[40]

In addition to purely geographic and logistical issues associated with upgrading the nation's transmission system, balkanized planning processes, fragmented siting authority and the issue of cost allocation are other significant barriers to accommodating renewable power as a viable source of energy.[41] These issues are discussed further in Chapter 6.

Intermittency Barriers

Further compounding the transmission capacity issue is the fact that wind and solar technologies are intermittent generators of electricity. This intermittency can complicate resource planning, lead to grid instability, and reduce the overall reliability and potential penetration of wind and solar resources. As a result, wind and solar power investments often need to be accompanied by investments in backup capacity or energy storage technologies that can provide electricity during times of poor sunlight or low wind. Backup electricity is often supplied by natural gas-fired power plants that have relatively low capital costs and that can be turned on and off more efficiently than most other types of power generation. It is unlikely that renewable power will successfully penetrate the electric power market on a large scale if it must rely on expensive backup capacity.[42]

A robust transmission system would support renewable power development by pooling renewable resources over larger geographic areas, facilitating the transmission of electricity surpluses in a region where the sun is shining or the wind is blowing to regions where the sun is not shining or the wind is not blowing. The more robust the grid, the less intermittent overall wind power production will be.

While it is unlikely that the wind will stop blowing in many places across a large geographic area at once, wind is often at its peak potential at night, when electricity demand is lowest. This means that wind power is not as valuable as it could be if it were deployed during peak times. Solar energy, on the contrary, is often available at system peaks but is unavailable at night or in the early morning. Without the ability to store electricity and better align the timing of renewable power supply with electricity demand, capturing many of the best solar and wind resources, even with a greatly improved transmission system, still may not be economical.

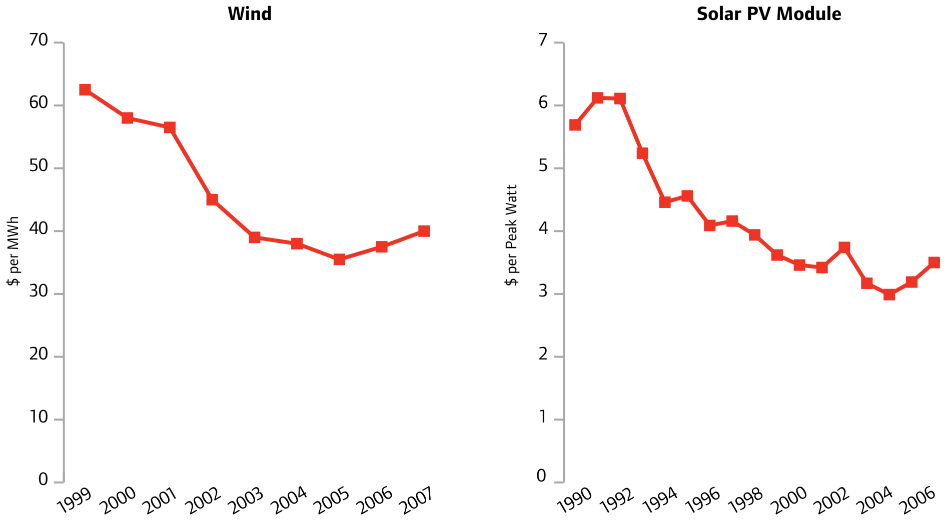
New technologies, however, offer the potential to store renewable generated electricity when it is not needed and dispatch it when it is. For example, molten salt is a new proposed technology to store energy from CSP. The first commercial facility to install it, a 50 MW plant with seven hours of storage, is being constructed in Spain.[43] In Alabama, PV plants have been operating reliably using compressed-air energy storage.[44] The compressed-air storage technology still uses natural gas as a supplementary fuel, but the turbines consume 60 percent less natural gas than if they were fueled by natural gas alone.[45] Improved weather forecasting also can assist with managing the variability of wind and solar generation.

The intermittency of wind and solar power is not a significant barrier at the low penetration rates that have been experienced in most parts of the United States. However, overcoming the intermittency barrier with an enhanced transmission system, improving energy storage technologies and developing efficient backup power sources will become far more important if wind and solar power grow to represent much larger fractions of overall electricity production capacity.

Economic Barriers

Even after the barriers associated with transmission and intermittency are addressed, renewable technologies may still be generally uncompetitive with lowest cost alternatives in the absence of a carbon price. Installed capacity prices for wind and solar, while falling, are still above those for coal and natural gas. DOE's Energy Information Administration (EIA) estimates that capital costs for utility deployment are the lowest for natural gas combined cycle facilities at approximately $700 to $1,000 per kilowatt (kW) of installed capacity. Wind facilities are estimated to cost almost $2,000 per kW of installed capacity, similar to the costs of some coal-fired power facilities.[46] The costs for offshore wind installations are nearly twice as high.[47] While wind power, unlike fossil fuel-fired plants,

Figure 3.3: Wind and Solar Energy Costs

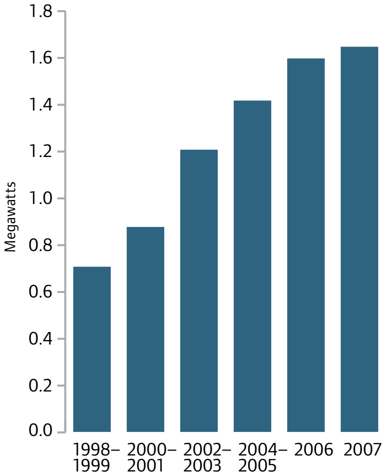


Source: DOE, EERE (2008), p. 17, Figure 13

Source: EAI (2007), AER 2007, Table 10.7

has low operating costs and no fuel costs, its total cost per unit of electricity generated is usually higher because wind plants do not operate at full capacity due to wind speed variance. Fossil-fuel-powered plants, on the other hand, can operate at their full capacity 80 to 90 percent of the time. Higher capital costs and similarly low rates of capacity utilization currently make solar power generation even more expensive.

Figure 3.4: Average Size of Installed Wind Turbines



Source: DOE, EERE (2008), p. 12, Figure 9

Significant material cost increases have been an issue for the wind energy sector, with turbine prices increasing by $400 per kW of installed capacity between 2002 and 2006, though recent declines in commodity prices may bring some relief.[48] Continued research and investment in the area of turbine design technology is needed to increase the efficiency and lower the costs of wind farms. Additional research and development (R&D) is still particularly needed to improve wind energy capture at low wind speeds and to optimize offshore wind harvesting, where there is substantial potential but also formidable challenges related to the sometimes harsh operating conditions. Past technological breakthroughs that have helped defray costs include larger turbines at higher hub heights, lighter materials and improved design.

With respect to solar power technologies, CSP currently costs approximately twice as much as wind power. PV is more expensive still, with silicon components particularly costly, though PV systems do have lower operating and maintenance costs than CSP and can be deployed on a more modular basis.[49] The use of PV-generated electricity makes economic sense in some remote locations without access to a larger grid. Without subsidies, however, current setup and operating costs are too high for widespread deployment. While some estimates predict that invested capital can be recovered in fewer than 10 years with utility and government incentives, the large initial capital investment required to set up PV and CSP power generation remains a significant economic barrier to the widespread deployment of solar energy technology. Technological advancements, including "thin film," nano and concentrating PV technologies, have the potential to significantly cut the per-kW costs of solar power by lowering manufacturing and equipment costs or increasing efficiency.[50] If costs decline enough, solar power could become competitive in places such as California, which has both strong solar resources and high electricity prices.

Policy Considerations

Wind

The U.S. wind energy sector has benefited from more than 16 years of policies encouraging investment in wind power. The Energy Policy Act of 1992 created a PTC that gave power producers 1.5 cents, adjusted for inflation, for every kWh of electricity produced from wind during the first 10 years of production.[51] Accounting for inflation, the PTC is currently equal to 2 cents per kWh.[52] The wind industry has grown rapidly in response to the PTC, as well as increasing concerns about climate change, rising fossil fuel prices and the existence of renewable portfolio standards in about half of the states. Due in large part to state and federal incentives, average wind power prices have been consistently at or below the low end of the wholesale power price range.[53]

Further work at the policy and technological levels is needed to sustain progress in wind technology. In May 2008, DOE released a report entitled *20% Wind Energy by 2030: Increasing Wind Energy's Contribution to U.S. Electricity Supply*, which examined the challenges, impacts and potential environmental effects associated with a 20 percent wind energy scenario. To meet 20 percent of expected electricity demand in 2030, U.S. wind power capacity would have to account for more than 300 gigawatts (GW), an increase of around 290 GW within 22 years. DOE estimates that achieving the 20 percent scenario would result in cumulative GHG emissions reductions of more than 7,600 million metric tons of CO_2 by 2030, avoiding 825 million metric tons annually by 2030.

Technological developments could lower production costs further, and DOE estimates that up to 600 GW of wind resources could be made available for 6 to 10 cents per kWh.[54] The potential benefits of wind power, as outlined in the 20 percent scenario, make it a promising approach for meeting a portion of the growing demand for electricity in a sustainable manner.

Solar

As with the wind industry, growth in the solar industry has been spurred by financial incentives provided by government policy. Under the Energy Policy Act of 2005, the ITC for solar energy provides a 10 percent credit for businesses and a 30 percent credit for residential property owners who install solar-powered hot water or PV electricity generation systems.[55] Policy support at the state level also has ramped up, with 22 state programs offering direct incentives for solar PV and a task force initiated by the governors of western states that is exploring prime sites for new solar-thermal power plants. The energy potential of these sites is estimated to be roughly 200 GW — equivalent to 20 percent of America's existing electricity generation capacity.

Globally, solar PV represented just 620 MW of total installations in 2003; however, that number is estimated to have reached nearly 3,000 MW in 2008.[56] This growth is projected to continue at a similar rate if policies promoting the wide-scale production of solar technology components and the development of more efficient technologies continue. Increased demand and investment, as well as technology improvements coupled with proactive policies, have the potential to drive down generation costs and help solar power become a viable and efficient alternative energy.

Biomass

Biomass has the potential to be an important fuel source in regions with few other renewable energy options. In 2005, DOE and the U.S. Department of Agriculture concluded that there are approximately 1.3 billion dry tons of biomass potential on both agricultural and forest land. However, funding for further investigation is required to better ascertain the costs of collecting and transporting available biomass on a large scale.[57] Policymakers must monitor the impacts of biofuels on food production, forest resources and GHG emissions, while seeking to minimize negative impacts on food supplies, forest sustainability and the existing industries that rely on a sustainable supply of these feedstocks.

Geothermal and Other Renewable Power Technologies

Geothermal and other renewable power technologies have received less attention than wind, solar and biomass technologies. Collectively, these technologies can provide significant amounts of electricity and GHG emissions reductions from the utility sector. Installed domestic capacity of geothermal power plants is nearly 3,000 MW, and industry associations predict that generating capacity in the United States will double over the next five years, driven in large part by state and federal incentives. DOE estimates that there are vast amounts of heat at depths from 3 to 10 kilometers and concluded that geothermal energy could provide 100,000 MW of electricity or more in 50 years by using enhanced geothermal system technologies. Federal support for R&D and early deployment of geothermal, wave, small hydro and other promising renewable technologies should continue.

Summary of Policy Considerations

Policy leadership has played an important role in the development and deployment of renewable power technologies during the past two decades. In particular, financial incentives for wind and solar investments have been critical to supporting these industries during their infancy and have allowed each to realize greater economies of scale. While existing policies provide a firm foundation for future growth in renewable power, several barriers must be removed to unlock the full potential of the renewable power pathway.

A carbon price will assist with making renewable technologies more competitive in the long run, but strong policy leadership is necessary to accelerate the deployment of these technologies in the short and medium terms.

Some experts believe that wind and solar power can each achieve market penetration of 15 to 20 percent of total power generation by 2050 with the assistance of aggressive policy leadership. Modernizing the nation's transmission system and smoothing the intermittency problem with cost-effective storage technologies will be important enabling forces for the widespread deployment of renewable technologies. Multiyear commitments to financial incentives also will be necessary to provide the predictability needed to overcome economic barriers in the short and medium terms while technological advances and learning effects drive down costs. The goal should be to make renewable power technologies economically self-sustaining so that government support can be phased out as quickly as possible.

Policy Recommendations[58]

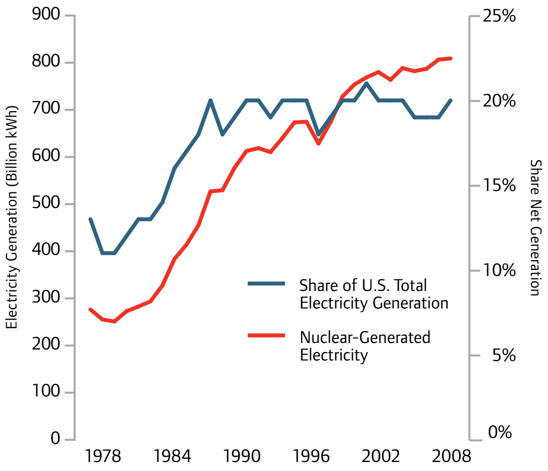
- Increase federal R&D support for electric storage technologies, solar PV, CSP, wave, tidal, geothermal, small hydro, biomass and offshore wind technologies.
- Demonstrate policy leadership at the federal level with respect to cost allocation, planning and siting of transmission needed to incorporate wind and solar resources into the grid.
- Make the biomass PTC available to industrial co-generators, not just to generators selling electricity to an unaffiliated third party.
- Continue to support and fund the existing PTC for wind facilities.

Chapter 4
Nuclear Power

While energy efficiency and renewable power generation can make important contributions to decarbonizing the nation's electric power mix, a more comprehensive portfolio of strategies will be required to successfully meet the sustainable growth challenge. The need for a more robust approach and the urgency of this challenge are highlighted by the advanced age of the existing electric power generation fleet and the expected retirement of the vast majority of the nation's baseload capacity in the first half of this century. Given the long-lived nature of such plants and their importance to the nation's electric power mix, accelerating the deployment of advanced baseload generation technologies will be a critical strategy to reducing the nation's greenhouse gas (GHG) emissions profile over the long term.

As the only existing, proven and scalable low-carbon baseload generation technology, nuclear power will be critical to managing the impending turnover in baseload capacity in a sustainable manner. Today, the current stock of nuclear plants, known as "Generation II" plants, provides approximately 20 percent of America's electricity.[59] In the future, America will need new nuclear plants to replace retiring plants and to maintain nuclear energy's current share of electricity supply, which will grow to meet rising demand. An expansion of nuclear energy beyond its current size will serve an additional purpose — reducing the nation's GHG emissions profile while providing affordable and reliable electricity to an expanding economy.

Figure 4.1: U.S. Nuclear Power Generation

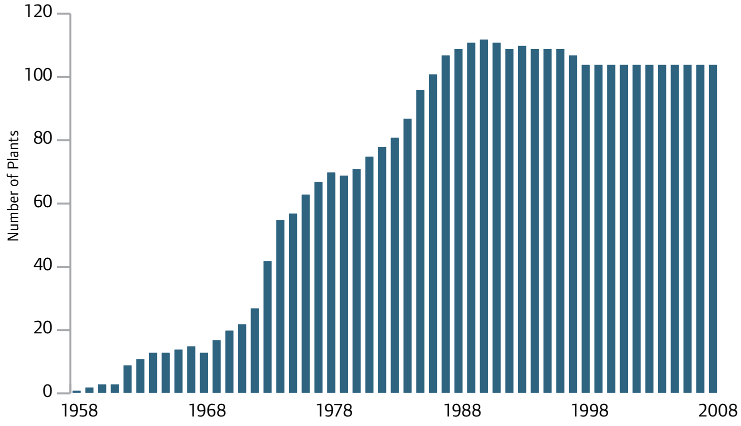


Source: EIA (February 2009), AER 2007, Table 9.2

Technology Pathway Overview

A nuclear power plant uses controlled nuclear fission reactions to heat water and produce steam, which turns a conventional turbine-powered electricity generator. Nuclear power is a well-established technology, and there are few technical obstacles to widespread deployment. France, for example, produces more than three-fourths of its electricity with nuclear power. Globally, more than 430 commercial nuclear power reactors operate in 30 countries, and more than 40 more reactors are currently under construction.[60]

Figure 4.2: Stock of U.S. Nuclear Power Plants



Source: EIA (February 2009), AER 2007, Table 9.1

Nuclear power has been a source of affordable and clean electricity in the United States for half a century. The first commercial plant was built in 1957, and the existing U.S. nuclear fleet includes 104 reactors with a capacity of approximately 100 gigawatts (GW).[61] After rapid deployment in the 1960s and 1970s, however, nuclear power's growth came to a halt, and no new plants have broken ground since 1979. Despite the lack of new construction for nearly three decades, the amount of electricity generated by U.S. nuclear power plants has continued to grow through gains in productivity and power uprates. Today, nuclear power represents about 70 percent of the nation's low- or no-carbon electricity generation.[62]

Other attractive features of nuclear power are its reliability and fuel security. Utilization rates for today's fleet of nuclear power plants are higher than 90 percent, meaning that they are rarely idle and can be relied on for a steady supply of electricity.[63] Fuel supplies for nuclear plants also are currently reliable and plentiful. Estimates suggest that there are sufficient supplies of uranium-235 (the most common fuel used by power plants) to support a significant expansion of global nuclear power for the next half century or more, with the largest reserves located in the United States, Australia, Canada, Kazakhstan and South Africa.[64] Technological advances and global cooperation could further extend fuel supplies.

The existing U.S. fleet of nuclear power plants also has an impressive history of safe and efficient operation, having accumulated more than 3,000 years of combined operating experience. The latest plant designs (i.e., "Generation III") have even more robust safety features and include simpler, more reliable designs. Generation III reactors are being built in Europe, Asia and South Africa, and the first steps toward significant nuclear expansion in the United States are in progress. Over the last several years, U.S. power generators have submitted combined operating and licensing applications to the Nuclear Regulatory Commission (NRC) for 26 new reactors.[65] Several of these are now in advanced stages of licensing. Some have already ordered long-lead items and will begin site preparation activities this year.

Assuming enabling policy, regulatory and political environments, one of the most important drivers of future nuclear power deployment will be the capital costs of a new nuclear plant. Nuclear power, like renewable power, is very capital intensive, and the relative importance of fuel and overall operating costs is much lower than it is for coal or natural gas electricity generation. This cost structure (i.e., high capital costs and low operating costs) makes nuclear power plants well suited for baseload generation, as high utilization rates justify high capital investments.

Most cost estimates, informed by experience in other countries, suggest that the costs of Generation III plants in the United States have the potential to be comparable to or slightly higher than those of modern coal or natural gas power plants.[66] In the presence of a carbon price or high fossil fuel prices, Generation III plants will be even more competitive with other baseload alternatives. For a variety of reasons, however, the true capital costs for a Generation III plant in the United States remain highly uncertain. There is no direct experience with building a Generation III plant in the United States, and potential delays in construction or permitting present significant financial risks. Furthermore, the costs of most construction materials (e.g., steel, cement, piping) have varied greatly in recent years, making construction costs unpredictable.

The nuclear power pathway is unique in that it is a proven, large-scale, low-carbon technology that is available today. Unlocking the full potential of nuclear power in the long term, however, will require an enabling policy, regulatory and political environment in the short term that purposefully targets and removes barriers to deployment. Removing these barriers could accelerate the deployment of advanced nuclear power to rates observed in the 1960s and 1970s — potentially expanding its role in the nation's electric power mix and providing a firm foundation for long-term sustainable growth.

Technology Pathway Barriers

Public policies are in place to support the construction of an initial tranche of Generation III plants, but it is unlikely that the majority of these will get built without some additional measures. Enabling a sustained nuclear power revival will require even more aggressive action to purposefully eliminate or reduce the following barriers to deployment.

Financial Barriers

The substantial capital costs associated with building a nuclear power plant present financial risks that are likely to constrain deployment. A modern 1.3 GW nuclear power plant is likely to cost as much as $5 billion to $7 billion — a cost large enough to strain the financing capacity of all but the world's largest firms.[67] Additionally, nuclear plants have long build times (three to five years in design, permitting and project development followed by four to five years of construction), which delay the point at which investors begin recouping costs. Finally, because of this long investment horizon and the lack of recent experience in building nuclear plants in the United States, investments in new nuclear plants are seen as riskier than investments in energy projects that offer quicker payouts and fewer challenges. Thus, the cost of capital for nuclear projects is expected to be higher than that for other energy projects.

Regulatory Barriers

Financial barriers to nuclear energy production are magnified by regulatory uncertainties, which create additional risks and are potential sources of delays to new projects. Experience in building the current fleet of nuclear power plants demonstrated that even modest regulatory delays can mean hundreds of millions of dollars in unanticipated costs to plant owners. Furthermore, the uncertainty associated with the old licensing process has contributed to the prolonged hiatus in nuclear plant construction. The NRC is now using a new licensing process designed to reduce regulatory uncertainty and other sources of institutional delay. Nonetheless, concern about regulatory uncertainty will continue to inhibit nuclear deployment until the new regulatory system is proven to be less burdensome and more predictable.

Political Barriers

An additional barrier to deployment is uncertainty about the nation's long-term policy for nuclear waste management. Nuclear plants have safely stored nuclear waste on site for decades, and on-site storage will remain a safe, effective solution as the industry expands in the short and medium term. However, a viable long-term policy is essential to bolster public confidence and support a sustained industry revival in the coming decades.

Market Barriers

Even if financial, regulatory and political barriers to deployment can be resolved, the nuclear power industry will need to overcome important market barriers. For example, the initial deployment of any first-of-a-kind technology entails costs and risks that will be borne by early adopters, while the benefits of experience and learning will be shared among subsequent developers. Individual companies thus have an incentive to wait for others to build the first plants, identify true capital costs, and decrease costs through learning-by-doing and economies of scale. Thus, even in the presence of a carbon price, incentives for early adopters are likely to be necessary to accelerate deployment in the short term.

Policy Considerations

Prudent, cost-effective expansion of the U.S. nuclear fleet, beyond the modest growth already supported by public policy, requires additional measures that will enable the industry to bear the high costs of nuclear plant construction, create an environment of regulatory stability and predictability, and forge a credible national policy for long-term management of nuclear waste.

Financial Support and Risk Sharing

Like other baseload power plants, nuclear units have high capital costs, which have varied in recent years as the prices of steel, cement and construction have fluctuated. In the United States, the electric power sector is not centralized as it is in other countries, where power plant fleets are owned by one or a few large and often state-owned entities. The regional companies that own most U.S. generation assets generally lack the financial capacity to undertake such large-scale, high-cost projects. Three types of governmental assistance can be critical for new nuclear plants: (1) federal loan guarantees, (2) production tax credits and (3) assurance of rate base recovery of capital investments by state rate-making bodies.

The loan guarantee program authorized by the 2005 Energy Policy Act, while a step in the right direction to strengthening the federal financing role, is not sufficient to spur nuclear plant construction on the necessary scale. The $18.5 billion in loan volume provided by Congress is inadequate given expected plant capital costs and will likely support only three to four new plants. This level of development will not yield sufficient experience to reduce perceived uncertainties in new plant construction and licensing or to realize the economies of scale needed to significantly lower plant costs and spur development. Moreover, as others have noted, implementation of the loan guarantee program has been frustrating. The U.S. Department of Energy (DOE) has been slow to issue a solicitation for loan guarantee applications, and a number of key ground rules (such as the methodology to calculate the cost to the federal government of the guarantee) are not yet in place. Thus far, there has been a distinct lack of commitment to the loan guarantee program by senior DOE management.

A substantial expansion of the loan guarantee program to $100 billion would permit the construction of at least 25 new plants. Credit subsidy costs (which represent a small portion of the overall loan amount) would be paid by the project sponsor, minimizing the financial burden on the federal government under all conditions short of project default. The industry today is following a number of practices not in place with the past generation of construction projects, which make it far less likely that new plants would default, and thus very unlikely that federal loan guarantees would be called upon. Responsibility for administering the loan guarantee program should be transferred to a new entity with greater financing expertise and motivation than DOE, and this entity could also implement the loan guarantee programs for deploying other advanced technologies in the electricity sector.

Regulatory Stability and Predictability

The industry and financial community must have confidence that the nuclear regulatory process provides the stability and predictability required to support a large multidecade capital investment program. An effective and predictable licensing process with transparent and well-understood procedures is essential. The federal government must ensure that the new combined construction and operating licensing process achieves these objectives. Furthermore, the president and Congress should ensure that the NRC has sufficient resources and expertise to handle the licensing workload efficiently and responsibly and that it is led by fair and qualified commissioners.

Long-Term Waste Management

The current policy of on-site management of used nuclear fuel using dry cask or other technology has been proven to provide adequate protection for the public and will continue to do so into the future. However, the public must have confidence that the federal government has a credible long-term policy for used-fuel management and disposal. Again, a new entity outside DOE should be tasked with developing interim storage facilities where needed and undertaking a research and development (R&D) program to support fuel recycling technologies to “close” the nuclear fuel cycle and reduce the volume and toxicity of waste by-products requiring permanent disposal. This new entity also should construct and operate a permanent repository, although creation of such a facility in the medium term (before 2025–30) is not technically necessary and may not be politically feasible.

Policy Recommendations

- Establish stability and predictability in the licensing and regulation of new plants and ensure success of the Nuclear Power 2010 program.
- Expand the existing federal loan guarantee program to support construction of at least 25 new plants (total guarantees in the range of $100 billion).
- Shift administration of the loan guarantee program from DOE to a new entity with greater financing expertise, facilitating the faster adoption of program rules and issuance of solicitations, among other efficiencies.
- Create a credible federal program outside of DOE for long-term management of nuclear waste. Responsibilities would include developing interim storage facilities where needed, undertaking an R&D program to support fuel recycling technologies that will “close” the fuel cycle and reduce the volume and toxicity of waste by-products, and constructing and operating a permanent repository.

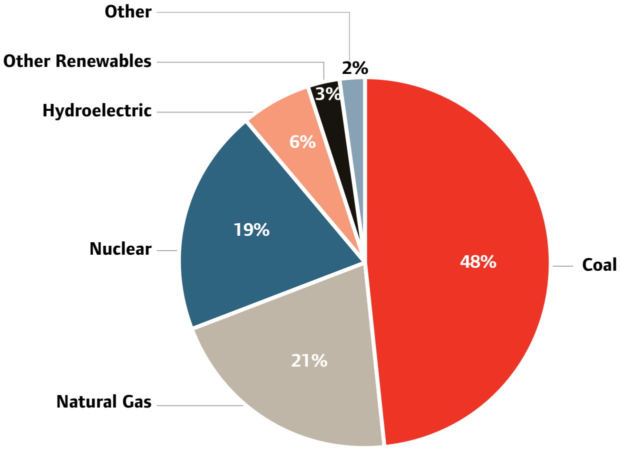
Chapter 5

Carbon Capture and Storage

Decarbonizing the electric power supply will not only require significant investments in low-carbon fuel technologies (e.g., wind, solar, nuclear) but also investments in technologies that fundamentally transform the way the world uses conventional fossil fuels. Fossil fuels remain the primary energy source for most of the world's economies, and coal, in particular, has the potential to power the U.S. economy for centuries to come. Major emerging economies, such as India and China, see similar appeal in coal. Consequently, timely development and deployment of technologies that enable coal to be consumed in a more environmentally acceptable manner are central to meeting the sustainable growth challenge.

Carbon capture and storage (CCS) is a promising technology that can transform the use of conventional fossil fuels to significantly reduce the greenhouse gas (GHG) emissions associated with fossil fuel consumption. The CCS pathway is especially important to reducing GHG emissions from coal-fired power plants, which represent one-third of total U.S. GHG emissions. Promising applications also exist for other large stationary GHG emitters, such as industrial gasification (IG) facilities, natural gas power plants, petroleum refineries, heavy oil production facilities and cement manufacturing plants.

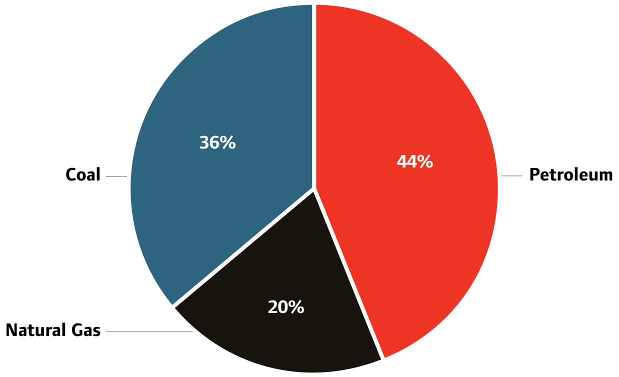
Figure 5.1: Electricity Generation Mix



Source: EIA (2009), Electric Power Monthly, Table 1.1

With the potential to eventually capture and store more than 90 percent of GHG emissions from large stationary sources, the CCS pathway has the capacity to deliver large-scale emissions reductions. Equally important, the CCS pathway can enable the continued use of coal, an abundant and affordable domestic fuel that is vital to U.S. economic and national security. In addition, exporting CCS technology to developing nations that depend on coal and other fossil fuels to power their economies is essential to reducing GHG emissions in the locations where coal power is growing fastest, such as China and India. Ultimately, by decoupling the link between the consumption of fossil fuels and the release of GHG emissions into the atmosphere, CCS technology can simultaneously advance the nation’s economic, environmental and security objectives.

Figure 5.2: U.S. CO_2 Emissions by Fossil Fuel Type



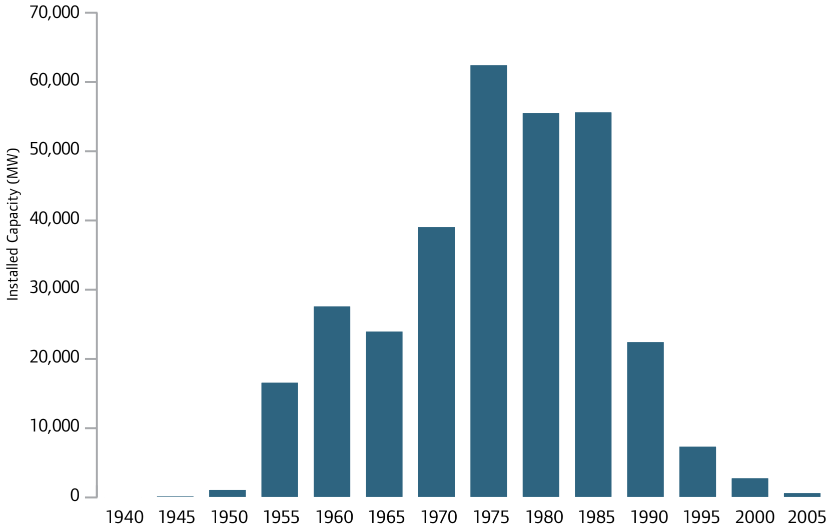
Source: EIA (June 2008), AER 2007, Table 12.3

Technology Pathway Overview

CCS consists of a three-step process: (1) capturing CO_2 from a stationary emitting source, (2) transporting it via pipeline or tanker to a suitable site and (3) storing it in a geological formation.

The capture of CO_2 can be done before or after fuel combustion. Precombustion capture involves the partial oxidation or reforming of a fossil fuel, which separates hydrocarbons into concentrated streams of CO_2 and hydrogen. Conventional postcombustion capture uses chemicals to absorb the CO_2 contained in flue gas before it enters the atmosphere. Another promising approach is oxyfuel combustion, which entails the burning of fossil fuels with pure oxygen. All three technologies have unique advantages and applications. For example, precombustion capture methods are more suitable for integrated gasification combined cycle (IGCC) plants, while postcombustion and oxyfuel combustion approaches are more amenable to conventional fossil-fuel power plants. Precombustion capture already occurs at IG facilities that convert fossil fuels, and organic materials like biomass into more efficient or useful fuels, such as gasoline, substitute natural gas or hydrogen gas.

Figure 5.3: Capacity of Existing Coal Fleet by Vintage



Source: EIA (2007), Form EIA-860

Once captured, CO_2 must be compressed for transportation via truck, ship or pipeline. The pressurization process requires additional energy, reducing overall plant efficiencies. Transportation costs can increase significantly with greater volumes and longer distances but are typically modest compared to capture costs.

Storage entails injecting the compressed CO_2 into a suitable geological formation, such as deep saline reservoirs or mature oil and gas fields. Injection of CO_2 into the subsurface is an established method for enhanced oil recovery (EOR), but long-term storage of CO_2 at the volume and injection rate required for storage emissions from a coal-fired power plant has yet to be demonstrated. Indeed, the revenues produced from sales of CO_2 for EOR could help partially offset the costs of capture and transportation from some CCS applications, although EOR fields have limited capacity and are not presently located near major emissions sources. Once stored, the site requires long-term monitoring and verification to ensure that the CO_2 remains sequestered.

Timely development and deployment of CCS technologies could result in substantial abatement opportunities. Coal-fired power plants have a typical lifespan of 40 to 60 years, which can be further extended by repowering, resulting in slow capital stock turnover and limited technology penetration. However, new construction of U.S. coal-fired plants peaked in the early 1970s, and an unusually large number of plants are likely to be replaced in the 2010–30 timeframe. This impending window of opportunity heightens the importance of accelerating the timetable for CCS technology and avoiding "lock in" of higher GHG emissions for the future U.S. electricity generation fleet. Timely deployment also will allow the United States to export CCS technologies to developing countries before they lock in GHG emissions from their own rapidly growing fleets of coal-fired power plants.

Considerable resources will be required to support the research and development (R&D), demonstration projects and commercial scale-up that will provide the foundation for broad-based CCS deployment. Marshalling these resources will require a shared commitment by government and industry. The ultimate goal of government support should be to make CCS economically self-sustaining so that government assistance can eventually be phased out.

Technology Pathway Barriers

Before deployment of CCS technology can become widespread, it will need to overcome technological, market, legal, regulatory and economic barriers. The United States will need to show tremendous leadership and devote significant resources to demonstrate how these barriers can be overcome. It also will be essential to forge strong public-private partnerships that leverage available resources and properly align incentives.

Technological Barriers

CCS faces technological hurdles that must be overcome before it can be considered a proven technology system. While some capture already occurs during industrial gas processing and gasification and carbon storage currently has several niche applications (e.g., those associated with EOR and injection into saline formations), storage methods beyond these need to be proven if CCS is to live up to its promise as a pathway to sustainable growth. Untested storage sites include saline reservoirs, unminable coal beds and other types of geological formations.

Market Barriers

Technological barriers also often translate into market barriers. Initial demonstration projects for storage methods entail greater market risks than subsequent demonstration projects, because much of the information gained from the initial trial projects will benefit developers of later projects. Utilities and private-sector investors thus have incentives to wait for others to develop and demonstrate new storage options before investing their own resources.

Legal and Regulatory Barriers

The federal government and most states lack a solid legal framework to address the many legal and regulatory issues associated with CCS. For example, stored CO_2 is meant to remain sequestered indefinitely. It is impractical, however, for companies to be responsible for stored emissions in perpetuity, and it is currently unclear where, when and how a company's responsibility over those emissions would end.

The regulatory process through which CCS projects will get approval also is unresolved and will need to be settled if CCS technologies are to be widely deployed. Cross-jurisdictional storage sites present additional difficulties in creating sound regulatory policies.

Furthermore, many power and industrial plants are likely to be in areas that lack adequate geological structures for carbon storage. Because the distances from plant to storage site are likely to be long and traverse many jurisdictions and private properties, private entities may not have the rights to invest in the infrastructure needed for CO_2 transport and storage.

Economic Barriers

Assuming the above barriers are resolved, there will still be significant incremental costs associated with capturing and storing carbon. Even if CCS technology is successfully demonstrated and carbon prices are established, costs in the short term may still be too high to incentivize deployment — a state known as the "valley of death" for new technologies. Additional incentives for early adopters of CCS technology will likely be needed for an extended period while technological learning and economies of scale drive down costs, improve efficiencies and increase capture rates.

Policy Considerations

Although the barriers to unlocking the CCS technology pathway are formidable, they are not insurmountable. Strong and innovative policy leadership coupled with private-sector ingenuity has the potential to both enable the commercial application of CCS technology and accelerate its deployment.

Research and Development

Before CCS can be commercially deployed, continued R&D on cutting-edge generation and capture technologies and experience with underground CO_2 storage under a range of geological conditions are required.

R&D FOR CARBON CAPTURE TECHNOLOGIES

Although the U.S. Department of Energy (DOE) Clean Coal program is providing funding for some CCS R&D projects, the scale of these efforts must be expanded. R&D programs should encompass not only coal conversion facilities but other fuels and major industrial sources of CO_2 emissions, such as petroleum refineries, heavy oil production facilities and cement plants. R&D should be focused on the efficiency of the underlying power generation technology (to reduce operating costs and lower CO_2 emissions) as well as the efficiency of the add-on capture process (to reduce costs and increase capture rates). Precombustion, postcombustion and oxygen-fired combustion capture processes need further investigation, including ways to apply the technology to new plants and retrofits of existing plants. Specific opportunities for R&D investment include advanced solvents or other separation methods for CO_2 capture systems, improved refractory materials for coal gasification, improved oxygen separation systems and advanced turbines able to combust pure hydrogen. As R&D advances, it will be important to make early decisions about the viability of different commercialization paths so that resources can be used effectively.

R&D FOR CARBON STORAGE TECHNOLOGIES

DOE is implementing a range of small-scale carbon storage pilot projects under its Phase II (2005–09) Regional Carbon Sequestration Partnership program. Although these projects have been technically successful, a more aggressive schedule for large-scale projects planned for Phase III (2008–17) is needed.

The oil and gas industry already has extensive experience in subsurface injection. This experience includes EOR using CO_2 injection in mature or abandoned fields, which provides a promising starting point for further advancements in the sequestration of CO_2 captured from power plants and other facilities.[68]

As many experts have emphasized, a number of carefully monitored sequestration tests (5 to 10) using large quantities of CO_2 (more than 1 million tons per year) are critical to obtaining data on the subsurface behavior of CO_2 and the potential for leakage under a range of geological conditions. Potential sites for testing include deep saline reservoirs, mature or abandoned oil and gas reservoirs, and other geological formations. R&D also is needed to improve operational and postoperational monitoring and verification methods, which will be crucial to optimizing performance and lowering risks at commercial-scale sequestration projects, as well as to assuring public confidence. Promising sites for CCS, as identified in the National Energy Technology Laboratory and other surveys, should undergo appropriate characterization to confirm their suitability for long-term CO_2 storage.

Commercial Demonstrations

The biggest unmet need is for a robust program of demonstration projects to gather performance and cost data from integrated CCS technology components at commercial scale power plants, IG facilities and noncoal facilities. Most observers believe six to eight such projects are required in the United States to provide a sound basis for broader national CCS deployment. Optimally, each power plant project should be between 250 and 500 megawatts (MW), depending on the technology being demonstrated, and should be directed at testing the effectiveness of various capture, compression and injection technologies (i.e., precombustion capture IGCC plants, postcombustion capture pulverized coal plants and oxygen-fired combustion-based systems).

Early demonstration facilities could be built in a modular design so that when more efficient capture technologies are developed they can be installed without delaying progress on scaling up CCS technologies. In addition to supporting CCS for the electricity generation sector, the government must continue to provide incentives for development of the nascent IG sector, which can augment the domestic supply of gas and liquid fuels and contribute significantly to U.S. energy security. IG facilities provide a near-term opportunity to demonstrate CCS at commercial scale, given that CO_2 is already being captured at these facilities.

The 250 MW FutureGen project, initiated under a public-private partnership but then cancelled by the federal government in early 2008, was designed to provide useful R&D experience with precombustion capture at an IGCC unit with the back-end production of hydrogen. FutureGen was close to the start of construction (Matoon, IL, had been selected as the project site after a thorough geological assessment) and could still become operational relatively quickly with commitment of sufficient funding.

Even if FutureGen is restarted, however, it will need to be augmented by several other demonstration plants. Because of their experimental nature and high cost, these projects will require substantial government financing. The total cost for six to eight plants is likely to be between $9 billion and $20 billion ($1.5 billion to $2.5 billion per plant). Since each demonstration plant will eventually be operated commercially, industry should cover the costs of the base (non-CCS) plant and then engage in a public-private partnership to share in the construction and operation of the CCS system. Government action is critical in this phase of CCS development because disincentives to making initial investments and conducting the first technology demonstrations act as barriers to deployment.

Commercial Deployment

Even with successful demonstration projects, broad CCS deployment may not occur because of the cost and performance differential between facilities with and without CCS, as well as the consequential decline in plant efficiency and the increases in electricity costs. These disincentives amount to economic barriers to deployment that are likely to persist even in the presence of a carbon price, given that the near-term price is likely to be lower than the per-ton cost of capturing and storing CO_2.

Several financial tools should be used to level the playing field for the deployment of CCS-equipped facilities. Some of these tools were authorized in the energy tax package, which was part of the financial rescue legislation that became law in October 2008. Important tools that reduce the capital and operational costs of CCS-equipped facilities and stimulate investment include:

- Loan guarantees for CCS-equipped power plants, IG facilities, refineries and other manufacturing operations;[69]
- Tax credits for each ton of CO_2 sequestered;[70] and
- Investment and production tax credits (PTCs) for CCS facilities.[71]

Consideration should be given to structuring these incentives to first support an "early mover" program and then, later, a larger "commercialization" program. The early mover program would apply to the first 15 gigawatts (GW) or equivalent (GWe) of CCS plants (some involving EOR) and would cost the government in the range of $20 billion to $25 billion over 15 years. This and the demonstration program would proceed in tandem with a timeframe of 2010–25. The commercialization program would provide a lower level of financial support (probably in the form of sequestration tax credits) than for early movers, but it would encompass a greater diversity of plants (as much as 50 GW of power plant and integrated gasification projects as well as large manufacturing operations, such as refineries) that meet minimum levels of CCS capture and storage. This program would be designed to apply in the post-2025 period, a time in which CCS costs would be expected to gradually decline due to technological improvements and more operating experience.

Enabling Regulatory Frameworks

A comprehensive program of CCS R&D investment, demonstration projects and commercial deployment will not succeed until the government's commitment to this technology pathway is expressed through the creation of a stable and practical legal and regulatory framework at the state and federal levels that permits prudent risk taking and investment by the private sector. Since CO_2 injection is uncharted territory outside oil- and gas-producing states and will involve lender commitments of many billions of dollars, this framework must clarify industry obligations, provide reasonable certainty that CCS projects will be approved without delay or unexpected costs, and impose limits on long-term financial exposure for CO_2 leakage and other unexpected events. The current economic downturn only increases lenders' and project developers' need for legal and regulatory stability.

The Environmental Protection Agency (EPA) is developing regulations that would provide for selection, characterization and permitting of sequestration sites, monitoring for potential leakage and site closure at the completion of the injection phase. A number of states have already developed a reliable framework for injection of CO_2 for EOR. These regulations will be essential for selecting sites that can safely and permanently store CO_2, monitoring the stability of the storage sites, and providing confidence that CO_2 will behave as predicted in its subsurface storage. The EPA proposal raises complex issues that must be carefully addressed to provide the predictable permitting and necessary site operation controls to encourage CCS deployment while fostering public confidence. Industry should be actively engaged as the rulemaking process is concluded. The support and goodwill of all parties (coupled with close congressional oversight) will be essential to ensure that worthy CCS projects are not blocked by unmeritorious technical and assurances challenges.

Enabling Legal Frameworks

Because of limits on EPA's authority, Congress will need to provide developers and operators of CCS plants with protection from long-term responsibility for stored CO_2. No company can assume responsibility for the thousands of years of containment that might be necessary. Further, insurers have signaled that they can only offer liability protection on a short-term basis and will require much more data and experience before any long-term financial mechanisms can be formulated. For demonstration and early mover projects, this transfer of responsibility should occur by having the government take title to the stored CO_2 at the plant gate. Once CCS is more mature, responsibility should be transferred after injection has ceased and a postclosure certificate has been issued.

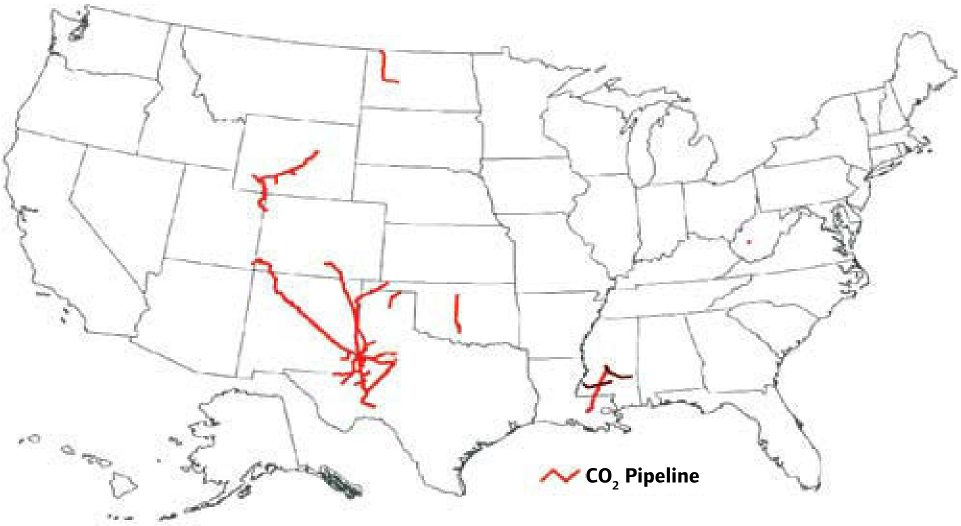
Congress also should provide for the government to take responsibility for managing and monitoring inactive sites lacking any potential for future EOR, with site operators contributing to a fund to cover the long-term costs of site management and related responsibilities. Any indefinite industry responsibility for overseeing these sites is impractical given the insistence of investors on defining risks, the finite lifespan of any business enterprise and the need for meaningful long-term site stewardship.

Congress, working with states, also will need to authorize use of eminent domain authority or other mechanisms to enable developers to responsibly acquire the necessary property interests required to store CO_2 in deep geological formations. Ownership of pore space in some states is unresolved. In addition, jurisdictions with complex rules governing ownership of subsurface rights may delay CCS projects for years unless a process is created for resolving ownership claims and compensating property owners fairly and expeditiously.

Infrastructure Issues

The national deployment of CCS across multiple U.S. regions will require an extensive network to transport CO_2 from sites where it is captured to storage sites. The necessary infrastructure will include pipeline, rail, barge and truck transportation systems. In some cases, storage sites 200 miles or more from the source of CO_2 emissions constitute serious geographic barriers to establishing an efficient system for transport and storage of CO_2. A 4,000-mile CO_2 pipeline system exists now, mostly in the Southwest, but is far too limited in reach and capacity to meet the demands created by widespread CCS deployment. Priority in building out the national pipeline network should be given to regions with the most promising storage sites and sources.

Figure 5.4: Existing CO_2 Transportation Pipelines



Source: Parfomak, Paul & Peter Folger (Jan 2008), *Carbon Dioxide Pipelines for Carbon Sequestration: Emerging Policy Issues,* Congressional Reporting Service Report, p. 5

Summary of Policy Considerations

A robust program combining R&D investment, cost-sharing, regulatory and legal frameworks, and financial incentives will be necessary to ensure that CCS technologies are developed and incorporated in the U.S. (and global) energy and manufacturing infrastructure as soon as possible. This program must not only provide incentives that will persuade plant developers to make substantial capital commitments but also must establish a sense of certainty about long-term government support for CCS technology, as well as provide the regulatory and legal stability required to justify private-sector risk taking on a large scale.

Policy Recommendations

- Invest \$1 billion per year (\$800 million in government funding) for 15 years in R&D for fossil fuel power plant efficiency and capture technologies.
- Accelerate large-scale sequestration testing under diverse geological conditions.
- Fund six to eight commercial-scale demonstration projects (roughly \$2 billion per 500 MW plant) for a range of technologies and engage in a public-private partnership to share the responsibilities for constructing and operating the added CCS technology.
- Create incentives for an "early mover" commercial deployment program (first 15 GW), including the beginning of a CO_2 pipeline transportation infrastructure, using loan guarantees, tax credits and other vehicles.
- Create incentives for a post-2025 "commercialization" program (up to 50 GW) with continuing government support at a declining level as CCS matures and costs decrease.
- Adopt a comprehensive regulatory and responsibility framework, including postclosure site management and responsibility protection and eminent domain or other mechanisms to resolve ownership issues and acquire property rights to pore space.
- Evaluate regulatory needs to create a national CO_2 pipeline network.
- Expand the National Transmission Corridor for Electricity to include CO_2 pipelines and authorize the expedition of pipeline permits.
- Structure financial incentives for infrastructure to include 100 percent expensing of new investments to handle and transport CO_2.

Chapter 6

Grid Modernization

Modernizing the electric power grid is essential for enabling and enhancing the benefits of advanced technology pathways, such as building efficiency, renewable power, nuclear power and carbon capture and storage (CCS) technologies. A modernized electric power grid can play a multifaceted role in meeting the sustainable growth challenge. Improving grid efficiencies can reduce the substantial losses associated with electricity transmission and distribution, decreasing the amount of generated electricity required to support a given level of demand. Integrating demand-side management technologies into the grid will provide consumers with information to make more economical decisions and the tools to implement them. Extending the grid to locations rich in renewable resources can enable greater deployment of renewable power technologies and reduce the nation's reliance on fossil fuels. Finally, modernizing the grid can improve security by enhancing the system's resiliency and reducing the probability that a targeted attack or cascading series of failures could bring the nation's financial, communications and security systems to a standstill.

Enabling Pathway Overview

The U.S. electric power grid is an extensive, complex network of interconnected power lines that connects generating stations to load centers and delivers electric power to end users. Constructed incrementally over the past century by vertically integrated local generation and distribution utilities, the grid currently consists of more than 300,000 miles of transmission lines connecting over 9,200 electric generating units with more than 950,000 megawatts (MW) of generating capacity.[72]

For most of the 20th century, the national electric grid was technologically advanced and an engine of economic growth. After decades of underinvestment, however, the grid has recently become a relatively antiquated, balkanized and geographically limited network that is poorly equipped to deal with the demands of a modern electric power sector. For instance:

- Investments in the grid have lagged behind what is required to meet rising demand, resulting in growing congestion, declining reliability, and more frequent "bottlenecks" and disruptions in delivery. Congested transmission paths now affect many parts of the grid across the country. It is estimated that power outages and service disturbances cost the U.S. economy somewhere between $25 billion and $180 billion in lost business and lost efficiency annually.[73]

- Managed by approximately 150 different control centers and owned by roughly 500 different entities, the grid's highly fractured organization results in a limited capacity to quickly and effectively respond to spikes in demand and increased congestion.
- Largely constructed well before utility-scale renewable power was economical, the existing grid does not extend into many resource-rich locations — limiting the ability to integrate renewable power technologies, such as wind and solar, in a cost-effective manner.

Grid modernization can be achieved through a three-pronged approach featuring: (1) upgrading the existing transmission network; (2) extending the transmission network to locations with high-quality renewable resources; and (3) deploying advanced technologies to make the grid smarter, more efficient and more resilient. Investments in the grid would increase the system's capacity to manage loads more effectively and thereby reduce the need for utilities to build additional peak generating capacity. Extending the grid to locations rich in renewable resources will facilitate the deployment of renewable power technologies and reduce the consumption of fossil fuels. A smarter grid will enable operators to control loads, provide consumers with real-time information to minimize on peak electricity consumption, facilitate greater penetration of renewable power and reduce the need for costly back-up power sources.

Pathway Barriers

Regulatory Barriers

Regulatory inertia is a significant impediment to grid modernization. One of the national grid's most persistent issues is its high degree of regulatory fragmentation, which reduces the ability of operators to respond quickly and effectively to peaks in demand and grid congestion. More than 3,000 different utilities exercise decisionmaking authority over system transmission, service and storage, including investor-owned utilities; federal, state and municipal government agencies; rural electric cooperatives; and independent transmission companies.[74] This decentralized regulatory structure may have been appropriate for transmission projects that were meant to improve the reliability of the grid in certain regions. Today, however, security and environmental objectives need to be considered to a much greater degree, and the current regulatory system makes the creation of a more modern national grid difficult to organize and coordinate.

Policy inconsistency between state and federal regulators also perpetuates fragmentation within the national framework.[75] Compounding the effects of these barriers, some state regulatory policies discourage investment in modern, more efficient technologies because of regulatory lag and uncertainty regarding full recovery of costs associated with these investments.

Market Barriers

Electricity consumers and public utility commissions are often unaware of or undervalue grid modernization improvements. The successful deployment of demand-side management technologies, such as "smart metering," depends in part on consumers' willingness and ability to monitor and modify their energy consumption patterns on a regular basis. Increased consumer education and engagement will provide additional assurances to utilities and energy providers that investments in such technologies will generate a sufficient return.

Economic Barriers

A substantial barrier to grid modernization is the challenge of attracting investment in the transmission system and the deployment of new "smart" technologies that keep pace with new demands placed on the system. The costs of deploying grid modernization technologies are significant and can have longer payback periods than other energy investments. They also are often borne by utilities and energy providers, while the benefits of an enhanced grid are shared by society.

Federal- and state-level financial incentive programs are urgently needed to enable projects to pass financial hurdles and kick-start investment on the part of utility companies. Companies should be financially rewarded for investment initiatives in the grid that will ultimately result in net societal gains, including reduced dependence on foreign oil, smaller environmental impact and heightened national security. Financial incentives also must address the need for greater research and development (R&D) in the electric utility sector, which currently comprises only 0.2 percent of total industry revenue yet is vital to accomplishing grid modernization.[76]

Policy Considerations

Spurring Investment

Without a national initiative to greatly expand interregional transmission capacity, it is expected that the utility industry will invest about $31.5 billion in transmission facilities between 2007 and 2010.[77] The higher level of investment required to build a reliable national grid, as well as effective and efficient long-term planning for grid modernization, may be hindered by the disaggregated ownership of system assets. Local investments in new transmission infrastructure and technology, unmatched at the regional or national levels, will not serve national energy policy goals as effectively as regional and interregional investment planning, particularly as relates to high-voltage transmission lines.

Deploying Smart Grid Technology

Advances in communications, materials, Internet and computer technologies have made a "smarter" electric grid achievable. Embedding advanced technologies in transmission assets can greatly improve the reliability, security and efficiency of the electric grid, as well as its ability to facilitate the use of electricity generated by renewable energies. Smart grid capabilities may also be critical for the potential electrification of the nation's transportation fleet because the charging of large numbers of electric vehicles would need to be wisely managed to be efficient and economical. In fact, charged electric vehicles might one day even serve to help supply temporary peak load power back to the grid via smart grid technology.

It is estimated that a 4 percent peak load reduction could be achieved using “smart grid” technologies.[78] Recognizing the potential of a smart grid, the U.S. Department of Energy (DOE) has identified key characteristics that grid modernization policy should seek to promote:

- The ability to “self heal” by performing continuous self-assessments to detect and analyze glitches and restore grid components or network sections;
- Greater feedback by consumers about transmission services and their electricity use to allow for improvements to both the grid and the environment, as well as reductions in the cost of delivered electricity;
- Deterrence of physical or cyber attack and improved public safety;
- Accommodation of renewable production with new grid transmission and storage options;
- More efficient markets through reduction of system waste and the limiting of transmission congestion; and
- Implementation of grid maintenance programs to optimize efficient asset and equipment use.[79]

The Energy Policy Act of 2005 included a number of smart metering provisions. These included a requirement that states and nonregulated utilities consider providing time-based rates and advanced metering to all consumers, that the Federal Energy Regulatory Commission (FERC) conduct an annual assessment on demand response and advanced metering,[80] that DOE issue a report to Congress on demand response potential, and that all federal buildings be equipped with advanced metering.[81]

In December 2007, new energy legislation entitled the Energy Independence and Security Act (EISA) of 2007 was signed into law.[82] The act designated the National Institute of Standards and Technology as the lead agency to develop standards and protocols for grid modernization. It also created the Smart Grid Regional Demonstration Initiative under DOE and established the Smart Grid Investment Matching Grant Program.[83] More recently, as part of the Emergency Economic Stabilization Act of 2008, Congress has provided incentives for the deployment of smart meters by accelerating the recovery period for depreciation of smart meters and smart grid systems.[84]

Advanced monitoring technologies, such as advanced metering infrastructure (AMI) technology and self-healing features, can increase system capacity and provide more cost-effective asset use by providing information feedback and incentives for consumers to reduce usage. AMI is not a single technology innovation but a fully reconfigured electricity infrastructure that includes improved home network systems, smart meters, more responsive communication networks, meter data management systems and data integration into software application platforms.[85]

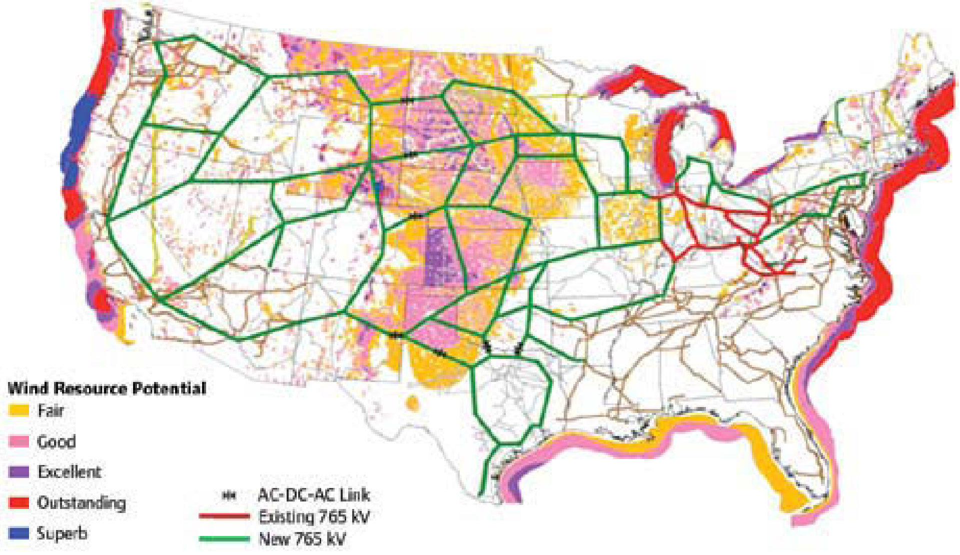
Other AMI technologies are still in development. For example, new technologies, such as a Programmable Communicating Thermostat (PCT), could connect with a customer's meter through a Home Area Network allowing the utility to change the settings on the thermostat based on load or other factors. PCTs are not yet commercially available but are expected to be available within a year.[86]

Enabling the Deployment of Renewables

New investments in a modern transmission system would ease significant constraints on the deployment of renewable and alternative energies by expanding grid capacity and promoting efficiency. A recent study by American Electric Power and the American Wind Energy Association analyzed transmission requirements associated with allowing wind energy to supply 20 percent of the nation's electricity needs by 2030. The study concluded that approximately 19,000 miles of extra-high-voltage (765 kilovolt [kV]) lines would provide a sufficiently robust interstate overlay grid at a cost of about $60 billion.[87] To put this into perspective, current estimates are that the utility industry will invest about $31.5 billion in transmission facilities from 2007 to 2010 in the absence of policies to ramp up investment.[88]

In addition to advocating increased investment, policymakers have championed the inclusion of an extra-high-voltage (EHV) overlay technology in any transmission modernization plan.[89] An EHV system would be a high-capacity interregional network of high-voltage (345 kV and higher) transmission lines that would augment, but not replace, existing lower-capacity networks.[90] This modernized system would link large-scale clean-energy facilities with major population centers, enhance the reliability and robustness of transmission, and be considerably more efficient than the current grid.

Figure 6.1: Potential Grid Investments to Facilitate 20 Percent Wind Energy Scenarios by 2030



Source: DOE, EERE (June 2008), *20% Wind Energy by 2030*, p. 12, Figure 1.10

Policy Recommendations

- Congress should fully appropriate funds for the programs authorized in EISA, including the DOE Smart Grid Regional Demonstration Initiative and the Smart Grid Investment Matching Grant Program to set in motion the grid modernization process as expeditiously as possible.
- Congress should provide the funds necessary for the National Institute of Standards and Technology (within the Department of Commerce) to help develop protocols and model standards to achieve interoperability of smart grid devices and systems.
- DOE, industry and the national labs should collaborate to share resources for the development of grid modernization technologies.
- DOE should develop a program to assist state regulators and utilities by cataloging and disseminating information regarding smart grid best practices and providing technical, educational and regulatory policy assistance.
- DOE should be given an important role to play in helping to ensure that measures are developed to protect the new grid from external threats.
- FERC should continue to exercise its authority under existing law to provide incentives for upgrading the nation's transmission system and investing in advanced transmission technologies.
- The federal government should demonstrate policy leadership with respect to cost allocation, planning and siting of transmission needed to incorporate wind and solar resources into the grid.
- State regulators should be encouraged to develop predictable cost recovery and return on investment methodologies for regulated utilities making investments in smart grid technologies.
- State regulators should consider educational initiatives to inform electricity consumers about the benefits of a smart grid.
- The electricity industry's engineers and technicians should undergo training and develop new skills to match the increasing "intelligence" of the electric grid.

Chapter 7

Advanced Vehicle Technologies

While strategies aimed at increasing building efficiency and decarbonizing the U.S. electric power system are necessary components of a sustainable growth agenda, they alone are insufficient to achieve the greenhouse gas (GHG) emissions targets or energy security goals advocated by some policymakers. A robust approach to the sustainable growth challenge also must include strategies aimed at transforming the U.S. transportation sector, which accounts for approximately one-third of the nation's CO_2 emissions and two-thirds of its petroleum consumption.[91]

In particular, the modernization of the vehicle fleet, especially light-duty vehicles, is essential to curbing energy consumption, diversifying fuel demand and reducing GHG emissions in the transportation sector. Light-duty vehicles, such as passenger cars and light trucks, represent 60 percent of energy consumption in the transportation sector. Accordingly, strategies that result in significant improvements in vehicle efficiency and fuel diversity in the light-duty vehicle fleet can have substantial impacts on the U.S. energy equation and carbon footprint. Many of the same strategies also could help to lower emissions from heavy-duty trucks, buses and other vehicles.

Fleet modernization and the benefits that accompany it will not materialize overnight. Given that new vehicle sales represent a small fraction (6 to 7 percent) of the stock of operational vehicles and that the typical passenger car or light truck has a lifetime of about 16 years, the natural rate of turnover of the light-duty vehicle stock is relatively low — impairing rapid market penetration for new technologies.[92] Turnover can be accelerated through policies that incentivize retirement of older vehicles and purchase of greatly improved newer ones, such as the "cash for clunkers" legislation currently being considered by Congress. Even with accelerated rates of vehicle retirement, however, fleet modernization will require far-sighted policies that accelerate the development of advanced vehicle technologies and facilitate their gradual, sustained deployment over an extended period of time.

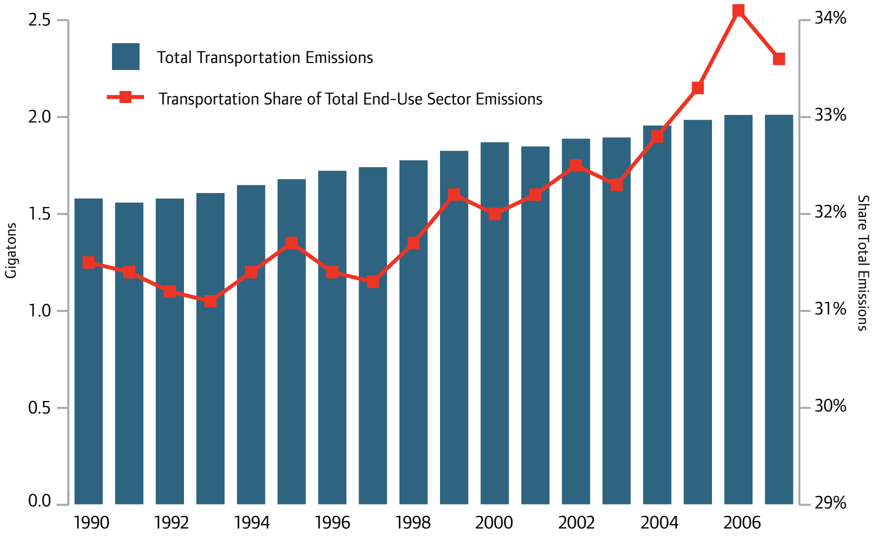
The vehicle manufacturing industry has already developed and deployed significant advanced vehicle technologies that improve fuel economy and reduce petroleum consumption. While the industry is devoting high levels of research and development (R&D) investment to these technologies, strong policy leadership can complement and enhance these efforts. All advanced vehicle technologies face unique challenges to commercialization, and formidable barriers will need to be overcome to bring these technologies to market. Strong policy leadership can help to resolve many of these challenges in the short and medium term, with the goal of accelerated and sustained technology deployment in a manner that is consistent with market competition and consumer demand.

Technology Pathway Overview

The transportation sector is both the lifeblood of economic growth and a significant source of GHG emissions. According to a recent Environmental Protection Agency (EPA) study, GHG emissions in the transportation sector rose from 29 percent of total U.S. energy-related CO_2 emissions in 1980 to 34 percent in 2007, increasing by a larger amount than emissions attributable to any other economic sector.[93] Despite existing laws that mandate significant improvements in fuel economy, transportation emissions are forecast to continue increasing because of factors such as economic growth, increased movement of freight by trucks and aircraft, and continued growth in personal travel.[94]

Given the decentralized, diverse and complex nature of transportation energy consumption and emissions, sustainable evolution and transformation in the sector will require a broad-based, multipronged approach. For example, a rising number of vehicle miles traveled can partially offset or even wholly erase hard-earned improvements in vehicle efficiency. Improved urban planning can measurably reduce miles traveled while increasing the availability, convenience and use of mass transit options — vital steps that incentivize the use of more efficient means of travel. Measures to relieve traffic congestion and decrease vehicle idling also can contribute to a more sustainable transportation system.

Figure 7.1: CO_2 Emissions in the Transportation Sector



Source: EIA, AER 2007, Environmental Indicators, Table 12.2

Improving energy efficiency and fuel diversity in the light-duty vehicle fleet offers the greatest potential to achieve large-scale emissions reductions in the transportation sector while also enhancing security. There is a wide range of advanced vehicle technologies both on the road and under development that are likely to offer cost-effective opportunities for reducing GHG emissions. Advanced features for conventional vehicle engines (e.g., cylinder deactivation, variable valve timing, direct injection, turbocharging), transmissions (e.g., six-speed, seven-speed, continuously variable transmission, microhybrids), and frames (e.g., aerodynamics, weight reduction, tire improvements) can substantially improve fuel economy and reduce CO_2 emissions. According to recent studies, for example, continuous improvements in gasoline internal combustion engine (ICE) technology may be able to deliver energy savings of as much as 45 percent by 2035 for vehicles with the same weight and performance characteristics as today's vehicles.[95] Such fuel economy improvements would exceed the gains called for in the Energy Independence and Security Act (EISA) and would contribute significantly to CO_2 reductions. Greater penetrations of advanced diesel and natural-gas-fueled vehicles also can reduce CO_2 emissions per vehicle mile traveled. Vehicles that can run on alternative fuels, such as flex-fuel or natural gas vehicles, can help to diversify the fuel mix of the light-duty transport sector.

Other advanced vehicle technologies will face more significant cost hurdles than the advances in ICEs described above but have the potential to fundamentally transform energy use in the transportation sector in the coming decades. These include hybrid electric vehicles (HEVs), plug-in electric vehicles, all-electric vehicles and fuel cell vehicles. Although these technologies are in various stages of development and most have not yet gained acceptance in mass consumer markets, they have the potential to measurably curb the consumption of fossil fuels, especially petroleum, and sharply reduce GHG emissions if widely deployed.

Hybrid Electric Vehicles

HEVs incorporate traditional ICEs with advanced electric motors and battery technologies to achieve lower GHG emissions through greater operating efficiency. HEVs run on a combination of liquid fuel and electrical energy generated onboard the vehicle and are typically manufactured in one of two configurations:

- **Series hybrids** (e.g., Chevy Volt) use the ICE only to generate electricity, which is stored in the battery and used to power the electric motor, which propels the wheels. Extended-range electric vehicles use this configuration.
- **Parallel hybrids** (e.g., Toyota Prius) connect both the ICE and electric motor to the vehicle's drive shaft, allowing driving conditions and acceleration levels to determine whether the motor or engine provides primary power.

In both HEV configurations, the combustion engine is designed to meet average power requirements, relying on the electric motor to help provide acceleration and respond to peak energy demand. This can result in smaller engines with lower emissions. There are many possible hybrid configurations that can deliver various efficiency levels in return for corresponding levels of increased vehicle cost and complexity. These configurations range from “mild” hybrids that may offer a 10 percent efficiency gain to “strong” hybrid designs that can offer efficiency gains as high as 45 percent over conventional vehicles.[96] Studies indicate that presently available HEVs are capable of achieving on-road fuel economies of roughly 50 miles per gallon (mpg).[97] It is estimated that HEVs have saved 230 million gallons in liquid transportation fuel in the United States since their introduction to the commercial market in 1999.[98]

HEVs are a mature advanced vehicle technology and have the potential for widespread deployment throughout the transportation sector, including in passenger vehicles, buses and light trucks. Partially spurred by a combination of tax credits and relatively high gasoline prices, HEVs accounted for more than 1 million vehicles on the road in 2007, up from fewer than 200,000 units in 2004.[99] Despite this growth, HEVs represented just 2.5 percent of new car sales in the United States in 2008, and they have experienced declines in sales volume and market share as gasoline prices have retreated from record highs.[100]

Plug-In Hybrid Electric Vehicles

Plug-in HEVs (PHEVs) apply additional technological innovations to the relatively mature technology already used in HEVs.[101] PHEVs have larger batteries than HEVs that are able to provide more electricity and improve vehicles’ all-electric drive range. Unlike batteries in standard hybrids, batteries in PHEVs also can be recharged through conventional electrical outlets found in residential and commercial buildings.

A PHEV’s more extensive use of its electric motor results in greater operating efficiency than either traditional combustion engine vehicles or current HEV models. This can result in lower GHG emissions, depending on the source of electricity used to charge the battery. Emissions reductions would be modest if the source is conventional coal-fired power but could be substantial if the source is a low-carbon electricity source, such as renewable power.

Estimates for the all-electric range of a PHEV — the maximum distance traveled before the vehicle’s combustion engine is needed — vary from 5 to 60 miles, depending on the size of the vehicle, the storage capacity of its battery and driver behavior. The range determines the extent to which electricity can supplant petroleum as the vehicle’s primary energy source. The Energy Information Administration estimates that, on average, PHEVs with an all-electric range of 40 miles could reduce petroleum consumption per vehicle by 58 percent as compared to similarly sized HEVs and even more when compared to conventional ICEs. It is estimated that PHEVs with all-electric ranges of 10 miles would, on average, eliminate 21 percent of petroleum consumption.[102] These savings would be higher for drivers with short commutes and lower for those with long commutes, as the percentage of miles driven using electricity would vary.

PHEVs have not yet been introduced to the U.S. commercial market, although technological developments continue to improve their cost competitiveness and viability. Attention focuses on issues of battery cost and durability, which are likely to improve as the technology matures through the early stages of development. This is likely to occur over the first decade of commercial sales, with higher volumes of mature PHEV technologies possible thereafter. Widespread deployment of PHEVs would diversify the transportation fuel mix by using energy sourced from the national electric grid. In addition, "vehicle-to-grid" concepts are being explored that may facilitate two-way electrical flows between PHEVs and the grid, allowing electricity stored in the vehicle battery of stationary, plugged-in vehicles to flow back into the grid to help supply electricity during peak demand.

All-Electric Vehicles

Unlike HEVs and PHEVs, all-electric vehicles (EVs) are powered solely by an electric motor. To accommodate its exclusive reliance on electrical energy, EV batteries are larger than those found in either HEVs or PHEVs and can be charged by plugging an onboard charging apparatus into a standard electrical outlet or at an external charging station. Several different kinds of batteries have been adapted for use in EVs. Traditional lead-acid batteries operate using proven technology but lack the power density and storage capacity of more recently developed batteries, such as nickel metal hydride, sodium "zebra" and lithium-ion batteries. As with hybrids, EVs use regenerative braking to recapture energy generated by the braking process, otherwise wasted in conventional vehicles, and return it to the battery.

EVs can reduce GHG emissions by even greater amounts than can HEVs or PHEVs, but actual reductions depend on the electricity source. Because there are no exhaust emissions from the vehicle itself, they are technically considered zero-emissions vehicles. They also have significantly lower operating costs under most gasoline and electricity price assumptions, costing hundreds of dollars less per year to fuel than combustion engine vehicles, according to some estimates.[103] Those fuel cost savings could, however, be reduced or even reversed if drivers recharge their vehicle batteries during times of peak or near-peak electricity demand. Electric motors also have far fewer parts than combustion engines, potentially reducing the frequency and cost of maintenance and part replacement.

Nevertheless, the overall costs of driving electric vehicles still exceed the cost of driving conventional vehicles because of the significantly higher purchase price of EVs. Despite positive developments in battery technology, their high costs currently make EVs largely unavailable to most consumers. Furthermore, EV models typically boast drive ranges of up to 100–150 miles per charge and take four to eight hours to fully recharge, falling short of many drivers' needs.[104] In addition, EVs lack sufficient infrastructure support (i.e., charging stations, battery changing stations) needed to allow drivers to conveniently travel long distances. Some local governments have begun purchasing EVs, however, using "neighborhood electric vehicle fleets" for commuting, hauling and delivery in local areas.[105]

Fuel Cell Vehicles

Fuel cell vehicles use hydrogen in clean chemical reactions that power an electric motor, which in turn powers the entire vehicle. Fuel cells are types of chemical batteries that facilitate the oxidization of hydrogen with oxygen from the outside air to produce electrical energy. They are typically arranged in stacks to deliver sufficient power. Hydrogen for the electrochemical reaction is supplied to the fuel cells either through a hydrogen-rich fuel (e.g., methanol, natural gas or gasoline) which is processed (reformed) on board the vehicle, or as pure hydrogen which has already been reformed. As much as 40 to 60 percent of the energy in the hydrogen fuel is used to power the vehicle.[106] This high operating efficiency contrasts with conventional combustion vehicles, which use at most 20 percent of the energy in a gallon of gasoline to power the vehicle.[107]

Fuel cell vehicles also have operating advantages over battery-powered vehicles. Although often likened to batteries in electric vehicles, fuel cells do not need to be recharged, producing electrical energy via chemical reaction as long as there is a steady supply of hydrogen fuel. Fuel cell vehicles using pure hydrogen fuel emit only water vapor as a by-product. Significant indirect (i.e., "nontailpipe") emissions result from the production of hydrogen using the most common methods available (i.e., natural gas reformation), although those emissions are lower on a lifecycle basis than the emissions produced by either internal combustion vehicles or HEVs.[108] More advanced methods, however, could apply carbon capture and storage (CCS), renewable power or nuclear power technologies to produce hydrogen with little or no resulting carbon emissions.

Technology Pathway Barriers

The most pressing barriers to the widespread deployment of some advanced vehicle technologies include insufficient infrastructure, high technology costs and other obstacles to consumer adoption. These barriers are inherently interrelated. For example, in the absence of sufficient and convenient refueling infrastructure, customers are understandably hesitant to invest in vehicles that depend on such networks. In the face of uncertain consumer acceptance and unreliable market demand, fuel suppliers are often unwilling to invest in building a network of refueling stations, and manufacturers are reluctant to invest in the mass production of advanced vehicles. Similarly, technology costs will be minimized as a national mass market for advanced vehicles develops, but a critical mass of advanced vehicles will be difficult to realize until vehicle costs reach generally affordable and cost-competitive levels. These challenges are compounded by consumers' reluctance to invest in new technologies and their tendency to undervalue future fuel savings. Thoughtful policies should seek to address these barriers holistically while clearly recognizing the costs and benefits to consumers and taxpayers of enabling advanced vehicle technologies.

Infrastructure Barriers

The widespread use of several advanced vehicle technologies will require investments in infrastructure, such as new stations for recharging electric vehicles and a fuel distribution network for hydrogen vehicles. The lack of infrastructure for advanced technology vehicles creates a paradoxical problem in which consumers are wary of investing in vehicles for which there is insufficient infrastructure, while the private sector is reluctant to invest in infrastructure before a critical mass of advanced technology vehicles has been reached to support it. Resolving these "chicken and egg" problems will require business leaders and policymakers to work cooperatively to forge strategies for developing refueling networks in concert with growing market demand and vehicle deployment.

Advanced gasoline, diesel and non-PHEVs do not face infrastructure barriers given their ability to use the existing transportation fuel infrastructure. Other advanced vehicles, however, will require extensive infrastructure investments to enable their widespread deployment and unlock their full potential. In some cases, these infrastructure challenges can be minimized by targeting infrastructure regionally to reduce the size of the initial "chicken and egg" problem and then grow the infrastructure geographically over time.

Infrastructure Barriers: The Electric Power Grid

The nation's electric power infrastructure does not present any immediate barriers to the gradual introduction of PHEVs or EVs, especially if vehicles are charged during off-peak hours. The limitations of an already stressed electric power grid, however, could impair the rapid and widespread deployment of such vehicles in the long term.[109] Consequently, grid modernization is a critical enabling strategy for unlocking the full potential of electric vehicles.

For example, by developing and deploying "smart metering" technologies and time-of-day pricing, consumers can monitor and respond to real-time market prices for electricity — incentivizing them to recharge their cars during off-peak hours when electricity is cheapest. Likewise, with the assistance of advanced grid technologies, grid operators may be able to extract small amounts of electricity from millions of grid-connected electric vehicles during peak hours. The capacity to draw electricity from vehicle batteries during peak hours and recharge them during off-peak hours has the potential to measurably smooth the electricity demand curve — enabling a more efficient deployment of both traditional baseload capacity and intermittent power sources, such as wind and solar.

Infrastructure Barriers: Refueling and Maintenance

ELECTRIC VEHICLES (PHEVs AND EVs)

The electrification of the vehicle fleet will require significant investments to expand the availability and convenience of recharging networks. Currently there are about 500 charging stations nationally, the vast majority of which are located in California, and there are ongoing efforts in California and Oregon to build additional infrastructure.[110] For example, the mayors of San Francisco, San Jose and Oakland recently announced a plan to spur electric vehicle deployment in the Bay Area, including policies to expedite permits for installing charging outlets, establish recharging outlets in government buildings and create incentives for employers to install charging outlets at workplaces.[111] In Oregon, Governor Kulongoski announced that Nissan will supply EVs for the state's vehicle fleet starting in 2009.[112] As part of that effort, the state and Nissan plan to collaborate in developing a supporting network of charging stations.

Despite this progress, the existing recharging infrastructure cannot accommodate the widespread electrification of the vehicle fleet. Nationally, public electric charging stations make up less than 10 percent of alternative fueling stations (including fuels such as compressed natural gas, E85 ethanol, biodiesel, hydrogen and liquefied natural gas) and a tiny fraction of total fueling stations.[113]

Individuals with home garages and other secure parking locations will be able to leverage existing electrical infrastructure to recharge vehicles overnight with inexpensive off-peak electricity. It is likely, however, that new infrastructure will be needed to assist individuals who lack convenient opportunities to recharge vehicles at home and to expand the total potential market for advanced electric vehicles. Additionally, many drivers who have garages where they will be able to charge their vehicles often have long commutes and will want to charge their car batteries while away from home. A ubiquitous network of recharging stations in common destinations (e.g., public parking areas, workplaces, etc.) would allow drivers to "top off" batteries during the day, maximizing the effective all-electric range and improving the convenience of owning and operating a PHEV or EV. However, if vehicles are recharged during times of peak or near-peak electricity demand, fuel cost savings may be significantly reduced and possibly reversed. The effective range and convenience of these vehicles also could be dramatically enhanced by advances in battery recharging times or the construction of a "battery swapping station" network, which would enable customers to acquire a fully charged battery in minutes.

FUEL CELL VEHICLES

In contrast to other advanced vehicle technologies, the widespread deployment of fuel cell vehicles would constitute a more significant paradigm shift in the transportation sector that would necessitate the construction of new infrastructure for producing, transporting, distributing and storing hydrogen. Nationally there are only 58 hydrogen fueling stations, and many of these are used to support test programs.[114] While substantial investments in hydrogen vehicle infrastructure would eventually be required to support the widespread deployment of hydrogen vehicles, such efforts will be premature until fuel cell vehicle technologies meet the economic and performance needs of consumers. The scale of these investments can be minimized initially by focusing on distinct geographic regions to begin the initial rollout of refueling infrastructure. Vehicle manufacturers, hydrogen producers and government will need to work cooperatively to develop transition strategies that will facilitate the construction of the initial hydrogen production, distribution and refueling infrastructure as fuel cell vehicles move closer to commercialization.

Technology Cost Barriers

Despite ongoing R&D and periodic technological breakthroughs, the costs associated with advanced vehicle technologies in many cases remain prohibitively high for successful market deployment and acceptance. Much of the cost disadvantage of HEVs and PHEVs can be attributed to expensive battery technology. Even hybrid models experiencing relative market success, such as the Toyota Prius and Honda Civic hybrids, are priced significantly higher than comparably sized conventional ICE vehicles.

Battery components account for an even greater proportion of the cost in EVs, which use larger batteries than either HEVs or PHEVs. Developing low-cost technology that provides high storage capacity, optimal energy-to-power ratios, and quick recharging capabilities at the smallest size and lightest weight poses challenges to vehicle and battery manufacturers. Technologies that look most promising to achieving these goals include sodium and lithium-ion batteries, currently among the most expensive available battery technologies. Without significant technological progress, battery costs for EVs and PHEVs are likely to remain sufficiently high so as to prevent mass deployment in the next 20 years.[115]

Fuel cell vehicles also employ costly technology. Rare metals, such as platinum, are used as catalysts in fuel cells, and the technology used to manufacture lightweight, compact fuel cells that are resistant to low temperatures is currently expensive.[116] Some studies project that production costs of the fuel cell stack must decline by roughly 50 percent for fuel cell vehicles to be priced in a range that would achieve the same level of market acceptance that HEVs currently enjoy.[117] Technology cost differentials for PHEVs, EVs and fuel cell vehicles, as compared to advanced ICEs, diesel and conventional HEVs, may prevent widespread deployment of those technologies absent either technological breakthroughs from current R&D efforts or the use of major incentives to encourage widespread deployment ahead of technological breakthroughs.

Market Barriers

Although the cost of producing advanced technology vehicles can be relatively high, the fuel costs associated with operating them can be lower than the fuel costs for conventional vehicles. The Congressional Research Service has estimated that, depending on fuel prices, these savings could be $250 or more per year.[118] However, customers typically focus on the purchase price of a vehicle and may undervalue future savings associated with improved vehicle energy efficiency. In addition, a typical consumer will own a particular vehicle for a limited number of years and may be unable to realize the full potential fuel savings over the period of ownership. Moreover, fuel costs and potential savings for hydrogen vehicles are difficult to determine, since hydrogen technology is still in development and little hydrogen infrastructure exists to support demand.

Policy Considerations

Regulatory Standards

In 2007, EISA overhauled the Corporate Average Fuel Economy (CAFE) program implemented by the Department of Transportation (DOT). Under EISA, Congress directed DOT to raise CAFE standards for passenger vehicles and light trucks so that the combined fleet would reach at least 35 mpg by 2020, a 40 percent increase over existing levels.[119] In April 2008, the National Highway Traffic Safety Administration used its new authority to propose regulations that would raise CAFE standards to 35.7 mpg for passenger vehicles and 28.6 mpg for light trucks by 2015 — an increase of 4.5 percent per year.[120] The incorporation of advanced vehicle technologies into new vehicles will play an important role in meeting these standards.

The costs to the domestic auto industry of meeting EISA's strengthened CAFE standards are projected to exceed $100 billion. Shouldering these costs is particularly challenging at a time of declining U.S. auto sales resulting from the economic downturn. EISA recognizes the important role of government financial support for the industry by authorizing a program of low-interest loans for retooling of manufacturing plants to improve vehicle fuel economy.

Financial Incentives

To spur cheaper production of advanced technology vehicles, EISA established an incentive program consisting of both grants and direct loans to support the development of advanced technology vehicles and associated components.[121] The U.S. Department of Energy (DOE) administers the program, known as the Advanced Technology Vehicles Manufacturing Loan Program (ATVM).[122] ATVM provides loans to automobile and automobile parts manufacturers for the cost of re-equipping, expanding or establishing manufacturing facilities in the United States to produce advanced technology vehicles or qualified components and for associated engineering integration costs.[123] The FY2009 Continuing Resolution, enacted in September 2008, appropriated $7.5 billion to support a maximum of $25 billion in loans under the ATVM.[124] Signaling the need for investments in technology, 75 applications requesting a total of $38 billion for the first tranche of loans were submitted by the deadline of December 31, 2008. Based on the first round of DOE revisions, 23 applications have been considered sufficiently complete to progress to a second round of review, which will determine the financial and technical eligibility of applicants to receive funding.[125]

Policy Recommendations

Policy leadership for advanced vehicle technologies will require federal support for increased investment and deployment, including:

- Over the next 10 to 12 years, Congress should authorize and appropriate funding to support the adoption of advanced vehicle technologies by the auto industry with low-interest loans totaling approximately $75 billion.[126]
- Congress should increase R&D funding for technology to improve energy efficiency and enable the use of alternative fuels in light and heavy-duty gasoline and diesel vehicles. This enhanced R&D funding should total at least $150 million to $200 million annually above current levels and should include advanced technologies on energy storage and battery power; plug-in electric, fuel cell and alternative fuel vehicles; and systems that improve fuel economy in light-duty vehicles and medium and heavy-duty trucks and buses, such as advanced engine technologies, intelligent cruise control, adaptive transmission and acceleration systems, visual fuel economy feedback information for drivers, and weight reduction.
- Congress should continue to provide consumer incentives for the purchase of advanced technology vehicles. Specifically, it should extend the existing consumer tax credit for plug-in electric vehicles of up to $7,500 per vehicle to an additional 4 million vehicles through 2020.
- Congress should encourage automakers to ramp up production of plug-in electric vehicles with advanced battery technology by enacting a public-private partnership to share the warrantee risks associated with putting the latest battery technologies into production.
- Congress should ensure that vehicles are subject to a single national performance standard under EISA to control vehicle efficiency and GHG emissions.

Chapter 8

Advanced Biofuels

In addition to modernizing the vehicle fleet, actions to expand, diversify and reduce the carbon footprint of the transportation fuel supply will be necessary to meet the sustainable growth challenge. This requires the encouragement of a coordinated evolution of vehicles and the fuels used to power them. This will take time as vehicle and fuel technologies mature, gain consumer acceptance and achieve significant market penetration. During this evolution, liquid fuels will maintain a dominant presence in the transportation fuel mix, and responsible policymaking must account for this reality. Accordingly, policies that support the expansion, diversification and decarbonization of the liquid transportation fuel supply are necessary to advance a variety of sustainable growth objectives, including enhanced resiliency to oil price volatility, decreased vulnerability to instability in other nations and reduced greenhouse gas (GHG) emissions.

First-generation biofuels that are derived primarily from food crops, such as corn, already contribute to some of these objectives. They currently represent about 4 to 5 percent of all motor gasoline blends, but their role is expected to continue increasing over the next decade.[127] Advanced biofuels have the potential to play an even greater role in enhancing the nation's supply of liquid transportation fuels. Advanced biofuels (e.g., cellulosic ethanol) are produced from a wider variety of feedstocks than those used to produce first-generation biofuels — greatly expanding biofuels' potential as a scalable solution to the nation's economic, environmental and security challenges. In addition, evidence suggests that advanced biofuels have the potential to deliver substantially greater GHG benefits than their predecessors on a lifecycle basis.[128]

Nevertheless, advanced biofuels remain a relatively immature technology, and formidable hurdles to commercialization remain. Existing policies and knowledge gained during the deployment of first-generation biofuels can provide the nascent industry with the time and tools needed to move down the technology development curve. The widespread deployment of advanced biofuels, however, will ultimately depend on their overall cost competitiveness with other liquid transportation fuels that are currently less costly, such as gasoline and diesel, as well as their competitiveness with other uses of biomass feedstocks, including traditional biomass uses and other GHG emissions reduction strategies that use biomass. Furthermore, expanded production and use of some biofuels, such as ethanol, will require significant changes to the nation's fueling infrastructure and an expanded fleet of vehicles that are capable of using them.[129] Finally, the potential direct and indirect impacts associated with widespread deployment of biofuels remain unclear. Policymakers must continue to monitor and remain sensitive to the collateral impact that the large-scale use of biofuels and their alternatives can have on the environment and on closely related markets.

Despite these obstacles, the widespread deployment of advanced biofuels remains an important element of a portfolio approach to addressing climate change and a promising pathway for augmenting the transportation fuel supply. To realize this promise, however, strong policy leadership is needed to remove barriers to deployment, resolve uncertainties and maximize the benefits that advanced biofuels can bring to meeting the sustainable growth challenge.

Technology Pathway Overview

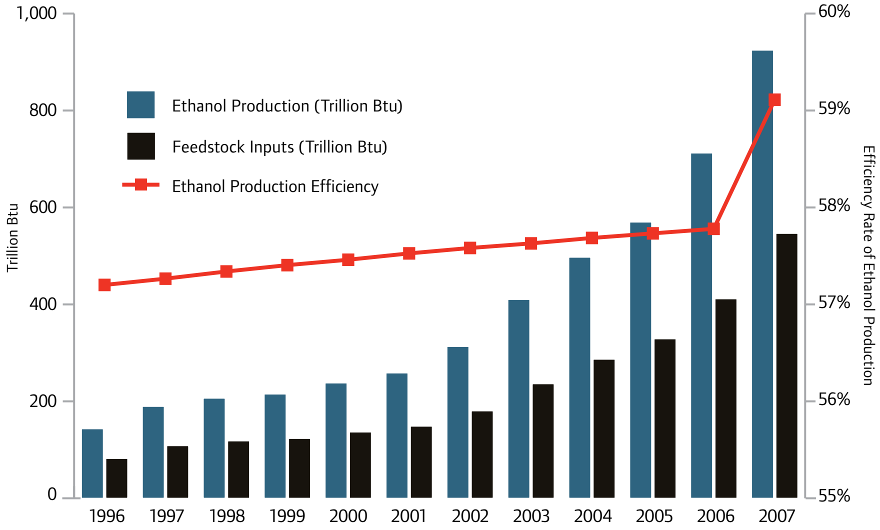
The production of conventional biofuels, including corn-based ethanol and biodiesel from soybeans, has expanded rapidly in recent years in response to increasing demand for transportation fuels, high gasoline prices and government policies. Although these first-generation biofuels will continue to make important contributions, they have limited ability to achieve the scale necessary to significantly expand, diversify and reduce the carbon footprint of the U.S. transportation fuel supply.

The desire to expand beyond first-generation biofuels has heightened interest in developing and deploying advanced biofuels produced from nonfood biomass using a number of different conversion technologies that fall into two major categories:

- **Biochemical processing** generally refers to the treatment of feedstocks with either diluted acid or enzymes to produce ethanol and butanol. Naturally occurring microbes also could be used to convert the materials.[130]
- **Thermochemical processing,** either by gasification or pyrolysis, includes converting feedstocks into a synthesis gas or "bio-oil" and then passing it through a reactor for conversion into bio-based fuels.[131]

There are many potential approaches that fall into each category and some that do not quite fit into either, each with a range of commercialization timeframes. A number of demonstration projects, both in the United States and abroad, are currently underway to more efficiently and cost-effectively generate biofuels from a variety of feedstocks, including perennial grasses, fast-growing trees, other woody materials, nonedible agricultural by-products and algae.[132] Although costs are still high and further demonstration initiatives and developments in cellulosic conversion technologies are needed, high-yield feedstocks and advanced biofuel technologies exhibit strong potential for full-scale commercialization. Improvements in feedstock yield efficiencies also will help to lower overall production costs.

Figure 8.1: Feedstock Efficiency of Fuel Ethanol Production



Source: EIA (2007), AER 2007, Renewable Energy, Table 10.3

In addition, evidence suggests that advanced biofuels have the potential to generate more favorable environmental impacts than existing fuels. For example, according to a study funded by the U.S. Department of Energy (DOE) and conducted by Argonne National Laboratory, the lifecycle GHG emissions of cellulosic ethanol are estimated to be 86 percent lower than those of conventional gasoline.[133] Science surrounding the environmental impacts of advanced biofuels is still evolving, however, and there is considerable debate over whether estimates of net GHG emissions reductions adequately reflect the effects of land-use changes.[134] Additional research into the direct and indirect impacts of large-scale biofuel production on GHG emissions, land use and water supplies is warranted.

Technology Pathway Barriers

Technological Barriers

Although progress has been made in overcoming technical challenges, advanced biofuels still face significant technological barriers to commercial deployment.

CONVERSION TECHNOLOGIES

To make advanced biofuels commercially viable, significantly more research is needed to improve the technologies necessary for efficient conversion processes, including increased enzyme and microorganism effectiveness.[135] Breaking down the lignin and complex sugar structures in the plant cell walls of advanced feedstocks is costly and time-intensive. Also, cellulosic feedstocks require more complex and higher cost fermentation processes than those used to ferment conventional corn-grain or sugarcane-based feedstocks into ethanol. As a result, the cost competitiveness of advanced biofuels hinges on the successful development of new conversion technologies, which in turn depends on adequate and timely investments from both private industry and the public sector.

Current large-scale national research projects are yielding progress in reducing conversion costs.[136] Several technologies, including both biochemical and thermochemical production, have already been proven in small-scale facilities, but scaling-up these technologies to commercial production levels requires further reductions in production costs and more financing for large-volume plants.[137]

Conversion technologies are still being refined and perfected, and it is unclear which methods will prove most efficient. Because of these unresolved issues, future production costs are uncertain. Additional technological developments, testing, commercial-scale demonstrations and increased investment in research and development (R&D) are required to identify and vet conversion technologies and increase the potential of large-scale economical production of next-generation biofuels.

BIOMASS COLLECTION AND HANDLING TECHNOLOGIES

New methods need to be developed to collect, store and preprocess biomass in a manner most conducive to refinery conversion. Such activities account for up to 20 percent of the cost of finished cellulosic ethanol and include the harvesting and collection of feedstock from cropland and forest; building storage facilities to accommodate biomass feedstocks en route to the refinery; transforming feedstocks to the proper moisture content, bulk density, viscosity and quality; and transporting feedstocks to the biorefinery.

Although studies predict that harvest and collection costs will decline significantly over time, preprocessing and transportation of feedstocks pose more substantial cost barriers to ramping up production.[138] Most feedstocks have high moisture contents and are considered too bulky to be refined without significant pretreatment. Additional research on methods to transform rough feedstocks into forms more suitable for conversion is still needed to decrease preconversion costs associated with advanced biofuels.[139]

Infrastructure Barriers

While the current U.S. infrastructure for producing, distributing and marketing transportation fuels can accommodate low-level blends of ethanol in gasoline, such as E10, higher ethanol-to-gasoline ratios pose significant challenges. For example, ethanol adheres to water, and the existing fuel pipeline transportation system in the United States is “wet.”[140] Pipelines will need to be sealed off and cleaned up to prevent the delivery of diluted biofuels to retailers. Alternative methods of fuel transport, including trucking and shipping, must be made similarly suitable for advanced biofuel transportation. Furthermore, high-level ethanol blends can erode certain soft metals and other materials that have been commonly used in older service station fueling systems. Some other plastics, rubber and cork materials used in pump gaskets also are corroded by ethanol over time.[141] Additionally, high-level blends of ethanol could present a drawback to drivers because they have a lower energy density than gasoline and diesel, which reduces driving range.

Some other advanced biofuels present similar challenges; biomethanol, for example, has similar infrastructure requirements as ethanol.[142] However, the development of biofuels that closely resemble petroleum gasoline or diesel in their fuel properties could enable industry to use the existing infrastructure while increasing biofuel usage if and when they become commercially viable.[143]

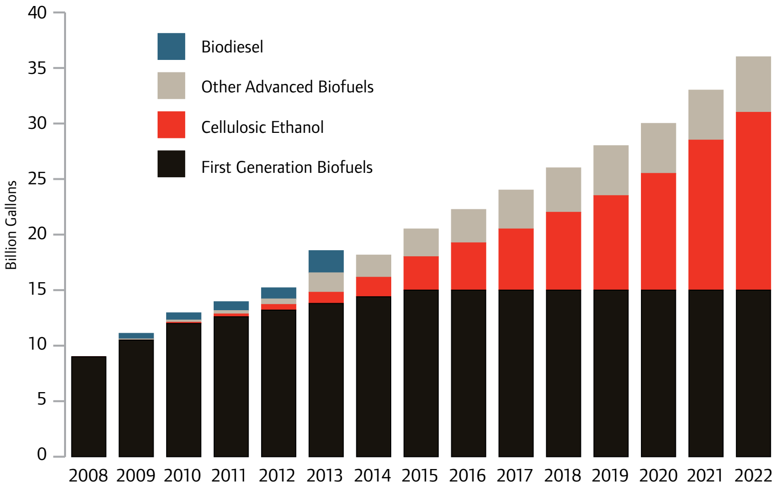
Policy Considerations

Implementing the Renewable Fuels Standard in the Energy Independence and Security Act

The Energy Indpendence and Security Act (EISA) charged the Environmental Protection Agency (EPA) with implementing a revised Renewable Fuel Standard (RFS) program, which requires that 36 billion gallons of biofuels be blended into transportation fuel by the year 2022. This includes at least 21 billion gallons from advanced biofuels that meet specific GHG reduction thresholds, including 16 billion gallons of cellulosic biofuels. In response to the revised RFS goals, recent federal government policies have tried to support industry efforts to develop and deploy advanced biofuel technologies. An increased presence of advanced biofuels in the transportation fuel mix will require continued cooperation and policy coordination between state and federal governments, automobile manufacturers, fuel suppliers, and biofuel producers.

Consumer acceptance of and favorable economics for these advanced fuels are ultimately essential to policy success. Meeting the RFS goals is expected to require ethanol blends that exceed the limits that most vehicles on the road today can use, presenting challenges for acceptance by vehicle owners and fuel retailers. Extensive research and testing will be required to determine whether retailers can sell and consumers can use slightly higher-level

Figure 8.2: Renewable Fuel Standards



Source: Energy Independence and Security Act of 2007 ethanol-gasoline blends without significant infrastructure investments or negative effects on engine or emissions control performance. These issues illustrate some of the difficulties in diversifying the transportation fuel mix over time.

Recent federal proposals to regulate transportation fuels under both a cap-and-trade program and a national Low Carbon Fuel Standard, on top of the existing RFS, will increase the complexity of the regulatory system and could increase overall costs. Multiple overlapping transportation fuel policies could ultimately frustrate the development of advanced biofuels.

Instead, biofuel policies should avoid unnecessary complexity. They also should be aggressive, pushing technology to its reasonable limit, but should allow for flexibility. EISA requirements provide for such flexibility, and the United States should proceed with this approach while allowing the requirements to be adjusted if warranted by a lack of progress in developing advanced biofuel technologies or infrastructure. If these technologies develop faster and at a lower cost than expected, significant increases in biofuel use above the current RFS may be possible.

Funding for Research and Development

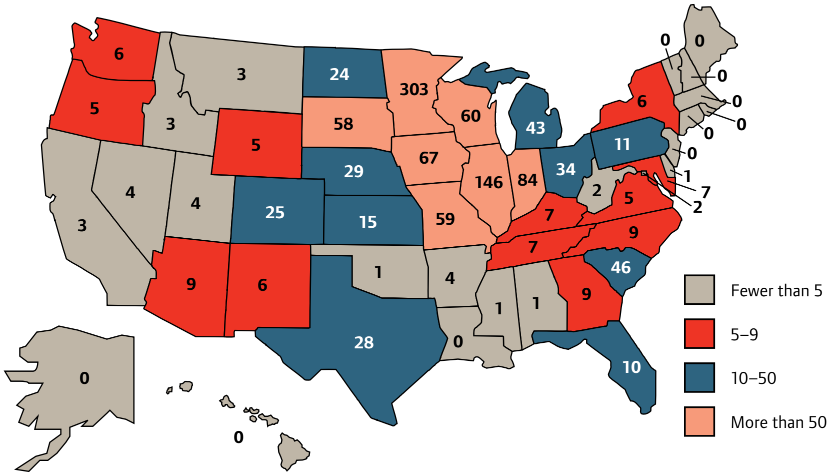
Government policy should strongly support and fund R&D programs devoted to advanced biofuel feedstocks, conversion processes and end-product evaluation. However, many projects remain heavily dependent on private-sector financing and cannot be sustained on federal government funding alone. With the recent turmoil in the financial markets, raising capital from private sources is proving increasingly difficult. It is important that government and industry support for R&D be maintained in both healthy and lean economic environments.

Furthermore, biofuel policy should be careful to avoid significant negative unintended consequences on markets for feedstocks and the businesses that rely on them.[144] Deployment of advanced biofuels may present direct and indirect environmental and land-use challenges. Validated science and thorough research are needed to survey and address the potential impacts of advanced biofuel production on GHG emissions, land-use practices and water supplies. As required by EISA, government and industry should jointly and expeditiously work to analyze the emissions and environmental impacts of both conventional and advanced biofuels. These analyses should include comparison with impacts from competing transportation fuels.

Creating a Fueling Infrastructure

By 2013, the revised RFS volume requirements are expected to propel the national transportation fuel mix beyond 10 percent ethanol and 90 percent gasoline. The majority of vehicles on the road today cannot use higher-level ethanol blends because, unlike flex-fuel vehicles, they were not specifically designed to run on those blends. Biofuel producers should work with transportation fuel producers, distributors and marketers to identify pathways to enable advanced biofuels (including ethanol and nonethanol options) to be competitive, easily accessible and widely available. The goal should be to move as expeditiously as possible to produce biofuels that are environmentally and economically acceptable. Furthermore, auto manufacturers, working with government, should continue to increase the availability of alternative fuel vehicles capable of running on higher blends of alternative fuels as those blends continue to become more common.

Figure 8.3: Distribution of E85 Fueling Stations by State



Source: DOE, EERE (June 2007), Vehicle Technologies Program

Finally, to encourage increased diversity of the transportation fuel mix, a collaborative process should be developed by government, automobile manufacturers, fuel suppliers and alternative fuel producers to advance a cost-effective plan for creating a biofuel fueling infrastructure that is responsive to existing fuel distribution networks and the evolving vehicle fleet. Financial support from the government for converting refueling stations to handle some high-level biofuel blends may be necessary as fuel suppliers seek to update station infrastructure. Pipelines, terminals, fuel blending facilities, and existing truck and rail transportation also may need to be updated to accommodate higher volumes and higher blends of biofuels. Accumulated knowledge and additional infrastructure developed during the deployment of the current generation of biofuels should be leveraged to facilitate the growth of advanced biofuels.

Policy Recommendations

- Strongly support government R&D in next-generation biofuels, including both ethanol and other biomass-derived hydrocarbons.
- Continue to pursue the goal of scaling up biofuel production to 36 billion gallons per year by 2022 with flexibility, as established in EISA, to revisit these requirements if technology development for advanced biofuels does not proceed as expected.
- Continue government support for R&D into the potential changes needed in the current infrastructure that may be required to facilitate significant growth of various biofuels.
- Continue to evaluate biofuel impacts on sustainability issues, such as food production, forest resources, land use and overall GHG emissions.

Chapter 9

Enhancing Domestic Supplies of Oil and Natural Gas

The transition to a low-carbon economy will be measured in decades, not years. Alternative sources of energy must be developed, new infrastructure must be constructed and advanced technologies must be deployed. While an alternative energy system emerges, evolves and matures, it is both prudent and imperative that the nation exercise good stewardship over the existing system and ensure the availability of affordable energy supplies. Measures that enhance domestic supplies of oil and natural gas, in particular, will be necessary to maximize the likelihood that the prevailing energy system will remain as secure, stable and affordable as possible. This will facilitate a smooth transition to a low-carbon economy by providing relief to American families, maintaining the competitiveness of American businesses and creating the economic conditions necessary to support large-scale investments in the nation's energy system.

In recent years, persistently high and volatile energy prices have placed enormous stress on family budgets, squeezed American businesses and slowed the U.S. economy. Elevated gasoline prices at the pump were particularly hard felt, but they were not unique. By mid-2008, natural gas prices were three to four times higher than they were in early 2000, while electricity prices increased by approximately 60 percent over the same period.[145] In short, the global energy system is under duress and, although prices have since receded in light of the current global economic recession, policymakers and political leaders must remain vigilant in their efforts to bring greater balance to the U.S. energy equation.

Despite its superficial appeal, energy independence (the elimination of energy imports) is not realistic. The United States depends on imports for more than 30 percent of its total energy requirements, including 60 percent of its petroleum consumption and 17 percent of its natural gas consumption, and the nation will need increasing quantities of energy in the coming decades to support a growing population and thriving economy. As a result, increasing and diversifying global supplies of oil and natural gas will be essential to enhancing the nation's economic and energy security. As stated in the *2007 National Petroleum Council Global Oil and Gas Study,* "there can be no U.S. energy security without global energy security."

While the concept of energy independence may be unrealistic, there is much that can be done to better manage energy interdependencies. This includes capitalizing on America's own oil and natural gas resources. Even with a rapid transition to a low-carbon economy, oil and natural gas will remain integral to the U.S. energy mix. A comprehensive and realistic approach to sustainable growth must leverage domestic resources to ensure stable energy supplies and reduce the occurrence and severity of energy price swings.

Ultimately achieving America's long-term environmental objectives need not and cannot come at the expense of its near-term economic or energy security. Significant barriers to enhanced domestic oil and natural gas supplies exist, but advanced technology combined with strong policy leadership can remove these barriers and leverage the nation's natural resources in a manner that protects the environment while growing the economy. Smart, targeted policy changes are needed now, and the business, environmental and policy communities must work cooperatively to exercise good stewardship over the existing energy system and ensure the availability of affordable oil and natural gas supplies.

Enabling Pathway Overview

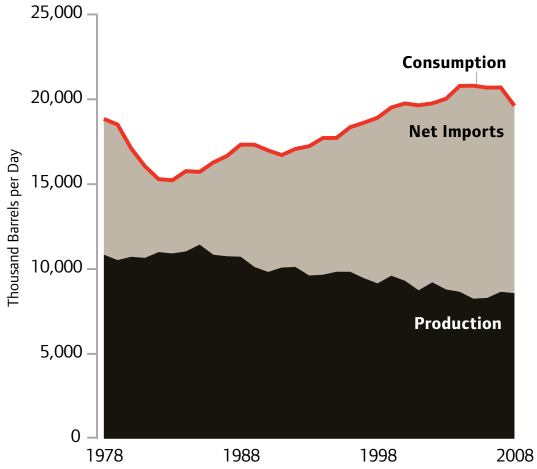
Enhanced Oil Supplies

In 2008, U.S. petroleum consumption averaged approximately 19 million barrels per day, a significant reduction from previous years because of elevated prices and the onset of the global recession. This represented roughly 37 percent of the nation's energy portfolio.[146] Although the United States is the world's largest oil consumer, domestic production has steadily declined since the 1980s. Between 1988 and 2008, petroleum consumption increased by 13 percent.[147] This stands in stark contrast to domestic petroleum production, which decreased by 31 percent during the same period.[148] As a result, petroleum imports have more than doubled in the past 20 years and now account for about 60 percent of total consumption.[149]

Oil is a fungible, globally traded commodity, and prices are determined by global supply and demand. Consequently, maximizing and diversifying oil supplies, regardless of their location, is essential to maintaining security of supply and moderating prices. In addition to maintaining access to global supplies through open markets, America must do its part by expanding access to both conventional and nonconventional domestic resources in an environmentally responsible manner. It also must boost recovery rates from existing wells and maximize the output of usable fuel from each barrel recovered. The combination of strategies that expand access and increase the yields from existing resources could dramatically reduce the growing gap between U.S. oil consumption and production. Transportation efficiency improvements could further close this gap.

In recent years, a variety of factors have resulted in growing global imbalances between oil supply and demand, including rapid global economic growth, supply disruptions, and increased geopolitical instability and uncertainty. These growing global imbalances resulted in a surge in world oil prices from roughly $50 per barrel in January 2007 to more than $140 per barrel in June 2008.[150] This placed substantial burdens on U.S. consumers, businesses and the larger economy. Although oil prices have dropped sharply in the face of a global economic slowdown, growing demand and the need for increased supplies will remain a significant challenge as global economic growth resumes.

Figure 9.1: U.S. Petroleum Production and Consumption



Source: EIA (June 2008), AER 2007, Table 5.1;
EIA (March 2009), Monthly Energy Review (MER), Table 3.1

A variety of exciting technologies are enabling producers to explore, extract and transport petroleum and natural gas supplies with minimal impact on the environment. Seismic surveys, for example, use high-energy sound waves to develop 3-D and 4-D maps of underground rock layers and allow producers to explore potential petroleum and natural gas reserves with exceptional precision. Engineers can then optimize field development and minimize the number of wells needed for exploration and production — substantially reducing a project's environmental footprint.[151] Other technologies, such as horizontal/directional drilling, are helping to minimize the environmental impact of both onshore and offshore drilling. Additionally, enhanced oil recovery (EOR) methods are sequestering carbon emissions and providing valuable experience for the development of carbon capture and sequestration technologies.

Advanced technologies also enable producers to maximize the output of existing wells. In every oil field a proportion of the oil in place cannot be economically recovered using conventional techniques. Although the recovery rate has constantly improved over time, continuing advances in technology will further boost recoveries from U.S. oil fields. One such advance that has been in use for many years is EOR, which uses concentrated underground injection of CO_2 into oil wells. In addition to increasing recovery rates, EOR could play a critical role in advancing carbon capture and storage (CCS) technologies in the fossil fuel-fired power sector and industrial gasification facilities. The oil and gas industry has more than 35 years' experience with handling, transporting and injecting CO_2 into the ground to enhance recovery rates, and harnessing that knowledge will be critical to unlocking the CCS technology pathway.[152]

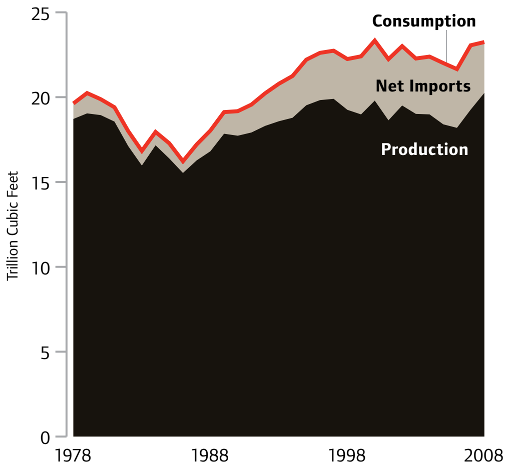
In addition to expanding access and increasing recovery rates, supply can be maximized by converting more of each barrel recovered into usable fuel. Upgrading today's refineries with deep conversion units using the latest technologies can minimize output of "heavy" fuel oil or petroleum coke, for which there is relatively little demand, and increase yields of gasoline, diesel and jet fuel. The United States currently leads the world in deep conversion capacity, although other regions, especially Asia-Pacific and the Middle East, are making large investments in this technology.

Substantial research and development (R&D) is required for the technological advances that will achieve the highest recoveries and yields. This R&D would be accelerated by increased support for joint government industry research partnerships and financial incentives for early deployment of new technologies, such as CCS.

Enhanced Natural Gas Supplies

In 2008, U.S. natural gas consumption totaled 23 trillion cubic feet — representing roughly 23 percent of the U.S. energy portfolio.[153] Although historically the United States has been self-sufficient in natural gas, a growing gap between consumption and domestic production has recently emerged. Between 1987 and 2007, natural gas consumption grew by 29 percent.[154] In fact, natural gas-fired power plants account for more than 90 percent of electric power capacity additions in the past two decades, and more than half of all homes are heated by natural gas.[155] Although domestic natural gas production has increased by 20 percent during the past 20 years, including a significant increase in the past two years due to production from unconventional sources, even more rapid growth in demand has meant that natural gas imports are responsible for 17 percent of consumption today compared to only 7 percent in 1988.[156]

Figure 9.2: U.S. Natural Gas Production and Consumption



Source: EIA (June 2008), AER 2007, Table 6.1;
EIA (March 2009), MER March 2009, Table 4.1

The vast majority of natural gas imports are traditionally delivered via pipeline from Canada, but it appears increasingly unlikely that Canada will be able to continue to bridge the U.S. domestic supply-demand gap. In the future, natural gas, like crude oil today, will gradually become a global commodity rather than a regional one. As a result, liquefied natural gas imports will become increasingly important in global markets and will bring a new set of geopolitical complexities to U.S. and global energy security.

While the largest consumer of natural gas is the industrial sector, significant quantities also are used in the electric power, residential and commercial sectors. Consequently, constraints on domestic supply and increased demand have placed significant burdens on American families and businesses. Between 2000 and mid-2008, natural gas wellhead prices nearly quadrupled before retreating to lower levels.[157] These price increases have translated into higher electricity and heating bills for households and businesses, and they have hurt the competitiveness of U.S. manufacturing companies, discouraging investment in the U.S. manufacturing sector. For example, the U.S. chemical industry — the largest industrial user of natural gas — has experienced substantial plant shutdowns and job losses as investment in new capacity has moved outside the United States because of lower natural gas prices.

The U.S. Department of Energy (DOE) projects that natural gas consumption will grow by more than 20 percent over the next 20 years — more than any other primary energy source.[158] Moreover, as the cleanest-burning fossil fuel, demand for natural gas is likely to surge in a carbon-constrained world as carbon costs encourage fuel switching from coal to gas by utilities and industrial users. Consequently, increased domestic supplies of natural gas will be essential to bring greater balance between supply and demand — thereby containing energy costs for American homes and businesses, preserving healthy economic growth, and enhancing security.

Pathway Barriers

Policy Barriers: Access

Too many significant oil and natural gas prospects are now officially or unofficially off limits. In 1982, Congress first enacted a prohibition on the use of funds to conduct leasing activities in a sizable portion of the Outer Continental Shelf (OCS). President George H. W. Bush issued an executive moratorium prohibiting offshore federal leasing on the East Coast, West Coast and eastern Gulf of Mexico through 2000, which was later extended by President Bill Clinton until 2012. The moratorium was recently rescinded by President George W. Bush by executive order in July 2008. In 2008, Congress passed a Continuing Resolution funding the Department of the Interior (DOI) through March 2009, also without the OCS moratorium language. However, a portion of the Central Gulf of Mexico Planning Area and most of the Eastern Gulf of Mexico Planning Area along the Florida coast, which is thought to contain more natural gas than oil, are under restriction until 2022 as part of the Gulf of Mexico Energy Security Act of 2006.

The lapse of the OCS leasing moratoria will not result in the immediate leasing of previously restricted areas. The Minerals Management Service (MMS) conducts all offshore leasing activities pursuant to a five-year plan. The only area currently in the five-year plan that also was subject to a moratorium is offshore Virginia, which was included at the request of the state. As the lifting of the executive moratorium takes effect, additional areas are likely to be included in the MMS revised five-year plan. The plan most recently proposed by MMS includes 10 leases in 6 areas that had been restricted by the moratorium.[159] A number of environmental reviews and approvals are required before exploration activities can commence on the OCS, including reviews under the National Environmental Policy Act, Coastal Zone Management Act, Clean Water Act and Clean Air Act. Accordingly, the lapse of the offshore moratoria will not result in additional leasing, exploration or production in the near future.

In addition, a congressional moratorium on the development of oil shale lands held by the Bureau of Land Management (BLM) also lapsed at the end of FY2008. While there are still significant technological challenges that must be overcome, the scale of potentially available resources makes oil shale a promising domestic resource. Although many leases authorized by the Bush administration were cancelled by the Obama administration, new leasing on BLM lands for oil shale research, development and demonstration can proceed unless Congress or the current administration suspends activities. In contrast, leasing activities cannot occur in the Arctic National Wildlife Refuge, another area with significant potential resources, without explicit congressional authorization.

Information Barriers

Although current estimates of domestic resource potential are impressive, they remain just that — estimates. This is particularly true in the case of the OCS, as estimates were made using data acquired pre-1980 using now-obsolete technology. In 1987, MMS estimated that there were 9 billion barrels of oil in the Gulf of Mexico. By 2006, after major advances in seismic technology and deepwater drilling techniques, the MMS revised resource estimate ballooned to 45 billion barrels.[160] Therefore, it is very possible that there are significantly more resources than currently estimated on federal lands. However, the real potential and location of the resources will only be known after new seismic exploration is conducted. Accurate information will be essential to making informed and responsible public policy decisions about which areas should be leased.

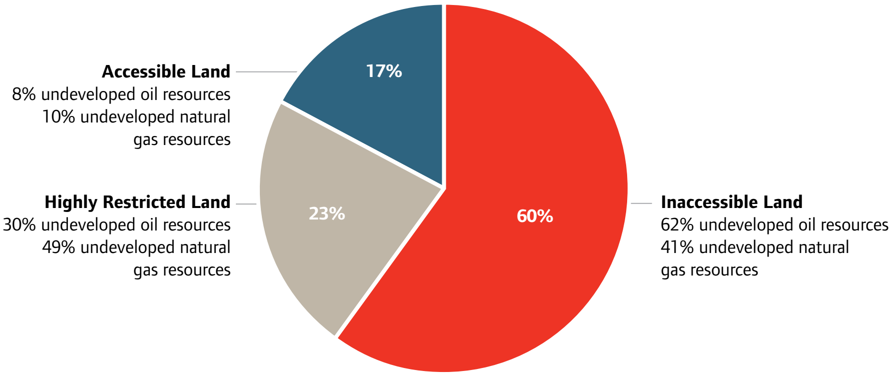
Policy Considerations

Expanding Access to Onshore Resources

Evidence suggests that undeveloped onshore oil and natural gas resources, including concentrations in Alaska and the western states, could be substantial. For example, the U.S. Geological Survey estimates that onshore conventional undiscovered technically recoverable resources of oil total about 45 billion barrels of oil.[161] A sizable portion of these resources lies under federal lands and remains either officially or practically off limits to exploration and development. In fact, two of the largest potential concentrations of undiscovered oil deposits, the National Petroleum Reserve — Alaska and the Arctic National Wildlife Refuge (ANWR) — are located on federal lands in Alaska's North Slope region. These two regions alone represent almost half of all undiscovered resources on U.S. lands.[162]

ANWR includes 19.6 million acres located in the northeast corner of Alaska. One and a half million acres of ANWR (the so-called "1002 study area," named after the section of the bill categorizing ANWR) located on the Arctic Coastal Plain have been set aside specifically for further evaluation, including potential oil and gas exploration, subject to congressional approval. In 1998, a report by the U.S. Geological Survey (USGS) estimated that there were between 4.3 billion and 11.8 billion barrels of technically recoverable reserves in the 1002 area.[163] Using the mean USGS estimates of potential reserves, DOE estimates that if ANWR exploration and production were permitted, production could begin in 2018 and would peak at 780,000 barrels per day in 2027.[164] Using the high USGS estimate of potential reserves, DOE projects that production could total 1.45 million barrels per day in 2028.[165]

Figure 9.3: Federal Restrictions on Onshore Drilling in Areas with Estimated Reserves



Source: DOI, DOE, U.S. Department of Agriculture (2008), "Inventory of Onshore Federal Oil and Natural Gas Resources and Restrictions to their Development"

Oil shale represents another potential source of supply in the future, especially when combined with CCS technology. The largest deposits of oil shale in the world are found in the Green River Formation, which covers parts of Colorado, Utah and Wyoming. DOI estimates that the Green River Formation contains 1.2 trillion to 1.8 trillion barrels of oil, with approximately 800 billion barrels of recoverable oil, based on mean estimates.[166] Recovering this oil in a cost-effective and environmentally responsible manner still presents numerous technological challenges. It is important to continue encouraging a broad range of technologies to find the best commercial solutions.

Attractive opportunities to enhance onshore natural gas production also exist. Shale gas resources hold great promise for domestically produced, cleaner burning energy supplies. These resources are more costly and difficult to develop than conventional resources, but they are abundant, and some deposits can be cost-effectively extracted at moderate natural gas prices. Most of these are currently on state and private lands, and federal attempts to preempt state regulation of hydraulic fracturing could slow growth of this abundant source of energy.

Conventional deposits in the Rocky Mountains also offer significant opportunities for growth in supply. The extent and pace of that growth, however, will depend on improved access. Although much of the Rocky Mountain natural gas resources are officially accessible to exploration and development, a significant portion remains effectively off limits due to onerous lease stipulations, conditions of approval that make development impractical or uneconomical, and cumbersome leasing and permitting procedures.

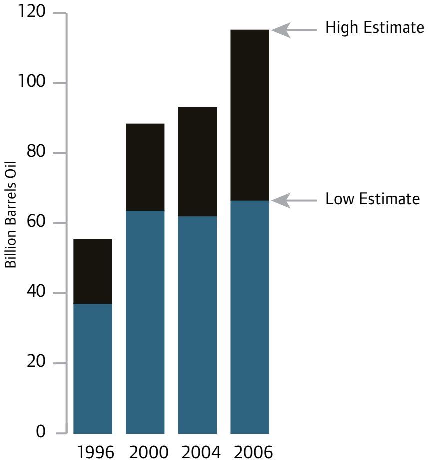
Finally, although Alaska's sizable onshore natural gas resources have been well known for decades, they remain underdeveloped and stranded in the absence of necessary infrastructure to cost-effectively deliver them to North American markets. A natural gas pipeline from Alaska to the lower 48 pipeline grid, as currently proposed, could substantially enhance U.S. natural gas production over the next 20 years and beyond.

Expanding Access to Offshore Resources

As onshore resources have been increasingly difficult to find and economically develop, a significant portion of U.S. oil and natural gas production has shifted offshore to the OCS. As the nation's energy needs grow, expanded access to resources off the Atlantic, Pacific and Gulf of Mexico coasts will be critical to replace output from maturing fields.

According to MMS, the Atlantic and Pacific OCS that was previously subject to moratoria contain 14.3 billion barrels of oil and 55 trillion cubic feet of natural gas.[167] Approximately three-fourths of the undiscovered oil resources and nearly half of the natural gas resources in the Atlantic and Pacific oceans are thought to be located within 50 miles of the shore, although as previously discussed, these estimates are based on old data and now-outdated technology.[168] These areas can be developed in an environmentally responsible manner with minimal impact on coastal communities. In the Gulf of Mexico, approximately 21.5 trillion cubic feet of natural gas still remains off limits to exploration and production until 2022.[169] Exploration using modern technology would give much more accurate estimates of these resources and could indicate that there are significantly more resources available.

Figure 9.4: Undiscovered Technically Recoverable Oil Reserves on the OCS by Year of Estimate



Source: MMS (1996, 2001, 2004, 2006)

Importance of Oil and Gas Revenues

Royalties from production on federal lands have resulted in billions of dollars of revenues for federal and state treasuries. According to DOI, the agency distributed more than $23 billion from onshore and offshore energy production to the federal government, states and American Indian tribes.[170] Moreover, a study by ICF International recently concluded that developing resources previously off limits due to the congressional moratorium could result in as much as $1.7 trillion in government revenues.[171] The vast majority of these revenues ($1.4 trillion) would come from offshore developments.[172] Combining these projections with estimates of royalties from areas that are already accessible, total government revenues from all U.S. oil and natural gas resources on federal lands on the OCS, ANWR and Rockies could exceed $4 trillion over the life of the resource.[173]

The "Idle Leases" Myth

Most leases do not contain economically viable oil or natural gas resources. Companies make significant payments to the federal government to acquire leases, as well as annual rentals to maintain their leases. They also invest millions of dollars in exploration costs in the hope of finding commercial quantities of oil and natural gas. By law, an oil company with a lease must "use it or lose it." If energy is not produced within the lease term (generally 5 or 10 years), the lease is transferred back to the government and the company forfeits all money invested, which can be hundreds of millions of dollars. Therefore, in addition to the diligent development provisions built into the fundamental structure of the regulations and leases, strong financial incentives already exist for oil and gas companies to develop their leases and commence production as quickly as possible.

While companies are actively developing all of the promising areas they have leased in the last 10 years, most notably in the deepwater Gulf of Mexico, and continue to maximize production on existing fields, much of the country's most prospective acreage remains "off limits." It is vitally important to take action today to enable access to the next generation of development prospects.

Policy Recommendations

- Congress should enact a broader lifting of the OCS moratoria and actively support greater access to allow oil and gas leasing in all areas off the Atlantic and Pacific coasts and in the Gulf of Mexico. Specifically, Congress should avoid reinstating OCS moratoria and other restrictions, such as buffer zones that carry the impact of a moratorium, and they should lift restrictions, such as those in the Gulf of Mexico Energy Security Act.
- Congress should improve access to public lands in the Rockies and Alaska.
- Federal land managers need to maintain flexibility with respect to exploration and production operations on existing leases, as well as provide additional access to unleased areas. Environmentally responsible energy development is being undertaken and should be expanded to include areas identified as "multiple use" lands.
- The federal government should develop policies to encourage technology development and enact legislation and regulations that encourage development of federal oil shale and tar sands resources in an economically and environmentally sustainable manner.
- All federal permits needed to initiate oil and gas activities should be approved within the time limits set by existing policy, and staffing levels in offices should be adjusted to facilitate the ability to respond to the level of activity faced by that office.

Chapter 10

Modeling Framework

The previous chapters of this report examine several promising technology pathways that are likely to form the foundation of any solution to the sustainable growth challenge. To complement these qualitative assessments, Business Roundtable undertook an extensive modeling exercise to quantitatively evaluate the potential economic, environmental and energy impacts associated with each technology pathway, including the implementation of the Roundtable's policy recommendations.

By incorporating assumptions and inputs from Business Roundtable's technology working groups into the University of Maryland's Long-term Interindustry Forecasting Tool (LIFT) model of the U.S. economy, the modeling exercise simulates a range of technology and policy scenarios that produce estimates for key macroeconomic, environmental and energy outcomes.[174] When compared to the appropriate reference case, these estimates provide a basis for assessing the potential benefits and costs associated with pursuing a balanced portfolio of technology pathways.

It is important to note that these simulations do not represent forecasts of what Business Roundtable or its member companies believe will happen. Rather, they are illustrative scenarios intended to examine the process by which carbon prices, technologies and policies may interact in the coming decades to influence key economic, environmental and energy variables. The goal is to identify and demonstrate mutually supportive technology and policy pathways that have the potential to lead to superior economic, environmental and security outcomes.

With this goal in mind, this chapter describes the modeling framework, including discussion of the University of Maryland's LIFT model, the modeling process, key underlying assumptions, and the construction of baseline and alternative scenarios. The model inputs, developed by Business Roundtable's technology working groups in collaboration with the Inforum-Keybridge modeling team, are described in Chapter 11. The modeling results are reported in Chapter 12.

The LIFT Model

The Business Roundtable modeling project relied on the University of Maryland's Inforum LIFT model — a widely respected econometric model of the U.S. economy. This model is well suited for studies of this type because it uses a dynamic, general equilibrium structure that portrays the economy in a unique "bottom-up" fashion and allows effects to be captured at the detailed industry and product level. The model estimates impacts on consumer spending, foreign trade, production, employment, income and prices at the industry level. These industry estimates are then aggregated to produce macroeconomic estimates of gross domestic product (GDP), net exports, unemployment and other key variables.

The LIFT model simulates the economy year by year, allowing modelers to analyze both the ultimate economic impact of a policy change and the dynamics of the economy's adjustment process over time. As a result of this dynamic and bottom-up framework, the model is well suited to explore the economic relationships among key energy industries and to examine the initial dislocation and subsequent adjustment to equilibrium associated with the transition to a low-carbon economy.

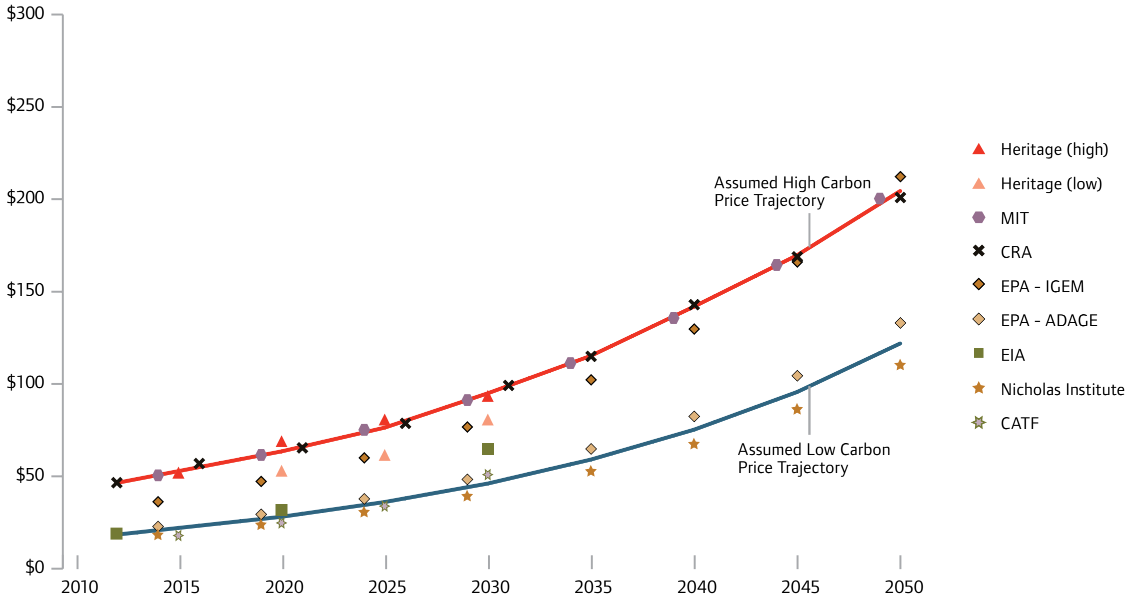
Importantly, the model imposes accounting and financing constraints on the economy. For instance, assumed increases in investment spending (e.g., for new nuclear plants or wind farms) mean that these funds are not available for investments in other sectors of the economy. The model also has a detailed government sector, which allows it to account for the effects of government revenue collection and spending that result from implementing a carbon pricing instrument.

Modeling Framework and Process

The economic, environmental and energy impacts of technologies and policies are estimated by comparing the results of four different model scenarios:

- **Business-as-Usual baseline (BAU)** assumes no carbon constraint and serves as an initial baseline for the analysis.
- **"Minimal Technology" scenarios** modify the BAU baseline by assuming a carbon-constrained world with minimal new technology deployment. These are not intended to be realistic scenarios but are instead intended to serve as alternative baselines that simulate the impact that carbon prices would have on a U.S. economy that has no advanced energy technology deployment beyond what is deployed in the BAU scenario.[175]
- **"Policy Inertia" scenarios** illustrate the development and deployment of technologies in response to carbon prices and existing government policies.
- **"Policy Leadership" scenarios** illustrate the estimated development and deployment of technologies in response to carbon prices, existing government policies and the adoption of the new policy recommendations discussed earlier in this report.

Figure 10.1: High and Low Carbon Price Assumptions Relative to Prices in Major Studies of Lieberman-Warner Bill



Source: Inforum/Keybridge Research

The first step in the modeling process was to develop the BAU baseline for the period from 2008 to 2050 that was consistent with the forecast contained in the U.S. Department of Energy's (DOE's) *Annual Energy Outlook 2008*. The second step was to develop the Minimal Technology scenarios. Based on a review of the price paths associated with several studies of the greenhouse gas (GHG) cap-and-trade proposal by senators Lieberman and Warner (S. 2191), the modeling team developed a lower carbon price profile ("low price") and a higher carbon price profile ("high price"). The model was then "shocked" by introducing these carbon prices into the economy and assuming minimal technological advancement. These synthetic scenarios capture the economic impact of carbon prices in the absence of an induced technological response to those prices.

Detailed technology pathway scenarios were then "layered" on top of the Minimal Technology scenarios to simulate the potential impact of induced technology response and Business Roundtable's policy recommendations, respectively.

- The first round of simulations, referred to as Policy Inertia scenarios, examined the impacts of individual technology pathways in a world in which federal legislation results in a carbon price but other policies remain unchanged and few additional policies are enacted.
- The second round of simulations, referred to as Policy Leadership scenarios, examined the impacts of individual technology pathways in a world in which federal legislation results in a carbon price and Business Roundtable's policy recommendations are adopted.

- The final round of simulations, referred to as Balanced Portfolio scenarios, examined the impacts of all six technology pathways when pursued in both the Policy Inertia and Policy Leadership states of the world.

It is important to note that this study assumes that federal legislation establishes a carbon price but it does not assume a particular policy instrument — that is, it is agnostic as to whether the prices are explicitly established by a carbon tax or implicitly established by a cap-and-trade system. Further, the study assumes carbon price trajectories that steadily increase over time. These carbon price trajectories are uniform across all six technology pathways, providing all of the technology working groups with consistent carbon price expectations for the construction of the technology deployment scenarios.

Key Underlying Assumptions

The Use of Government Revenues

Both a carbon tax and a cap-and-trade system could generate substantial government revenues, and the use of those revenues can have important implications for the economy.[176] Using these revenues to reduce fiscal deficits or run larger fiscal surpluses will withdraw money from private consumption and could impose a contractionary drag on economic growth. Policies that return these revenues to the private sector through lump-sum rebates will largely offset this initial contractionary effect, while policies that return these revenues to the private sector through a reduction in distortionary taxes (e.g., corporate income taxes, capital gains taxes or payroll taxes) may actually boost economic growth. Accordingly, assumptions about the use of government revenues can have important implications for economic modeling analyses.

All scenarios in this study assume deficit neutrality — that is, government revenues accruing from the carbon price are recycled back to the economy. It is assumed that half of the revenues are returned to households through lump-sum rebates; one-third of the revenues are returned to companies through a reduction in the corporate income tax; and the remaining portion is spent by the federal government on various policy initiatives, including many of the initiatives recommended in this study.[177] In the absence of full revenue recycling, the economic impacts are likely to be far less favorable than those projected in this study.

International Climate Change Action

Another crucial factor in determining the economic impact of the United States taking action to address global climate change is the extent of action taken by other nations — especially major U.S. trading partners. If few nations take similar action, many U.S. businesses are likely to lose international competitiveness as energy commodities, electricity and other inputs become more expensive. Although the burden is likely to be shared by many sectors of the economy, it would be particularly harmful to energy intensive and globally competitive sectors. All else being equal, U.S. manufacturers of energy intensive products could lose significant market share to competitors located in nations that do not impose policies with similar costs. In the long run, production in such sectors will tend to relocate to nations with less restrictive environmental policies — potentially offsetting GHG reductions in the United States. As a result, assumptions about international action on climate change have important economic and environmental consequences for modeling analyses.

The assumptions used in the Business Roundtable modeling analyses are broadly consistent with a world in which:

- Major industrialized trading partners (e.g., the European Union, Japan and Canada) implement or continue policies of similar stringency to those adopted in the United States.
- Major nonindustrialized trading partners (e.g., China, Mexico) implement climate change policies but those policies are less stringent than those adopted in the United States.

Specifically, the modeling analysis assumes a world in which, on average, a policy-induced price increase of $1 for goods and services produced in the United States is matched by a price increase of 80 cents for goods and services produced by U.S. trading partners. This price increase differential results in some loss of international competitiveness, especially for energy intensive and globally competitive industries. The extent of that loss, however, is relatively modest compared to the loss of competitiveness that would result if the United States takes unilateral action and the international community fails to follow. In such a case, the economic and environmental impacts are likely to be far less favorable than those projected in this study.

Defining the Baseline and Alternative Scenarios

The Business-as-Usual Baseline

The BAU baseline assumes that the United States does not impose constraints on GHG emissions over the 2009–50 timeframe. The BAU scenario is primarily based on the projections provided by the Energy Information Administration's *Annual Energy Outlook (AEO) 2008*. The practice of calibrating baseline assumptions to the AEO is common to nearly all of the major economic studies of recent legislative proposals addressing climate change. The modeling team and Business Roundtable members chose to follow this practice for projections through 2030, the last year for which the AEO provides projections. The BAU baseline extends the AEO projections to 2050 by continuing the growth trends observed prior to 2030. The vast majority of the assumptions were derived in this manner, including projections of energy demand in all major end-use sectors (i.e., residential, commercial, industrial and transportation), as well as deployment estimates for most energy supply technologies.

There were a few notable deviations from the AEO projections. First, experts from Business Roundtable companies felt that the deployment levels for nuclear power generation projected in the AEO were overly optimistic considering existing barriers to deployment. Therefore, the BAU case assumes only slight growth in nuclear power over the next decade — about six new plants and some improvements to existing plants. After this initial growth, nuclear power generation capacity is assumed to remain constant, meaning that new generation capacity is built only to replace retired capacity.

Second, the baseline also deviates from AEO in its energy price assumptions. Energy prices and energy futures prices have varied significantly over the past two years, making price forecasting challenging at best. Experts from Business Roundtable companies believed that the AEO 2008 projections for oil prices were significantly lower than what is likely to be realized. The baseline assumes that the real price of oil remains relatively flat at approximately $100 per barrel — a projection that is higher than the AEO 2008 numbers but lower than the AEO 2009 projections. The baseline also assumes that the real price of natural gas will gradually increase until 2030, when it equalizes with the price of oil on a British thermal unit (Btu)-equivalent basis. Thereafter, both natural gas and oil prices are assumed to remain constant in inflation-adjusted terms.

Minimal Technology Scenarios

The Minimal Technology scenarios assume that the United States imposes carbon prices through a carbon tax or cap-and-trade system but that the induced technological response is minimal. It also assumes that the federal government does not adopt additional policy measures aimed at accelerating technology development and deployment. To construct the Minimal Technology scenarios, the modeling team applied carbon prices to the BAU baseline while curtailing any significant technological response to the carbon prices. In short, the Minimal Technology scenarios represent synthetic highest-cost scenarios in which compliance with GHG controls is done almost entirely through the payment of carbon taxes or purchasing of emissions permits. The structure of the nation’s energy sector remains almost the same as it is in the BAU baseline. The only significant changes are some significant reductions in output as a result of higher energy prices.

Although the Minimal Technology scenarios are highly unlikely to materialize, they serve an analytical purpose. Along with the BAU scenario, they establish a second benchmark that helps to bound the analysis and improve the evaluation of various technology pathways in a carbon-constrained world. They do not include any additional deployment of the six technologies assessed in this study, and they serve as baselines that, like the BAU scenario, are common across all of the technology pathways modeled, allowing for the subsequent “layering” of pathway scenarios to determine the impact of the technology response under both Policy Inertia and Policy Leadership assumptions.

Policy Inertia Scenarios

Like the Minimal Technology scenarios, the Policy Inertia scenarios assume that the United States adopts a climate change policy that establishes a price on carbon. However, the Policy Inertia scenarios recognize that the establishment of a carbon price will accelerate the development and deployment of advanced technologies that decrease the burden of those carbon prices and increase GHG emissions reductions. The Policy Inertia scenarios do not assume, however, that additional policy measures are taken to remove barriers to those advanced technologies. As a result, the presumption is that key technologies are not implemented on a commercial scale to their fullest potential. The extent to which a given technology is constrained varies on a case-by-case basis, depending on the unique nature and severity of the barriers associated with its development and deployment.

To construct the Policy Inertia scenarios, each technology working group was first presented with a range of carbon price trajectories, as developed by the modeling team. Each working group was then asked to identify key policies currently in place and develop expectations about their status over the 2009–50 timeframe. Working groups also were asked to identify existing barriers to technology deployment and develop expectations about the status of those barriers under the assumed carbon price trajectories. Finally, working groups were charged with developing a detailed technology template for each pathway, quantifying the key variables, such as technology costs and deployment levels, under Policy Inertia assumptions.

Policy Leadership Scenarios

The Policy Leadership scenarios assume that the introduction of a carbon price is complemented with smart, targeted and aggressive policies that remove the barriers associated with each of the six technology pathways. In these scenarios, the removal of barriers enables a greater technology response to carbon prices and accelerates the development and deployment of key technologies.

To construct the Policy Leadership scenarios, each working group was first asked to develop concrete recommendations that would remove or mitigate existing barriers to technology development and deployment. Once these policies were identified and clearly defined, working groups were instructed to update their technology projections from the Policy Inertia scenarios under the expectation that the identified policies would be implemented as part of a comprehensive climate change policy. Again, working groups were asked to quantify deployment levels and other key economic and environmental assumptions associated with each technology under these conditions.

Chapter 11

Modeling Inputs

Business Roundtable's modeling exercise was based on a collaborative, consensus-driven process that brought together engineers, economists and public policy experts from more than 30 Roundtable member companies, including many leading energy technology producers, consumers and innovators. Organized into working groups corresponding to the individual pathways, these experts developed critical modeling inputs under a variety of carbon price, technology and policy assumptions, including investment costs, technology adoption rates and deployment levels, and incremental greenhouse gas (GHG) savings.[178] These estimates were then used by the Inforum-Keybridge modeling team as inputs to the Long-term Interindustry Forecasting Tool (LIFT) model to simulate scenarios and estimate the impact on key economic, environmental and energy variables.[179]

The following sections describe the technology inputs provided by the working groups for each scenario. The first six sections discuss the modeling inputs for each of the six individual technology pathways under both Policy Inertia and Policy Leadership assumptions. The last section of the chapter examines the integrative assumptions used to construct the Balanced Portfolio scenarios that combine all six technology pathways. Generally speaking, modeling inputs are presented as ranges that reflect the variation in estimates associated with "low" and "high" carbon price trajectories.

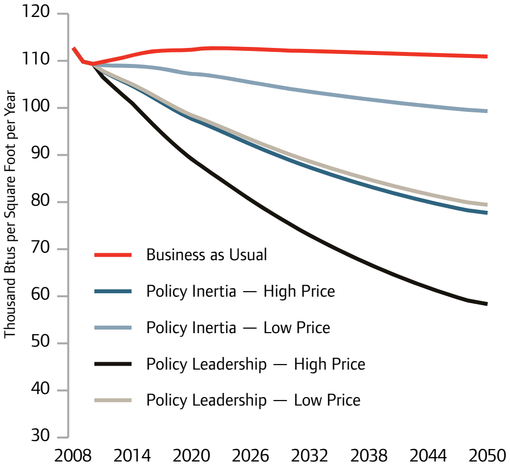
Building Efficiency

As noted in Chapter 2, many technologies needed to improve energy efficiency in residential and commercial buildings are available today, but opportunities to implement them are likely to remain untapped unless several key barriers are reduced or eliminated. Moreover, some building efficiency strategies can be implemented over a relatively short period while others will take many decades to fully implement, and the modeling framework reflects this variation in the timing of opportunities. The modeling framework also includes separate deployment curves for existing and new residential and commercial buildings, reflecting the fact that strategies that affect building shells are likely to be more cost-effective and more quickly implemented in new buildings than in existing buildings.

Policy Inertia Scenarios

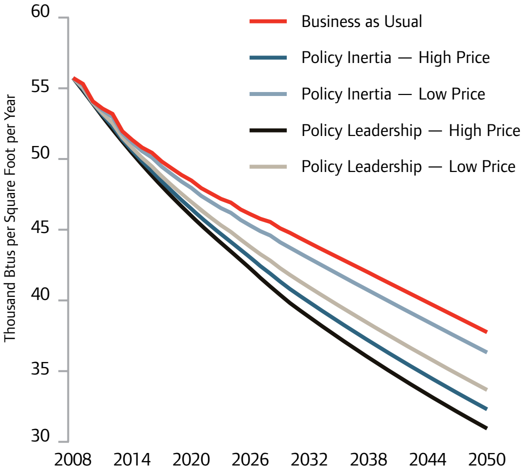
The Policy Inertia scenarios assume that minimal additional policy actions, primarily at the state and local levels, are taken to improve building efficiency. As a result, the Policy Inertia scenarios are consistent with a world in which carbon prices induce significant efficiency improvements, though many cost-effective opportunities remain untapped due to unresolved barriers to deployment. Specifically, it is estimated that the assumed carbon prices will result in a 4 to 14 percent efficiency improvement in residential buildings and a 10 to 30 percent improvement in commercial building efficiency by 2050 relative to Business as Usual (measured in British thermal unit [Btu] per square foot).[180]

Figure 11.1: Improvements in Commercial Building Efficiency



Source: Business Roundtable Building Efficiency Working Group

Figure 11.2: Improvements in Residential Building Efficiency



Source: Business Roundtable Building Efficiency Working Group

Policy Leadership Scenarios

The Policy Leadership scenarios assume that targeted policy efforts, such as those recommended in Chapter 2, remove or reduce existing barriers to deployment. As a result, key technology decisionmakers (e.g., building owners, tenants and builders) recognize and implement building efficiency strategies as they become cost-effective rather than waiting until carbon prices have risen to the point at which failure to implement such strategies becomes prohibitively expensive. Under these assumptions, it is estimated that the combination of greater deployment of energy efficient appliances, near-term adoption of stricter efficiency standards for new buildings and gradual improvements in the envelope of existing buildings lower energy use per square foot by 11 to 18 percent in residential buildings and 28 to 47 percent in commercial buildings by 2050.[181]

Renewable Power

Although there are many promising sources of renewable power that may contribute increasingly significant shares of the nation's electricity, the renewable power working group's modeling efforts focus on wind and solar power. The modeling framework allows for separate assumptions about a variety of technology types, including onshore wind, offshore wind, solar photovoltaic (PV) and concentrated solar power (CSP). These include assumptions about technology costs, efficiency, capacity factors and deployment rates.

Figure 11.3: Cost and Performance Assumptions for New Wind and Solar Power Technologies (High Price — Policy Leadership)

		2010	2020	2050
Onshore Wind	Capital Costs (2008$/kW)	$1,859	$1,778	$1,720
	Operating Costs (2008$/MWh)	$9.80	$8.46	$7.99
	Capacity Factor	39%	42%	42%
Offshore Wind	Capital Costs (2008$/kW)	$2,730	$2,556	$2,440
	Operating Costs (2008$/MWh)	$21.12	$19.31	$15.80
	Capacity Factor	47%	49%	50%
Solar PV	Capital Costs (2008$/kW)	$5,663	$4,384	$4,384
	Operating Costs (2008$/MWh)	$9.50	$9.50	$9.50
	Capacity Factor	18%	21%	21%
Solar CSP	Capital Costs (2008$/kW)	$3,646	$2,823	$2,823
	Operating Costs (2008$/MWh)	$25.50	$25.50	$25.50
	Capacity Factor	24%	25%	27%

Policy Inertia Scenarios

The Policy Inertia scenarios assume that carbon prices result in significant incentives to adopt wind and solar power, though insufficient policy action and inadequate investment in the national grid and storage technologies result in deployment constraints. Without these enabling policies and technologies, wind and solar power will likely require more investments in backup generation, a role generally played by natural gas turbines. Under such assumptions, it is estimated that assumed carbon prices will drive wind and solar power deployment to 18 to 19 percent of total electricity generation by 2050.

Policy Leadership Scenarios

In the Policy Leadership scenarios, it is assumed that a short-run extension of the production tax credit for wind is assumed to accelerate wind power deployment, resulting in an estimated 50 to 75 percent more wind power generation in 2020 than what would be generated under Policy Inertia assumptions. The Policy Leadership scenarios also envision that public and private investments in facilitating technologies, including energy storage and transmission capacity, will greatly increase the potential for wind and solar technologies by reducing intermittency and the need for backup generating capacity. Given this enabling environment, it is projected that wind and solar power could potentially represent 27 to 37 percent of electricity generation in 2050.

Advanced Nuclear Power

As noted in Chapter 4, new advanced nuclear power plants have the potential to be a competitive source of electricity in the future, especially in a carbon-constrained world, though numerous nontechnical barriers may hinder or delay deployment. The widespread commercialization of advanced nuclear power will be influenced by several considerations, including the number of reactors already being planned, the maximum rate at which additional nuclear plants can be built, carbon price expectations, and the absence or presence of an enabling policy environment. The modeling exercise incorporates all of these factors.

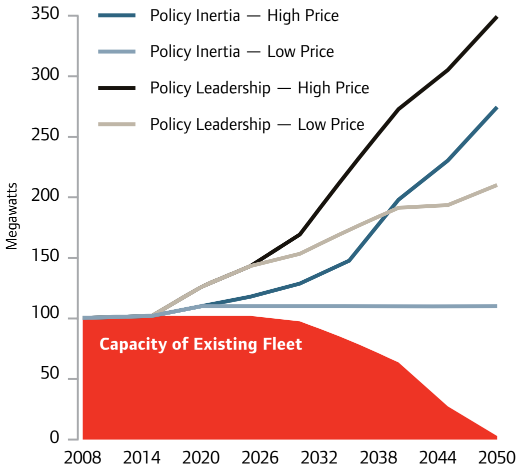
Figure 11.4: Assumed Characteristics for Advanced Nuclear Power Technologies (High Price — Policy Leadership)

	2020	2050
Capital Costs (2008$/kW)	$3,850	$3,632
Fuel Costs (2008$/MWh)	$15.00	$15.00
Operating Costs (2008$/MWh)	$6.81	$6.81
Average Plant Capacity (GW)	1.33	1.33
Capacity Factor	90%	90%
Construction Time (years)	6	6

Policy Inertia Scenarios

The Policy Inertia scenarios assume an unaggressive approach to nuclear power deployment. Specifically, given policy measures currently in place, it is estimated that six plants will be built in the next decade. After this initial deployment, however, the Policy Inertia scenarios envision slow progress in new plant construction due to multiple policy failures. This is consistent with the view that, in the absence of an enabling policy environment, many investors are likely to wait on the sidelines until early adopters test the permitting process, demonstrate economic competitiveness, and drive down costs through learning and economies of scale. Even with a high-carbon price trajectory, the Policy Inertia scenarios envision that only 24 new plants come online by 2030 — fewer than the number of reactors for which construction and operating license applications have been submitted to date.

Figure 11.5: Estimated Nuclear Power Deployment



Source: Business Roundtable Nuclear Working Group

After 2030, as carbon prices continue to rise, it is envisioned that the economics of nuclear power will become more attractive and deployment will increase. At lower carbon prices, it is estimated that nuclear power plant deployment after 2030 is just large enough to displace retiring nuclear plants and marginally increase total nuclear power generation. At higher carbon prices, it is estimated that new reactor construction accelerates to a pace of approximately 10 new reactors coming online every year from 2035 to 2050, a pace roughly the same as that observed in the United States during the 1970s and equal to the maximum pace envisioned in the Policy Leadership scenarios.

Policy Leadership Scenarios

In the Policy Leadership scenarios, policymakers take aggressive steps to promote nuclear power deployment, including the rapid adoption of Business Roundtable's policy recommendations. It is estimated that such policies will result in the construction of 18 new plants by 2020, as compared to just six in the Policy Inertia scenarios. This pace of deployment is sustained throughout the scenarios, as the new combined construction and operating licensing process is assumed to deliver efficiencies and the economics of nuclear power becomes increasingly attractive and more widely appreciated. By 2030, the Policy Leadership scenarios envision 42 to 54 new nuclear power plants becoming operational as compared to just 9 to 24 in the Policy Inertia scenarios. After 2030, 6 to 11 new nuclear power plants are being completed every year.

Carbon Capture and Storage

As noted in Chapter 5, wide-scale deployment of carbon capture and storage (CCS) technologies can transform the use of conventional fossil fuels to reduce GHG emissions while maintaining coal's essential role in the U.S. energy mix. The modeling framework includes the application of CCS technologies to three types of electricity generation plants — natural gas combined cycle (NGCC), integrated gasification combined cycle (IGCC) and pulverized coal (PC) — and three industrial gasification (IG) plant types, including facilities that produce liquid fuels, substitute natural gas and hydrogen gas. The working group has specified a number of modeling inputs, including capital costs, plant efficiencies, carbon capture rates and deployment.

Figure 11.6: Assumed Characteristics for Electric Power Technologies with CCS (High Price — Policy Leadership)

		2010	2020	2050
NGCC (CCS)	Capital Costs (2008$/kW)	$1,707	$1,707	$1,278
	Fuel Costs (2008$/MWh)	$65	$104	$145
	Operating Costs (2008$/MWh)	$11.60	$11.60	$7.80
	Plant Efficiency	45%	45%	45%
	Carbon Capture Efficiency	83%	83%	83%
PC (CCS)	Capital Costs (2008$/kW)	$3,547	$3,547	$2,654
	Fuel Costs (2008$/MWh)	$23.45	$22.57	$23.20
	Operating Costs (2008$/MWh)	$32.20	$32.20	$26.80
	Plant Efficiency	30.7%	30.7%	30.7%
	Carbon Capture Efficiency	88%	88%	88%
IGCC (CCS)	Capital Costs (2008$/kW)	$3,166	$3,166	$2,575
	Fuel Costs (2008$/MWh)	$22.43	$21.47	$22.19
	Operating Costs (2008$/MWh)	$28.30	$28.30	$24.80
	Plant Efficiency	32.1%	32.1%	32.1%
	Carbon Capture Efficiency	90%	90%	90%

Policy Inertia Scenarios

In the Policy Inertia scenarios, it is estimated that carbon prices are high enough to support CCS in a range of applications and scenarios. These scenarios assume continued government support for CCS technology development and deployment that is equivalent to present levels of support, including support for research and development (R&D) and tax credits to incentivize investment, production and sequestration. Due to these incentives, 1 to 3 percent of electricity in the Policy Inertia scenarios is produced using CCS technologies in 2030 and 6 to 12 percent in 2050. Under these assumptions, the majority of the power plants built with CCS technologies are expected to be IGCC plants.

The Policy Inertia scenarios also assume that carbon prices result in the application of CCS at IG facilities. These facilities already include CO_2 separation as an inherent step in their production process but vent the concentrated streams of CO_2 into the atmosphere, which is likely to become prohibitively expensive when carbon is priced at significant levels. It is estimated that, for a relatively small additional cost, these facilities can capture and store those carbon emissions. In the Policy Inertia scenarios, IG facilities produce 2.4 quadrillion to 3.9 quadrillion Btus of gasoline, substitute natural gas and hydrogen gas in 2050.

Policy Leadership Scenarios

The Policy Leadership scenarios envision that the adoption of policy recommendations and heightened support for CCS technologies will accelerate deployment by several years. On average, deployment of CCS for electricity generation is assumed to be accelerated by three to five years relative to Policy Inertia scenarios, and deployment of CCS for IG facilities is assumed to be accelerated by 5 to 10 years.[182] Under these assumptions, electric power producers generate roughly 14 to 18 percent of electricity with CCS technology by 2050, and IG facilities produce 4.5 quadrillion to 6.7 quadrillion Btus of energy with CCS technology.[183]

In both the Policy Inertia and Policy Leadership scenarios, coal-fired power plants represent the majority of CCS applications in the electric power industry. NGCC power plants play a relatively small role in CCS applications, due in part to the assumed price of natural gas.[184]

Advanced Vehicle Technologies

As noted in Chapter 7, several advanced vehicle technologies have the potential to transform and modernize the vehicle fleet in the coming decades. Although there are many potential cost-effective emissions reduction opportunities in the transportation sector, the advanced vehicle technology working group focused on the light-duty vehicle market, which represents nearly 60 percent of CO_2 emissions in the transportation sector.

A wide range of advanced vehicle technologies are modeled, including more efficient internal combustion, advanced diesel and hybrid-electric vehicles. The modeling analysis, however, focuses mostly on the potential of plug-in hybrid electric and fuel cell vehicles

Figure 11.7: Assumed Characteristics of New Advanced Vehicles (High Price — Policy Leadership)

		2009	2012	2020	2030	2050
HEV	MPG (On-Road)	31.8	32.7	38.6	38.6	38.6
	MPG % Improvement over ICE	43%	40%	33%	32%	32%
	Additional Initial Cost (2008$)	$3,993	$4,042	$3,298	$2,975	$2,709
	Fuel Costs (cents/mile)	9.4	10.1	8.4	8.9	11.7
PHEV-40	MPG (On-Road)	52.3	53.2	59.7	62.3	63.9
	MPG % Improvement over ICE	135%	128%	105%	113%	118%
	Additional Initial Cost (2008$)	—	$13,814	$4,649	$4,649	$4,649
	Fuel Costs (cents/mile)	5.2	6.6	6.1	6.2	7.9
HFCV	MPG (On-Road)	42.0	45.0	54.9	63.5	85
	MPG % Improvement over ICE	89%	93%	89%	117%	190%
	Additional Initial Cost (2008$)	$69,120	$60,552	$20,500	$7,000	$5,350
	Fuel Costs (cents/mile)	8.6	8.1	6.8	5.8	4.3
ICE	MPG (On-Road)	22.2	23.4	29.1	29.3	29.3
	Initial Cost (2008$)	$29,125	$29,400	$30,895	$31,026	$31,236
	Fuel Costs (cents/mile)	13.4	14.1	11.2	11.7	15.4

to improve transportation efficiency in the light-duty vehicle market over the longer term.[185] The modeling framework incorporates input assumptions about vehicle costs, fuel economy, fuel type, vehicle fleet turnover rates and vehicle sales by type.

Policy Inertia Scenarios

The Policy Inertia scenarios envision that carbon prices drive efficiency gains in light-duty vehicles beyond those already called for by the new Corporate Average Fuel Economy (CAFE) standards set forth in the Energy Independence and Security Act of 2007. As carbon prices increase, it is expected that consumer preferences gradually shift toward more fuel efficient internal combustion engines (ICEs), advanced diesel vehicles and hybrid electric vehicles (HEVs). In the absence of policy leadership, however, the cost differentials between conventional vehicles and plug-in HEVs (PHEVs) or fuel cell vehicles are assumed to remain significantly higher than the potential fuel savings. This results in a "chicken and egg" dilemma for PHEVs and fuel cell vehicles because decreases in technology costs depend substantially on greater vehicle deployment, but greater vehicle deployment cannot occur without a decrease in technology costs. In the Policy Inertia scenarios, this dilemma is not resolved and the deployment of PHEVs and fuel cell vehicles is very limited.

Given Policy Inertia assumptions, it is expected that the majority of the light-duty vehicle fleet in 2050 will consist of ICE vehicles that are measurably more efficient than the existing ICE vehicles. In addition, advanced diesel vehicles and HEVs enjoy larger market shares. As a result, the Policy Inertia scenarios reflect a world in which average on-road fuel economy of the light-duty vehicle fleet reaches 32 miles per gallon (mpg) in 2050.

Policy Leadership Scenarios

The Policy Leadership scenarios envision that aggressive policy actions result in strong incentives over the next decade to produce and purchase PHEVs.[186] It is assumed that the policies will directly and indirectly contribute to greater R&D funding, investment and deployment levels for PHEVs. This faster deployment is assumed to drive battery improvements and other key technological developments, enabling the auto industry to produce electric-powered vehicles with longer ranges and shorter charge times at lower costs.

Under Policy Leadership assumptions, the all-electric range of the average PHEV is estimated to increase from 10 miles in 2010 to 40 miles by 2030. As a result, the share of vehicle miles traveled in PHEVs that is powered by electricity increases from 21 percent to 58 percent over the same period.[187] After 2030, this percentage remains constant, although additional advances in battery technology and changes in driving behavior could increase this percentage further. Ultimately, Policy Leadership scenarios reflect a world in which PHEVs represent one-third of new light-duty vehicles sales and approximately 40 percent of light-duty vehicles on the road in 2050.

While Policy Leadership assumptions result in strong deployment levels for PHEVs within the next decade — on the order of magnitude that President Obama has set as an industry goal — the development and deployment of hydrogen fuel cell vehicles is assumed to lag that of PHEVs by approximately five years. This delay occurs because PHEVs, such as the Chevy Volt, are expected to be in production by 2010, whereas fuel cell technologies remain relatively immature. Even with the assistance of targeted and aggressive public policies, fuel cell vehicle technology is likely to remain relatively expensive in the near term. It is assumed, however, that strong and sustained public and private support, particularly for R&D in the short term, help bring down the incremental costs of fuel cell vehicles. Along with additional investments in hydrogen infrastructure, lower incremental costs are assumed to facilitate significant fuel cell vehicle deployment after 2020. In the policy leadership scenarios, fuel cell vehicles represent 41 percent of new light-duty vehicle sales and 24 percent of light-duty vehicles on the road in 2050.

Advanced Biofuels

As noted in Chapter 8, advanced biofuels have the potential to measurably diversify the transportation fuel mix, though significant barriers to widespread commercialization remain, including concerns about collateral impacts on other industries and land use. Although there are several advanced biofuels under development with a wide variety of potential feedstocks, the modeling analysis focuses on the production of one biofuel (cellulosic ethanol) using three feedstocks (switchgrass, corn stover and woody materials). The development and deployment of cellulosic ethanol is assumed to serve as a proxy for the development and deployment of many other advanced biofuels, particularly those that come from cellulosic feedstocks.

Assumptions were generated through a "bottom-up" framework that considered a variety of key variables, including the availability of productive land, agricultural yields, biomass costs and plant conversion efficiencies. The analysis assumes that the lifecycle emissions of ethanol are 86 percent lower than those of conventional gasoline.[188] Furthermore, it is assumed that the biomass collected and used for cellulosic ethanol production is only that which can be sustainably harvested, meaning that significant proportions of biomass residue will be left on croplands to ensure that the levels of carbon and other nutrients are not being depleted over time.[189]

Policy Inertia Scenarios

The Policy Inertia scenarios envision that falling production costs and improved conversion efficiencies result in cellulosic ethanol production approaching 1 billion gallons by 2015 and 9 billion to 11 billion gallons by 2022. This is the result of an aggressive effort to achieve the 2022 renewable fuel mandates for advanced biofuels, including substantial and rapid investments in infrastructure and feedstock production and collection. After 2022, improved feedstock yields and higher biomass collection rates drive further increases in production. As cellulosic production reaches higher levels, decreasing land availability and the growing needs of forest product industries begin to offset gains from increasing yields — limiting the availability of biomass and constraining production growth.

Under these assumptions, cellulosic ethanol production is projected to reach 27 billion to 30 billion gallons in 2030 and 66 billion to 69 billion gallons in 2050. These production levels require that most sustainably removable cellulosic materials not used by traditional feedstock users (e.g., paper, lumber, etc.) are devoted to biofuel production, though biomass electricity generation and other GHG reducing technologies could alter the availability or raise the price of cellulosic materials.

Figure 11.8: Assumed Characteristics of Cellulosic Ethanol from Different Feedstocks (High Price — Policy Leadership)

		2010	2020	2050
	Capital Costs (2008$/gal)	$4.95	$3.98	$3.50
Corn Stover	Feedstock Costs (2008$/ton)	$35	$35	$35
	Sustainable Yield (tons/acre)	1.5	1.6	2.5
	Conversion Efficiency (gallons/ton)	85	100	110
Switchgrass	Feedstock Costs (2008$/ton)	$55	$45	$40
	Sustainable Yield (tons/acre)	4.2	5.0	8.0
	Conversion Efficiency (gallons/ton)	80	100	100
Woody Biomass	Feedstock Costs (2008$/ton)	$65	$65	$65
	Sustainable Yield (tons/acre)	N/A*	N/A*	N/A*
	Conversion Efficiency (gallons/ton)	79	90	90

*Woody biomass is assumed to be nonplantation, forest residues.

Policy Leadership Scenarios

The Policy Leadership scenarios envision aggressive effort to achieve the 2022 renewable fuel mandates for advanced biofuels. It also is assumed that increased research and development support in the near term accelerates conversion efficiency improvements by five years as compared to the Policy Inertia scenarios. This has the effect of accelerating a decrease in overall production costs and encouraging producers to increase the amount of biomass they make available for biofuel production. Consequently, ethanol production is estimated to be slightly higher in the short run. After 2030, however, production levels in the Policy Leadership scenarios converge with production levels in the Policy Inertia cases. Under these assumptions, it is estimated that cellulosic ethanol represents 17 to 18 percent of transportation fuel use in 2050.

Integrative Assumptions for a Balanced Portfolio of All Six Technology Pathways

The modeling inputs discussed so far were developed by the individual technology working groups for each individual technology pathway. The next phase of the modeling — the construction of Balanced Portfolio scenarios that incorporate all six technology pathways to be discussed in Chapter 12 — required some modifications to the assumptions of the individual working groups to help form an integrated set of internally consistent inputs. This section describes these modifications.

Accounting for Existing Electric Power Production Assets

Over the next four decades, the vast majority of the nation's current electricity generation plants are expected to be retired. Low-carbon electricity generation technologies will be needed not only to meet new electricity demand but also to replace these retiring assets. However, under the most optimistic assumptions, working group estimates show that new low-carbon electricity generation technologies could be deployed fast enough to meet new demand and replace some of the existing infrastructure before it reaches the end of its useful economic life. However, the premature replacement of the existing electric power generation fleet will not necessarily be cost-effective, especially if such assets are fully depreciated.

Some working groups, such as that for advanced nuclear power, directly accounted for existing nuclear plant retirements in their modeling inputs for all policy scenarios. Other working groups did not, and technology deployment estimates were modified where appropriate to reflect assumptions about the retirement schedules for existing capital.

Specifically, existing conventional coal-fired facilities were generally assumed to retire after reaching an age of 55 years. This resulted in a majority of retirements by 2030 and more than 90 percent by 2040, prior to the point at which operating costs, including the cost of carbon, for a fully depreciated plant are unlikely to exceed competitive electricity rates projected by the model.

Existing conventional gas-fired electricity production is generally assumed to change in proportion with conventional coal — roughly in a two-to-five ratio. Natural gas-fired power plants have relatively low capital costs, and their competitiveness is largely determined by natural gas prices and carbon prices. Under lower natural gas price assumptions that are more consistent with 2009 prices, natural gas-fired power would likely represent a larger proportion of conventional fossil fuel electricity production.

Technology Pathway "Crowd Out"

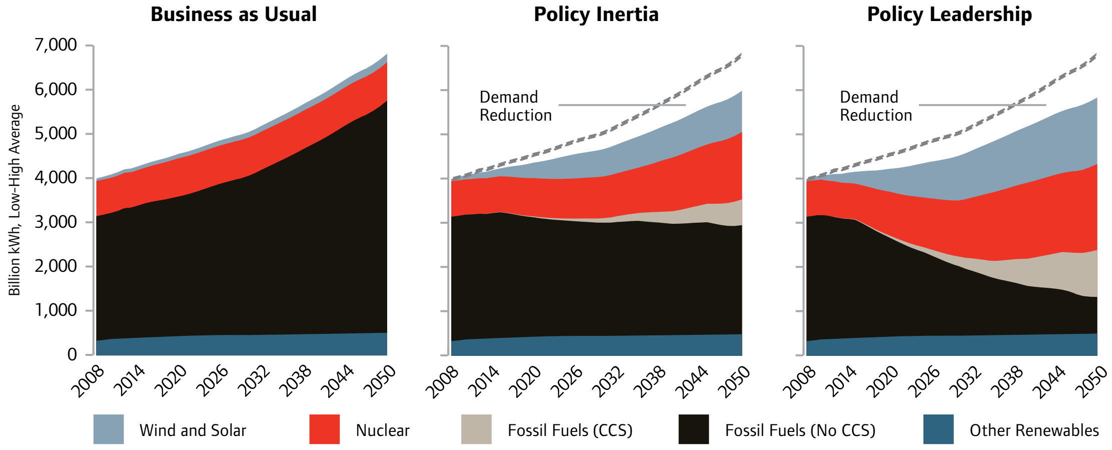
In some scenarios, deployment estimates for individual technology pathways exceed demand and must be scaled appropriately. For example, in one of the Policy Leadership scenarios, aggressive efforts to improve building efficiency result in substantial reductions in electric power demand. When combined with aggressive deployment estimates for electricity generation from renewable, nuclear and CCS technologies, the result is that electricity supply exceeds demand. In such instances, deployment schedules for power supply technologies were scaled according to projections for levelized production costs and additional constraints that were agreed to by the working groups.

The modeling inputs developed by the working groups showed that production cost assumptions for electric power from nuclear, wind and CCS technologies would be roughly similar. The cost estimates for solar power that were developed by the renewable power working group, however, assumed that solar power would be significantly more costly than the three other primary electricity generation technologies under all scenarios examined. Based on these cost projections, solar power was assumed to have a lower deployment schedule than assumed in the more isolated individual technology pathway modeling stage.[190] Technological breakthroughs for solar power beyond those modeled would likely result in higher levels of deployment than those envisioned in this study.

Similarly, adjustments were made to account for competition among liquid fuels. The nonconventional liquid fuels modeled in this report include gasoline from coal from the coal-to-liquids (CTL) gasification facilities and cellulosic ethanol. It was assumed that market forces would eventually determine timing and extent of supply expansion of these nonconventional fuels.[191]

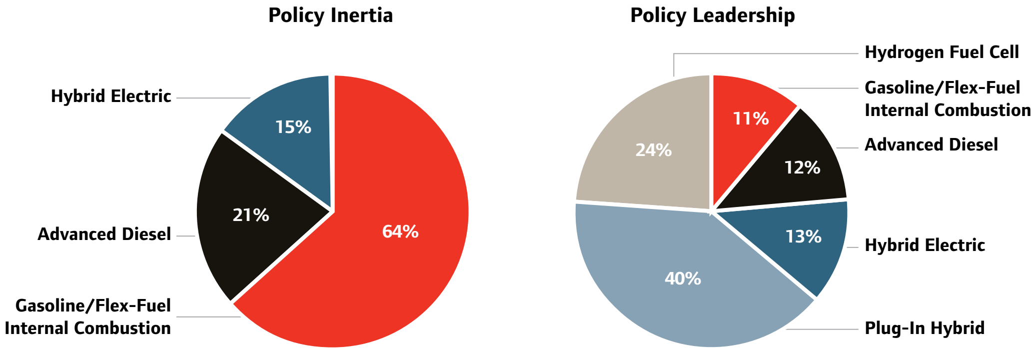
Technology Deployment Estimates: Balanced Portfolio Scenarios

Electricity Generation by Source

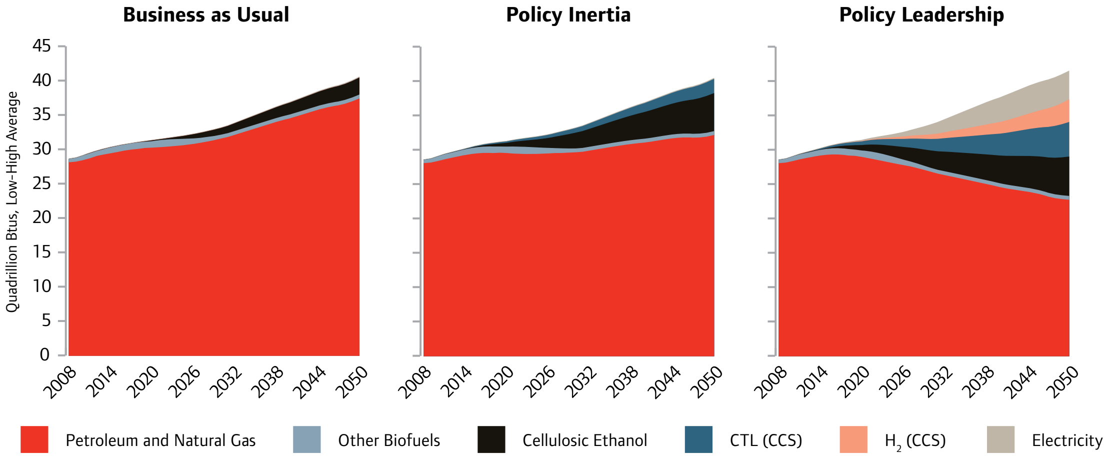


Light-Duty Vehicle Use by Type in 2050

(Percentage of Vehicle Miles Traveled, Low-High Average)



Transportation Fuels by Source



Source: Inforum/Keybridge Research and Business Roundtable Working Groups

Chapter 12

Modeling Results

Each of the six individual technology pathways focused on in this study — building efficiency improvements, renewable power generation, advanced nuclear power, carbon capture and storage (CCS), advanced vehicle technologies and advanced biofuels — has the potential to make a significant contribution to meeting the sustainable growth challenge. Optimal economic, environmental and security outcomes, however, are most likely to be achieved through a comprehensive approach that pursues all six technology pathways simultaneously. Indeed, the combination of these technology pathways and the two enabling pathways — grid modernization and enhanced domestic production of oil and natural gas — form the foundation of a balanced portfolio approach that is likely to be in America's best interests for a variety of reasons, including:

- **Technology uncertainty:** While all of the technology pathways demonstrate great promise, success is not ensured. Technological development is notoriously difficult to predict. Of the technologies examined in this study, some will undoubtedly outperform expectations, some will underperform, while others may simply never become commercially competitive and may languish. The unpredictability of technological development must not be ignored. Rather, it must be effectively managed, and government and industry must work cooperatively to advance a balanced portfolio of technologies that widely distributes the risks of any one technology underperforming.
- **Energy diversity and flexibility:** In transforming the U.S. energy system, it is important to not simply exchange one unsustainable pathway for another. Overreliance on any one energy source, regardless of origin, or any one technology, regardless of effectiveness, increases our vulnerability to market volatility, geopolitical instability, or unintended and unforeseeable negative side effects of that technology. In contrast, a balanced portfolio of technologies can improve both the diversity and the flexibility of the energy system, enhancing the economy's resiliency to energy market shocks or other unanticipated events.
- **Scale:** No single pathway currently appears capable of delivering the large-scale emissions reductions advocated by many policymakers.[192] The scale of the challenge is enormous and spans all sectors of the economy. Approaches that are narrow or unbalanced are more likely to fall short of aggressive emissions reduction targets or risk pushing carbon prices to unsustainably high levels.

- **Pathway synergies:** Maximizing the benefits of some technology pathways requires advances in other areas. For example, realizing the full potential of fuel cell vehicles to contribute to emissions reductions in the transportation sector will require a cost-effective, low-carbon source of hydrogen fuel (e.g., coal with CCS technology). A balanced portfolio approach can harness these "positive synergies" to enhance environmental, economic and security outcomes as some technology pathways may combine to achieve greater greenhouse gas (GHG) reductions at a lower economic cost than they can achieve independently.
- **Knowledge spillovers:** An important benefit of technology research and development (R&D) is "knowledge spillovers" that stimulate innovation in other areas of the economy. For example, breakthroughs in battery technologies for electric vehicles will likely result in enormous benefits for a wide range of industries, including renewable power generation, computers and home appliances. Pursuing a balanced portfolio of technologies expands the breadth and scope of scientific discovery, increasing the likelihood of widespread knowledge spillovers throughout the economy.
- **Competitiveness effects:** Deploying a portfolio of technologies will result in a complex and positive interplay of competitive forces within the U.S. economy. Technologies must compete with each other and other economic activities for capital, raw materials, labor and market share. Pursuing multiple technology fronts will encourage innovation and drive entrepreneurial responses that will lead to superior outcomes.

To explore the potential benefits of a balanced portfolio approach, a series of modeling scenarios were constructed that simulate the implementation of all six technology pathways simultaneously. These Balanced Portfolio scenarios illustrate how the pathways might cooperate, compete and evolve over time to influence key economic, environmental and energy variables, such as gross domestic product (GDP), household consumption and GHG emissions.

The Scope of Analysis

The Balanced Portfolio scenarios measure the potential impacts that a combination of six technology pathways might have on economic and environmental outcomes. They do not consider the potential impacts of other technologies or the spillover effects that these technologies may have on sectors that are not explicitly modeled in this study. Ultimately, the Balanced Portfolio scenarios do not include potential emissions reduction opportunities in sectors that represent about one-third of U.S. emissions. These sectors include large portions of the industrial and transportation sectors and the entire agricultural sector. Additional emissions reduction strategies would almost certainly be pursued in these sectors if a carbon price were imposed on the economy. Many sectors also would benefit from technology spillovers that would flow from the strategies pursued as part of the pathways modeled in this study. Examples of possible technology effects that are not explicitly quantified in this study include:

- Applying CCS technologies to some coal- or natural gas-burning industrial facilities;
- Substituting hydrogen gas produced from coal or natural gas at industrial gasification facilities for the direct burning of natural gas in many industrial applications;
- Applying fuel cell, battery and other transportation technologies to other forms of transportation, including trucks, buses, trains and airplanes; and
- Using biofuels in aviation, freight and other liquid fuel applications.

To the extent that these additional benefits would materialize, the benefits of pursuing all six technology pathways as part of a balanced portfolio are likely to be understated.

Portfolio Modeling Results and Policy Conclusions

The Policy Inertia scenarios are broadly consistent with a world in which the federal government establishes a price of carbon but fails to adopt complementary policies that may help resolve key technological, market and institutional barriers to technology development and deployment. As a result, the carbon price induces a strong technological response from the six pathways that significantly reduces emissions, but environmental and economic benefits may not be maximized as noneconomic barriers hamper the efficiency of carbon price signals.

In contrast, the Policy Leadership scenarios are representative of a world in which the federal government both establishes a carbon price and adopts the Business Roundtable policy recommendations that are designed to resolve technological, market and institutional barriers and thereby accelerate the development and deployment of advanced technologies. The effect is to enhance the efficacy of carbon prices — resulting in lower GHG emissions and higher economic growth than would otherwise be the case. The primary focus of this analysis is to estimate the potential incremental environmental and economic benefits of policy leadership.

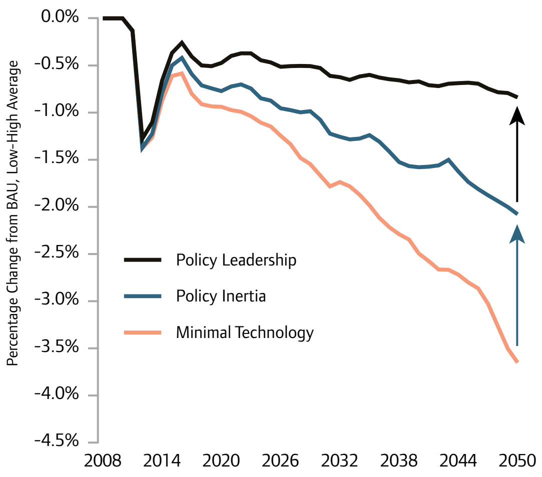
In simplest terms, the modeling analysis confirms the central thrust of Business Roundtable's recommendations: While putting a price on carbon is likely to place a significant drag on the economy, a balanced portfolio of technologies combined with strong policy leadership will dramatically increase the nation's prospects for meeting the sustainable growth challenge.

Specifically, the analysis finds that:

- **In the absence of policies that remove barriers to technology development and deployment, imposing a price on carbon is likely to result in significantly lower U.S. economic growth in coming decades.**

In the Policy Inertia scenarios (i.e., scenarios in which a carbon price is established but Business Roundtable's policy recommendations are not adopted), real GDP declines by approximately 2 percent by 2050, while CO_2 emissions are reduced by 19 to 44 percent.[193] Under such assumptions, efforts to mandate a higher level of GHG mitigation — either directly by establishing a more ambitious GHG emissions cap or indirectly by imposing a more aggressive carbon tax — are likely to result in significantly lower rates of economic growth than those envisioned in this study.

Figure 12.1: Real Gross Domestic Product



Source: Inforum/Keybridge Research

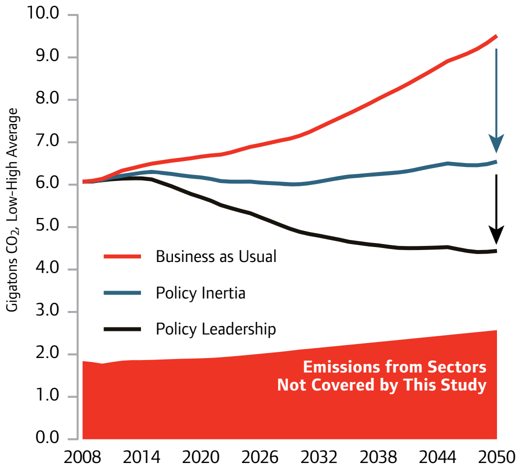
- **In contrast, a balanced portfolio of technologies coupled with policy leadership can significantly mitigate the negative effects on U.S. economic growth while achieving greater reductions in GHG emissions.**

In the Policy Leadership scenarios (i.e., scenarios in which a carbon price is established and Business Roundtable's recommendations *are* adopted), real GDP declines by less than 1 percent by 2050, while CO_2 emissions are reduced 45 to 62 percent. In short, the Roundtable's policy recommendations for removing barriers to technology development and deployment are estimated to deliver almost twice the GHG mitigation at roughly half the economic cost.[194]

- **A balanced portfolio approach is the only approach that is likely to achieve both aggressive GHG targets and economically sustainable carbon prices.**

In the Business as Usual (BAU) scenario, U.S. CO_2 emissions continue rising from approximately 6.1 gigatons in 2008 to roughly 9.5 gigatons in 2050 — a 57 percent increase from today's levels. In contrast, many policymakers have suggested that GHG emissions reductions of as much as 83 percent from today's levels are necessary by 2050 if the United States is going to do its part in combating global climate change. To meet this goal, CO_2 emissions would likely need to be reduced by 8.5 gigatons from BAU emissions levels in 2050.

Figure 12.2: CO_2 Emissions



Source: Inforum/Keybridge Research

The CO_2 reductions achieved through a combination of policy leadership and a balanced portfolio approach are substantial. CO_2 emissions in the Policy Leadership scenarios decrease by an average of 5.1 gigatons by 2050 — approximately two-thirds of the mitigation required to achieve the most stringent targets advocated by some policymakers. Combined with emissions reductions from sectors not examined in this study, which represent one-third of current emissions, these six technologies could potentially put the nation on track to achieve the emissions reductions needed to meet the most stringent 2050 targets being debated today. Key emissions reduction opportunities not assessed in this study include:

- The application of the six technology pathways to sectors in which improvements over BAU are not studied or modeled (e.g., the use of fuel cells and electrification in heavy-duty trucks and other forms of transportation);
- The application of other promising emissions-reducing technologies, such as biomass for power generation, improved mass transit and improved agricultural practices; and
- The application of technologies to reduce emissions from the industrial sector.

The modeling also suggests that while these technology pathways form a solid foundation of a balanced portfolio approach to meet some of the more aggressive emissions reduction goals, an even broader set of technologies will need to be pursued. The differences between the emissions reductions achieved in the Policy Leadership scenarios and those being debated by policymakers suggest that whatever targets are set by policymakers, a portfolio approach that leverages all of the technology pathways examined in this study (as well as others not examined) is likely to be the only approach that has the potential to meet those targets. Ultimately, a strategy that relies on anything less than a balanced portfolio will likely require significantly higher carbon prices and substantially greater economic costs to achieve a given level of mitigation.

- **A balanced portfolio of technologies combined with policy leadership can reduce energy consumption, diversify the transportation fuel mix and enhance energy security.**

In scenarios in which both a carbon price is established and Business Roundtable's recommendations are adopted, the electrification of the transportation sector combined with the deployment of hydrogen fuel cell vehicles, increased penetration of advanced biofuels and continued advancement in internal combustion engine (ICE) technology reduces energy consumption and greatly diversifies the transportation fuel supply. Specifically, it is estimated that alternative fuels have the potential to constitute nearly 43 percent of the transportation fuel mix by 2050, as opposed to an average of 19 percent in scenarios in which a carbon price is established but the Roundtable's recommendations are not adopted. At the same time, the analysis suggests that the increased deployment of some advanced vehicles is likely to enhance consumers' capacity to alternate among fuels and respond to evolving market conditions. This combination of fuel supply diversity and fuel choice flexibility is likely to reduce the nation's vulnerability to instability in any one energy market and improve the economy's resiliency in the face of fuel price volatility.

- **Policy leadership can provide relief to American households from the costs associated with reducing GHG emissions.**

In scenarios in which a carbon price is established but Business Roundtable's recommendations are not adopted, average annual household consumption — a common measure of household welfare — decreases by $800 to $1,500 per year relative to the BAU baseline, or 0.7 to 1.2 percent of average annual household consumption over the 2010–50 period. This decrease represents the costs to U.S. households of transitioning to a low-carbon economy.

The study finds, however, that this cost can be cut in half through policy leadership that accelerates technology development and deployment. In the Policy Leadership scenarios, average annual household consumption is reduced by $400 to $800 (2008$) per year, or 0.3 to 0.7 percent of average annual household consumption over the 2010–50 period. In short, the cumulative benefits associated with Business Roundtable's policy package could substantially reduce the cost of transitioning to a low-carbon economy for American households.

- **Policy instruments that are transparent, consistent and gradual will be more effective and more likely to minimize the economic impact of climate change policies.**

Every model simulation conducted for this study indicates that, especially in the initial years of the policy, the imposition of a carbon price will result in significant dislocations within the economy. This is likely to reduce real GDP growth, household consumption and other indicators associated with economic welfare, particularly if the nation is expected to adapt abruptly to the carbon constraint. On the other hand, transparent and steady policy instruments introduced gradually and incrementally are likely to enable businesses, investors, workers and consumers to better prepare and take appropriate action to minimize costs.

Additional Policy Considerations

- **The economic and environmental impacts of U.S. climate change policies are highly dependent on the policies adopted by major trading partners.**

This study assumes that America's major trading partners adopt climate change policies that, on average, result in less substantial price increases than those experienced in the United States. Specifically, it is assumed that a policy-induced price increase of $1 for goods and services produced in the United States is matched by a price increase of 80 cents for goods and services produced by U.S. trading partners. This price increase differential reflects a loss in U.S. competitiveness that registers as a small but significant decrease in net exports, which reduces real GDP. If foreign prices were set to reflect even less reciprocal action by trading partners, the additional loss of U.S. competitiveness would likely further reduce GDP.

This underscores the importance of ensuring that U.S. actions on climate change are both cost-effective and matched with credible commitments by other countries. Although not explicitly examined in this study, the loss of competitiveness that results from sharply asymmetric climate change policies could potentially shift production and investment to less regulated jurisdictions. In addition to the economic damages such a shift in production and investment would cause the U.S. economy, it also could result in so-called "emissions leakage" — an offsetting increase in emissions in other less heavily regulated countries. Consequently, policymakers must remain sensitive to the prospect of emissions leakage in energy intensive and globally competitive industries and design policy frameworks that have the potential to level the carbon playing field for these uniquely challenged sectors.

- **The economic costs required to achieve large-scale reductions in GHG emissions will not be shared equally by all industries or regions.**

It is important to note that the economic costs required to achieve large-scale reductions in GHG emissions will not be shared equally by all industries or regions of the country. The aggregate macroeconomic impacts reported in this study mask the significant dislocation and adjustment process that would accompany any climate change policy and do not reveal the hardships and challenges that businesses, investors, workers and consumers in particular sectors of the economy will experience in adapting to a carbon-constrained world. Policymakers must endeavor to make this transition as smooth as possible.

Conclusion

The modeling results suggest that addressing the issue of climate change by either directly or indirectly placing a price on carbon is likely to place a significant strain on the U.S. economy. The results also suggest, however, that strong policy leadership can significantly mitigate these negative economic impacts by accelerating the development and deployment of advanced technologies. These technologies have the potential to cost-effectively reduce GHG emissions in the residential and commercial buildings, electric power, and transportation sectors of the economy, which are responsible for the bulk of GHG emissions. Meeting the sustainable growth challenge will not be easy, however, and policy leadership will require practical solutions, political compromise and bipartisan cooperation.

In addition, the results illustrate that there is no single technological solution to the sustainable growth challenge. Any policy that fails to leverage the full potential of a balanced portfolio of technologies is likely to either fail to achieve a desired level of emissions reductions or achieve a mandated level of emissions reductions by imposing unacceptable costs on the U.S. economy — thereby simply exchanging one unsustainable pathway for another.

The key lesson for policymakers is that any sustainable climate change policy must be based on a robust approach to technology development and deployment. Climate change policy must not only reflect current technological expectations but also must acknowledge the likelihood that some promising technologies may underperform expectations while other technologies that are less visible today may emerge as cost-effective solutions. Given the long-term nature of climate change policies and the uncertainties associated with technological progress, a balanced portfolio approach coupled with strong policy leadership is likely to be the only approach that can simultaneously and sustainably advance the nation's economic, environmental and security objectives.

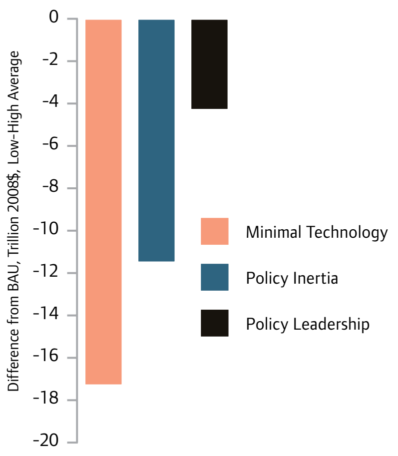
Economic and Environmental Impacts: Balanced Portfolio

	2030						2050					
	Minimal Technology		Policy Inertia		Policy Leadership		Minimal Technology		Policy Inertia		Policy Leadership	
Input Assumptions	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
Carbon price (2008$)	$44	$92	$44	$92	$44	$92	$118	$197	$118	$197	$118	$197
ENERGY EFFICIENCY												
Commercial building energy use per sq. ft.	0%	0%	-7%	-21%	-20%	-33%	0%	0%	-10%	-30%	-28%	-47%
Residential building energy use per sq. ft.	0%	0%	-2%	-9%	-7%	-11%	0%	0%	-4%	-14%	-11%	-18%
*POWER GENERATION (SHARES OF ELECTRICITY PRODUCTION)**												
Wind	2%	2%	9%	10%	16%	20%	3%	3%	10%	10%	17%	20%
Solar	0%	0%	3%	5%	3%	6%	0%	0%	5%	6%	6%	8%
Nuclear	17%	17%	18%	23%	26%	31%	13%	13%	14%	39%	27%	41%
Fossil fuel (CCS)	0%	0%	1%	4%	3%	7%	0%	0%	6%	14%	15%	21%
Coal (no CCS)	56%	55%	47%	38%	33%	19%	61%	61%	46%	18%	21%	1%
Gas (no CCS)	15%	15%	13%	10%	9%	7%	15%	15%	11%	4%	5%	0%
Other sources	10%	10%	10%	10%	10%	11%	9%	9%	9%	9%	8%	9%
FUEL PRODUCTION												
Fuels from coal at IG facilities (quads)	0	0	0.5	0.8	1.4	2.2	0	0	2.4	3.9	4.5	6.7
Cellulosic ethanol feedstock (million tons)	122	122	258	288	286	329	309	309	651	687	666	737
Cellulosic ethanol production (billion gallons)	12	12	27	30	30	33	30	30	66	69	68	73
as a share of liquid transportation fuel use	3%	3%	7%	8%	8%	9%	6%	6%	14%	15%	18%	20%
TRANSPORTATION EFFICIENCY												
Plug-in HEVs as share of LDV sales	0%	0%	0%	0%	39%	40%	0%	0%	0%	1%	33%	35%
Hydrogen FCVs as share of LDV sales	0%	0%	0%	0%	10%	10%	0%	0%	0%	0%	40%	41%
On-road fuel economy of LDV stock (MPG equivalent)	29	29	29	29	33	33	31	31	32	32	54	56
LDV gasoline use	0%	0%	-1%	-1%	-16%	-17%	0%	0%	-3%	-6%	-53%	-57%
Energy and Environment Impacts**												
Average delivered electricity price	18%	36%	15%	28%	10%	16%	51%	78%	46%	44%	30%	29%
Electricity demand (billion kWh)	0%	0%	-4%	-11%	-7%	-14%	-1%	-2%	-6%	-18%	-9%	-19%
Natural gas demand	0%	-1%	-7%	-16%	-15%	-23%	-3%	-4%	-14%	-34%	-24%	-37%
Petroleum demand	0%	-1%	-4%	-5%	-11%	-12%	-4%	-5%	-12%	-15%	-29%	-33%
CO_2 emissions	0%	-1%	-11%	-21%	-26%	-38%	-2%	-3%	-19%	-44%	-45%	-62%
Captured CO_2 emissions (MMT)	0	0	101	236	302	507	0	0	631	1,153	1,394	1,830
Macroeconomic Impacts												
Gross domestic product	-0.8%	-1.8%	-0.6%	-1.2%	-0.2%	-0.6%	-2.4%	-4.1%	-1.6%	-2.3%	-0.3%	-0.9%
Personal consumption expenditures per household	-0.6%	-1.4%	-0.5%	-1.1%	-0.3%	-0.6%	-1.8%	-3.1%	-1.5%	-2.1%	-0.8%	-1.3%
Gross private fixed investment	-0.5%	-1.8%	0.4%	0.2%	1.2%	1.4%	-3.6%	-5.9%	-1.2%	-1.7%	1.4%	1.4%

*The Balanced Portfolio estimates, as shown here, may differ from estimates for the individual pathways as discussed in Chapter 11.

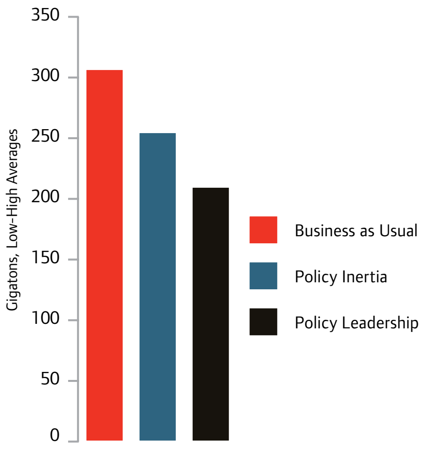
**All impacts are shown as the percent difference from BAU except where otherwise noted.

Cumulative Reduction in Real GDP



Source: Inforum/Keybridge Research

Cumulative CO_2 Emissions 2009–50



Source: Inforum/Keybridge Research

Appendix A

Business Roundtable Climate Change Policy Statement: Selecting the Right Policy Tools

Different policy tools for achieving emissions reductions are being considered, including carbon taxes, cap-and-trade programs, and standards that dictate carbon content or maximum allowable emissions for fuels, products or technologies.

Business Roundtable believes policymakers should judge the potential value of these tools by whether they:

(1) Are effective in reducing projected emissions,
(2) Are flexible and maximize use of markets,
(3) Encourage technology solutions,
(4) Minimize complexity and transaction costs,
(5) Are cost-effective,
(6) Operate in a transparent manner,
(7) Provide predictability and certainty to business,
(8) Minimize undesirable competitive imbalances in the domestic or global economy, and
(9) Foster innovation and business opportunities.

An effective set of policy tools will be one that provides a clear and stable long-term, economywide framework for emissions reductions that enables rational business planning and investment.

Appendix B
Business Roundtable Policy Recommendations

Residential and Commercial Building Efficiency

- Congress should provide full and stable funding for energy efficiency programs authorized in the Energy Policy Act of 2005 and the Energy Independence and Security Act (EISA) of 2007. These acts contain a plethora of energy efficiency programs, ranging from updated appliance efficiency standards, green building research and demonstration, new lighting requirements, federal building efficiency standards, and authorization for a variety of research programs.
- Lenders and builders are encouraged to promote "green mortgages," which recognize the lower monthly expenses associated with energy efficient homes and provide consumers with a greater awareness that improved efficiency can provide long-term financial savings.
- States and local governments should consider requiring that a home energy audit be done on homes offered for sale and that audit results be disclosed to prospective homebuyers.
- State regulatory authorities should adopt policies to make the delivery of energy efficiency a core part of utilities' businesses, including adoption of policies that put energy efficiency on an equal footing with energy supply.
- State and local governments should continuously update and enforce modern building codes, including standards that will potentially accommodate future energy efficiency devices (e.g., time-of-use metering, occupancy controls, etc.).
- All levels of government should continue to educate consumers regarding the difference between one-time, out-of-pocket and lifetime costs of various efficiency investments.
- Business Roundtable members and others are encouraged to be active participants in the National Action Plan's process and proceedings and in other energy efficiency efforts being led by conservation and efficiency organizations, standards-setting organizations, and trade associations focusing on efficiency.

Renewable Power

- Increase federal research and development (R&D) support for electric storage, solar photovoltaic, concentrated solar power, wave, tidal, geothermal, small hydro, biomass and offshore wind technologies.
- Demonstrate policy leadership at the federal level with respect to cost allocation, planning and siting of transmission needed to incorporate wind and solar resources into the grid.
- Make the biomass production tax credit (PTC) available to industrial co-generators, not just to generators selling electricity to an unaffiliated third party.
- Continue to support and fund the existing PTC for wind facilities.

Nuclear Power

- Establish stability and predictability in the licensing and regulation of new plants and ensure success of the Nuclear Power 2010 program.
- Expand the existing federal loan guarantee program to support construction of at least 25 new plants (total guarantees in the range of $100 billion).
- Shift administration of the loan guarantee program from U.S. Department of Energy (DOE) to a new entity with greater financing expertise, facilitating the faster adoption of program rules and issuance of solicitations, among other efficiencies.
- Create a credible federal program outside of DOE for long-term management of nuclear waste. Responsibilities would include developing interim storage facilities where needed, undertaking an R&D program to support fuel recycling technologies that will “close” the fuel cycle and reduce the volume and toxicity of waste by-products, and constructing and operating a permanent repository.

Carbon Capture and Storage

- Invest $1 billion per year ($800 million in government funding) for 15 years in R&D for fossil fuel power plant efficiency and capture technologies.
- Accelerate large-scale sequestration testing under diverse geological conditions.
- Fund six to eight commercial-scale demonstration projects (roughly $2 billion per 500 megawatt [MW] plant) for a range of technologies and engage in a public-private partnership to share the responsibilities for constructing and operating the added carbon capture and storage (CCS) technology.
- Create incentives for an “early mover” commercial deployment program (first 15 gigawatts [GW]), including the beginning of a CO_2 pipeline transportation infrastructure, using loan guarantees, tax credits and other vehicles.

- Create incentives for a post-2025 "commercialization" program (up to 50 GW) with continuing government support at a declining level as CCS matures and costs decrease.
- Adopt a comprehensive regulatory and responsibility framework, including postclosure site management and responsibility protection and eminent domain or other mechanisms to resolve ownership issues and acquire property rights to pore space.
- Evaluate regulatory needs to create a national CO_2 pipeline network.
- Expand the National Transmission Corridor for Electricity to include CO_2 pipelines and authorize the expedition of pipeline permits.
- Structure financial incentives for infrastructure to include 100 percent expensing of new investments to handle and transport CO_2.

Grid Modernization

- Congress should fully appropriate funds for the programs authorized in EISA, including the DOE Smart Grid Regional Demonstration Initiative and the Smart Grid Investment Matching Grant Program to set in motion the grid modernization process as expeditiously as possible.
- Congress should provide the funds necessary for the National Institute of Standards and Technology (within the Department of Commerce) to help develop protocols and model standards to achieve interoperability of smart grid devices and systems.
- DOE, industry and the national labs should collaborate to share resources for the development of grid modernization technologies.
- DOE should develop a program to assist state regulators and utilities by cataloging and disseminating information regarding smart grid best practices and providing technical, educational and regulatory policy assistance.
- DOE should be given an important role to play in helping to ensure that measures are developed to protect the new grid from external threats.
- The Federal Energy Regulatory Commission (FERC) should continue to exercise its authority under existing law to provide incentives for upgrading the nation's transmission system and investing in advanced transmission technologies.
- The federal government should demonstrate policy leadership with respect to cost allocation, planning and siting of transmission needed to incorporate wind and solar resources into the grid.
- State regulators should be encouraged to develop predictable cost recovery and return on investment methodologies for regulated utilities making investments in smart grid technologies.
- State regulators should consider educational initiatives to inform electricity consumers about the benefits of a smart grid.
- The electricity industry's engineers and technicians should undergo training and develop new skills to match the increasing "intelligence" of the electric grid.

Advanced Vehicle Technologies

- Over the next 10 to 12 years, Congress should authorize and appropriate funding to support the adoption of advanced vehicle technologies by the auto industry with low-interest loans totaling approximately $75 billion.[195]
- Congress should increase R&D funding for technology to improve energy efficiency and enable the use of alternative fuels in light and heavy-duty gasoline and diesel vehicles. This enhanced R&D funding should total at least $150 million to $200 million annually above current levels and should include advanced technologies on energy storage and battery power; plug-in electric, fuel cell and alternative fuel vehicles; and systems that improve fuel economy in light-duty vehicles and medium and heavy-duty trucks and buses, such as advanced engine technologies, intelligent cruise control, adaptive transmission and acceleration systems, visual fuel economy feedback information for drivers, and weight reduction.
- Congress should continue to provide consumer incentives for the purchase of advanced technology vehicles. Specifically, it should extend the existing consumer tax credit for plug-in electric vehicles of up to $7,500 per vehicle to an additional 4 million vehicles through 2020.
- Congress should encourage automakers to ramp up production of plug-in electric vehicles with advanced battery technology by enacting a public-private partnership to share the warrantee risks associated with putting the latest battery technologies into production.
- Congress should ensure that vehicles are subject to a single national performance standard under EISA to control vehicle efficiency and greenhouse gas (GHG) emissions.

Advanced Biofuels

- Strongly support government R&D in next-generation biofuels, including both ethanol and other biomass-derived hydrocarbons.
- Continue to pursue the goal of scaling up biofuel production to 36 billion gallons per year by 2022 with flexibility, as established in EISA, to revisit these requirements if technology development for advanced biofuels does not proceed as expected.
- Continue government support for R&D into the potential changes needed in the current infrastructure that may be required to facilitate significant growth of various biofuels.
- Continue to evaluate biofuel impacts on sustainability issues, such as food production, forest resources, land use and overall GHG emissions.

Enhancing Domestic Supplies of Oil and Natural Gas

- Congress should enact a broader lifting of the Outer Continental Shelf (OCS) moratoria and actively support greater access to allow oil and gas leasing in all areas off the Atlantic and Pacific coasts and in the Gulf of Mexico. Specifically, Congress should avoid reinstating OCS moratoria and other restrictions, such as buffer zones that carry the impact of a moratorium, and they should lift restrictions, such as those in the Gulf of Mexico Energy Security Act.
- Congress should improve access to public lands in the Rockies and Alaska.
- Federal land managers need to maintain flexibility with respect to exploration and production operations on existing leases, as well as provide additional access to unleased areas. Environmentally responsible energy development is being undertaken and should be expanded to include areas identified as "multiple use" lands.
- The federal government should develop policies to encourage technology development and enact legislation and regulations that encourage development of federal oil shale and tar sands resources in an economically and environmentally sustainable manner.
- All federal permits needed to initiate oil and gas activities should be approved within the time limits set by existing policy, and staffing levels in offices should be adjusted to facilitate the ability to respond to the level of activity faced by that office.

Appendix C

The Inforum LIFT Model of the U.S. Economy

The Inforum Long-term Interindustry Forecasting Tool (LIFT) model is unique among large-scale models of the U.S. economy. Combining an interindustry (input-output) formulation with extensive use of regression analysis, it employs a "bottom-up" approach to macroeconomic modeling. For example, aggregate investment, total exports and employment are not determined directly but are computed by the sum of their parts: investment by industry, exports by commodity and employment by industry. Indeed, LIFT contains full demand and supply accounting for 97 productive sectors.

In short, the demand/production block of LIFT uses econometric equations to predict the behavior of real final demand (consumption, investment, imports, exports, government) at a detailed level. Then, the detailed predictions for demand are used in input-output production identity to generate gross output (total revenue adjusted for inflation). LIFT's approach to projecting industry prices is similar. Behavioral equations estimate each value-added component (e.g., compensation, profits, interest, rent, indirect taxes) for each industry. Value-added per unit of output is then combined with the prices of intermediate goods and services with the input-output price identity to form an indicator for industry prices. Prices by industry also are dependent on measures of slack in each industry, and, in some cases, international prices. Thus, income and prices are directly related and are consistent. In turn, relative price terms and income flows are included as independent variables in the regression equations for final demand, creating a simultaneity between final demand and value-added.

This bottom-up technique possesses several desirable properties for analyzing the economy. First, the model works like the actual economy, building the macroeconomic totals from details of industry activity rather than distributing predetermined macroeconomic quantities among industries. Second, the model describes how changes in one industry, such as increasing productivity or changing international trade patterns, affect related sectors and the aggregate quantities. Third, parameters in the behavioral equations differ among products, reflecting differences in consumer preferences, price elasticities in foreign trade and industrial structure. Fourth, the detailed level of disaggregation permits the modeling of prices by industry, allowing one to explore the causes and effects of relative price changes.

Despite its industry basis, LIFT is a full macroeconomic model with more than 800 macroeconomic variables determined consistently with the underlying industry detail. This macroeconomic "superstructure" contains key functions for household savings behavior, interest rates, exchange rates, unemployment, taxes, government spending and current account balances. As in an aggregate macroeconomic model, this structure ensures that LIFT exhibits "Keynesian," demand-driven behavior over the short run but neoclassical growth characteristics over the longer term. For example, while monetary and fiscal policies and changes in exchange rates can affect the level of output in the short-to-intermediate term, in the long term, supply forces — available labor, capital and technology — will determine the level of output.

Another important feature of the LIFT model is the importance given to the dynamic determination of endogenous variables. For example, investment depends on a distributed lag in the output growth of investing industries, and imports and exports depend on a distributed lag of foreign price changes. Therefore, LIFT model solutions are not static but are fully capable of projecting a time path for the endogenous quantities.

Finally, the LIFT model is linked to other, similar models with the Inforum Bilateral Trade Model. Countries included in this system include the United States, Japan, China and the major European economies. Through this system, sectoral exports and imports of the U.S. economy respond to sectoral-level demand and price variables projected by models of U.S. trading partners. In summary, the LIFT model is particularly suited for examining and assessing the macroeconomic and industry impacts of the changing composition of consumption, production, foreign trade and employment as the economy grows through time.

The current model is the fourth discrete version of a modeling framework that has been in continuing existence since 1967. Since its inception, LIFT has continued to develop and change. We have learned more about the properties of the model through working with clients and in doing our own simulation tests. We have learned about the behavior of the general Inforum type of model from work with our partners in other countries. Finally, through many experiments, we have learned that many principles of economics, while attractive theoretically, are difficult to implement practically. We will continue to experiment, share ideas and bring the models closer to our vision of what they should be. A detailed description of the LIFT model can be found at www.inforum.umd.edu/papers/wp/wp/2001/wp01002.pdf.

Appendix D

Detailed Data Tables on Modeling Inputs and Results

Table D.1: Business-as-Usual Baseline

Description	Units	2010	2012	2015	2020	2025	2030	2035	2040	2045	2050
Key Outputs											
Gross domestic product	billion 2008$	15,244	16,329	17,607	19,637	22,008	24,855	28,006	31,270	34,873	38,652
Personal consumption expenditures	billion 2008$	10,891	11,614	12,484	13,979	15,565	17,365	19,340	21,628	24,370	27,542
Gross private fixed investment	billion 2008$	2,382	2,639	2,873	3,093	3,475	3,932	4,411	4,936	5,617	6,312
Exports	billion 2008$	2,165	2,479	3,062	4,167	5,542	7,282	9,373	11,515	13,817	16,625
Imports	billion 2008$	2,716	2,936	3,365	4,209	5,223	6,382	7,734	9,430	11,633	14,781
Government	billion 2008$	2,438	2,479	2,549	2,687	2,848	3,033	3,226	3,439	3,677	3,954
Personal consumption expenditures per houshold	2008$	93,891	97,830	101,722	108,237	115,334	123,522	132,286	142,457	154,792	168,905
Carbon dioxide emissions	million metric tons	6,137	6,331	6,495	6,660	6,891	7,153	7,674	8,256	8,912	9,512
ENERGY DEMAND											
Electricity production	billion kWh	4,068	4,188	4,310	4,544	4,799	5,032	5,414	5,834	6,316	6,793
Total demand (or supply) of coal	million short tons	1,162	1,203	1,233	1,343	1,440	1,530	1,671	1,829	2,010	2,175
Natural gas demand	trillion cubic feet	24	24	24	24	24	25	26	28	30	31
Crude demand	million bbl	5,280	5,214	5,084	5,036	4,869	4,675	4,697	4,735	4,785	4,814
ENERGY PRICES											
Real carbon price	2008$/ton	—	—	—	—	—	—	—	—	—	—
Average delivered price of electricity	2008 cents/kWh	9.8	10.1	10.2	10.5	10.9	11.5	12.0	12.5	13.1	13.8
Natural gas price, wellhead	2008$/tcf	8.0	8.8	9.4	10.6	12.2	14.3	14.3	14.3	14.3	14.3
Coal price, minemouth	2008$/ton	2.1	2.1	2.0	2.0	2.0	2.1	2.1	2.1	2.1	2.1
Gasoline price	2008$/gal	3.0	3.0	3.0	3.0	3.0	3.0	3.1	3.1	3.2	3.3
Crude oil price, AEO light sulfur	2008$/bbl	100	100	100	100	100	100	100	100	100	100
*POWER GENERATION (SHARES OF ELECTRICITY PRODUCTION)**											
Wind	percent	2	2	2	2	2	2	3	3	3	3
Solar	percent	—	0	0	0	0	0	0	0	0	0
Nuclear	percent	20	19	19	19	18	17	16	15	14	13
Fossil fuel (CCS)	percent	—	—	—	—	—	—	—	—	—	—
Coal (no CCS)	percent	49	50	50	52	54	56	57	59	60	61
Gas (no CCS)	percent	20	19	19	16	16	15	15	15	15	15
Other sources	percent	10	10	10	11	10	10	10	9	9	9

*The Balanced Portfolio estimates, as shown here, may differ from estimates for the individual pathways as discussed in Chapter 11.

Table D.2: Low Carbon Price/Policy Leadership Scenario

Description	Units	2010	2012	2015	2020	2025	2030	2035	2040	2045	2050
Key Outputs											
Gross domestic product	billion 2008$	15,251	16,250	17,587	19,614	21,965	24,809	27,983	31,257	34,823	38,539
Personal consumption expenditures	billion 2008$	10,898	11,551	12,471	13,962	15,530	17,316	19,299	21,569	24,254	27,323
Gross private fixed investment	billion 2008$	2,382	2,626	2,892	3,113	3,499	3,979	4,473	5,013	5,701	6,399
Exports	billion 2008$	2,165	2,475	3,044	4,134	5,484	7,183	9,224	11,324	13,569	16,285
Imports	billion 2008$	2,718	2,926	3,369	4,207	5,208	6,353	7,680	9,350	11,518	14,596
Government	billion 2008$	2,439	2,496	2,569	2,715	2,882	3,076	3,291	3,534	3,807	4,128
Personal consumption expenditures per houshold	2008$	93,949	97,293	101,615	108,104	115,072	123,177	132,004	142,066	154,049	167,566
Carbon dioxide emissions	million metric tons	6,112	6,187	6,221	5,915	5,647	5,328	5,293	5,268	5,352	5,250
ENERGY DEMAND											
Electricity production	billion kWh	4,065	4,118	4,184	4,297	4,471	4,673	5,042	5,428	5,818	6,155
Total demand (or supply) of coal	million short tons	1,153	1,160	1,160	1,157	1,155	1,170	1,273	1,401	1,589	1,710
Natural gas demand	trillion cubic feet	24	24	23	22	21	21	21	22	23	24
Crude demand	million bbl	5,298	5,218	5,080	4,926	4,653	4,366	4,265	4,180	4,116	4,046
ENERGY PRICES											
Real carbon price	2008$/ton	—	18	21	27	35	44	57	73	92	118
Average delivered price of electricity	2008 cents/kWh	9.8	10.8	11.0	11.4	12.0	12.7	13.5	14.6	16.2	18.0
Natural gas price, wellhead	2008$/tcf	8.0	9.0	9.9	11.7	13.6	16.1	16.1	16.1	16.1	16.1
Coal price, minemouth	2008$/ton	2.1	2.1	2.0	2.0	2.0	2.1	2.1	2.1	2.1	2.1
Gasoline price	2008$/gallon	3.0	3.1	3.1	3.1	3.1	3.2	3.4	3.6	3.8	4.0
Crude oil price, AEO light sulfur	2008$/bbl	100	100	100	100	100	100	100	100	100	100
*POWER GENERATION (SHARES OF ELECTRICITY PRODUCTION)**											
Wind	percent	2	3	5	8	11	16	16	17	17	17
Solar	percent	0	1	1	2	3	3	4	5	6	6
Nuclear	percent	20	19	19	23	25	26	27	28	26	27
Fossil fuel (CCS)	percent	—	—	0	1	2	3	5	9	12	15
Coal (no CCS)	percent	49	48	47	43	38	33	30	27	24	21
Gas (no CCS)	percent	20	19	18	13	11	9	8	7	6	5
Other sources	percent	10	10	10	11	10	10	9	9	9	8
Key Building Efficiency Inputs											
Commercial, total square feet	billions	79	81	84	89	96	104	113	124	135	148
Commercial, btus per square foot	ratio	109	107	104	98	94	90	87	84	81	79
Commercial investment for efficiency improvements	million 2008$	14	11	11	12	11	10	10	9	8	9
Residential households	millions	116	119	123	129	135	141	146	152	157	163
Average square feet per house	square feet	1,858	1,882	1,916	1,965	2,008	2,046	2,078	2,104	2,124	2,139
Residential, btus per square foot	ratio	54	53	50	47	44	42	40	38	36	34
Residential investment for efficiency improvements	million 2008$	33	33	36	31	31	27	25	26	27	27
Key Nuclear Power Inputs											
Generation II production	billion kWh	797	801	807	807	807	772	649	504	217	23
Generation III production	billion kWh	—	—	—	189	325	441	720	1,009	1,314	1,639
Generation III non-fuel costs	million 2008$	—	—	—	2,835	4,882	6,614	10,797	15,138	19,708	24,588
Generation III fuel costs	million 2008$	—	—	—	1,287	2,216	3,003	4,902	6,873	8,947	11,163
Generation III capital costs	2008$/kW	3,850	3,850	3,850	3,850	3,725	3,632	3,632	3,632	3,632	3,632
Generation III operating costs	2008 cents/kWh	—	—	—	2.2	2.2	2.2	2.2	2.2	2.2	2.2

(continued)

*The Balanced Portfolio estimates, as shown here, may differ from estimates for the individual pathways as discussed in Chapter 11.

Description	Units	2010	2012	2015	2020	2025	2030	2035	2040	2045	2050
Key Renewable Power Inputs											
Electricity generated from wind	billion kWh	93	135	198	350	507	725	811	895	980	1,063
Electricity generated from solar	billion kWh	7	19	37	72	110	148	203	259	321	384
Annual incremental grid investment	million 2008$		3,000	3,000	3,000	3,000	3,000				
Wind production, land based	billion kWh	93	135	198	347	499	714	752	777	799	820
Capacity factor	percent	31	33	35	37	39	40	40	40	41	41
Capital costs	2008$/kW	1,859	1,836	1,801	1,778	1,743	1,720	1,720	1,720	1,720	1,720
Fixed and variable operating costs	2008$/MWh	10.2	9.7	9.2	8.5	8.3	8.1	8.0	8.0	8.0	8.0
Wind production, offshore	billion kWh	—	—	—	4	7	11	59	118	180	242
Capacity factor	percent	—	—	—	41	42	43	44	44	44	44
Capital costs	2008$/kW	2,730	2,684	2,614	2,556	2,498	2,440	2,440	2,440	2,440	2,440
Fixed and variable operating costs	2008$/MWh	—	—	—	19.4	18.2	15.9	15.9	15.8	15.8	15.8
Solar production, photovoltaic	billion kWh	4	10	20	43	66	90	121	153	191	229
Capacity factor	percent	18	19	20	21	21	21	21	21	21	21
Capital costs	2008$/kW	5,663	5,151	4,384	4,384	4,384	4,384	4,384	4,384	4,384	4,384
Operation, maintenance and distribution cost	2008$/MWh	10	10	10	10	10	10	10	10	10	10
Solar production, thermal	billion kWh	3	8	16	29	43	58	83	105	132	156
Capacity factor	percent	24	24	24	25	25	25	26	26	27	27
Capital costs	2008$/kW	3,646	3,317	2,823	2,823	2,823	2,823	2,823	2,823	2,823	2,823
Operation, maintenance and distribution cost	2008$/MWh	26	26	26	26	26	26	26	26	26	26
Key CCS Inputs											
NGCC (with CCS) production	billion kWh	—	—	—	—	—	—	—	—	4	14
Capture efficiency	percent	83	83	83	83	83	83	83	83	83	83
Net plant HHV efficiency	percent	45	45	45	45	45	45	45	45	45	45
Operating costs (including carbon costs)	2008$/MWh	16	69	84	99	114	135	135	135	135	135
Capital costs	2008$/kW	1,707	1,707	1,707	1,707	1,707	1,707	1,707	1,631	1,564	1,492
PC (with CCS) production	billion kWh	—	—	—	4	11	19	34	49	67	86
Capture efficiency	percent	88	88	88	88	88	88	88	88	88	88
Net plant HHV efficiency	percent	31	31	31	31	31	31	31	31	31	31
Operating costs (including carbon costs)	2008$/MWh	56	57	57	58	58	60	61	62	63	65
Capital costs	2008$/kW	3,547	3,547	3,547	3,547	3,547	3,547	3,547	3,388	3,249	3,095
IGCC (with CCS) production	billion kWh	—	—	4	23	63	133	243	419	653	845
Capture efficiency	percent	90	90	90	90	90	90	90	90	90	90
Net plant HHV efficiency	percent	32	32	32	32	32	32	32	32	32	32
Operating costs (including carbon costs)	2008$/MWh	51	52	52	52	53	54	55	56	57	58
Capital costs	2008$/kW	3,166	3,166	3,166	3,166	3,166	3,166	3,166	3,065	2,979	2,878
CTL production	billion kWh-t	—	5	27	71	137	219	313	417	537	669
Capture efficiency (on-site)	percent	97	97	97	97	97	97	97	97	97	97
Net plant HHV efficiency	percent	51	51	51	51	51	51	51	51	51	51
Operating costs (including carbon costs)	2008$/MWh-t	28	29	27	26	26	25	25	25	25	26
Capital costs	2008$/kWt	2,299	2,299	2,299	2,299	2,299	2,299	2,299	2,226	2,163	2,090
SNG production	billion kWh-t	—	—	19	63	78	88	100	111	127	129
Capture efficiency (on-site)	percent	96	96	96	96	96	96	96	96	96	96
Net plant HHV efficiency	percent	53	53	53	53	53	53	53	53	53	53
Operating costs (including carbon costs)	2008$/MWh-t	28	28	27	27	27	27	27	27	27	27
Capital costs	2008$/kWt	1,693	1,693	1,693	1,693	1,693	1,693	1,693	1,640	1,594	1,539
H_2 production	billion kWh-t	—	—	0	9	47	110	189	277	386	535
Capture efficiency (on-site)	percent	93	93	93	93	93	93	93	93	93	93
Net plant HHV efficiency	percent	56	56	56	56	56	56	56	56	56	56
Operating costs (including carbon costs)	2008$/MWh-t	27	28	28	28	28	29	30	30	31	31
Capital costs	2008$/kWt	1,552	1,552	1,552	1,552	1,552	1,552	1,552	1,502	1,459	1,411
CO_2 transport costs, per ton	2008$	7	7	7	7	7	7	7	7	7	7
CO_2 storage and monitoring costs, per ton	2008$	3	3	3	3	3	3	3	3	3	3
Total captured emissions	million metric tons	—	2	20	78	168	302	491	747	1,079	1,394

(continued)

Description	Units	2010	2012	2015	2020	2025	2030	2035	2040	2045	2050
Key Advanced Biofuels Inputs											
Cellulosic ethanol capacity	billion gallons	0	0	1	11	24	37	48	58	68	85
Cellulosic ethanol production	billion gallons	0	0	1	9	19	30	39	46	55	68
Cellulosic ethanol incremental capital cost	2008$/gallon	4.96	4.76	4.47	3.99	3.50	3.50	3.50	3.50	3.50	3.50
Switchgrass actually used for ethanol production	million tons	—	0	0	14	35	81	153	217	287	361
Switchgrass yield per acre	tons/acre	4.2	4.2	4.2	5.0	5.9	6.7	7.0	7.3	7.7	8.0
Switchgrass cost per ton	2008$/ton	55	53	50	45	40	40	40	40	40	40
Switchgrass conversion efficiency	gallons/ton	80	84	90	100	100	100	100	100	100	100
Corn stover actually used for ethanol production	million tons	0	3	8	61	110	153	169	182	194	206
Corn stover yield per acre	tons/acre	1.5	1.5	1.5	1.6	1.8	1.9	2.1	2.2	2.4	2.5
Corn stover cost per ton	2008$/ton	35	35	35	35	35	35	35	35	35	35
Corn stover conversion efficiency	gallons/ton	85	87	90	100	110	110	110	110	110	110
Wood stover actually used for ethanol production	million tons	0	0	1	17	43	52	53	53	53	99
Wood stover cost per ton	2008$/ton	65	65	65	65	65	65	65	65	65	65
Wood stover conversion efficiency	gallons/ton	79	81	85	90	90	90	90	90	90	90
Biomass transport cost	2008$/ton	20	20	20	20	20	20	20	20	20	20
Ethanol transport, storage and distribution costs	2008 cents/gallon	19	19	19	19	19	19	19	19	19	19
Carbon emissions reduction relative to gasoline	percent	86	86	86	86	86	86	86	86	86	86
Key Advanced Vehicle Technology Inputs											
Total light-duty vehicle (LDV) sales	thousands	15,509	16,820	16,806	16,528	17,378	18,226	19,118	20,059	21,049	22,088
Total LDV stock	thousands	239,328	247,028	257,802	271,119	282,023	293,306	303,865	317,028	330,889	345,464
Average LDV stock fuel economy	mpg	22	22	23	25	29	33	39	44	49	54
Average vehicle miles traveled	miles per vehicle	13	13	13	13	13	13	14	14	14	14
Internal combustion (IC) new car sales	thousands	14,484	15,106	14,304	11,364	7,808	4,164	1,617	1,505	753	—
IC stock	thousands	232,024	237,154	242,226	238,372	217,052	176,215	123,882	81,679	55,278	41,425
Average cost of new IC vehicles	2008$	29,230	29,414	29,857	30,854	30,950	30,996	31,042	31,089	31,136	31,183
Fuel economy of new IC vehicles	mpg	23	23	25	29	29	29	29	29	29	29
Advanced diesel (AD) new car sales	thousands	453	718	867	1,489	1,836	2,359	3,018	3,018	3,018	3,018
AD stock	thousands	4,854	5,720	7,473	12,074	18,041	25,123	33,356	40,491	45,365	47,389
Incremental cost of AD over IC	2008$	2,504	2,274	2,039	1,687	1,626	1,607	1,588	1,569	1,550	1,532
Fuel economy of new AD vehicles	mpg	30	30	33	36	37	37	37	37	37	37
Hybrid electric (HEV) new car sales	thousands	571	894	1,364	2,274	2,528	2,720	2,922	2,922	2,922	2,922
HEV stock	thousands	2,449	4,019	7,363	15,978	25,735	34,122	39,713	42,382	43,953	44,560
Incremental cost of HEV over IC	2008$	4,103	4,107	3,423	3,336	3,072	3,006	2,942	2,879	2,818	2,757
Fuel economy of new HEV vehicles	mpg	32	33	35	39	39	39	39	39	39	39
Plug-in hybrid (PHEV) new car sales	thousands	0	100	250	1,000	4,006	7,159	8,856	8,602	8,403	7,313
PHEV stock	thousands	0	130	700	3,795	16,196	45,192	83,501	115,919	131,849	131,309
Incremental cost of PHEV over IC	2008$	8,083	5,993	3,683	3,187	3,918	4,649	4,649	4,649	4,649	4,649
Fuel economy of new PHEV vehicles	mpg equivalent	36	37	39	44	44	44	44	44	44	44
Electricity fuel economy	mpkWh	2.3	2.4	2.5	2.6	2.8	2.9	2.9	2.9	2.9	2.9
Combustion fuel economy	mpg	32	33	35	39	39	39	39	39	39	39
Share of PHEV miles powered by electricity	percent	21	25	30	40	49	58	58	58	58	58
Hydrogen fuel cell (HFCV) new car sales	thousands	0.6	2.5	20	400	1,200	1,823	2,705	4,012	5,954	8,835
HFCV stock	thousands	1.1	4.8	40	900	4,999	12,653	23,413	36,556	54,442	80,781
Incremental cost of HFCV over IC	2008$	66,340	60,512	54,339	20,500	10,000	7,000	6,500	6,000	5,500	5,350
Fuel economy of new HFCV vehicles	mpg equivalent	42	45	51	55	59	63	68	73	79	85

Table D.3: High Carbon Price/Policy Leadership Scenario

Description	Units	2010	2012	2015	2020	2025	2030	2035	2040	2045	2050
Key Outputs											
Gross domestic product	billion 2008$	15,250	16,097	17,535	19,534	21,893	24,710	27,819	31,038	34,609	38,292
Personal consumption expenditures	billion 2008$	10,897	11,435	12,438	13,924	15,497	17,265	19,239	21,475	24,159	27,195
Gross private fixed investment	billion 2008$	2,381	2,587	2,919	3,109	3,502	3,985	4,466	5,004	5,713	6,398
Exports	billion 2008$	2,165	2,468	3,012	4,083	5,406	7,068	9,020	11,054	13,247	15,913
Imports	billion 2008$	2,718	2,902	3,373	4,201	5,202	6,347	7,663	9,329	11,508	14,591
Government	billion 2008$	2,439	2,515	2,592	2,742	2,917	3,121	3,343	3,600	3,886	4,216
Personal consumption expenditures per houshold	2008$	93,939	96,316	101,346	107,810	114,827	122,813	131,591	141,453	153,447	166,779
Carbon dioxide emissions	million metric tons	6,096	6,099	6,027	5,493	5,006	4,448	4,015	3,753	3,703	3,626
ENERGY DEMAND											
Electricity production	billion kWh	4,063	4,064	4,100	4,123	4,218	4,335	4,610	4,916	5,224	5,474
Total demand (or supply) of coal	million short tons	1,141	1,143	1,099	1,046	1,015	973	1,000	1,096	1,248	1,427
Natural gas demand	trillion cubic feet	24	23	23	21	19	19	19	19	20	20
Crude demand	million bbl	5,299	5,203	5,067	4,888	4,599	4,299	4,185	4,094	4,023	3,939
ENERGY PRICES											
Real carbon price	2008$/ton	—	45	51	61	74	92	111	137	164	197
Average delivered price of electricity	2008 cents/kWh	9.8	11.7	12.1	12.3	12.7	13.4	13.6	14.6	16.0	17.8
Natural gas price, wellhead	2008$/tcf	8.0	9.2	10.3	12.8	14.9	17.9	17.9	17.9	17.9	17.9
Coal price, minemouth	2008$/ton	2.1	2.1	2.0	2.0	2.0	2.1	2.1	2.1	2.1	2.1
Gasoline price	2008$/gallon	3.0	3.3	3.2	3.3	3.3	3.4	3.7	4.0	4.2	4.5
Crude oil price, AEO light sulfur	2008$/bbl	100	100	100	100	100	100	100	100	100	100
*POWER GENERATION (SHARES OF ELECTRICITY PRODUCTION)**											
Wind	percent	2	4	7	12	18	20	20	20	20	20
Solar	percent	0	1	1	3	5	6	8	8	9	8
Nuclear	percent	20	20	20	24	27	31	38	39	39	41
Fossil fuel (CCS)	percent	—	0	0	2	4	7	11	16	19	21
Coal (no CCS)	percent	48	47	44	36	29	19	10	4	1	0
Gas (no CCS)	percent	20	18	18	12	7	7	4	3	3	—
Other sources	percent	10	10	10	11	11	11	10	10	9	9
Key Building Efficiency Inputs											
Commercial, total square feet	billions	79	81	84	89	96	104	113	124	135	148
Commercial, btus per square foot	ratio	109	105	99	89	82	75	70	65	61	58
Commercial investment for efficiency improvements	million 2008$	22	21	23	20	19	16	15	14	13	13
Residential households	millions	116	119	123	129	135	141	146	152	157	163
Average square feet per house	square feet	1,858	1,882	1,916	1,965	2,008	2,046	2,078	2,104	2,124	2,139
Residential, btus per square foot	ratio	54	52	50	46	43	40	37	35	33	31
Residential investment for efficiency improvements	million 2008$	37	37	37	36	36	33	29	29	29	29
Key Nuclear Power Inputs											
Generation II production	billion kWh	797	801	807	807	807	772	649	504	217	23
Generation III production	billion kWh	—	—	—	185	319	555	1,087	1,425	1,834	2,197
Generation III capital costs	2008$/kW	3,850	3,850	3,850	3,850	3,725	3,632	3,632	3,632	3,632	3,632
Generation III operating costs	2008 cents/kWh	—	—	—	2.2	2.2	2.2	2.2	2.2	2.2	2.2

(continued)

*The Balanced Portfolio estimates, as shown here, may differ from estimates for the individual pathways as discussed in Chapter 11.

Description	Units	2010	2012	2015	2020	2025	2030	2035	2040	2045	2050
Key Renewable Power Inputs											
Electricity generated from wind	billion kWh	93	163	267	501	758	872	928	989	1,051	1,102
Electricity generated from solar	billion kWh	7	19	37	116	195	276	357	406	456	460
Annual incremental grid investment	million 2008$		3,000	3,000	3,000	3,000	3,000				
Wind production, land based	billion kWh	93	163	267	444	643	717	737	746	798	850
Capacity factor	percent	31	34	36	38	39	40	40	40	40	41
Capital costs	2008$/kW	1,859	1,836	1,801	1,778	1,743	1,720	1,720	1,720	1,720	1,720
Fixed and variable operating costs	2008$/MWh	10.2	9.6	9.0	8.4	8.2	8.1	8.1	8.0	8.0	8.0
Wind production, offshore	billion kWh	—	—	—	56	115	156	191	243	252	252
Capacity factor	percent	—	—	—	42	43	43	43	44	44	44
Capital costs	2008$/kW	2,730	2,684	2,614	2,556	2,498	2,440	2,440	2,440	2,440	2,440
Fixed and variable operating costs	2008$/MWh	—	—	—	19.3	18.1	15.9	15.9	15.9	15.8	15.8
Solar production, photovoltaic	billion kWh	4	10	20	70	119	168	216	245	274	303
Capacity factor	percent	18	19	20	21	21	21	21	21	21	21
Capital costs	2008$/kW	5,663	5,151	4,384	4,384	4,384	4,384	4,384	4,384	4,384	4,384
Operation, maintenance and distribution cost	2008$/MWh	10	10	10	10	10	10	10	10	10	10
Solar production, thermal	billion kWh	3	8	16	46	76	106	142	160	185	204
Capacity factor	percent	24	24	24	25	25	25	26	26	27	27
Capital costs	2008$/kW	3,646	3,317	2,823	2,823	2,823	2,823	2,823	2,823	2,823	2,823
Operation, maintenance and distribution cost	2008$/MWh	26	26	26	26	26	26	26	26	26	26
Key CCS Inputs											
NGCC (with CCS) production	billion kWh	—	—	—	—	—	—	4	11	22	36
Capture efficiency	percent	83	83	83	83	83	83	83	83	83	83
Net plant HHV efficiency	percent	45	45	45	45	45	45	45	45	45	45
Operating costs (including carbon costs)	2008$/MWh	13	66	85	105	122	146	146	146	146	146
Capital costs	2008$/kW	1,707	1,707	1,707	1,707	1,631	1,556	1,492	1,419	1,349	1,278
PC (with CCS) production	billion kWh	—	—	4	15	30	49	71	101	135	169
Capture efficiency	percent	88	88	88	88	88	88	88	88	88	88
Net plant HHV efficiency	percent	31	31	31	31	31	31	31	31	31	31
Operating costs (including carbon costs)	2008$/MWh	56	60	60	61	62	63	64	66	68	71
Capital costs	2008$/kW	3,547	3,547	3,547	3,547	3,388	3,233	3,095	2,946	2,799	2,654
IGCC (with CCS) production	billion kWh	—	4	16	55	121	235	415	657	814	970
Capture efficiency	percent	90	90	90	90	90	90	90	90	90	90
Net plant HHV efficiency	percent	32	32	32	32	32	32	32	32	32	32
Operating costs (including carbon costs)	2008$/MWh	51	54	54	55	55	57	58	59	61	63
Capital costs	2008$/kW	3,166	3,166	3,166	3,166	3,065	2,964	2,878	2,777	2,676	2,575
CTL production	billion kWh-t	—	11	33	88	175	280	400	532	675	828
Capture efficiency (on-site)	percent	97	97	97	97	97	97	97	97	97	97
Net plant HHV efficiency	percent	51	51	51	51	51	51	51	51	51	51
Operating costs (including carbon costs)	2008$/MWh-t	28	29	27	26	25	24	25	25	26	26
Capital costs	2008$/kWt	2,299	2,299	2,299	2,299	2,226	2,152	2,090	2,016	1,943	1,870
SNG production	billion kWh-t	—	13	39	115	181	256	346	423	517	604
Capture efficiency (on-site)	percent	96	96	96	96	96	96	96	96	96	96
Net plant HHV efficiency	percent	53	53	53	53	53	53	53	53	53	53
Operating costs (including carbon costs)	2008$/MWh-t	28	28	27	27	27	27	27	27	26	26
Capital costs	2008$/kWt	1,693	1,693	1,693	1,693	1,640	1,586	1,539	1,486	1,432	1,378
H_2 production	billion kWh-t	—	0	0	9	47	110	189	277	386	535
Capture efficiency (on-site)	percent	93	93	93	93	93	93	93	93	93	93
Net plant HHV efficiency	percent	56	56	56	56	56	56	56	56	56	56
Operating costs (including carbon costs)	2008$/MWh-t	27	29	29	29	30	31	31	32	33	34
Capital costs	2008$/kWt	1,552	1,552	1,552	1,552	1,502	1,453	1,411	1,361	1,312	1,262
CO_2 transport costs, per ton	2008$	7	7	7	7	7	7	7	7	7	7
CO_2 storage and monitoring costs, per ton	2008$	3	3	3	3	3	3	3	3	3	3
Total captured emissions	million metric tons	—	12	44	142	291	507	807	1,174	1,490	1,830

(continued)

Description	Units	2010	2012	2015	2020	2025	2030	2035	2040	2045	2050
Key Advanced Biofuels Inputs											
Cellulosic ethanol capacity	billion gallons	0	1	2	13	27	41	53	66	79	91
Cellulosic ethanol production	billion gallons	0	0	1	10	21	33	42	52	63	73
Cellulosic ethanol incremental capital cost	2008$/gallon	4.96	4.76	4.47	3.99	3.50	3.50	3.50	3.50	3.50	3.50
Switchgrass actually used for ethanol production	million tons	—	0	0	8	39	95	145	199	261	323
Switchgrass yield per acre	tons/acre	4.2	4.2	4.2	5.0	5.9	6.7	7.0	7.3	7.7	8.0
Switchgrass cost per ton	2008$/ton	55	53	50	45	40	40	40	40	40	40
Switchgrass conversion efficiency	gallons/ton	80	84	90	100	100	100	100	100	100	100
Corn stover actually used for ethanol production	million tons	0	2	5	41	72	99	115	128	142	153
Corn stover yield per acre	tons/acre	1.5	1.5	1.5	1.6	1.8	1.9	2.1	2.2	2.4	2.5
Corn stover cost per ton	2008$/ton	35	35	35	35	35	35	35	35	35	35
Corn stover conversion efficiency	gallons/ton	85	87	90	100	110	110	110	110	110	110
Wood stover actually used for ethanol production	million tons	0	3	7	61	106	135	168	206	236	261
Wood stover cost per ton	2008$/ton	65	65	65	65	65	65	65	65	65	65
Wood stover conversion efficiency	gallons/ton	79	81	85	90	90	90	90	90	90	90
Biomass transport cost	2008$/ton	20	20	20	20	20	20	20	20	20	20
Ethanol transport, storage and distribution costs	2008 cents/gallon	19	19	19	19	19	19	19	19	19	19
Carbon emissions reduction relative to gasoline	percent	86	86	86	86	86	86	86	86	86	86
Key Advanced Vehicle Technology Inputs											
Total light-duty vehicle (LDV) sales	thousands	15,572	16,710	16,716	16,593	17,328	18,116	18,891	19,691	20,525	21,394
Total LDV stock	thousands	239,412	247,076	257,204	270,696	281,419	292,609	302,174	314,082	325,876	338,178
Average LDV stock fuel economy	mpg	22	22	23	25	29	33	39	45	50	56
Average vehicle miles traveled	miles per vehicle	13	13	13	13	13	13	14	14	14	14
Internal combustion (IC) new car sales	thousands	14,475	14,926	14,143	11,509	7,833	4,072	2,268	1,134	—	—
IC stock	thousands	231,973	236,914	241,156	237,791	216,901	176,246	125,438	81,254	52,461	36,074
Average cost of new IC vehicles	2008$	29,230	29,400	29,855	30,895	30,976	31,026	31,078	31,130	31,183	31,236
Fuel economy of new IC vehicles	mpg	23	23	25	29	29	29	29	29	29	29
Advanced diesel (AD) new car sales	thousands	520	755	901	1,424	1,788	2,352	2,352	2,352	2,352	2,352
AD stock	thousands	4,984	5,967	7,822	12,148	17,696	24,606	31,002	35,174	36,923	36,923
Incremental cost of AD over IC	2008$	2,467	2,261	2,023	1,659	1,610	1,583	1,558	1,534	1,510	1,487
Fuel economy of new AD vehicles	mpg	30	31	33	37	37	37	37	37	37	37
Hybrid electric (HEV) new car sales	thousands	572	927	1,403	2,259	2,500	2,709	2,709	2,709	2,709	2,709
HEV stock	thousands	2,449	4,054	7,481	16,058	25,627	33,911	38,820	40,573	41,188	41,188
Incremental cost of HEV over IC	2008$	4,103	4,042	3,393	3,299	3,047	2,975	2,906	2,839	2,773	2,709
Fuel economy of new HEV vehicles	mpg	32	33	35	39	39	39	39	39	39	39
Plug-in hybrid (PHEV) new car sales	thousands	5	100	250	1,000	4,006	7,159	8,856	9,484	9,510	7,497
PHEV stock	thousands	5	135	705	3,800	16,196	45,192	83,501	120,524	140,862	143,213
Incremental cost of PHEV over IC	2008$	8,083	5,993	3,683	3,187	3,918	4,649	4,649	4,649	4,649	4,649
Fuel economy of new PHEV vehicles	mpg equivalent	36	37	39	44	44	44	44	44	44	44
Electricity fuel economy	mpkWh	2.3	2.4	2.5	2.6	2.8	2.9	2.9	2.9	2.9	2.9
Combustion fuel economy	mpg	32	33	35	39	39	39	39	39	39	39
Share of PHEV miles powered by electricity	percent	21	25	30	40	49	58	58	58	58	58
Hydrogen fuel cell (HFCV) new car sales	thousands	0.6	2.5	20	400	1,200	1,823	2,705	4,012	5,954	8,835
HFCV stock	thousands	1.1	4.8	40	900	4,999	12,653	23,413	36,556	54,442	80,781
Incremental cost of HFCV over IC	2008$	66,339	60,552	54,356	20,500	10,000	7,000	6,500	6,000	5,500	5,350
Fuel economy of new HFCV vehicles	mpg equivalent	42	45	51	55	59	63	68	73	79	85

Table D.4: Low Carbon Price/Policy Inertia Scenario

Description	Units	2010	2012	2015	2020	2025	2030	2035	2040	2045	2050
Key Outputs											
Gross domestic product	billion 2008$	15,251	16,232	17,576	19,577	21,892	24,712	27,807	30,996	34,484	38,036
Personal consumption expenditures	billion 2008$	10,898	11,539	12,463	13,942	15,496	17,274	19,222	21,456	24,117	27,123
Gross private fixed investment	billion 2008$	2,381	2,614	2,888	3,094	3,465	3,948	4,418	4,939	5,610	6,239
Exports	billion 2008$	2,165	2,475	3,043	4,132	5,476	7,167	9,189	11,254	13,445	16,082
Imports	billion 2008$	2,718	2,921	3,368	4,204	5,207	6,366	7,702	9,379	11,550	14,619
Government	billion 2008$	2,439	2,496	2,569	2,714	2,881	3,075	3,289	3,531	3,804	4,124
Personal consumption expenditures per houshold	2008$	93,947	97,197	101,548	107,955	114,819	122,875	131,480	141,327	153,180	166,337
Carbon dioxide emissions	million metric tons	6,117	6,248	6,358	6,339	6,377	6,395	6,691	7,043	7,468	7,749
ENERGY DEMAND											
Electricity production	billion kWh	4,067	4,157	4,265	4,451	4,661	4,849	5,181	5,550	5,971	6,369
Total demand (or supply) of coal	million short tons	1,155	1,179	1,193	1,255	1,309	1,362	1,471	1,618	1,803	1,970
Natural gas demand	trillion cubic feet	24	24	24	23	23	23	24	25	26	27
Crude demand	million bbl	5,298	5,219	5,086	4,976	4,757	4,480	4,427	4,383	4,344	4,285
ENERGY PRICES											
Real carbon price	2008$/ton	—	18	21	27	35	44	57	73	92	118
Average delivered price of electricity	2008 cents/kWh	9.8	10.7	11.0	11.5	12.3	13.3	14.4	15.9	17.7	20.1
Natural gas price, wellhead	2008$/tcf	8.0	9.0	9.9	11.7	13.6	16.1	16.1	16.1	16.1	16.1
Coal price, minemouth	2008$/ton	2.1	2.1	2.0	2.0	2.0	2.1	2.1	2.1	2.1	2.1
Gasoline price	2008$/gallon	3.0	3.1	3.1	3.1	3.1	3.2	3.4	3.5	3.7	4.0
Crude oil price, AEO light sulfur	2008$/bbl	100	100	100	100	100	100	100	100	100	100
*POWER GENERATION (SHARES OF ELECTRICITY PRODUCTION)**											
Wind	percent	2	3	3	5	7	9	10	10	10	10
Solar	percent	0	0	1	2	2	3	4	4	5	5
Nuclear	percent	20	19	19	20	19	18	17	16	15	14
Fossil fuel (CCS)	percent	—	—	—	0	0	1	2	3	4	6
Coal (no CCS)	percent	49	49	49	48	48	47	47	46	46	46
Gas (no CCS)	percent	20	19	18	15	14	13	12	12	11	11
Other sources	percent	10	10	10	11	10	10	10	9	9	9
Key Building Efficiency Inputs											
Commercial, total square feet	billions	79	81	84	89	96	104	113	124	135	147
Commercial, btus per square foot	ratio	109	109	109	107	106	104	103	101	100	99
Commercial investment for efficiency improvements	million 2008$	14	3	1	4	4	5	4	4	4	4
Residential households	millions	116	119	123	129	135	141	146	152	157	163
Average square feet per house	square feet	1,858	1,882	1,916	1,965	2,008	2,046	2,078	2,104	2,124	2,139
Residential, btus per square foot	ratio	54	53	51	48	46	44	42	40	38	36
Residential investment for efficiency improvements	million 2008$	32	30	35	26	25	21	22	24	25	26
Key Nuclear Power Inputs											
Generation II production	billion kWh	797	801	807	807	807	772	649	504	217	23
Generation III production	billion kWh	—	—	—	61	61	97	219	365	651	846
Generation III capital costs	2008$/kW	3,850	3,850	3,850	3,850	3,740	3,674	3,674	3,632	3,632	3,632
Generation III operating costs	2008 cents/kWh	—	—	—	2.2	2.2	2.2	2.2	2.2	2.2	2.2

(continued)

*The Balanced Portfolio estimates, as shown here, may differ from estimates for the individual pathways as discussed in Chapter 11.

Description	Units	2010	2012	2015	2020	2025	2030	2035	2040	2045	2050
Key Renewable Power Inputs											
Electricity generated from wind	billion kWh	90	111	142	232	324	417	500	559	590	630
Electricity generated from solar	billion kWh	7	19	37	72	110	148	190	234	280	328
Annual incremental grid investment	million 2008$		3,000	3,000	3,000	3,000	3,000				
Wind production, land based	billion kWh	90	111	142	231	321	413	481	519	530	549
Capacity factor	percent	34	35	36	38	39	40	40	40	41	41
Capital costs	2008$/kW	1,859	1,836	1,801	1,778	1,743	1,720	1,720	1,720	1,720	1,720
Fixed and variable operating costs	2008$/MWh	9.8	9.5	9.1	8.5	8.3	8.1	8.0	8.0	8.0	8.0
Wind production, offshore	billion kWh	—	—	—	1	3	4	19	40	60	81
Capacity factor	percent	—	—	—	41	42	43	44	44	44	44
Capital costs	2008$/kW	2,730	2,684	2,614	2,556	2,498	2,440	2,440	2,440	2,440	2,440
Fixed and variable operating costs	2008$/MWh	—	—	—	19.3	18.1	15.9	15.9	15.8	15.8	15.8
Solar production, photovoltaic	billion kWh	4	10	20	43	66	90	114	140	168	196
Capacity factor	percent	18	19	20	21	21	21	21	21	21	21
Capital costs	2008$/kW	5,663	5,151	4,384	4,384	4,384	4,384	4,384	4,384	4,384	4,384
Operation, maintenance and distribution cost	2008$/MWh	10	10	10	10	10	10	10	10	10	10
Solar production, thermal	billion kWh	3	8	17	29	44	59	75	93	112	131
Capacity factor	percent	24	24	24	25	25	26	26	26	27	27
Capital costs	2008$/kW	3,646	3,317	2,823	2,823	2,823	2,823	2,823	2,823	2,823	2,823
Operation, maintenance and distribution cost	2008$/MWh	26	26	26	26	26	26	26	26	26	26
Key CCS Inputs											
NGCC (with CCS) production	billion kWh	—	—	—	—	—	—	—	—	4	14
Capture efficiency	percent	83	83	83	83	83	83	83	83	83	83
Net plant HHV efficiency	percent	45	45	45	45	45	45	45	45	45	45
Operating costs (including carbon costs)	2008$/MWh	13	66	81	96	111	131	131	131	131	131
Capital costs	2008$/kW	1,707	1,707	1,707	1,707	1,707	1,707	1,707	1,631	1,564	1,492
PC (with CCS) production	billion kWh	—	—	—	—	4	7	15	26	41	60
Capture efficiency	percent	88	88	88	88	88	88	88	88	88	88
Net plant HHV efficiency	percent	31	31	31	31	31	31	31	31	31	31
Operating costs (including carbon costs)	2008$/MWh	56	57	57	58	58	60	61	62	63	65
Capital costs	2008$/kW	3,547	3,547	3,547	3,547	3,547	3,547	3,547	3,388	3,249	3,095
IGCC (with CCS) production	billion kWh	—	—	—	4	16	35	74	133	211	309
Capture efficiency	percent	90	90	90	90	90	90	90	90	90	90
Net plant HHV efficiency	percent	32	32	32	32	32	32	32	32	32	32
Operating costs (including carbon costs)	2008$/MWh	51	52	52	52	53	54	55	56	57	58
Capital costs	2008$/kW	3,166	3,166	3,166	3,166	3,166	3,166	3,166	3,065	2,979	2,878
CTL production	billion kWh-t	—	—	5	22	49	82	121	165	214	269
Capture efficiency (on-site)	percent	97	97	97	97	97	97	97	97	97	97
Net plant HHV efficiency	percent	51	51	51	51	51	51	51	51	51	51
Operating costs (including carbon costs)	2008$/MWh-t	28	29	27	26	26	25	25	25	25	26
Capital costs	2008$/kWt	2,299	173	2,299	2,299	2,299	2,299	2,299	2,226	2,163	2,090
SNG production	billion kWh-t	—	—	—	—	—	6	13	45	109	206
Capture efficiency (on-site)	percent	96	96	96	96	96	96	96	96	96	96
Net plant HHV efficiency	percent	53	53	53	53	53	53	53	53	53	53
Operating costs (including carbon costs)	2008$/MWh-t	28	14	27	27	27	27	27	27	27	27
Capital costs	2008$/kWt	1,693	1,693	1,693	1,693	1,693	1,693	1,693	1,640	1,594	1,539
H_2 production	billion kWh-t	—	3	7	14	34	61	95	135	183	237
Capture efficiency (on-site)	percent	93	93	93	93	93	93	93	93	93	93
Net plant HHV efficiency	percent	56	56	56	56	56	56	56	56	56	56
Operating costs (including carbon costs)	2008$/MWh-t	27	28	28	28	28	29	30	30	31	31
Capital costs	2008$/kWt	1,552	1,552	1,552	1,552	1,552	1,552	1,552	1,502	1,459	1,411
CO_2 transport costs, per ton	2008$	7	7	7	7	7	7	7	7	7	7
CO_2 storage and monitoring costs, per ton	2008$	3	3	3	3	3	3	3	3	3	3
Total captured emissions	million metric tons	—	1	5	18	52	101	176	287	438	631

(continued)

Description	Units	2010	2012	2015	2020	2025	2030	2035	2040	2045	2050
Key Advanced Biofuels Inputs											
Cellulosic ethanol capacity	billion gallons	0	0	1	8	17	33	45	57	68	83
Cellulosic ethanol production	billion gallons	0	0	1	6	14	27	36	46	54	66
Cellulosic ethanol incremental capital cost	2008$/gallon	4.96	4.76	4.47	3.99	3.50	3.50	3.50	3.50	3.50	3.50
Switchgrass actually used for ethanol production	million tons	0	0	0	7	21	63	133	203	272	340
Switchgrass yield per acre	tons/acre	4.2	4.2	4.2	5.0	5.9	6.7	7.0	7.3	7.7	8.0
Switchgrass cost per ton	2008$/ton	55	53	50	45	40	40	40	40	40	40
Switchgrass conversion efficiency	gallons/ton	50	62	80	90	100	100	100	100	100	100
Corn stover actually used for ethanol production	million tons	0	3	7	46	84	139	161	182	194	203
Corn stover yield per acre	tons/acre	1.5	1.5	1.5	1.6	1.8	1.9	2.1	2.2	2.4	2.5
Corn stover cost per ton	2008$/ton	35	35	35	35	35	35	35	35	35	35
Corn stover conversion efficiency	gallons/ton	72	77	85	90	100	110	110	110	110	110
Wood stover actually used for ethanol production	million tons	0	0	1	16	39	56	60	63	63	108
Wood stover cost per ton	2008$/ton	65	65	65	65	65	65	65	65	65	65
Wood stover conversion efficiency	gallons/ton	79	79	79	85	90	90	90	90	90	90
Biomass transport cost	2008$/ton	20	20	20	20	20	20	20	20	20	20
Ethanol transport, storage and distribution costs	2008 cents/gallon	19	19	19	19	19	19	19	19	19	19
Carbon emissions reduction relative to gasoline	percent	86	86	86	86	86	86	86	86	86	86
Key Advanced Vehicle Technology Inputs											
Total light-duty vehicle (LDV) sales	thousands	15,509	16,820	16,806	16,528	17,378	18,226	19,118	20,059	21,049	22,133
Total LDV stock	thousands	239,328	247,028	257,802	271,119	282,023	293,306	303,865	317,028	330,889	345,698
Average LDV stock fuel economy	mpg	22	22	23	25	28	29	30	31	31	32
Average vehicle miles traveled	miles per vehicle	13	13	13	13	13	13	14	14	14	14
Internal combustion (IC) new car sales	thousands	14,484	15,207	14,571	12,757	13,005	13,134	13,160	13,038	12,704	12,120
IC stock	thousands	232,024	237,286	242,956	243,029	238,172	233,945	230,635	230,842	229,051	224,431
Average cost of new IC vehicles	2008$	29,230	29,414	29,857	30,854	30,950	30,996	31,042	31,089	31,136	31,183
Fuel economy of new IC vehicles	mpg	23	23	25	29	29	29	29	29	29	29
Advanced diesel (AD) new car sales	thousands	453	718	867	1,489	1,836	2,359	3,018	3,855	4,921	6,281
AD stock	thousands	4,854	5,720	7,473	12,074	18,041	25,123	33,356	42,924	55,075	70,557
Incremental cost of AD over IC	2008$	2,504	2,274	2,039	1,687	1,626	1,607	1,588	1,569	1,550	1,532
Fuel economy of new AD vehicles	mpg	30	30	33	36	37	37	37	37	37	37
Hybrid electric (HEV) new car sales	thousands	571	894	1,364	2,274	2,528	2,720	2,922	3,137	3,368	3,616
HEV stock	thousands	2,449	4,019	7,363	15,978	25,735	34,122	39,713	43,022	46,356	49,930
Incremental cost of HEV over IC	2008$	4,103	4,107	3,423	3,336	3,072	3,006	2,942	2,879	2,818	2,757
Fuel economy of new HEV vehicles	mpg	32	33	35	39	39	39	39	39	39	39
Plug-in hybrid (PHEV) new car sales	thousands	—	0	0	1	2	4	10	22	48	109
PHEV stock	thousands	—	0	2	7	14	28	60	132	298	671
Incremental cost of PHEV over IC	2008$	8,965	8,819	8,150	7,813	7,815	7,790	7,554	7,318	7,081	6,940
Fuel economy of new PHEV vehicles	mpg equivalent	36	37	39	44	44	44	44	44	44	44
Electricity fuel economy	mpkWh	2.3	2.4	2.5	2.6	2.6	2.6	2.6	2.6	2.6	2.6
Combustion fuel economy	mpg	33	34	36	39	39	39	39	39	39	39
Share of PHEV miles powered by electricity	percent	21	21	21	21	21	21	21	21	21	21
Hydrogen fuel cell (HFCV) new car sales	thousands	0.4	1.2	3	6	7	8	8	8	8	8
HFCV stock	thousands	0.9	2.6	8	31	60	88	102	107	109	109
Incremental cost of HFCV over IC	2008$	66,340	60,512	54,339	42,463	35,937	30,969	26,717	23,053	19,893	17,166
Fuel economy of new HFCV vehicles	mpg equivalent	42	43	40	41	41	40	40	40	40	40

Table D.5: High Carbon Price/Policy Inertia Scenario

Description	Units	2010	2012	2015	2020	2025	2030	2035	2040	2045	2050
Key Outputs											
Gross domestic product	billion 2008$	15,251	16,080	17,510	19,469	21,794	24,559	27,620	30,722	34,201	37,760
Personal consumption expenditures	billion 2008$	10,898	11,424	12,420	13,884	15,440	17,180	19,119	21,318	23,964	26,960
Gross private fixed investment	billion 2008$	2,382	2,576	2,907	3,082	3,464	3,938	4,412	4,895	5,571	6,204
Exports	billion 2008$	2,165	2,468	3,011	4,078	5,394	7,040	8,994	10,964	13,089	15,657
Imports	billion 2008$	2,718	2,899	3,368	4,196	5,196	6,343	7,671	9,314	11,466	14,514
Government	billion 2008$	2,439	2,515	2,592	2,741	2,915	3,119	3,339	3,595	3,882	4,212
Personal consumption expenditures per houshold	2008$	93,947	96,223	101,202	107,505	114,408	122,206	130,775	140,416	152,211	165,336
Carbon dioxide emissions	million metric tons	6,114	6,173	6,246	6,001	5,767	5,628	5,692	5,528	5,532	5,338
ENERGY DEMAND											
Electricity production	billion kWh	4,064	4,095	4,170	4,253	4,374	4,459	4,693	4,953	5,268	5,561
Total demand (or supply) of coal	million short tons	1,154	1,161	1,167	1,166	1,143	1,174	1,247	1,260	1,352	1,399
Natural gas demand	trillion cubic feet	24	23	23	22	21	21	21	21	21	21
Crude demand	million bbl	5,298	5,208	5,074	4,940	4,695	4,406	4,343	4,278	4,224	4,148
ENERGY PRICES											
Real carbon price	2008$/ton	—	45	51	61	74	92	111	137	164	197
Average delivered price of electricity	2008 cents/kWh	9.8	11.8	12.2	12.7	13.5	14.8	16.0	16.9	18.3	19.9
Natural gas price, wellhead	2008$/tcf	8.0	9.2	10.3	12.8	14.9	17.9	17.9	17.9	17.9	17.9
Coal price, minemouth	2008$/ton	2.1	2.1	2.0	2.0	2.0	2.1	2.1	2.1	2.1	2.1
Gasoline price	2008$/gallon	3.0	3.3	3.2	3.2	3.3	3.4	3.6	3.9	4.2	4.5
Crude oil price, AEO light sulfur	2008$/bbl	100	100	100	100	100	100	100	100	100	100
*POWER GENERATION (SHARES OF ELECTRICITY PRODUCTION)**											
Wind	percent	2	3	3	7	10	10	10	10	10	10
Solar	percent	0	1	1	3	5	5	5	6	6	6
Nuclear	percent	20	20	19	21	21	23	25	32	35	39
Fossil fuel (CCS)	percent	—	0	0	1	2	4	6	8	11	14
Coal (no CCS)	percent	49	48	48	45	40	38	35	28	24	18
Gas (no CCS)	percent	20	19	18	14	12	10	9	7	6	4
Other sources	percent	10	10	10	11	11	10	10	9	9	9
Key Building Efficiency Inputs											
Commercial, total square feet	billions	79	81	84	89	96	104	113	123	135	147
Commercial, btus per square foot	ratio	109	107	103	98	93	89	85	82	80	78
Commercial investment for efficiency improvements	million 2008$	14	12	12	13	12	11	10	9	9	9
Residential households	millions	116	119	123	129	135	141	146	152	157	163
Average square feet per house	square feet	1,858	1,882	1,916	1,965	2,008	2,046	2,078	2,104	2,124	2,139
Residential, btus per square foot	ratio	54	52	50	46	44	41	38	36	34	32
Residential investment for efficiency improvements	million 2008$	33	35	37	34	33	30	27	27	28	28
Key Nuclear Power Inputs											
Generation II production	billion kWh	797	801	807	807	807	772	649	504	217	23
Generation III production	billion kWh	—	—	—	63	126	247	518	1,061	1,604	2,148
Generation III capital costs	2008$/kW	3,850	3,850	3,850	3,850	3,740	3,674	3,632	3,632	3,632	3,632
Generation III operating costs	2008 cents/kWh	—	—	—	2.2	2.2	2.2	2.2	2.2	2.2	2.2

(continued)

*The Balanced Portfolio estimates, as shown here, may differ from estimates for the individual pathways as discussed in Chapter 11.

Description	Units	2010	2012	2015	2020	2025	2030	2035	2040	2045	2050
Key Renewable Power Inputs											
Electricity generated from wind	billion kWh	90	111	142	286	433	448	472	499	532	563
Electricity generated from solar	billion kWh	7	19	37	116	195	224	253	282	311	341
Annual incremental grid investment	million 2008$		3,000	3,000	3,000	3,000	3,000				
Wind production, land based	billion kWh	90	111	142	267	395	396	404	412	442	472
Capacity factor	percent	34	35	36	38	39	40	40	40	40	41
Capital costs	2008$/kW	1,859	1,836	1,801	1,778	1,743	1,720	1,720	1,720	1,720	1,720
Fixed and variable operating costs	2008$/MWh	9.8	9.5	9.1	8.4	8.2	8.1	8.1	8.1	8.0	8.0
Wind production, offshore	billion kWh	—	—	—	19	39	52	67	86	90	91
Capacity factor	percent	—	—	—	42	43	43	43	43	44	44
Capital costs	2008$/kW	2,730	2,684	2,614	2,556	2,498	2,440	2,440	2,440	2,440	2,440
Fixed and variable operating costs	2008$/MWh	—	—	—	19.3	18.1	15.9	15.9	15.9	15.8	15.8
Solar production, photovoltaic	billion kWh	4	10	20	70	119	134	149	165	180	195
Capacity factor	percent	18	19	20	21	21	21	21	21	21	21
Capital costs	2008$/kW	5,663	5,151	4,384	4,384	4,384	4,384	4,384	4,384	4,384	4,384
Operation, maintenance and distribution cost	2008$/MWh	10	10	10	10	10	10	10	10	10	10
Solar production, thermal	billion kWh	3	8	16	46	76	88	104	116	134	147
Capacity factor	percent	24	24	24	25	25	25	26	26	27	27
Capital costs	2008$/kW	3,646	3,317	2,823	2,823	2,823	2,823	2,823	2,823	2,823	2,823
Operation, maintenance and distribution cost	2008$/MWh	26	26	26	26	26	26	26	26	26	26
Key CCS Inputs											
NGCC (with CCS) production	billion kWh	—	—	—	—	—	—	4	11	22	36
Capture efficiency	percent	83	83	83	83	83	83	83	83	83	83
Net plant HHV efficiency	percent	45	45	45	45	45	45	45	45	45	45
Operating costs (including carbon costs)	2008$/MWh	13	66	85	105	122	146	146	146	146	146
Capital costs	2008$/kW	1,707	1,707	1,707	1,707	1,631	1,556	1,492	1,419	1,349	1,278
PC (with CCS) production	billion kWh	—	—	—	4	15	34	60	94	135	184
Capture efficiency	percent	88	88	88	88	88	88	88	88	88	88
Net plant HHV efficiency	percent	31	31	31	31	31	31	31	31	31	31
Operating costs (including carbon costs)	2008$/MWh	56	60	60	61	62	63	64	66	68	71
Capital costs	2008$/kW	3,547	3,547	3,547	3,547	3,388	3,233	3,095	2,946	2,799	2,654
IGCC (with CCS) production	billion kWh	—	4	12	35	70	129	207	305	422	559
Capture efficiency	percent	90	90	90	90	90	90	90	90	90	90
Net plant HHV efficiency	percent	32	32	32	32	32	32	32	32	32	32
Operating costs (including carbon costs)	2008$/MWh	51	54	54	55	55	57	58	59	61	63
Capital costs	2008$/kW	3,166	3,166	3,166	3,166	3,065	2,964	2,878	2,777	2,676	2,575
CTL production	billion kWh-t	—	5	16	38	71	115	165	219	280	345
Capture efficiency (on-site)	percent	97	97	97	97	97	97	97	97	97	97
Net plant HHV efficiency	percent	51	51	51	51	51	51	51	51	51	51
Operating costs (including carbon costs)	2008$/MWh-t	28	29	27	26	25	24	25	25	26	26
Capital costs	2008$/kWt	2,299	173	2,299	2,299	2,226	2,152	2,090	2,016	1,943	1,870
SNG production	billion kWh-t	—	—	—	—	6	39	103	200	328	489
Capture efficiency (on-site)	percent	96	96	96	96	96	96	96	96	96	96
Net plant HHV efficiency	percent	53	53	53	53	53	53	53	53	53	53
Operating costs (including carbon costs)	2008$/MWh-t	28	14	27	27	27	27	27	27	26	26
Capital costs	2008$/kWt	1,693	1,693	1,693	1,693	1,640	1,586	1,539	1,486	1,432	1,378
H_2 production	billion kWh-t	—	3	7	20	41	68	108	162	230	311
Capture efficiency (on-site)	percent	93	93	93	93	93	93	93	93	93	93
Net plant HHV efficiency	percent	56	56	56	56	56	56	56	56	56	56
Operating costs (including carbon costs)	2008$/MWh-t	27	29	29	29	30	31	31	32	33	34
Capital costs	2008$/kWt	1,552	1,552	1,552	1,552	1,502	1,453	1,411	1,361	1,312	1,262
CO_2 transport costs, per ton	2008$	7	7	7	7	7	7	7	7	7	7
CO_2 storage and monitoring costs, per ton	2008$	3	3	3	3	3	3	3	3	3	3
Total captured emissions	million metric tons	—	7	20	58	125	236	395	600	853	1,153

(continued)

Description	Units	2010	2012	2015	2020	2025	2030	2035	2040	2045	2050
Key Advanced Biofuels Inputs											
Cellulosic ethanol capacity	billion gallons	0	0	1	9	21	37	49	62	75	87
Cellulosic ethanol production	billion gallons	0	0	1	7	17	30	39	49	60	69
Cellulosic ethanol incremental capital cost	2008$/gallon	4.96	4.76	4.47	3.99	3.50	3.50	3.50	3.50	3.50	3.50
Switchgrass actually used for ethanol production	million tons	—	0	0	11	44	114	166	218	298	380
Switchgrass yield per acre	tons/acre	4.2	4.2	4.2	5.0	5.9	6.7	7.0	7.3	7.7	8.0
Switchgrass cost per ton	2008$/ton	55	53	50	45	40	40	40	40	40	40
Switchgrass conversion efficiency	gallons/ton	50	62	80	90	100	100	100	100	100	100
Corn stover actually used for ethanol production	million tons	0	3	7	54	89	129	140	148	169	187
Corn stover yield per acre	tons/acre	1.5	1.5	1.5	1.6	1.8	1.9	2.1	2.2	2.4	2.5
Corn stover cost per ton	2008$/ton	35	35	35	35	35	35	35	35	35	35
Corn stover conversion efficiency	gallons/ton	72	77	85	90	100	110	110	110	110	110
Wood stover actually used for ethanol production	million tons	0	0	1	17	36	45	81	125	126	120
Wood stover cost per ton	2008$/ton	65	65	65	65	65	65	65	65	65	65
Wood stover conversion efficiency	gallons/ton	79	79	79	85	90	90	90	90	90	90
Biomass transport cost	2008$/ton	20	20	20	20	20	20	20	20	20	20
Ethanol transport, storage and distribution costs	2008 cents/gallon	19	19	19	19	19	19	19	19	19	19
Carbon emissions reduction relative to gasoline	percent	86	86	86	86	86	86	86	86	86	86
Key Advanced Vehicle Technology Inputs											
Total light-duty vehicle (LDV) sales	thousands	15,572	16,710	16,716	16,593	17,328	18,116	18,891	19,691	20,525	21,468
Total LDV stock	thousands	239,412	247,076	257,204	270,696	281,419	292,609	302,174	314,082	325,876	338,413
Average LDV stock fuel economy	mpg	22	22	23	25	28	29	31	31	31	32
Average vehicle miles traveled	miles per vehicle	13	13	13	13	13	13	14	14	14	14
Internal combustion (IC) new car sales	thousands	14,480	15,027	14,409	12,902	13,030	13,042	12,851	12,428	11,692	10,595
IC stock	thousands	231,978	237,051	241,892	242,452	238,020	233,973	229,390	226,969	220,898	210,584
Average cost of new IC vehicles	2008$	29,230	29,400	29,855	30,895	30,976	31,026	31,078	31,130	31,183	31,236
Fuel economy of new IC vehicles	mpg	23	23	25	29	29	29	29	29	29	29
Advanced diesel (AD) new car sales	thousands	520	755	901	1,424	1,788	2,352	3,091	4,062	5,337	7,014
AD stock	thousands	4,984	5,967	7,822	12,148	17,696	24,606	33,138	43,810	57,792	76,167
Incremental cost of AD over IC	2008$	2,467	2,261	2,023	1,659	1,610	1,583	1,558	1,534	1,510	1,487
Fuel economy of new AD vehicles	mpg	30	31	33	37	37	37	37	37	37	37
Hybrid electric (HEV) new car sales	thousands	572	927	1,403	2,259	2,500	2,709	2,929	3,166	3,422	3,699
HEV stock	thousands	2,449	4,054	7,481	16,058	25,627	33,911	39,476	43,034	46,696	50,649
Incremental cost of HEV over IC	2008$	4,103	4,042	3,393	3,299	3,047	2,975	2,906	2,839	2,773	2,709
Fuel economy of new HEV vehicles	mpg	32	33	35	39	39	39	39	39	39	39
Plug-in hybrid (PHEV) new car sales	thousands	—	0	0	1	2	5	12	27	65	153
PHEV stock	thousands	—	0	2	7	15	31	69	161	382	904
Incremental cost of PHEV over IC	2008$	2,008	9,025	8,826	8,353	7,775	7,858	7,643	7,423	7,203	6,984
Fuel economy of new PHEV vehicles	mpg equivalent	36	37	39	44	44	44	44	44	44	44
Electricity fuel economy	mpkWh	2.3	2.4	2.5	2.6	2.6	2.6	2.6	2.6	2.6	2.6
Combustion fuel economy	mpg	32	33	35	39	39	39	39	39	39	39
Share of PHEV miles powered by electricity	percent	21	21	21	21	21	21	21	21	21	21
Hydrogen fuel cell (HFCV) new car sales	thousands	0.4	1.2	3	6	7	8	8	8	8	8
HFCV stock	thousands	0.9	2.6	8	31	61	88	102	107	108	108
Incremental cost of HFCV over IC	2008$	66,339	60,552	54,356	42,360	35,863	30,895	26,642	22,980	19,822	17,097
Fuel economy of new HFCV vehicles	mpg equivalent	42	43	40	41	41	40	40	40	40	40

Endnotes

1. Climate change is expected to have a range of impacts, with some viewed as beneficial and others viewed as adverse. Business Roundtable members support prudent actions to mitigate the adverse impacts of climate change and prepare the global community so that it is better able to adapt to climate impacts if and when they occur.
2. Business Roundtable has not endorsed any specific legislation. It has, however, proposed a series of criteria against which climate change policy proposals should be measured. See Appendix A for a list of the criteria, as presented in the Roundtable's 2007 policy statement on climate change.
3. "Policy leadership" refers specifically to the adoption of Business Roundtable's recommendations outlined in this report. See Appendix B for a complete list of the recommendations.
4. Estimates expressed as ranges represent outcomes under low carbon price and high carbon price assumptions. In instances in which estimates are not expressed as ranges, the outcomes under low carbon price and high carbon price assumptions were deemed to be similar.
5. Expressed differently and more generally, Business Roundtable's recommendations combined with a carbon pricing mechanism have the potential to achieve a given level of GHG emissions reductions at a much lower cost than a carbon pricing mechanism alone.
6. Climate change is expected to have a range of impacts, with some viewed as beneficial and others viewed as adverse. Business Roundtable members support prudent actions to mitigate the adverse impacts of climate change and prepare the global community so that it is better able to adapt to climate impacts if and when they occur.
7. In this report, "security" is defined to include environmental, economic and energy security, all critical components of national security.
8. Business Roundtable has not endorsed any specific legislation. It has, however, proposed a series of criteria against which climate change policy proposals should be measured. See Appendix A for a list of the criteria, as presented in the Roundtable's 2007 policy statement on climate change.
9. "Policy leadership" refers specifically to the adoption of Business Roundtable's recommendations outlined in this report. See Appendix B for a complete list of the recommendations.
10. Technology pathways that are not addressed include some that will be needed to make industrial, agricultural and forestry practices more sustainable. Additionally, even within the pathways that were chosen, not all relevant technologies are discussed. For example, the transportation efficiency pathway in this report focuses primarily on light-duty vehicles, but strategies will be needed to make heavy-duty trucks, trains, ships and airplanes more sustainable. The pathways analyzed will have applications that are relevant for segments of the economy that are not explicitly discussed or modeled in this report.
11. The authors of the McKinsey Report analyzed more than 250 options for reducing or preventing GHG emissions "encompassing efficiency gains, shifts to lower-carbon energy sources and expanded carbon sinks."

12. Indeed, energy efficiency has contributed more value to the economy in recent decades than any conventional energy resource — meeting three-fourths of all new demand. *See* American Council for an Energy-Efficient Economy (February 2008). *Information and Communication Technologies: The Power of Productivity*, p. 6, Figure 1.
13. Energy Information Administration (November 2008). "Consumption, Prices, and Expenditures," Table S1.
14. U.S. Department of Energy (September 2007). *2007 Building Energy Data Book,* at 1-1. If one factors in the natural gas that is used to generate electricity used in buildings and assigns it to the buildings sector, then 31 percent of natural gas is used in the buildings sector.
15. U.S. Department of Energy, Energy Efficiency and Renewable Energy (September 2008). *2006 Buildings Energy Data Book,* Table 1.1.3.
16. U.S. Department of Energy, Energy Efficiency and Renewable Energy (September 2008). *2006 Buildings Energy Data Book,* Table 1.1.4.
17. American Council for an Energy-Efficient Economy (February 2007). *Quantifying the Effects of Market Failures in the End-Use of Energy.*
18. National Governors Association (June 2008). *Securing a Clean Energy Future — A Governor's Guide to Clean Power Generation and Energy Efficiency,* p. 3.
19. Gentry, Thomas A. (July 17, 2008). Written testimony before the House Energy and Commerce Subcommittee on Energy, p. 4, footnote 2.
20. Recent trends indicate that most states are beginning to address this problem. In addition, the Energy Independence and Security Act of 2007 requires each state regulatory authority to consider adoption of federal standards relating to integrated resource planning, load management techniques and rates that allow utility investment in and expenditures for energy conservation, energy efficiency resources and other demand-side management measures. These are at least as profitable as investments in and expenditures for the construction of new-generation, transmission and distribution equipment. See 16 U.S.C. § 2621(d)(7) and (8).
21. American Council for an Energy-Efficient Economy (May 2008). *The Size of the U.S. Efficiency Market: Generating a More Complete Picture,* p. 18.
22. Energy Information Administration (April 2008). *Residential Energy Consumption Survey,* Table HC 1.1.1; and Energy Information Administration (March 2009). *2009 Annual Energy Outlook,* Table 5.
23. Architecture 2030 (2006). "The Building Sector: An Historic Opportunity."
24. National Governors Association. *Securing a Clean Energy Future,* p. 10.
25. Energy Information Administration (April 2008). *2005 Residential Energy Consumption Survey,* Table HC 5.1.
26. American Council for an Energy-Efficient Economy (February 2008). *Information and Communication Technologies: The Power of Productivity,* p. 9. Also see Chapter 6, Grid Modernization, for the application and benefits of smart-metering technology to enhancing building efficiency.
27. U.S. Department of Energy (2008). *Annual Report on U.S. Wind Power Installation, Cost and Performance Trends: 2007.*
28. *Ibid.*
29. 26 U.S.C. § 48 (2008). American Wind Energy Association. *Legislative Priorities: Production Tax Credit Extension.*
30. Energy Information Administration (February 2009). *Monthly Energy Review,* Table 7.2a.

31. U.S. Department of Energy, Energy Efficiency and Renewable Energy (July 2008). *20% Wind Energy by 2030: Increasing Wind Energy's Contribution to U.S. Electricity Supply*.
32. Solar Energy Industry Association (March 2009). *U.S. Solar Industry Year In Review: 2008*.
33. Emerging Energy Research (December 2007). "Concentrated Solar Power Resurges as a Scalable Energy Alternative," Press Release, Cambridge, MA.
34. Energy Information Administration (March 2009). *Electric Power Monthly,* Table 1.1.A and 1.1.
35. Energy Information Administration (2008). *Renewable Energy Consumption and Electricity Preliminary 2007 Consumption*.
36. *Ibid*.
37. Energy Information Administration (2008). *Electricity Net Generation from Renewable Energy by Energy Use Sector and Energy Source*.
38. Edmonds, J.A., et al. (May 2007). *Wind and Solar Energy: A Core Element of a Global Energy Technology Strategy to Address Climate Change.* Global Energy Technology Strategy Program.
39. Tomasky, Susan (2008). "AEP Transmission." Testimony before the United States Senate Committee on Energy and Natural Resources.
40. *Ibid*.
41. A more detailed discussion of the barriers associated with improving the U.S. electric power grid is provided in Chapter 6, Grid Modernization.
42. The existence of gas, hydro or other more easily adjustable power sources can significantly lower the need to build new backup capacity.
43. Zweibel, Ken, et al. (2007). "A Solar Grand Plan: By 2050 Solar Power Could End U.S. Dependence on Foreign Oil and Slash Greenhouse Gas Emissions." *Scientific American Magazine*.
44. *Ibid*.
45. *Ibid*.
46. Energy Information Administration (2009). *Assumptions to the Annual Energy Outlook 2009*.
47. *Ibid*.
48. U.S. Department of Energy (2006). *Annual Report on U.S. Wind Power Installation, Cost and Performance Trends*.
49. Solar PV is still two to three times the cost of most retail electricity rates in the United States at 15 to 32 cents per kWh. *See, for example,* Clean Edge. *Utility Solar Assessment (USA) Study,* at 4.
50. Amorphous silicon, copper indium gallium selenide (CIGS) and cadmium telluride are all thin film technologies that use less silicon, therefore decreasing cost. However, all of these currently are less energy efficient. CIGS can be printed directly onto glass sheets or other substrates, making it ideal for buildings, and amorphous silicon can be most cost-effective when space is not a premium. Nanotechnologies are not in production today but have the potential to substantially reduce the cost of PV. Concentrating PV concentrates the sunlight onto the silicon using mirrors or reflectors, therefore reducing the amount of silicon needed. *See* Clean Edge (2008). *Utility Solar Assessment (USA) Study*.
51. 26 U.S.C. § 48 (2008).
52. *Ibid*.
53. However, these prices do not fully reflect integration, resource adequacy or transmission costs. *See* U.S. Department of Energy (2006). *Annual Report on U.S. Wind Power,* p. 20.
54. U.S. Department of Energy (2008). *20% Wind Energy by 2030: Increasing Wind Energy's Contribution to U.S. Electricity Supply*.
55. While the tax credit for businesses has no cap, the act places a $2,000 cap on credits to residential property owners.

56. Clean Edge (2008).
57. U.S. Department of Energy (2005). *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion Ton Annual Supply*.
58. The American Recovery and Reinvestment Act, which was passed by Congress and signed into law while this study was being conducted, included a number of renewable power incentives. These provisions are largely consistent with the policy recommendations contained in this study. Specifically, section 1101 of the Act extended the renewable energy production tax credit for wind facilities for property placed in service before January 1, 2013; extended ITCs available for biomass, geothermal, solar, small irrigation power, landfill gas, trash combustion and qualified hydropower for property placed in service before January 1, 2014; and provided a two-year extension for marine renewables for property placed in service before January 1, 2014. In addition, section 1102 provides the option for facilities placed in service in 2009–13 to make an irrevocable election to claim a 30 percent ITC under Internal Revenue Code (IRC) section 48 in lieu of the PTC under IRC section 45. The ITC option is co-extensive with the duration of the underlying PTC available for wind property. The Energy Improvement and Extension Act of 2008, enacted as part of the Emergency Economic Stabilization Act, extended the solar ITCs for eight years, through 2016.
59. Energy Information Administration (February 2009). *Monthly Energy Review,* Table 8.1.
60. World Nuclear Association (February 2009). "Table of World's Nuclear Power Reactors," *Nuclear Power Facts.*
61. Energy Information Administration (February 2009). Table 8.1.
62. Energy Information Administration (February 2009). *Monthly Energy Review,* Table 7.2b.
63. Energy Information Administration (February 2009). Table 8.1.
64. Edmonds, J.A., et al. (2007). *Addressing Climate Change: Phase 2 Findings from an International Public-Private Sponsored Research Program.* Global Energy Technology Strategy Program.
65. United States Nuclear Regulatory Commission (2009). *Combined License Applications for New Reactors*.
66. Energy Information Administration (2008). "Electricity Market Module," *Annual Energy Outlook 2008. Also see* Lazard (2008). *Levelized Cost of Energy Analysis.*
67. Lazard (2008).
68. Whereas CO_2 can improve (but not resolve) the economic challenges of CCS, this option is not available in many industrial regions and should thus be regarded as a niche opportunity.
69. U.S. Department of Energy is already authorized to offer such loan guarantees and announced on September 22, 2008, a solicitation for up to $8 billion in guarantee applications.
70. This is one element of the energy tax package recently enacted by Congress. The tax credit is $20 per ton of captured CO_2 unless the captured CO_2 is used for EOR, in which case the credit is $10 per ton.
71. The recently enacted energy tax expands existing tax credits for IG, IGCC and other advanced coal-based generation technologies and for coal gasification projects if they capture and sequester at least 65 percent of the unit's CO_2 emissions. This percentage is too high for initial first-of-a-kind projects. It should either be adjusted downward or the value of the tax credits should be tied to the amount of CO_2 actually captured with no minimum percentage.
72. Congressional Research Service (Updated December 20, 2007). *Smart Grid Provisions in H.R. 6,* 110th Congress, p. 1.
73. U.S. Department of Energy, Office of Electric Transmission and Distribution (2003). *Grid 2030, A National Vision for Electricity's Second 100 Years,* p. 5.

74. National Energy Technology Laboratory (2007). "Barrier to Achieving the Modern Grid," *The NETL Modern Grid Initiative: Powering Our 21st-Century Economy*.
75. *Ibid,* pp. 4–6.
76. *Ibid,* p. 11.
77. Tomasky, Susan (2008).
78. Congressional Research Service (2007). pp. 5–6.
79. U.S. Department of Energy, Office of Electricity Delivery and Energy Reliability (2007). *What Will the Modern Grid Look Like?,* pp. 1–2.
80. This assessment takes the form of a national survey designed to determine the penetration and saturation of advanced metering.
81. National Energy Technology Laboratory for the U.S. Department of Energy (February 2008). *Advanced Metering Infrastructure,* p. 18.
82. Congressional Research Service (2007). pp. 6–8.
83. *Ibid.*
84. Public Law 104-343 (2008). "The Emergency Economic Stabilization Act of 2008, H.R. 1424."
85. National Energy Technology Laboratory for the U.S. Department of Energy (February 2008). p. 5.
86. Congressional Research Service (2007).
87. Tomasky, Susan (2008). p. 8. *See also* American Electric Power (2008). *Interstate Transmission Vision for Wind Integration.*
88. *Ibid.*
89. U.S. Department of Energy (2008). "Remarks as Prepared for U.S. Secretary of Energy Samuel W. Bodman," Press Release.
90. *Ibid.*
91. U.S. Department of Energy (2008). *Annual Energy Review 2007.*
92. U.S. Department of Energy (2008). *Transportation Energy Data Book, Edition 27,* Chapter 4. Data suggest that the median lifetime for passenger cars and light trucks made in 1990 (the latest data available) were 16.9 years and 15.5 years, respectively. Given the increases in median lifetimes observed over time, the median lifetime for cars and light trucks on the road today is likely to be even higher.
93. U.S. Department of Energy (2008). *Annual Energy Review 2007,* Table 12.2; and U.S. Department of Energy (2008). *Emissions of Greenhouse Gases Report,* Table 6.
94. *Ibid.*
95. Massachusetts Institute of Technology, Laboratory for Energy and the Environment (2008). *On the Road in 2035: Reducing Transportation's Petroleum Consumption and GHG Emissions,* Report No. LFEE 2008-05 RP.
96. National Renewable Energy Laboratory (2007). "NREL Estimates U.S. Hybrid Electric Vehicle Fuel Savings," *Press Release NR-1507*.
97. Argonne National Laboratory, Transportation Technology R&D Center (June 2007). "Just the Basics: Hybrid Electric Vehicles."
98. National Renewable Energy Laboratory (2007).
99. International Energy Agency (2008). "Number of EVs and HEVs in Different Countries," *Hybrid and Electric Vehicle Implementing Agreement.*
100. International Energy Agency (2008). "Outlook for Hybrid and Electric Vehicles," p. 6.

101. Extended Range Electric Vehicles (EREVs) like the Chevy Volt are considered Plug-in Hybrid Electric Vehicles (PHEV) in this report because, like PHEVs, they are powered by a blend of liquid fuels and electricity from outside sources. EREVs are often distinguished from PHEVs because their series engine/battery configuration more easily facilitates the use of electricity as a vehicle's sole power source until battery power is sufficiently exhausted than the parallel configuration used by other PHEVs does.
102. U.S. Department of Energy (2009). *2009 Annual Energy Outlook Assumptions Book*.
103. Jacobson, Mark Z. (2008). *Review of Solutions to Global Warming, Air Pollution, and Energy Security;* and Yacobucci, Brent D. (2004). *Advanced Vehicle Technologies: Energy, Environment, and Development Issues,* Congressional Research Service Report, p. 3.
104. National Governors Association (2008). *Greener Fuels, Greener Vehicles: A State Resource Guide,* p. 9.
105. *Ibid.*
106. U.S. Department of Energy, Energy Efficiency and Renewable Energy (2003). "Just the Basics: Fuel Cells," *FreedomCAR & Vehicle Technologies Program*.
107. *Ibid.*
108. U.S. Department of Energy, Hydrogen Program Record (March 2009). *Well-to-Wheels Greenhouse Gas Emissions and Petroleum Use.*
109. For a more extensive discussion of this issue, see Chapter 6, Grid Modernization.
110. U.S. Department of Energy, Energy Efficiency and Renewable Energy (Updated January 13, 2009). *Alternative Fueling Station Total Counts by State and Fuel Type*.
111. Office of the Mayor of the City and County of San Francisco (November 20, 2008). "Mayors Aim to Make San Francisco Bay Area the Electric Vehicle Capital of the U.S.," Press Release.
112. Office of Oregon Governor Ted Kulongoski (November 19, 2008). "Governor, Nissan and PG&E Partner to Promote Zero-Emission Vehicles," Press Release.
113. U.S. Department of Energy, Energy Efficiency and Renewable Energy (Updated January 13, 2009).
114. *Ibid.*
115. Pesaran, Ahmad and Tony Markel (2007). *Battery Requirements and Cost-Benefit Analysis for Plug-In Hybrid Vehicles.* National Renewable Energy Laboratory, p. 4.
116. National Academy of Sciences (2004). *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs. National Academics Press.*
117. *Ibid.*
118. Congressional Research Service (December 17, 2004). *Advanced Vehicle Technologies: Energy, Environment and Development Issues,* p. 7.
119. It also authorized, for the first time, a program of fuel economy standards for heavy-duty vehicles.
120. U.S. Department of Transportation: National Highway Traffic Safety Administration (2009). *Average Fuel Economy Standards: Passenger Cars and Light Trucks: Model Year 2011Final Rule,* p. 23.
121. The Energy Independence and Security Act of 2007, Public Law 110-140, Section 137 (signed by the president on December 19, 2007).
122. *See* U.S. Department of Energy, Final Rule: Advanced Technologies Vehicle Manufacturing Incentive Program, 10 C.F.R. Part 611, November 5, 2008.
123. *Ibid.*
124. The Consolidated Security, Disaster Assistance, and Continuing Appropriations Act 2009, Public Law 110-329, Section 129(a) (signed by the president on September 30, 2008).

125. U.S. Department of Energy (January 16, 2008). "Update to Status: ATVM Loan Program," Press Release.
126. The $75 billion in loans requested for the auto industry and its suppliers is to support research, development and deployment of advanced vehicle technologies that will be required to reduce GHG emissions from the transportation sector. While GM and Chrysler have received federal assistance to help them restructure in response to the current unprecedented auto industry downturn, this assistance is not targeted at the development or deployment of advanced vehicle technologies. In addition, assistance has not been provided to other companies or suppliers in the auto industry. Accordingly, the level of investment recommended here is unaffected by the assistance that has already been provided.
127. This percentage represents the energy content of ethanol as a portion of the energy content of all motor gasoline used in 2008.
128. Argonne National Laboratory and the Department of Energy (2005). *The Debate on Energy and Greenhouse Gas Emissions Impacts of Fuel Ethanol,* p. 21. *See also* Karsner, Alexander (June 12, 2008). Testimony before United States Senate Committee on Energy and Natural Resource, p. 5. Nevertheless, deployment of advanced biofuels in the U.S. transportation sector may present direct and indirect environmental and land-use challenges in other markets, and policymakers must be sensitive to the potential impacts of advanced biofuels on global food prices, water supplies and GHG emissions from changing land-use practices.
129. There would be less need for these changes with advanced biofuels that are fully fungible with petroleum-based gasoline and diesel fuels, such "green gasoline" or renewable diesel produced from biomass.
130. Badger, P.C. (2002). "Ethanol from Cellulose: A General Review." In: J. Janick and A. Whipkey (editors), *Trends in New Crops and New Uses,* ASHS Press, pp. 17–21. *See also* National Renewable Energy Laboratory (last updated on July 25, 2008). *Biochemical Conversion Technologies.*
131. *Ibid. See also* National Renewable Energy Laboratory (last updated on July 25, 2008). *Thermochemical Conversion Technologies.*
132. Biomass Research and Development Board (co-chaired by the U.S. Department of Agriculture and the U.S. Department of Energy) (2008). *National Biofuels Action Plan,* p. 5.
133. Wang, Michael (2005). "Energy and Greenhouse Gas Emissions Impacts of Fuels Ethanol," *NCGA Renewable Fuels Forum,* Argonne National Laboratory, p. 15.
134. Searchinger, Timothy, et al. (February 2008). "Use of U.S. Croplands for Biofuels Increase Greenhouse Gases Through Emissions from Land-use Change," *Science Express.* Vol. 319, No. 5867, pp. 1238–240; and Wang, Michael and Zia Haq (Mar 2008). "Letter to *Science."*
135. *Ibid.*
136. Biomass Research and Development Board (2008). p .9.
137. *Ibid.*
138. Sokhansanj, Sahab (2007). "Biomass Supply Systems Logistics," Oak Ridge National Laboratory.
139. Biomass Research and Development Board (2008). p. 9.
140. Energy Information Administration (2008).
141. Tearne, a lead-tin alloy, is one common soft metal found in fueling station equipment parts.
142. Commonwealth of Massachusetts (Spring 2008). *Advanced Biofuels Task Force Report,* pp. 63–64.
143. *Ibid.*
144. The health and sustainability of our nation's forest cover, for example, should be carefully considered as these policies are developed.
145. Energy Information Administration (2009). *Natural Gas Navigator: Monthly City Gate Price & Electric Power Monthly: Average Retail Price of Electricity.*

146. Energy Information Administration (2009). *Annual Energy Review 2008,* Tables 1.3 and 5.1; and Energy Information Administration (March 2009). *Monthly Energy Review*, Table 3.1.
147. *Ibid.*
148. *Ibid.* Using data from 2008 dilutes the divergence of supply and demand because high oil prices and recession subverted demand while high prices encouraged production that would not have been cost-effective at lower prices.
149. *Ibid.*, Table 5.1.
150. Energy Information Administration (2009). *Petroleum Navigator: WTI Spot Price.*
151. American Petroleum Institute (2009). *America's Oil and Natural Gas Industry: Offshore Access to America's Oil and Natural Gas Resources,* p. 8.
152. American Petroleum Institute (2008). *Summary of Carbon Dioxide Enhanced Oil Recovery Injection Well Technology*.
153. Energy Information Administration (2009). *Annual Energy Review 2008,* Table 6.1; and Energy Information Administration (March 2008). *Monthly Energy Review*, Table 1.
154. *Ibid.*
155. *Ibid.*, Tables 2.6 and 8.11c.
156. *Ibid.*, Table 6.3. Using data from 2008 understates the divergent trend of supply and demand because high natural gas prices and recession subverted demand while high prices encouraged production that would not have been cost-effective at lower prices.
157. Energy Information Administration (2009). *Natural Gas Navigator: Monthly City Gate Price.*
158. Energy Information Administration (February 2007). *Annual Energy Outlook 2007.*
159. Minerals Management Service (January 2009). *Draft Proposed Outer Continental Shelf (OCS) Oil and Gas Leasing Program 2010-2015.*
160. Minerals Management Service (2006). *Assessment of Undiscovered Technically Recoverable Oil and Gas Resources of Nation's Outer Continental Shelf, 2006.*
161. U.S. Department of the Interior, U.S. Geological Survey (November 2005). *Mean Conventional Oil Resources: Undiscovered Technically Recoverable Resources.*
162. U.S. Department of the Interior, U.S. Geological Survey (November 2005). *National Assessment of Oil and Gas Resources Update.*
163. U.S. Department of the Interior, U.S. Geological Survey (1998). *Arctic National Wildlife Refuge, 1002 Area, Petroleum Assessment, 1998, Including Economic Analysis,* p. 4.
164. Energy Information Administration (May 2008). *Analysis of Crude Oil Production in the Arctic National Wildlife Refuge.*
165. *Ibid.*
166. U.S. Department of the Interior (June 2008). *Western Oil Shale Potential: 800 Billion Barrels of Recoverable Oil,* Press Release.
167. American Petroleum Institute (2009). *America's Oil and Natural Gas Industry: Offshore Access to America's Oil and Natural Gas Resources,* p. 5.
168. *Ibid.*
169. *Ibid.*, p. 6.
170. *Ibid.*, p. 1.
171. ICF International (2008). *Strengthening Our Economy: The Untapped U.S. Oil and Gas Resources,* p. 7.
172. *Ibid.*, p. 8.
173. *Ibid.*, p. 9.

174. Chapter 1 describes what the working groups are and their central role in the project. Chapter 11 describes their modeling inputs in detail.
175. These scenarios are not meant to be realistic but are instead intended to be alternative baselines that show the impact that carbon prices could have in a U.S. economy that is structurally the same as the BAU scenario. The only major adjustments that occur in the transition from the BAU scenario to the Minimal Technology scenarios are that carbon prices drive down output.
176. For instance, under the carbon prices assumed in this study, the total carbon revenues collected reach 2.6 to 4.2 percent of GDP by 2050.
177. Recommended policy initiatives include, for example, increased R&D for carbon capture and storage pilot projects, tax credits for plug-in hybrid vehicles, production and ITCs for renewable power, and loan guarantees for new nuclear power plants. Within the LIFT model, these are credited to the "federal nondefense spending, other services category."
178. See Chapter 1 for a discussion of the individual technology working groups.
179. See Chapter 12 for a discussion of the modeling scenario results.
180. The improvements are greater in commercial buildings because the baseline already assumes significant improvements in residential efficiency due to existing policies, such as those included in EISA. Consequently, there is less room for improvement in residential efficiency. Also, the commercial sector is expected to have a much higher proportion of new buildings, which are more amenable to energy efficiency improvements than the residential sector.
181. These improvements are relative to the 2050 baseline. They translate into reducing energy use per square foot in new and existing buildings by 32 to 54 percent and 22 to 37 percent, respectively, as compared to current energy use.
182. This acceleration is the result of direct support for early demonstration and commercialization as well as falling technology costs through learning by doing. The costs of CCS and IGCC technologies are assumed to fall by 10 to 25 percent depending on deployment levels of the particular technology. Some experts believe that the costs will fall much further with significant deployment levels.
183. Policy leadership accelerates CCS deployment in industrial gasification facilities more rapidly than in electricity generation facilities because those applications are already on the verge of widespread commercial deployment.
184. Natural gas price assumptions were formed during the summer of 2008, when energy prices were particularly high. If actual prices turn out to be significantly lower than those assumed in the model, as they are today, then natural gas could be a much more common feedstock for CCS applications.
185. It should be noted that additional improvements in fuel efficiency beyond those assumed for the other three vehicle types also could contribute to further emissions reductions, as could greater use of natural gas powered vehicles. After 2020, the Policy Inertia and Policy Leadership scenarios consider the demand response for advanced internal combustion, diesel and (non-plug-in) hybrid vehicles as carbon prices increase. They do not include significant fuel efficiency gains in those vehicle types beyond the gains assumed by the EIA in their analysis of S2191.
186. The Policy Leadership scenarios focus explicitly on how policy leadership can reduce costs and accelerate deployment of PHEV and hydrogen fuel cell technologies in the light-duty vehicle sector. Alternative paths also could help to lower fuel consumption in the light-duty vehicle sector but are not modeled. For example, fuel economy improvements through advanced engine technologies, dieselization and hybridization could achieve significant emissions reductions in the light-duty vehicle fleet beyond those assumed in these scenarios.

187. This improvement in vehicle range is assumed not to take place in the Policy Inertia scenarios because PHEV sales never reach a high enough level to drive significant investment in improving the technology.

188. The percentage of GHG emissions that are saved by substitution of cellulosic ethanol for gasoline is a subject of considerable debate. Some argue it should be higher and some that it should be much lower. This is discussed more in Chapter 8.

189. Estimates of how much of a plant must be left in the fields are taken from Oak Ridge National Laboratory (2005).

190. Specifically, solar power production growth was reduced by 70 percent in all scenarios for all years after 2016, the year when solar power ITC expires.

191. After 2022, the last year for which there is a specific advanced biofuel volume as set by federal mandate, adjustments were made to reduce the expansion of ethanol from particular feedstocks and gasoline from coal if overall production and transportation costs of that fuel exceed the energy-content adjusted price assumed for conventional gasoline. Under the advanced biofuels working group's assumptions, cellulosic ethanol from certain feedstocks is generally uncompetitive with gasoline by 2023, particularly in the low carbon price scenarios. However, as carbon prices rise, cellulosic ethanol from all three cellulosic feedstocks eventually become competitive with gasoline, and their production growth is assumed to resume. Under the assumptions developed by the CCS working group, gasoline from coal is competitive in 2023 and thereafter.

192. As part of the modeling process, each of the individual technology pathways was modeled in isolation. Even with the ambitious but realistic deployment levels estimated by the technology working groups in the most aggressive policy scenarios, the emissions reductions from pursuing any one technology pathway were not sufficient to offset the estimated growth in emissions under the BAU assumptions. Hence, none of the individual technology pathways led to a reduction in carbon emissions as compared to today's emissions.

193. Estimates expressed as ranges represent outcomes under low carbon price and high carbon price assumptions. In instances in which estimates are not expressed as ranges, the outcomes under low carbon price and high carbon price assumptions were deemed to be similar.

194. Expressed differently and more generally, Business Roundtable's recommendations combined with a carbon pricing mechanism have the potential to achieve a given level of GHG emissions reductions at a much lower cost than a carbon pricing mechanism alone.

195. The $75 billion in loans requested for the auto industry and its suppliers is to support research, development and deployment of advanced vehicle technologies that will be required to reduce GHG emissions from the transportation sector. While GM and Chrysler have received federal assistance to help them restructure in response to the current unprecedented auto industry downturn, this assistance is not targeted at the development or deployment of advanced vehicle technologies. In addition, assistance has not been provided to other companies or suppliers in the auto industry. Accordingly, the level of investment recommended here is unaffected by the assistance that has already been provided.

For more information, contact Marian Hopkins,
mhopkins@businessroundtable.org.

Business
Roundtable℠

1717 Rhode Island Avenue, NW
Suite 800
Washington, DC 20036

Telephone 202.872.1260
Facsimile 202.466.3509
Website businessroundtable.org

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