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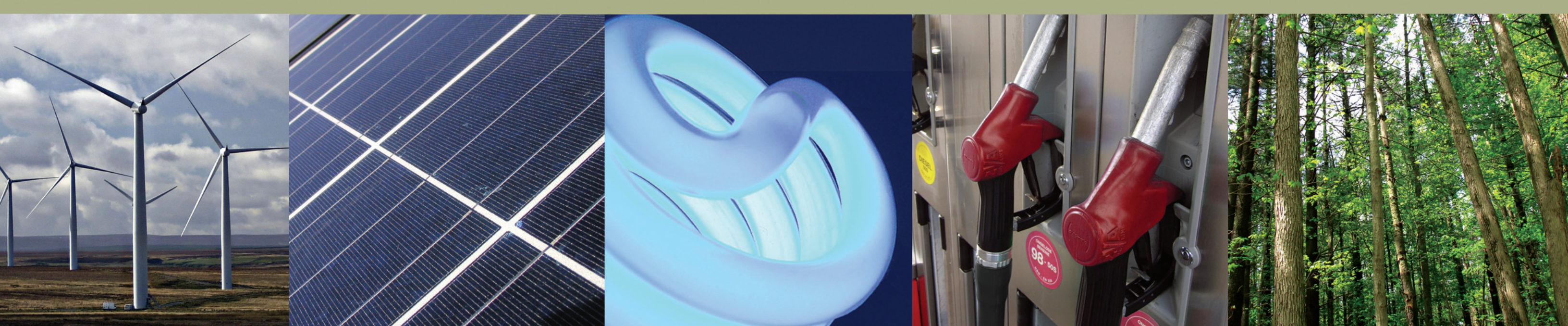
Reducing U.S. Greenhouse Gas Emissions: *How Much at What Cost?*



U.S. Greenhouse Gas Abatement Mapping Initiative

Executive Report

December 2007

This report was produced in association with seven leading global institutions with a strong commitment to engaging the public in constructive debate.

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Jon Creyts
Anton Derkach
Scott Nyquist
Ken Ostrowski
Jack Stephenson

Preface

Over the past 2 years, McKinsey & Company has worked with leading institutions and experts to develop a framework and fact base to understand the costs and potentials of different options for reducing greenhouse gas (GHG) emissions – first at a global level, then through country-specific analyses for major GHG-emitting nations.

In February 2007, we launched the U.S. Greenhouse Gas Abatement Mapping Initiative (US GHG AMI) in collaboration with leading U.S.-based companies and environmental nongovernmental organizations (NGOs). Our effort examined opportunities to reduce GHG emissions from human activity within U.S. borders using tested approaches and high-potential emerging technologies. This report is the product of that work.

Our project has been greatly strengthened and enriched by contributions from many participants. They helped our team gain access to data, test emerging conclusions, and prepare for the release of this report. We especially acknowledge our environmental and corporate sponsors for providing their expertise, as well as contributing underwriting support for this effort:

¶ **DTE Energy**

¶ **Environmental Defense**

¶ **Honeywell**

¶ **National Grid**

¶ **Natural Resources Defense Council**

¶ **PG&E**

¶ **Shell**

In addition, we have been encouraged and challenged by our academic review panel, who provided important guidance throughout the project and later reviewed project findings prior to the publication of this report:

¶ **Robert Socolow**, Professor of Mechanical and Aerospace Engineering, Co-Director of the Carbon Mitigation Initiative, Princeton University, and Chair of the US GHG AMI's Academic Review Panel.

- ¶ **Dallas Burtraw**, Senior Fellow, Resources for the Future.
- ¶ **John Heywood**, Professor of Mechanical Engineering, Director of the Sloan Automotive Laboratory, Massachusetts Institute of Technology.
- ¶ **Bruce McCarl**, Regents Professor of Agricultural Economics, Texas A&M University.
- ¶ **Alan Meier**, Lawrence Berkeley National Laboratory and University of California, Davis.
- ¶ **Stephen Pacala**, Professor of Biology, Director of Princeton Environmental Institute, Princeton University.

During this effort, the team conducted more than 100 interviews with representatives of government agencies, public and private companies, academic institutions and research foundations, as well as many independent experts. While too numerous to cite by name, these individuals have given generously of their time and knowledge and deserve our warmest thanks.

We are also grateful to our co-publishers, The Conference Board, for their able assistance in publishing and distributing this report.

While the work presented in “Reducing U.S. Greenhouse Gas Emissions: How Much at What Cost?” has benefited immensely from these contributions, **the views it expresses are solely the responsibility of McKinsey & Company** and do not necessarily reflect the views of our sponsors, academic reviewers, The Conference Board, or any of our other contributors.

Contents

A letter from The Conference Board

Sustainability, which includes meeting the challenge of greenhouse gas emissions (GHG) and other aspects of environmental preservation, is rapidly becoming a priority for American business and for public policy.

In a recent survey by The Business Council, which counts many of the largest U.S. companies among its members, more than 40 percent of CEOs responding said that environmental and global warming issues are a very important, and in some cases, the most important policy challenge facing the U.S. While these concerns still rank behind issues such as education, healthcare, tax policy, and innovation, the percentage of respondents putting a high priority on sustainability issues has doubled in just the past 18 months. These shifting attitudes are further supported by responses to The Conference Board's own global CEO Challenge survey as well as other polls of business and public attitudes.

Many U.S. businesses are beginning to establish aggressive greenhouse gas abatement plans as part of their corporate sustainability objectives. Indeed, many American corporations are changing strategies, developing new products and technologies, and investing heavily in alternative fuels and energy delivery infrastructure to capture the business opportunities presented by the concern over greenhouse gas emissions. At the same time, U.S. consumers are adapting to higher energy price levels by curbing their energy use and there seems to be momentum for adopting carbon-reducing products and habits.

Nevertheless, as McKinsey reports, a composite of official U.S. government agency projections indicates that, if unchecked, annual greenhouse gas emissions will increase from 7.2 gigatons of carbon-dioxide equivalents (CO_2e) to 9.7 gigatons by 2030. Legislative proposals now before the U.S. Congress are seeking to address this issue in various ways. Many interest groups and industries argue that the economic cost required to reach these targets does not match the benefit and is too large for the economy to bear.

Amid the opportunities and tensions, ambitions, and controversies there are simply too few facts on which to base intelligent discussion and action. For this reason, The Conference Board is joining with McKinsey & Company in publishing this report. The McKinsey effort brings together evidence from a wide-ranging group of companies, academics, researchers, and interest groups to estimate the long-term costs and emissions reduction impact of a large number of abatement options. Creating analytical structures and quantitative metrics to better inform business, government, and the public on greenhouse gas abatement choices is an important contribution of this project, and we hope it will serve as a robust starting point for further development of these critical tools. It is also consistent with the mission of The Conference Board Center for Corporate Citizenship & Sustainability.

The Conference Board is a not-for-profit, non-advocacy, research and educational institution and, as such, does not take positions on matters of public policy. For this reason, we do not associate ourselves with the policy implications discussed in this report. The Conference Board was founded on the principle that fact-based analysis and debate will produce constructive changes in the U.S. economy and the health and prosperity of the free enterprise system and American society. We believe this report helps achieve those objectives.

The Conference Board was not involved in the original research underlying this report. However, we have reviewed the methodology and findings and believe, despite some qualifications described in this letter, the report represents an important contribution toward establishing an empirical and analytical base for public discussion of carbon policies. It also provides a way for businesses and consumers to judge their actions and gauge progress toward a lower carbon environment. A unique contribution of this report is the decision-aiding framework based on detailed, bottom-up data and analysis to calculate the cost of reducing these emissions.

McKinsey researchers have estimated the net costs and abatement benefit in terms of CO_2 equivalent reduction of more than 250 abatement options, grouping these options into abatement clusters that approximate the energy use patterns and technology fields of key sectors of the economy. These options are then grouped according to the magnitude of change that would be required in behaviors, policy, technology (or all three). The research then groups them to form a cost/abatement curve, sequencing the options and estimating the relative long-term net cost of the composite of options.

There are a significant number of options where the long-term savings in terms of lower operating costs and/or lower energy usage levels outweigh the initial costs of adoption. In simple terms, the savings outweigh the costs and significant GHG abatement can be achieved.

The report highlights three cases to demonstrate how differences in national will, policies and approaches might lead to different levels of GHG abatement:

1. While the "low-range case" is also the least costly, it would reduce annual emissions by only about 1.3 gigatons by 2030, not sufficient to bring the projected levels of GHG back to current levels.

2. The "mid-range case" would bring annual emissions below current levels but would not be enough to reach the goals laid out in current legislative proposals.

3. The "high-range case" would be required to meet the objectives proposed in current legislation. However, the report notes that this case would require an extraordinarily high level of national commitment.

These conclusions are subject to a number of important caveats which, if the assumptions were changed and methodology were made more interactive to include changes caused by consumers and technology, would be likely to substantially change the results. Many of these caveats are recognized by McKinsey in the study and provide an opportunity for continuing research.

1. The assumed demand for energy is based on a reference case, which was created by harmonizing the most recent official projections of several U.S. government agencies. Changes in the projected GDP growth rates and forecasts of technological change in addition to the sensitivity of energy demand to energy prices – all subject to fluctuations in our dynamic economy – could change the reference case in a significant way.

2. The demand side is also crucial to assess the attractiveness of different abatement options. The McKinsey team looked primarily at the technical feasibility and cost of those options. How quickly consumers modify their behavior and adopt different options will have a major effect on the ultimate economic benefit of those options. In addition to energy prices, many other price and non-price factors create incentives that help drive consumer behavior. Therefore, expanding this framework to cover factors that influence both the supply of abatement costs and the demand for these new opportunities will provide a powerful tool for evaluating the feasibility of achieving emissions goals.

3. The McKinsey team took on a difficult challenge – the issue of interactions among the various abatement options – a factor of complexity that, again, will impact the costs of, and the ability to attain, specific emission-reduction goals. Such interactions range from the sequence of when different abatement options are deployed, to the substitution effects of various options or the deployment of complementary options. The team addressed these possible effects and identified the most likely scenarios. But trade-offs and alternative scenarios to the ones examined in this report may also have substantive effects that need to be studied further to create a more meaningful decision-making framework.

The overall task of reducing greenhouse gases can appear daunting. However, as we have seen from past environmental debates, the market system can work in ways unanticipated by initial analyses to reduce the costs of achieving social objectives. We welcome McKinsey's important contribution to the discussion of greenhouse gas abatement, and the opportunity to join with them in the publication and discussion of this report. We expect it to contribute to the exchange and debate on this topic among business leaders, and we plan to use our convening capacity to further public and private understanding of this topic. We also hope that the publication of this report will inspire others to develop and extend this and related analyses to improve the private and public response to this important issue.

The Conference Board

New York

November 2007

Executive summary

Consensus is growing among scientists, policy makers and business leaders that concerted action will be needed to address rising greenhouse gas (GHG) emissions. The discussion is now turning to the practical challenges of where and how emissions reductions can best be achieved, at what costs, and over what periods of time.

Starting in early 2007, a research team from McKinsey & Company worked with leading companies, industry experts, academics, and environmental NGOs to develop a detailed, consistent fact base estimating costs and potentials of different options to reduce or prevent GHG emissions within the United States over a 25-year period. The team analyzed more than 250 options, encompassing efficiency gains, shifts to lower-carbon energy sources, and expanded carbon sinks.

THE CENTRAL CONCLUSION OF THIS PROJECT

The United States could reduce greenhouse gas emissions in 2030 by 3.0 to 4.5 gigatons of CO_2*e using tested approaches and high-potential emerging technologies.*[1] *These reductions would involve pursuing a wide array of abatement options available at marginal costs less than $50 per ton, with the average net cost to the economy being far lower if the nation can capture sizable gains from energy efficiency. Achieving these reductions at the lowest cost to the economy, however, will require strong, coordinated, economy-wide action that begins in the near future.*

Although our research suggests the net cost of achieving these levels of GHG abatement could be quite low on a societal basis, issues of timing and allocation would likely lead various stakeholders to perceive the costs very differently -- particularly during the transition to a lower carbon economy. Costs will tend to concentrate more in some sectors than others, and involve "real" up-front outlays that would be offset by "avoided" future outlays. Given the timing of investments relative to savings, the economy might well encounter periods of significant visible costs, with the costs and benefits shared unequally among stakeholders. Nonetheless, a

1 CO_2e, or "carbon dioxide equivalent," is a standardized measure of GHG emissions designed to account for the differing global warming potentials of GHGs. Emissions are measured in metric tons CO_2e per year, i.e., millions of tons (megatons) or billions of tons (gigatons). All emissions values in this report are per-year CO_2e amounts, unless specifically noted otherwise. To be consistent with U.S. government forecasts, the team used the 100-year global warming potentials listed in the Intergovernmental Panel on Climate Change's Second Assessment Report (1995).

concerted, nationwide effort to reduce GHG emissions would almost certainly stimulate economic forces and create business opportunities that we cannot foresee today and that may accelerate the rate of abatement the nation can achieve, thereby reducing the overall cost.

We hope that the fact base provided in this report will help policymakers, business leaders, academics and other interested parties make better informed decisions and develop economically sensible strategies to address the nation's rising GHG emissions.

RISING EMISSIONS POSE AN INCREASING CHALLENGE

Annual GHG emissions in the U.S. are projected to rise from 7.2 gigatons CO_2e in 2005 to 9.7 gigatons in 2030 – an increase of 35 percent – according to an analysis of U.S. government reference forecasts.[2] The main drivers of projected emissions growth are:

- Continued expansion of the U.S. economy
- Rapid growth in the buildings-and-appliances and transportation sectors, driven by a population increase of 70 million and rising personal consumption
- Increased use of carbon-based power in the electric-power generation portfolio, driven by projected construction of new coal-fired power plants without carbon capture and storage (CCS) technology.

Growth in emissions would be accompanied by a gradual decrease in the absorption of carbon by U.S. forests and agricultural lands. After rising for 50 years, carbon absorption is forecast to decline from 1.1 gigatons in 2005 to 1.0 gigatons in 2030.

On this path – with emissions rising and carbon absorption starting to decline – U.S. emissions in 2030 would exceed GHG reduction targets contained in economy-wide climate-change bills currently before Congress by 3.5 to 5.2 gigatons.[3]

2 The research team used the "reference" scenario in the U.S. Energy Information Administration's Annual Energy Outlook 2007 report as the foundation of its emissions reference case for emissions through 2030, supplementing that with data from Environmental Protection Agency and Department of Agriculture sources: Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2005; Global Anthropogenic non-CO_2 Greenhouse Gas Emissions: 1990-2020; Global Mitigation of non-CO_2 Greenhouse Gases; and Forest Service RMRS-GTR-59 (2000). Our analyses excluded HCFCs, which are being retired under the Montreal Protocol.

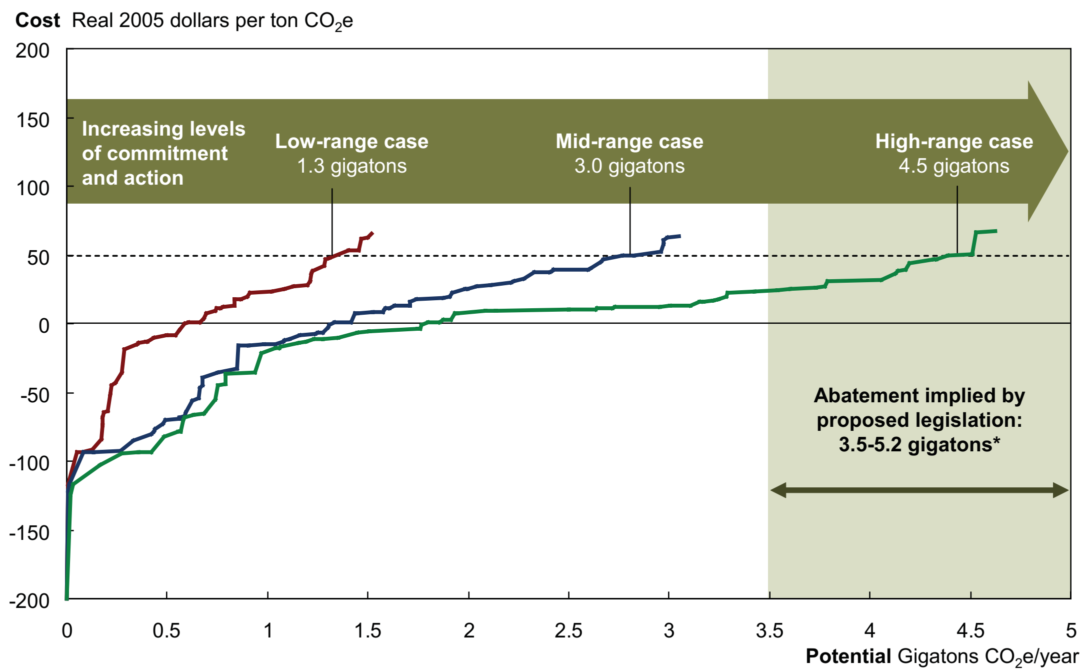
3 The research team defined an illustrative range of GHG reduction targets relative to the emissions reference case using a sampling of legislation that had been introduced in Congress at the time this report was written. The team focused on bills that address global warming and/or climate change on an economy-wide basis and contain quantifiable reduction targets. Use of these possible targets as reference points should not be construed as an endorsement of those targets nor the policy approaches contained in any particular legislative initiative.

SIGNIFICANT POTENTIAL TO REDUCE U.S. EMISSIONS

We analyzed resource costs and abatement potentials for more than 250 opportunities to reduce or prevent GHG emissions.[4] We projected a range of three outcomes for each option and, for analytical purposes, integrated the values into three abatement supply curves. The supply curves are not optimized scenarios, rather they represent different approximations of national commitment (e.g., degree of incentives, investments, regulatory reforms, and urgency for action) and different rates for innovation, learning, and adoption of various technologies. We have called the three curves "cases": the low-range case involves incremental departures from current (i.e., reference case) practices; the mid-range case involves concerted action across the economy; and the high-range case involves urgent national mobilization. In this way, the cases illustrate an envelope of abatement potential for the United States by 2030 (Exhibit A).[5]

Exhibit A

U.S. GREENHOUSE GAS ABATEMENT POTENTIALS – 2030



* Based on bills introduced in Congress that address climate change and/or GHG emissions on an economy-wide basis and have quantifiable targets; targets calculated off the 2030 U.S. GHG emissions of 9.7 gigatons CO_2e/year (reference case)

Source: McKinsey analysis

4 The cost of an abatement option reflects its resource (or techno-engineering) costs – i.e., capital, operating, and maintenance costs – offset by any energy savings associated with abating 1 ton of CO_2e per year using this option, with the costs/savings levelized over the lifetime of the option using a 7-percent real discount rate. We excluded transaction costs, communication/information costs, taxes, tariffs, and/or subsidies. We also have not assumed a "price for carbon" (e.g., a carbon cap or tax) that might emerge as a result of legislation, nor any impact on the economy of such a carbon price. Hence, the per-ton abatement cost does not necessarily reflect the total cost of implementing that option.

5 Only the high-range case reaches the target levels of GHG abatement (3.5 to 5.2 gigatons in 2030) suggested by our sampling of proposed federal legislation that addresses climate change on an economy-wide basis. For this reason, we focus most of our abatement analysis on the upper part of the envelope, from 3.0 gigatons (mid-range case) to 4.5 gigatons (high-range case).

Relying on tested approaches and high-potential emerging technologies, the U.S. could reduce annual GHG emissions by as much as 3.0 gigatons in the mid-range case to 4.5 gigatons in the high-range case by 2030. These reductions from reference case projections would bring U.S. emissions down 7 to 28 percent below 2005 levels, and could be made at a marginal cost less than $50 per ton,[6] while maintaining comparable levels of consumer utility.[7]

We made no assumptions about specific policy approaches that might be taken – e.g., a carbon cap or tax, mandates, or incentives – nor responses in consumer demand that might result. Nonetheless, unlocking the full abatement potential portrayed in our mid- and high-range curves would require strong stimuli and policy interventions of some sort. *Without a forceful and coordinated set of actions, it is unlikely that even the most economically beneficial options would materialize at the magnitudes and costs estimated here.*

Our analysis also found that:

- **Abatement opportunities are highly fragmented and widely spread across the economy (Exhibit B).** The largest option (CCS for a coal-fired power plant) offers less than 11 percent of total abatement potential. The largest sector (power generation) only accounts for approximately one-third of total potential.

- **Almost 40 percent of abatement could be achieved at "negative" marginal costs,** meaning that investing in these options would generate positive economic returns over their lifecycle. The cumulative savings created by these negative-cost options could substantially offset (on a societal basis) the additional spending required for the options with positive marginal costs. Unlocking the negative cost options would require overcoming persistent barriers to market efficiency, such as mismatches between who pays the cost of an option and who gains the benefit (e.g., the homebuilder versus homeowner), lack of information about the impact of individual decisions, and consumer desire for rapid payback (typically 2 to 3 years) when incremental up-front investment is required.

- **Abatement potentials, costs, and mix vary across geographies.** Total abatement available at less than $50 per ton ranges from 330 megatons in the Northeast to 1,130 megatons in the South (mid-range case). These potentials are roughly

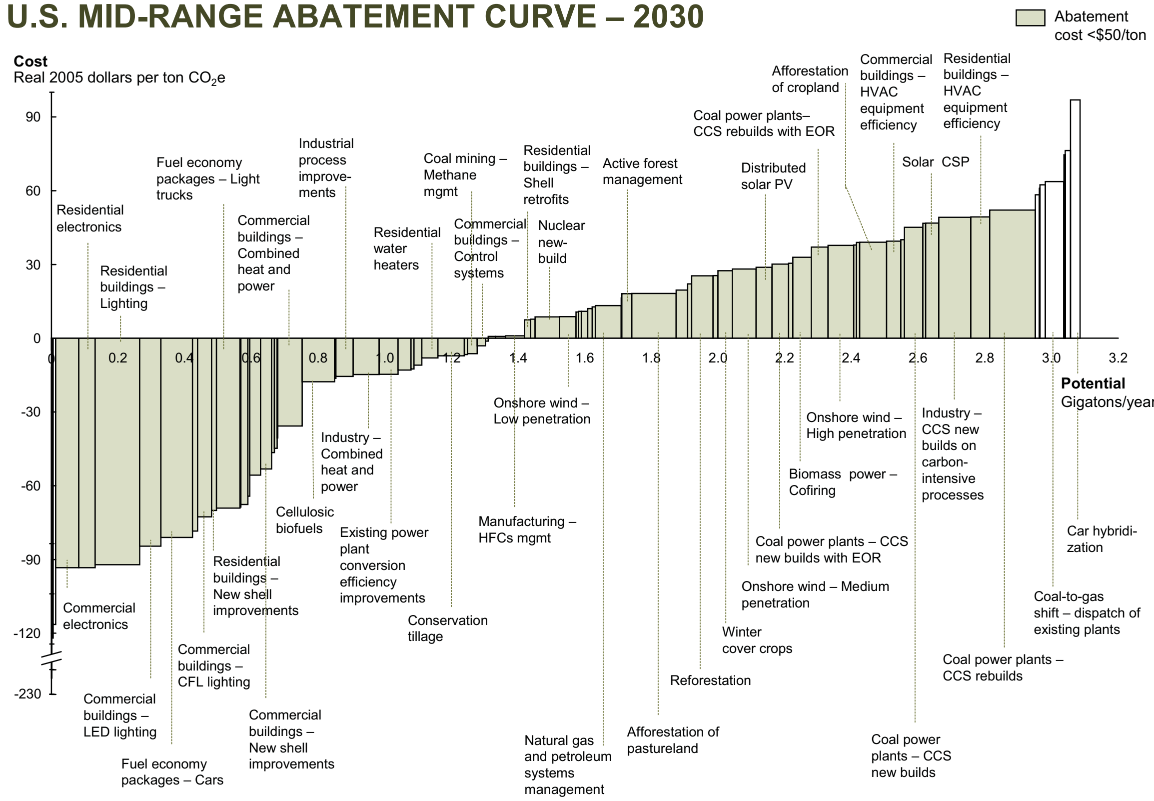
6 The team set an analytical boundary at $50 per ton in marginal cost after considering consumer affordability and the estimated long-term cost for adding carbon capture and storage to an existing coal-fired power plant, a solution that, if successfully deployed, would likely set an important benchmark for emission-control costs. Abatement costs are expressed in 2005 real dollars. The team examined a number of options with marginal costs between $50 and $100 per ton, but did not attempt a comprehensive survey of options in this range. For simplicity of expression in this report, we refer to the threshold with the phrase "below $50 per ton."

7 By "consumer utility" we mean functionality or usefulness for people, including level of comfort; in this context, holding consumer utility constant would imply, e.g., no change in thermostat settings or appliance use; no downsizing of vehicles, homes, or commercial space; traveling the same mileage annually relative to levels assumed in the government reference case. In a strict economic sense, maintaining constant consumer utility assumes a constant economic surplus for the consumer while delivering against a common benefit. We have not attempted to calculate potential changes in utility that might result from energy price changes associated with pursuing the options outlined in our abatement curve.

proportional to total GHG emissions from the regions, but there are significant variations relative to GDP and population.

Exhibit B

U.S. MID-RANGE ABATEMENT CURVE – 2030



Source: McKinsey analysis

Reducing GHG emissions would require capital spending increases and a change in investment patterns relative to the government reference case. For example, the incremental capital costs associated with capturing the 3.0 gigatons of abatement in our mid-range case would average approximately $50 billion annually through 2030. Cumulative net new investment through 2030 would be $1.1 trillion, or roughly 1.5 percent of the $77 trillion in real investment the U.S. economy is expected to make over this period. This number would be higher if our projected savings from energy efficiency gains do not materialize and/or if the nation chooses to achieve emissions reductions by mandating higher-cost options. These incremental investments would be highly concentrated in the power and transportation sectors; if pursued, they would likely put upward pressure on electricity prices and vehicle costs. Policymakers and legislators would need to weigh these added costs against the energy efficiency savings, opportunities for technological advances, and other societal benefits.

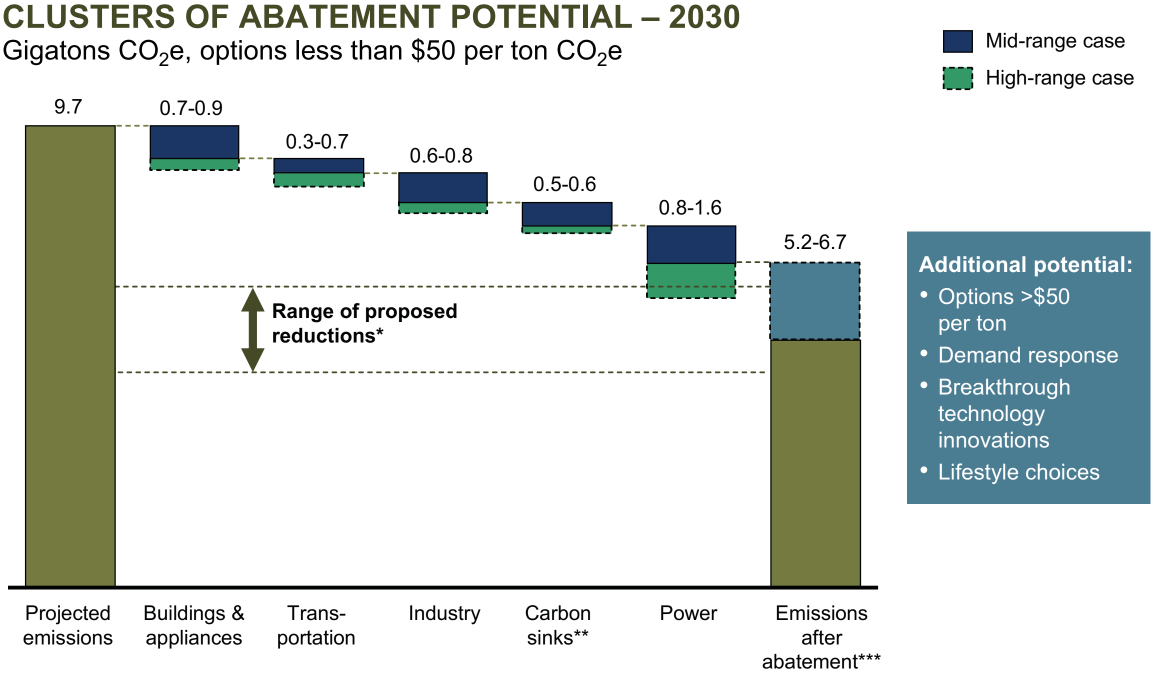
FIVE SECTORS OFFER CLUSTERS OF ABATEMENT POTENTIAL

Five clusters of initiatives, pursued in unison, could create substantial progress – 3.0 gigatons (mid-range case) to 4.5 gigatons (high-range case) of abatement per year – against proposed GHG-reduction targets for 2030 (Exhibit C). We will discuss these clusters in order, from least to highest average cost.

Exhibit C

CLUSTERS OF ABATEMENT POTENTIAL – 2030

Gigatons CO_2e, options less than $50 per ton CO_2e



* Based on bills introduced in Congress that address climate change and/or GHG emissions on an economy-wide basis and have quantifiable targets; targets calculated off the 2030 U.S. GHG emissions of 9.7 gigatons CO_2e/year (reference case)

** Including abatement in the agriculture sector

*** Adjusted for cumulative rounding errors

Source: U.S. EIA; EPA; USDA; McKinsey analysis

1. **Improving energy efficiency in buildings and appliances – 710 megatons (mid-range) to 870 megatons (high-range).** This large cluster of negative-cost options includes: lighting retrofits; improved heating, ventilation, air conditioning systems, building envelopes, and building control systems; higher performance for consumer and office electronics and appliances, among other options. While this category of abatement options would cost the least from a societal point of view, persistent barriers to market efficiency will need to be overcome.

2. **Increasing fuel efficiency in vehicles and reducing carbon intensity of transportation fuels – 340 megatons to 660 megatons.** Improved fuel efficiency could provide 240 megatons to 290 megatons of abatement: much of the benefit would come from fuel

economy packages (e.g., lightweighting, aerodynamics, turbocharging, drive-train efficiency, reductions in rolling resistance) and increased use of diesel for light-duty vehicles. Though the savings from fuel efficiency may offset the incremental cost of the abatement option over a vehicle's 12- to 15-year lifecycle, these options require up-front investment by automakers and thus higher vehicle costs for consumers. Lower-carbon fuels, such as cellulosic biofuels, could abate 100 megatons to 370 megatons of emissions, though this potential is highly dependent on innovation rates and near-term commercialization of these technologies. Plug-in hybrid vehicles offer longer-term potential if vehicle cost/performance improves and the nation moves to a lower-carbon electricity supply.

3. **Pursuing various options across energy-intensive portions of the industrial sector – 620 megatons to 770 megatons.** This potential is in addition to 470 megatons assumed in the government reference case. It involves a multitude of fragmented opportunities within specific industries (e.g., equipment upgrades, process changes) and across the sector (e.g., motor efficiency, combined heat and power applications). Despite offering direct bottom-line benefit, these options must compete for capital and, without clear incentives to control GHG emissions, may not receive funding.

4. **Expanding and enhancing carbon sinks – 440 megatons to 590 megatons.** Increasing forest stocks and improving soil management practices are relatively low-cost options. Capturing them would require linkages to carbon-offset mechanisms to access needed capital, plus improved monitoring and verification.

5. **Reducing the carbon intensity of electric power production – 800 megatons to 1,570 megatons.** This potential derives from a shift toward renewable energy sources (primarily wind and solar), additional nuclear capacity, improved efficiency of power plants, and eventual use of carbon capture and storage (CCS) technologies on coal-fired electricity generation. Options in the power sector were among the most capital-intensive ones evaluated. These options also tend to have the longest lead times, given bottlenecks in permitting, materials and equipment manufacturing, and design, engineering, and construction.

The theme of greater energy productivity pervades these clusters. Improving energy efficiency in the buildings-and-appliances and industrial sectors, for example, could (assuming substantial barriers can be addressed) offset some 85 percent of the projected incremental demand for electricity in 2030, largely negating the need for the incremental coal-fired power plants assumed in the government reference case. Similarly, improved vehicle efficiency could roughly offset the added mobility-related emissions of a growing population, while providing net economic gains.

NEED FOR STRONG, ECONOMY-WIDE APPROACHES

The U.S. will need to develop and implement a strong, coordinated program of economy-wide abatement actions in the near future, if it is to achieve emissions reductions proposed (in bills currently before Congress) for 2030 at the lowest cost to the economy.

We believe a comprehensive abatement program for the U.S. should be built on three principal actions:

1. **Stimulate action through a portfolio of strong, coordinated policies to capture GHG reductions efficiently across industry sectors and geographies.** These policies would need to support development of:

    - Visible, sustained signals to create greater certainty about the price of carbon and/or required emissions reductions; this will help encourage investment in options with long lead times and/or lifecycles
    - A coordinated economy-wide abatement program or set of programs. Because abatement options are highly fragmented and widely distributed across sectors and geographies, any approach that does not simultaneously unleash a full range of abatement options risks missing proposed 2030 reduction targets and/or driving up total cost to the economy
    - Exchange mechanisms (e.g., trading schemes, offsets, tax credits) to create fungibility across fragmented markets, create greater market transparency, and drive least-cost solutions
    - Verification, monitoring, management, and enforcement systems to ensure sustained abatement impact
    - Safeguards against "leakage" and transfer of GHG-emitting activities overseas.

2. **Pursue energy efficiency and negative-cost options quickly.** Many of the most economically attractive abatement options we analyzed are "time perishable": every year we delay producing energy-efficient commercial buildings, houses, motor vehicles, and so forth, the more negative-cost options we lose. The cost of building energy efficiency into an asset when it is created is typically a fraction of the cost of retrofitting it later, or retiring an asset before its useful life is over. In addition, an aggressive energy efficiency program would reduce demand for fossil fuels and the need for new power plants. These energy efficiency savings are not being captured today, however, suggesting that strong policy support and private sector innovation will be needed to address fundamental market barriers. Policy support might consist of standards, mandates and/or incentives to promote carbon-efficient buildings, appliances, and vehicles. Mechanisms to better align all stakeholders (e.g., end users, manufacturers, utilities, and supporting businesses) should also be considered.

3. **Accelerate development of a low-carbon energy infrastructure.** Transitioning to a lower-carbon economy will require significant changes in the country's energy infrastructure. To accelerate development of a lower-carbon energy infrastructure, the U.S. would need to:

   - **Encourage research and development of promising technologies and stimulate deployment.** Of the options we analyzed, some 25 percent (e.g., solar photovoltaics, plug-in hybrid electric vehicles, cellulosic biofuels, CCS) would require additional R&D investment and/or cost compression to achieve the learning rates and scale required to accelerate widespread adoption. This support might include gap-closing financial incentives (e.g., investment tax credits, feed-in tariffs, or direct subsidies) and/or industry or regulatory standards to help achieve scale economies as soon as possible.

   - **Streamline approval and permitting procedures.** Many energy infrastructure investments (e.g., nuclear power, transmission lines, and pipelines) have long lead times and can face substantial delays in getting necessary approvals. Permitting and approval delays can substantially increase the risk and cost to investors and, if not specifically addressed, may inhibit pursuit of these capital-intensive abatement options. Some emerging technologies, such as geologic storage of CO_2, currently have no defined approval and permitting process. Anticipating and addressing potential regulatory hurdles – e.g., siting, liability, and monitoring issues associated with permanently storing large amounts of CO_2 – and developing public and technical review processes to address those issues will be essential to avoid impeding the pursuit of these capital-intensive abatement options.

To address rising GHG emissions comprehensively, the nation would also need to consider abatement options outside the scope of this project. Additional reductions could be achieved by encouraging changes in consumer lifestyles and behaviors (e.g., driving habits, spending decisions) through measures such as price signals or education and awareness campaigns; they could also be achieved by pursuing abatement options with marginal costs greater than $50 per ton. Finally, we are confident that, in the years ahead, many new ideas and innovations not included in our analysis will emerge. These new technologies, products, processes, and methods could well offer additional abatement potential and lower overall costs.

* * *

This project evaluated the costs and potentials of more than 250 abatement options available in the U.S. We did not examine economy-wide effects associated with abating greenhouse gases, such as shifts in employment, impact on existing or new industries, or changes in the global competitiveness of U.S. businesses. The project did not attempt to assess the benefits to society from reducing global warming. The report also did not attempt to address other societal benefits from abatement efforts, such as improved public health from reducing atmospheric pollution or improving national energy security. Policymakers would undoubtedly want to weigh these factors – and possibly others – when developing comprehensive approaches for reducing GHG emissions in the U.S.

Creating comprehensive approaches will be challenging: they will need to combine durable policies and a slate of strong near-term actions that mobilize economic sectors and geographies across the U.S. The pursuit of GHG abatement, however, will undoubtedly stimulate new businesses and economic opportunities not covered by our cost-focused analysis.

Introduction

Over the past year, McKinsey & Company has led a study to understand the cost of various options for reducing greenhouse gas (GHG) emissions within the United States. The primary goal of the U.S. Greenhouse Gas Abatement Mapping Initiative (US GHG AMI) is to create a consistent, detailed fact base to support policy design and inform economically sensible strategies on the issue of climate change.

Using forecasts from U.S. government agencies and information provided by their staffs, the US GHG AMI research team built a harmonized "reference case" forecast for U.S. emissions from 2005 to 2030.[1] The reference case provides an integrated view of emissions and absorption of greenhouse gases across seven sectors of the economy: residential and commercial buildings (including appliances), power generation, transportation, industry, waste management, agriculture, and forestry.

Working with major U.S.-based companies, industry experts, leading academics, and environmental NGOs, the team then estimated potentials and resource costs[2] for more than 250 options to reduce or prevent GHG emissions, including efficiency gains, investments in low-carbon energy supply, and expanded carbon sinks. We did not assume major technology breakthroughs, focusing instead on abatement measures that are reasonably understood and likely to be commercially available in the future. Furthermore, we envisioned consumers of 2030 who do not differ materially in their preferences or behaviors from consumers today.

For each abatement opportunity we attempted to estimate its realistic potential for reducing emissions by 2030, given economic, technical, and regulatory constraints. We tightened or

1 The research team used the "reference" scenario in the U.S. Energy Information Administration's Annual Energy Outlook 2007 report as the foundation of its reference case for emissions through 2030, supplementing that with data from Environmental Protection Agency and Department of Agriculture sources: Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2005; Global Anthropogenic non-CO_2 Greenhouse Gas Emissions: 1990-2020; Global Mitigation of non-CO_2 Greenhouse Gases; and Forest Service RMRS-GTR-59 (2000). Our analyses excluded HCFCs, which are being retired under the Montreal Protocol.

2 The cost of an abatement option reflects its resource (or techno-engineering) costs – i.e., capital, operating, and maintenance costs – offset by any energy savings associated with abating 1 ton of CO_2e per year using this option, with the costs/savings levelized over the lifetime of the option using a 7-percent real discount rate. We excluded transaction costs, communication/information costs, taxes, tariffs, and/or subsidies. We also have not assumed a "price for carbon" (e.g., a carbon cap or tax) that might emerge as a result of legislation, nor any impact on the economy of such a carbon price. Hence, the per-ton abatement cost does not necessarily reflect the total cost of implementing that option.

loosened constraints to define low, medium and high levels of penetration. We then calculated resource costs for each option from the bottom up. The team conducted more than 100 interviews with industry experts and leading thinkers to test and refine the work, in addition to leveraging McKinsey's internal network of experts. The result is a highly granular analysis of the potential cost and effectiveness of a wide range of abatement options available in the U.S.

By arraying abatement options from lowest to highest cost, we then created internally consistent low-range, mid-range, and high-range cases that capture the interplay between costs and volumes, with costs expressed in real 2005 dollars. Each abatement curve is presented in an integrated fashion, eliminating any double-counting. The cases differ primarily in the assumed degree of will the nation might exert to develop and deploy abatement options.

The project did not attempt to address broad policy questions regarding what regulatory regime or government incentive structures might be considered in federal legislation. It should be expressly noted that McKinsey & Company in no way endorses any specific legislative proposals, nor any specific mechanism (e.g., cap and trade, carbon tax, or mandates) to foster abatement. The purpose of the US GHG AMI is solely to show the likely cost and potential emissions reduction associated with a wide range of abatement options.

Our analysis was constrained in several important respects. Specifically, we:

¶ Focused on emissions produced by human activity within the borders of the U.S., and did not attempt to analyze the impact of "imported" carbon

¶ Assumed no material changes in consumer utility or lifestyle preferences[3]

¶ Did not attempt to estimate the dynamic implications of price signals (e.g., elasticity of energy demand) from potential changes in energy commodities or emissions reduction policies, such as a possible carbon cap or tax

¶ Analyzed technologies with predictable cost and development paths. The team sorted technology-related options based on evidence of maturity, commercial potential, and presence of compelling forces at work in the marketplace to separate "credible" options from "speculative" ones:

- Most of the technology options we reviewed have been proven at commercial scale. They account for roughly 80 percent of the abatement potential identified. The uncertainty associated with them primarily relates to execution.

3 By "consumer utility" we mean functionality or usefulness for people, including level of comfort; in this context, holding consumer utility constant would imply, e.g., no change in thermostat settings or appliance use; no downsizing of vehicles, homes, or commercial space; traveling the same mileage annually relative to levels assumed in the government reference case. In a strict economic sense, maintaining constant consumer utility assumes a constant economic surplus for the consumer while delivering against a common benefit. We have not attempted to calculate potential changes in utility that might result from energy price changes associated with pursuing the options outlined in our abatement curve.

- We examined a number of high-potential emerging technologies (e.g., carbon capture and storage, cellulosic biofuels, plug-in hybrid vehicles and light-emitting diode lights), which comprise some 20 percent of the abatement potential. We found consensus among experts that these technologies would likely be commercially available by 2030.
- Beyond this, we were very conservative in our assessment of future technology. It is reasonable to assume that over the next 25 years important process and technology breakthroughs will occur that we have not imagined or tried to model in this report. It is highly likely that a concerted effort to abate emissions would stimulate innovation, leading to unexpected opportunities for further low-cost abatement.

¶ Our analysis furthermore did not attempt to estimate the:

- Broader social costs or benefits to the economy associated with climate change, such as the cost of relocating communities away from low-lying coastal areas or the benefits of avoiding adverse consequences of climate change
- Environmental and national energy security benefits associated with moving to a lower-carbon economy, such as lower levels of local and regional air pollution or reduced dependence on foreign oil
- Differential economic effects across sectors or geographies linked to specific implementation approaches
- Policy-dependent structural and transaction costs associated with pursuing specific abatement options beyond direct capital, operating, and maintenance costs; that is, we focused on what are referred to as "techno-engineering" or "resource" costs and did not attempt to estimate welfare cost or regulatory/compliance costs.

Throughout the report, we refer to costs on a "societal basis" and have analyzed the net resource costs of abatement by examining the incremental initial investments, operating and maintenance costs, replacement costs, and avoided costs associated with energy efficiency or other benefits. We applied a 7-percent discount rate to account for the time difference between initial investments and resulting savings. Our analysis shows that many abatement options could be achieved at negative or very low societal costs. The cumulative benefit from these options (if fully achieved) would substantially offset the increased societal cost of the remaining abatement options with marginal costs up to $50 per ton.

We note that though our research indicates the total cost of GHG abatement on a societal basis could be quite low, issues of timing and allocation of costs and benefits across the economy – especially during the transition to a lower-carbon economy – would likely result in very different perceptions regarding the cost of GHG abatement. Many costs will likely be incurred early, concentrated in a few economic sectors, and involve "real" outlays that will be offset by future "avoided" outlays.

Given the timing of investments relative to savings, and the likelihood that costs and benefits will be shared unequally among stakeholders, some economic sectors and periods will experience significant, visible costs. Investments in transportation efficiency, for example, will raise the cost of vehicles, which consumers will recognize immediately. As consumers and other end users shift to more fuel-efficient vehicles, the benefit of improved gas mileage may exceed the initial incremental cost of the abatement measures incorporated in the vehicles, though the original owner may not receive the full savings. Similarly, investments in low-carbon energy production would have high initial costs related to moving up the learning curve for that technology and building out the energy infrastructure. These investments could be large enough to drive up electricity base rates, though the investments would deliver greater benefits over time, as scale and technology effects drive down future investment costs and reduce fuel costs.

Certain sectors will likely benefit from abatement options while others will be negatively affected, as happens through the normal evolution of a dynamic economy. The possibility of such changes will almost certainly be a factor raised in the debate about GHG abatement. Our hope is that the fact base provided in this report will help policymakers, business leaders, academics and other interested parties make more fully informed decisions and define economically sensible approaches to address the nation's rising GHG emissions.

The report discusses the principal findings of the US GHG AMI's research and is organized in four chapters:

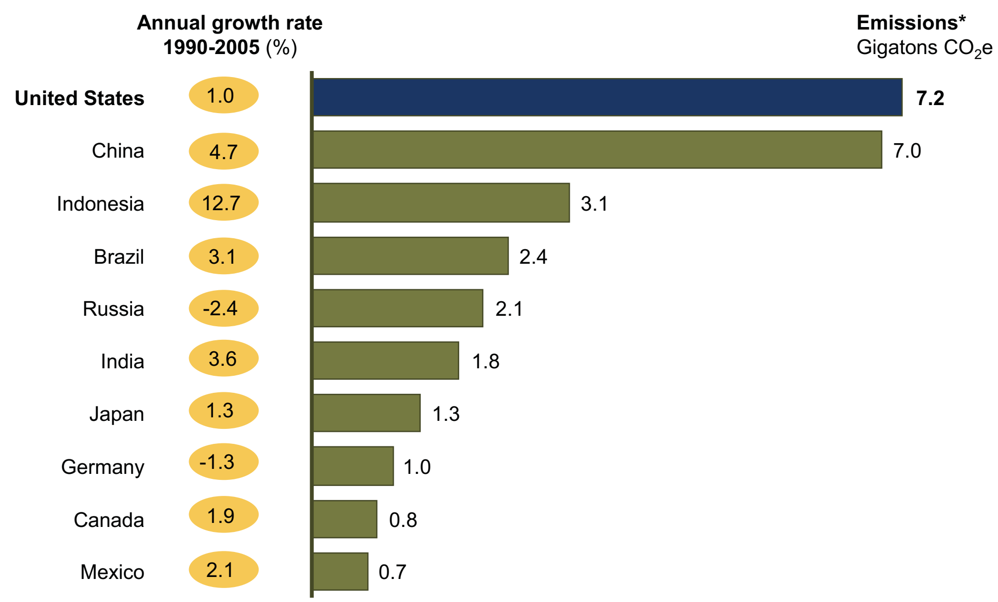
1. The challenge of rising emissions
2. The potential for reducing U.S. emissions
3. Five clusters of abatement potential
4. Project conclusions.

1 The challenge of rising emissions

The United States is home to 5 percent of the world's population and produces nearly 18 percent of global greenhouse gas emissions. As of 2005, the U.S. produced more emissions per year than any other nation, although based on projected growth rates China may now be the largest emitter (Exhibit 1). While the U.S. has the third-highest per-capita emissions rate, its GHG intensity is comparatively modest when measured against the nation's $13-trillion annual economic output (Exhibit 2).

Exhibit 1

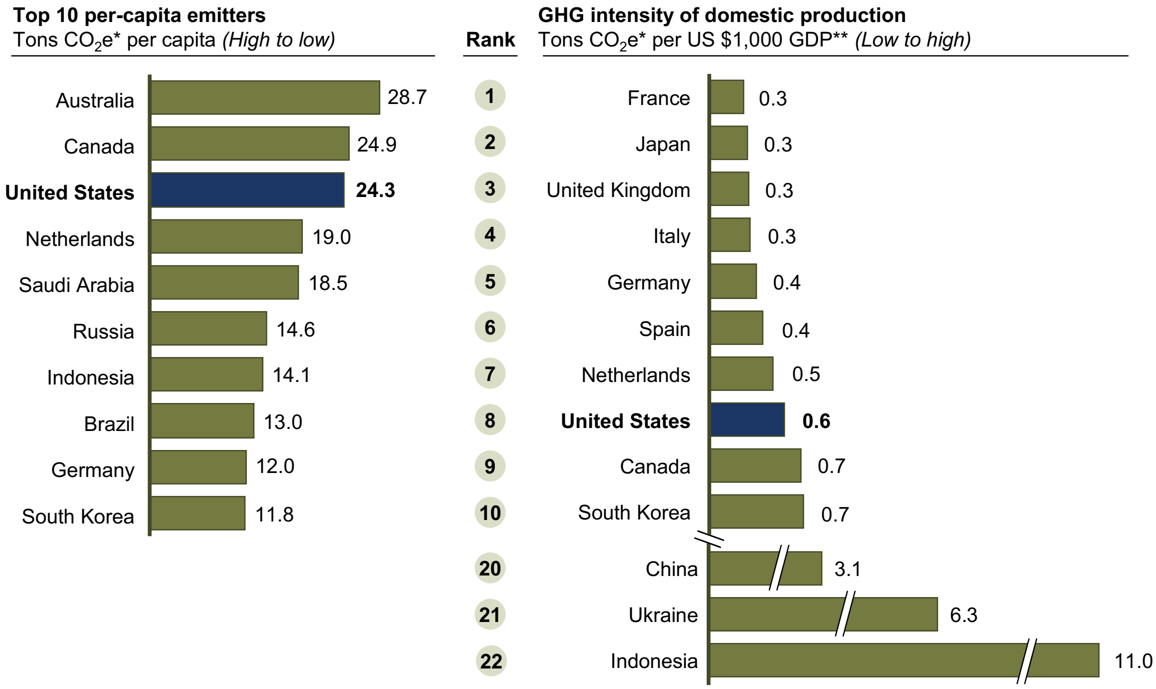
GHG EMISSIONS FOR SELECT COUNTRIES – 2005



* Includes emissions associated with deforestation and land-use changes
Source: IEA; EPA; WRI; UNFCCC; McKinsey analysis

Exhibit 2

GHG EMISSIONS BY POPULATION AND GDP – 2005



* Includes emissions associated with deforestation and land-use changes

** Includes only countries with annual greenhouse gas emissions greater than 250 megatons CO_2e

Source: UNFCCC; IEA; EPA; Global Insight; McKinsey analysis

As a physically large nation with a highly developed, service-based economy, the U.S. emits a greater proportion of GHGs from the buildings, transportation, and electric power sectors than do other great industrialized countries that are more compact and densely populated, like Germany and Japan. Because the U.S. is less dependent on agriculture and forestry for economic growth than many large developing countries, its forests and agricultural lands represent a net carbon sink. This contrasts starkly with countries like Brazil and Indonesia, where deforestation, burning of biomass, and conversion of land to agriculture constitute major contributors to GHG emissions (Exhibit 3).

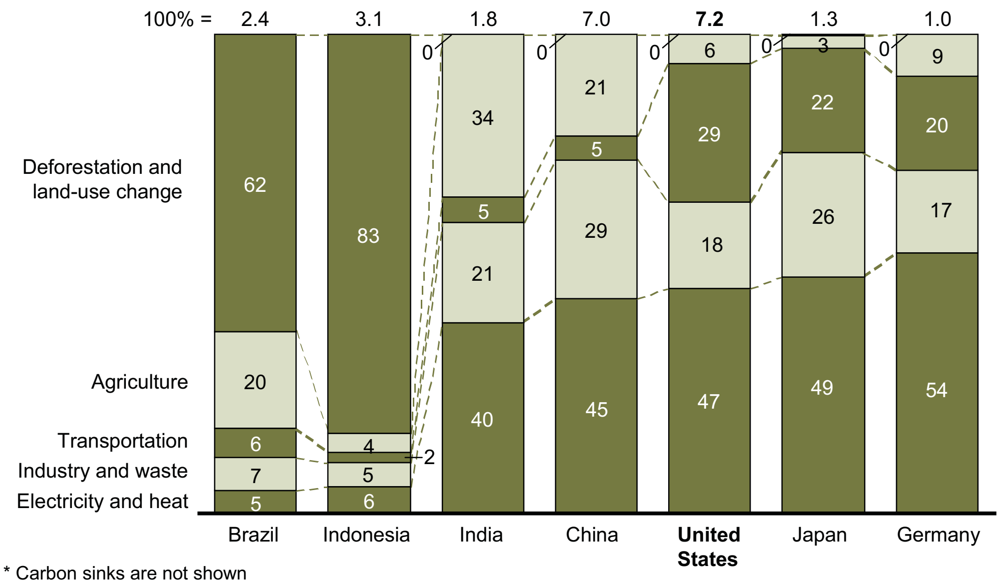
According to an analysis of U.S. government forecasts, the nation's GHG emissions are projected to rise by 2.5 gigatons, from 7.2 gigatons CO_2e per year in 2005 to 9.7 gigatons in 2030, at an average annual rate of 1.2 percent (Exhibit 4).[4] Though the annual rate of change may appear small, it would produce a 35 percent increase in projected annual emissions by 2030.

4 CO_2e, or "carbon dioxide equivalent," is a standardized measure of GHG emissions designed to account for the differing global warming potentials of GHGs. Emissions are measured in metric tons CO_2e per year, i.e., millions of tons (megatons) or billions of tons (gigatons). All emissions values in this report are per-year CO_2e amounts, unless specifically noted otherwise. To be consistent with U.S. government forecasts, the team used the 100-year global warming potentials listed in the Intergovernmental Panel on Climate Change's Second Assessment Report (1995).

Exhibit 3

GHG EMISSIONS PROFILES FOR SELECT COUNTRIES – 2005*

Percent, Gigatons CO_2e

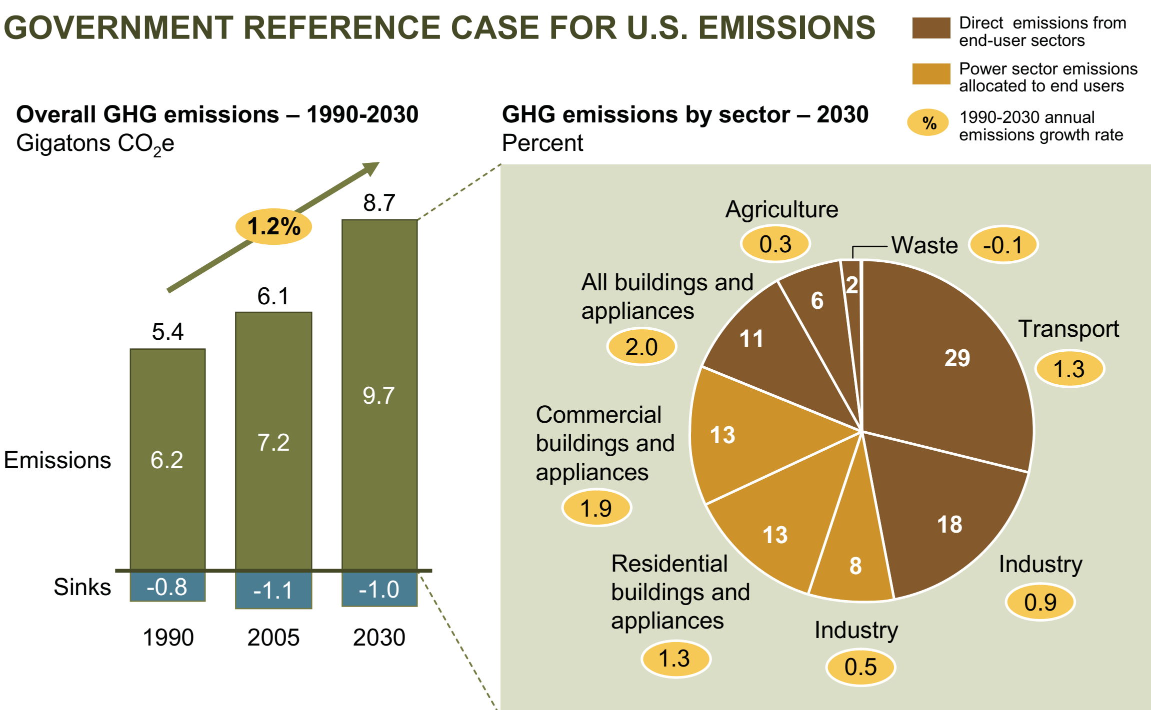


* Carbon sinks are not shown

Source: UNFCCC, WRI, IEA, EPA, McKinsey analysis

Exhibit 4

GOVERNMENT REFERENCE CASE FOR U.S. EMISSIONS

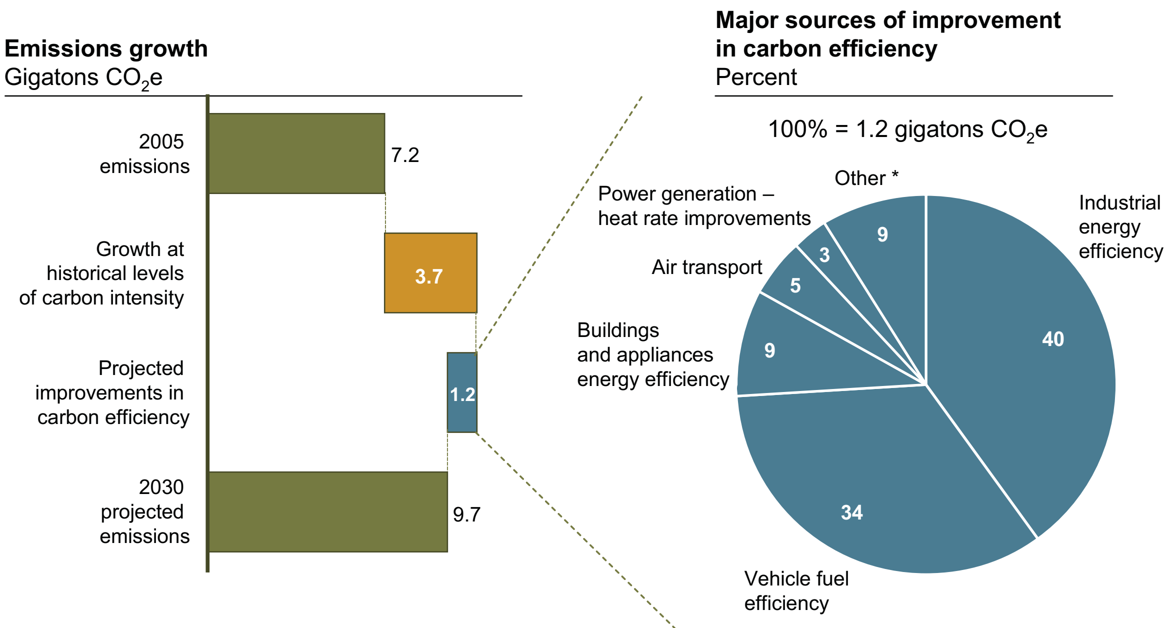


Source: U.S. EIA Annual Energy Outlook (2007) “Reference case”; U.S. EPA; USDA

Government forecasts that underlie the emissions reference case assume that gains in energy efficiency will reduce emissions by some 1.2 gigatons over this period (Exhibit 5).[5] These gains are expected to come from improvements in energy intensity in the industrial sector, increases in miles-per-gallon for air and automotive transportation, improved heat rates in electric power generation, and better building efficiency. Without this degree of improvement, emissions from the U.S. economy would climb by 3.7 gigatons by 2030.

Exhibit 5

CARBON REDUCTIONS EMBEDDED IN THE REFERENCE CASE



* "Other" includes other transport (7%), agriculture (1%) and waste (1%)
Source: U.S. EIA Annual Energy Outlook (2007) "Reference case," U.S. EPA; USDA; McKinsey analysis

This growth in emissions is accompanied by a projected decrease in the absorption of carbon. After rising for 50 years, carbon absorption by U.S. forests and agricultural lands is forecast to decline by 7 percent, from roughly 1.1 gigatons in 2005 to nearly 1.0 gigatons in 2030. This trend results from fewer net additions to forested lands within the U.S. and slower rates of carbon absorption in maturing forests.

These broad trends – a 35-percent increase in emissions and a 7-percent decrease in carbon sinks through 2030 – are sharply at odds with global reductions being suggested by climate scientists, including the Intergovernmental Panel on Climate Change. They are also

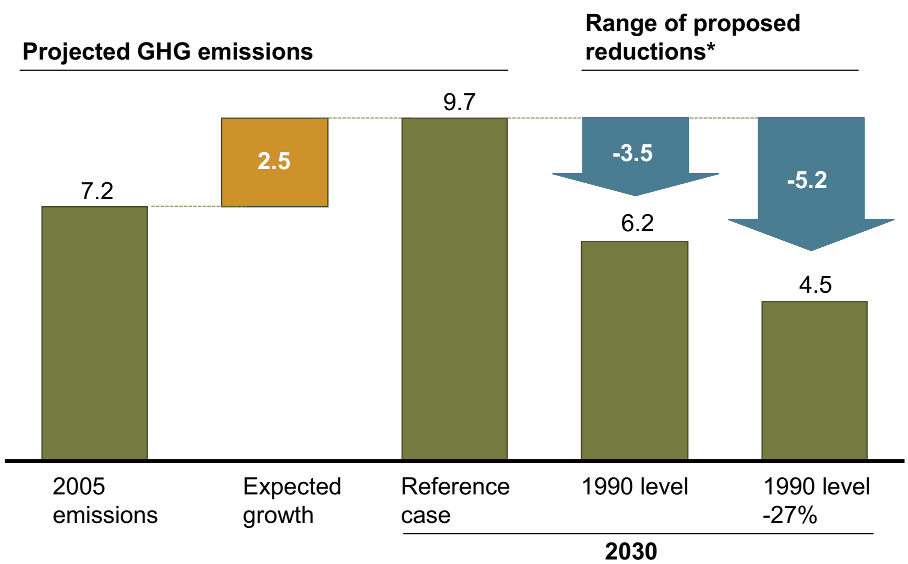
5 The Department of Energy "reference" scenario assumes that the price of imported low-sulfur light crude oil varies between $50 and $69 per barrel from 2005 to 2030 and is $59 in 2030, and that natural gas moves between $5.46 and $8.60 per million Btu at Henry Hub, stabilizing at $6.52 in 2030.

dramatically out of line with the emissions reductions being called for in proposed federal legislation. A sampling of bills that address climate change on an economy-wide basis call for U.S. annual GHG emissions to be 3.5 to 5.2 gigatons lower in 2030 than projected in the government reference case (Exhibit 6).

Exhibit 6

THE CHALLENGE OF RISING U.S. EMISSIONS

Gigatons CO_2e



* Based on bills introduced in Congress that address climate change and/or GHG emissions on an economy-wide basis and have quantifiable targets

Source: U.S. EIA Annual Energy Outlook (2007) “Reference case," U.S. EPA; Pew Center On Global Climate Change; McKinsey analysis

The emissions reference case is not static, of course, and much has happened related to carbon awareness since the release of these government data. However, the projections do provide a view of the trajectory of U.S. emissions absent any meaningful carbon-related policy or intervention. The main drivers of projected U.S. emissions growth are:

- Strong impact from continued population and GDP growth
- Rapid growth in the buildings-and-appliances and transportation sectors
- Increased use of carbon-based power in the U.S. generation portfolio.

STRONG IMPACT FROM CONTINUED POPULATION AND GDP GROWTH

According to government projections, U.S. greenhouse gas emissions are highly sensitive to overall economic output: each percentage point above or below the 2.9-percent average GDP growth rate used in government forecasts increases or decreases expected U.S. emissions in 2030 by approximately 1.5 gigatons. For example, if the economy grew through 2030 at the pace it did in 2006 – 3.3 percent – U.S. emissions would reach 10.3 gigatons in 2030, instead of the 9.7 gigatons projected in the emissions reference case.

RAPID GROWTH IN THE BUILDINGS-AND-APPLIANCES AND TRANSPORTATION SECTORS

Population growth and rising personal consumption will increase demand for energy. The U.S. population is expected to grow by 20 percent by 2030, rising from approximately 300 million in 2005 to 365 million. The faster the U.S. moves toward a services-oriented, consumer-driven economy featuring larger houses, more electrical devices, and more miles traveled, the more its energy consumption and emissions will rise. Above-average growth in commercial and residential building stock – and the electrical devices used in those buildings – are major drivers of increased electricity demand. At the same time, increases in vehicle miles traveled and the number of vehicles on the road would boost transportation emissions.

Growth in buildings and appliances

Emissions associated with buildings and appliances are projected to grow faster than those from any other sector. The combination of low efficiency and fast growth make buildings and appliances together a major contributor to expected increases in U.S. emissions: direct emissions from on-site combustion of natural gas, petroleum, and biomass for heating, cooling, and power generation are projected to expand from 9 percent in 2005 to 11 percent of emissions by 2030. When we add emissions associated with the electricity consumed by commercial and residential buildings, the sector's share becomes much larger. Taking direct and indirect emissions together, the buildings sector would see its share of U.S. annual emissions rise from 33 percent in 2005 to 37 percent in 2030.[6]

Emissions from commercial buildings and their equipment and appliances are expected to grow 1.8 percent annually, with those from residential buildings and appliances growing 1.5 percent:

¶ **Commercial buildings.** A large increase in commercial space and greater reliance on electricity would lead to nearly 600 megatons of additional emissions in 2030. Commercial building stock is forecast to increase by 48 percent by 2030 (rising from 73 billion to 108 billion square feet). Over the same period, the energy supply used for heating, cooling, water heating, lights and electrical devices will shift from 51 percent electricity in 2005 to 57 percent in 2030.

6 In calculating emissions for individual sectors, the team estimated electricity consumption in those sectors and allocated the associated emissions back to those sectors. Additional information about the methodology is located in the Appendix.

¶ **Residential buildings.** Between 2005 and 2030, the U.S. would see a net increase of 34 million new homes, with the average size of all homes rising by 14 percent to approximately 2,000 square feet. This would be the equivalent of adding a room 16 feet long by 15 feet wide to every household. Despite the increase in numbers and size, the carbon intensity of U.S. residential buildings will remain flat through 2030, at nearly 11 tons per household per year. While the reference case assumes a 17-percent reduction in energy needed for heating-ventilation-air conditioning (HVAC) systems, lighting, and appliances over this period, those efficiency gains are expected to be offset by an increase in demand for energy associated with heating and cooling additional space, plus more appliances and electronic equipment in every home, and greater use of those devices.

Increases in transportation

Projected improvements in vehicle efficiency and lower-carbon fuels would be more than offset by growth in vehicle miles traveled, which is a function of the number of vehicles on the road and the average miles per vehicle. As a result, the transportation sector, the nation's second-largest direct emitter of GHGs, would see its emissions grow 1.3 percent per year, rising from 2.1 gigatons in 2005 to 2.8 gigatons by 2030. This growth would come primarily from the addition of 96 million light-duty vehicles (such as passenger cars and light trucks) to the nation's fleet and an 11-percent increase in miles traveled by each vehicle annually.

The government emissions reference case assumes relatively small improvements in vehicle fuel efficiency. By 2030, cars are projected to average 33 miles per gallon versus 28 today, and the penetration of hybrid electric vehicles would reach 5 percent of new vehicle sales.

The use of alternative fuels and improvements in fuel efficiency would moderate, but not substantially offset, growth in demand. The projected rate of adoption of biofuels would result in an estimated penetration of 8 percent (nearly 15 billion gallons) by volume of the fuel supply for light-duty vehicles by 2030. Of this amount, starch-based ethanol – primarily from corn, as forecast in the government reference case – would provide some 10.8 billion gallons. While cellulosic biofuels are expected to be commercially available by 2020 in the emissions reference case, less than 4 billion gallons would penetrate the automotive fuel supply by 2030. Diesel penetration is projected to remain similarly limited, at 4 percent of the light-duty vehicle fuel supply. These trends would result in a slight reduction in the carbon intensity of the transportation fuel supply by 2030.

INCREASED USE OF CARBON-BASED POWER IN THE GENERATION PORTFOLIO

The Department of Energy's reference case forecast assumes that future growth in electricity demand will be met primarily by the construction of new coal-fired generation capacity. This would lead to a modest increase in the carbon intensity of the U.S. electricity supply by 2030.

Demand for electricity is expected to grow from roughly 3,865 terawatt-hours in 2005 to 5,385 terawatt-hours in 2030. Coal-fired generation is projected to remain the cheapest form of electricity in most regions, making up 81 percent of the incremental load for electric power through 2030. As a result, the nation would have built plants producing an additional 145 gigawatts of coal-fired power (pulverized coal and integrated gasification combined cycle [IGCC] units) by 2030.

The reference case also assumes that no carbon capture and storage (CCS) technology will be installed by then. Operational improvements (e.g., better heat rate) coupled with construction of some nuclear power and renewables capacity (13 gigawatts and 17 gigawatts, respectively, by 2030) would temper emissions growth, but not enough to reduce carbon intensity of the power supply.

As a result, power sector emissions are expected to grow by 1.4 percent annually, reaching 3.4 gigatons in 2030, up from 2.4 gigatons in 2005. Over this period, the carbon intensity of the generation fleet would rise less than 2 percent, from 0.61 tons CO_2e per megawatt-hour to 0.62 tons.

* * *

If the U.S. energy infrastructure were to evolve through 2030 in line with the Department of Energy projections – which, importantly, do not assume any carbon price or policy – the nation would have built numerous coal-fired power plants without carbon capture technology (and with lives up to 75 years), developed relatively low levels of renewable energy and nuclear power, increased vehicular emissions, and constructed many more inefficient commercial and residential buildings and appliances (Exhibit 7). If this were to occur, the U.S. would then likely need even greater levels of intervention, expenditure, and innovation to meet the escalated greenhouse gas reductions likely to be called for in the period from 2030 to 2050.

Exhibit 7

DRIVERS OF ENERGY USE AND EMISSIONS GROWTH

EMISSIONS
REFERENCE CASE

POWER SECTOR

Gigawatts	2005	2030	*Change*
Coal-fired capacity*	306	446	*140*
Nuclear power	100	113	*13*
Renewables **	32	49	*17*

BUILDINGS AND APPLIANCES SECTOR

	2005	2030	*Change*
Residential units Millions	113	147	*34*
Buildings floor space Billion square feet	275	404	*129*
Household energy intensity Million BTUs per year	108	90	*-18*

TRANSPORTATION SECTOR

	2005	2030	*Change*
Light-duty vehicles Millions	220	316	*96*
Efficiency of light duty vehicles Miles per gallon	25	29	*4*
Light trucks among new light-duty vehicles Percent of sales	50	57	*7*

INDUSTRIAL SECTOR

	2005	2030	*Change*
Refining energy intensity 1,000 BTUs/$ shipped	16.7	21.3	*4.6*
Chemicals energy intensity 1,000 BTUs/$ shipped	33.1	30.5	*-2.6*
Liquid fuel from coal Billion gallons	0	6.8	*6.8*

* Includes incremental 2005-2030 capacity build-up of 145 GW and 5 GW of retirements; excludes coal-fired CHP (5 GW in 2005; 4 GW in 2030)

** Excludes large hydroelectric; includes end-use generators

Source: U.S. EIA Annual Energy Outlook (2007) "Reference case"

2 The potential for reducing emissions

The research team analyzed costs and potentials of more than 250 abatement options across the economy. We focused on existing or high-potential emerging technologies and maintained relatively constant consumer utility. Taxes and subsidies were stripped out of cost estimates to avoid their distorting effects, and we have not included policy-dependent structural and transaction costs, building our analysis instead on direct capital, operating and maintenance costs.

We analyzed each abatement opportunity in four steps:

1. Established current penetration, costs, and underlying cost drivers
2. Evaluated the potential for cost reductions, in light of possible constraints, such as production capacity, supply chain inputs, permitting requirements
3. Estimated the potential for technology improvement, triangulating with a number of methods, including learning curves, industry and academic experts and technology analogues
4. Calibrated the range of penetration from low to high based on potential cost reductions and technology advances by evaluating the critical paths for technologies and consulting with subject-matter experts.

Our work through these four steps was informed by expert judgment, provided by more than 100 experts and institutions that we engaged to complement the insights provided by McKinsey and its research partners.

The team established filtering criteria to identify the most promising and feasible abatement options. To ground the analysis in analyzable facts, we eliminated options judged to be "speculative" or in experimental stages. We screened for economic feasibility, dismissing options with marginal costs greater than $50 per ton in 2030.[7] We then built three illustrative

7 The team set an analytical boundary at $50 per ton in marginal cost after considering consumer affordability and the estimated long-term cost for adding carbon capture and storage to an existing coal-fired power plant, a solution that, if successfully deployed, would likely set an important benchmark for emission-control costs. Abatement costs are expressed in 2005 real dollars. The team examined a number of options with marginal costs between $50 and $100 per ton, but did not attempt a comprehensive survey of options in this range. For simplicity of expression in this report, we refer to the threshold with the phrase "below $50 per ton."

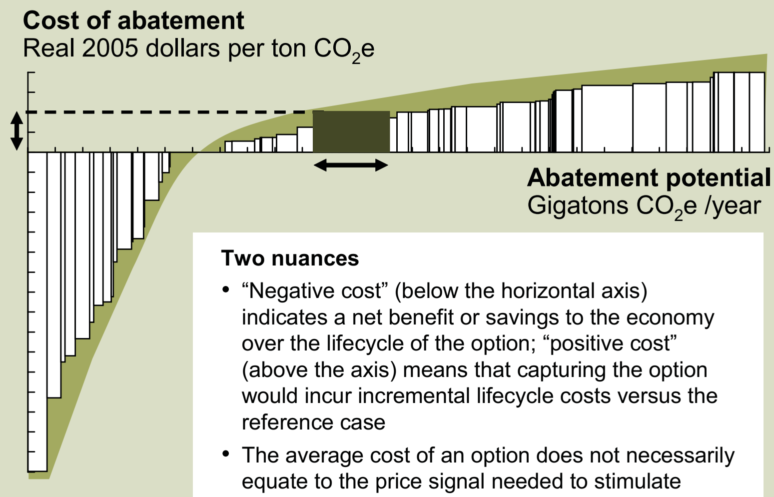
abatement supply curves (low-range, mid-range, high-range), harmonizing the abatement options against a common set of assumptions and eliminating double-counting. The appendix on methodology contains additional discussion of our analytical approach.

How to read an abatement curve

Two dimensions

Each bar represents one option or a group of closely related options (e.g., "improvements to residential buildings")

- Width: amount of CO_2e that can be reduced annually by means of this option
- Height: average cost of avoiding 1 ton CO_2e with this option, as measured against emissions reference case. Cost is averaged across sub-options, regions, and years



Two nuances

- "Negative cost" (below the horizontal axis) indicates a net benefit or savings to the economy over the lifecycle of the option; "positive cost" (above the axis) means that capturing the option would incur incremental lifecycle costs versus the reference case
- The average cost of an option does not necessarily equate to the price signal needed to stimulate capture of that option

This chapter is organized in six sections, covering the major findings of our analysis:

1 Wide range of potential abatement outcomes for 2030

2 Distributed array of abatement opportunities

3 Many economically beneficial opportunities

4 Variation in regional abatement profiles

5 Substantial impact of sequencing and interaction effects

6 Significant changes in infrastructure, investment, and commodity profiles.

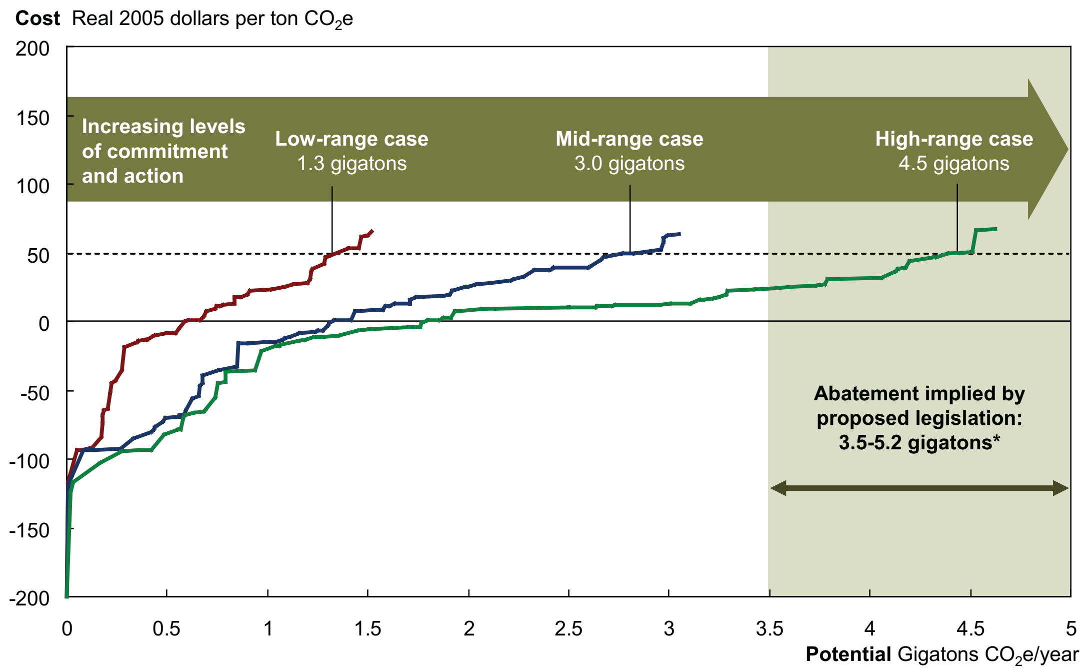
1 WIDE RANGE OF POTENTIAL ABATEMENT OUTCOMES FOR 2030

The illustrative cases define an abatement envelope for the U.S. in 2030 that ranges from 1.3 gigatons in the low-range case to 4.5 gigatons in the high-range case, at marginal costs below $50 per ton (Exhibit 8). The mid-range case identified 3.0 gigatons of GHG-reduction potential.

Only the high-range case approaches the GHG reduction targets of 3.5 to 5.2 gigatons in proposed federal legislation. For this reason, we focus the remainder of our abatement analysis on the upper part of the envelope, from 3.0 gigatons (mid-range) to 4.5 gigatons (high-range).[8]

Exhibit 8

U.S. GREENHOUSE GAS ABATEMENT POTENTIALS – 2030



* Based on bills introduced in Congress that address climate change and/or GHG emissions on an economy-wide basis and have quantifiable targets; targets calculated off the 2030 U.S. GHG emissions of 9.7 gigatons CO_2e/year (reference case)

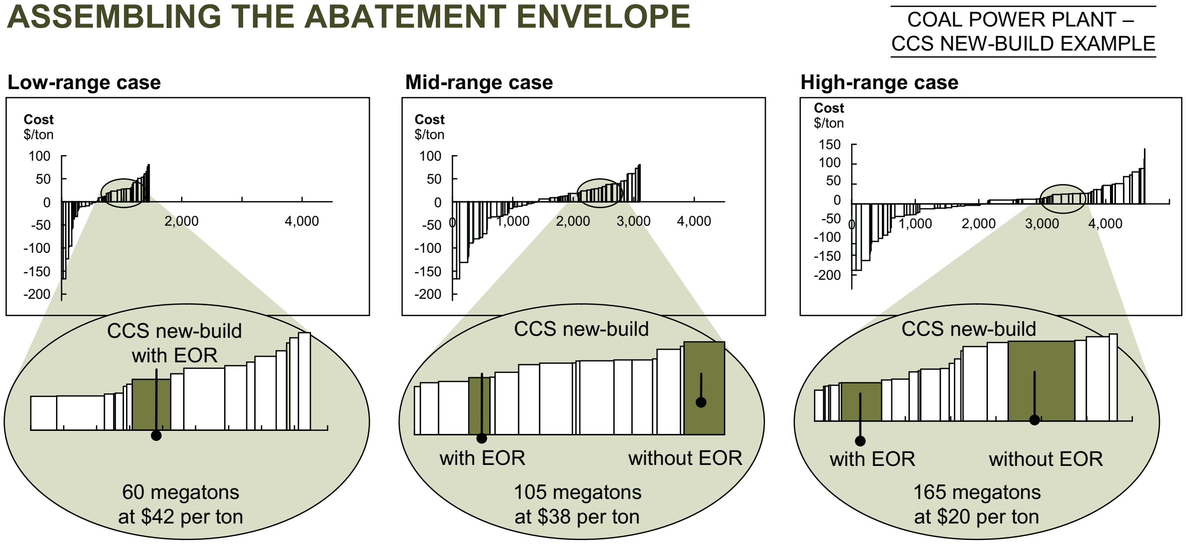
Source: McKinsey analysis

These abatement potentials reflect the combined impact of economic, technology and policy assumptions. Moving from the reference case to the low-range case or from the mid-range to high-range cases is like turning a dial to a higher setting; it increases the intensity of presumed commitment, which leads to greater penetration for each abatement option. Increases in intensity do not translate into uniform increases in potential, however, given the varied nature of the underlying characteristics and constraints of each option. Some options, such as energy efficiency in appliances, would require a relatively low level of action (e.g., tightening national standards) to achieve nearly full potential. Other options, such as CCS, would require much greater levels of commitment (e.g., proving commercial-scale application, building skills and infrastructure, addressing liability issues) and offer increasing abatement potential across the low-range, mid-range, and high-range cases (Exhibit 9).

8 The sentiment of the country has changed considerably since the government reference case was published 10 months ago; even so, achieving even the low-range level of abatement would require strong, targeted actions by policymakers, businesses, and consumers and would represent a departure from current practices.

Exhibit 9

ASSEMBLING THE ABATEMENT ENVELOPE



- Available at scale by 2025
- Capital cost – $3,100 / kW *
- Modest learning and performance improvement
- Per-ton cost below $50 only if coupled with EOR

- Available at scale by 2020
- Capital cost – $2,800 / kW *
- Steady learning and performance improvement
- Moderate injection costs

- Available at scale by 2015
- Capital cost – $2,600 / kW *
- Accelerated learning and performance improvement
- Low injection costs

Increasing levels of commitment and action

* 2005 real dollars; average cost for a new CCS-equipped coal-fired power plant, excluding the financing costs

Source: McKinsey analysis

Major differences that characterize our abatement curves are described in the following paragraphs on each case.

¶ **Low-range case.** The low-range case is chiefly characterized by a variety of incremental efforts to capture a portion of energy efficiency potential, including residential and commercial lighting improvements and combined heat and power (CHP) applications, increased penetration of wind at the most attractive sites, integration of land-use practices into carbon policy, including forestry management and conservation tillage, and early piloting of CCS.

¶ **Mid-range case.** This case demands a concerted national effort to capture full energy efficiency potentials and support the development and deployment of low-carbon technologies. The abatement efforts would involve all sectors and geographies, and would include improving building efficiencies, substantially enhancing fuel economy in light-duty vehicles; developing low-carbon energy supplies (e.g., solar photovoltaics, biofuels, nuclear, CCS); and pursuing early retirement inefficient power generation facilities.

¶ **High-range case.** Here the approach would involve aggressive, simultaneous, successful actions across all sectors and geographies fueled by a sense of great urgency. The high-range case assumes significant streamlining of nuclear power permitting and construction processes; aggressive development of renewables (particularly solar), biofuels and afforestation potentials; additional improvement of fuel economies within vehicle fleets; and expanded CCS new builds and retrofits for existing coal-fired plants.

It should be noted that *the cases and their curves illustrate abatement potential (i.e., what could happen if the appropriate support and incentives are provided), and represent illustrative groupings of possible outcomes rather than optimized scenarios.* The high-range case suggests an extremely ambitious effort across all sectors of the economy and parts of the country. Increasing the nuclear generation fleet by 50 percent net of retirements, building 80 gigawatts of CCS-equipped generation capacity, and expanding biofuels to 67 billion gallons (reaching 30 percent of the forecast gasoline pool) could each be considered challenging goals. Achieving an entire set of such ambitious goals is thus unlikely without widespread and sustained national commitment. Nonetheless, individual opportunities could realistically be pursued to the edge of the high-range case within a broader portfolio of abatement options (Exhibit 10).

Exhibit 10

DRIVERS OF GHG ABATEMENT POTENTIAL – 2030

x = Abatement potential below $50/ton, gigatons

	2005	Low-range case	Mid-range case	High-range case
Coal with CCS Gigawatts	• Rebuilds – 0 • New builds – 0	9 13	32 23	50 33
Nuclear Gigawatts	• Nuclear - 100	113	129	153
Renewables Gigawatts	• Wind – 10 • Solar CSP } <1 • Solar PV } <1	70 10 28	116 30 50	164 80 148
Biofuels Billion gallons	• Starch - 4 • Cellulosic - 0	12 5	16 14	16 51
Light-duty vehicles	• Cars* – 28 mpg • Light trucks* – 22 mpg • Alternatives** – 3%	34 mpg 27 mpg 14%	47 mpg 34 mpg 60%	53 mpg 38 mpg 71%
Buildings energy efficiency* **	• Efficient lighting: 8% • Efficient homes: N/A	15% 25 million	70% 37 million	75% 49 million
		1.3	3.0	4.5

* Average for new vehicle sales; average across gasoline internal combustion, diesel, hybrid electric and plug-in hybrid electric vehicles; includes opportunities above $50 per ton

** Alternatives to conventional gasoline propulsion: diesel, hybrid electric and plug-in electric hybrid vehicles; share of new sales

*** Lighting: CFLs and LEDs, share of new residential sales. Homes: incremental total built (or rebuilt) to Energy Star efficiency or highe

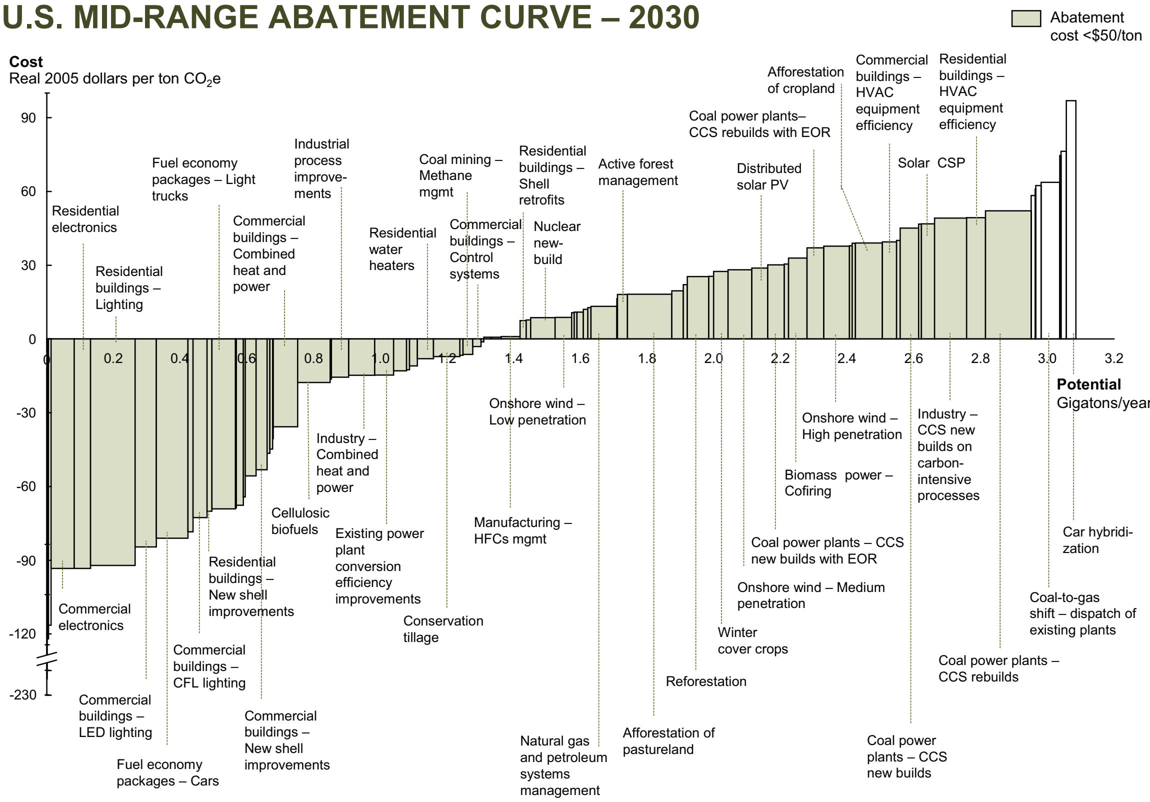
Source: US EIA; McKinsey analysis

2. DISTRIBUTED ARRAY OF ABATEMENT OPPORTUNITIES

Abatement opportunities are widely dispersed across economic sectors. The largest opportunity in our category breakdown accounts for less than 10 percent of total abatement potential in our mid-range case (Exhibit 11) and 11 percent in the high-range case. By sequencing each abatement option from lowest to highest cost, we can construct a curve for any given case to illustrate the magnitude of abatement potential at increasingly higher levels of marginal cost.

Exhibit 11

U.S. MID-RANGE ABATEMENT CURVE – 2030



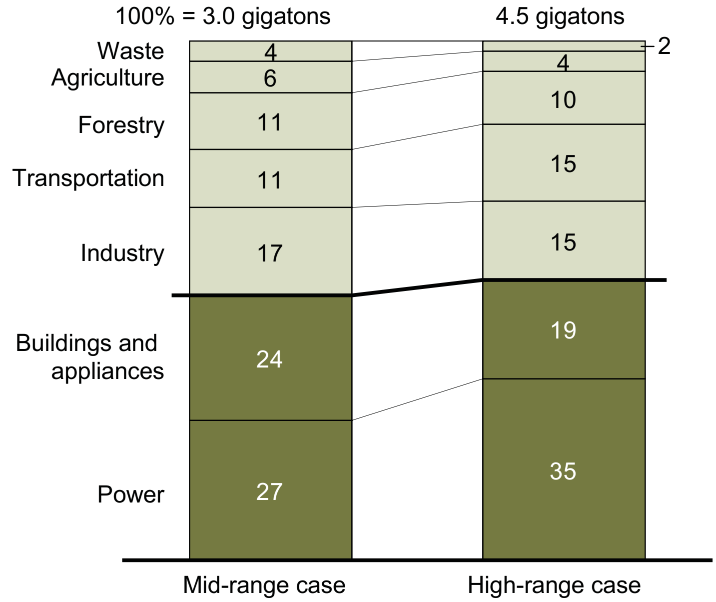
Source: McKinsey analysis

Grouping abatement options by sector reveals that the buildings-and-appliances and power sectors together contain slightly more than 51 percent of the abatement potential in the mid-range case (54 percent in the high-range case) for 2030 (Exhibit 12). Capturing the potential in these two interdependent sectors at the same time would be complicated by misaligned incentives that pervade the utility system today. These misaligned incentives often place power producers' sustained earnings growth at odds with resource efficiency. A related obstacle is public perception: utility-led energy efficiency programs can help reduce total bills (by decreasing consumption) but often result in unpopular rate increases needed to cover program costs and spread remaining fixed costs.

Exhibit 12

ABATEMENT POTENTIAL BY SECTOR – 2030

Opportunities less than $50/ton CO_2e



Source: McKinsey analysis

Pursuing the remaining 49 percent of the abatement identified in the mid-range case (46 percent in the high-range case) would involve the industrial, transportation, forestry, agricultural, and waste sectors. This level of dispersion poses one of the greatest challenges to managing GHG emissions: reduction opportunities are distributed widely across our economy and depend upon a broad range of producer and consumer choices. Because many sectors offer sizeable potentials, a comprehensive and integrated approach will be important in achieving a least-cost solution.

3. MANY ECONOMICALLY BENEFICIAL OPPORTUNITIES

The curves show a high variation in cost and abatement potential across options. Forty to forty-five percent of the potential below $50 per ton – 1.3 gigatons in the mid-range case and 2.0 gigatons in the high-range case – has zero or negative marginal costs. Investments in these abatement options are therefore economically profitable over their lifecycle and would lead to improved energy productivity. The remaining 1.7 gigatons in the mid-range case and 2.5 gigatons in the high-range case are positive cost, suggesting that additional incentives may be needed to stimulate businesses and consumers to pursue them.

Broadly speaking, the negative-cost options relate to a range of consumer decisions. These options have positive returns and, therefore, economic appeal. Significant barriers to market efficiency prevent them, however, from being fully captured today. Agency issues complicate alignment of businesses and consumers toward desirable abatement outcomes; the builder of a condominium, for example, is usually not responsible for paying the energy bill. Although these abatement options are economic over the lifecycle of the investment, consumers typically are not willing to make the up-front investment unless they can expect to be paid back within 2 or 3 years. Inadequate information frequently limits the ability of individuals to choose products based on energy efficiency and GHG impact, as is the case with the high energy consumption of torchiere lights. There are other barriers as well, such as perceived quality or availability at the time of purchase. Put simply, the potential for energy efficiency is real and large, but without a change in policy or approach, this potential will remain out of reach.

Assuming the barriers can be overcome and all abatement options with marginal costs below $50 per ton can be implemented – capturing the entire 3.0 gigatons in the mid-range case and 4.5 gigatons in the high-range case – the sum of the abatement options with negative marginal costs would roughly offset the sum of those with positive marginal costs. Our analysis does not, however, account for the cost of implementing, verifying and monitoring abatement initiatives. In addition, the separation of agents, the steepness of the curve (and the resulting spread between average and marginal costs), and the degree of fragmentation among opportunities within and across sectors suggests that significant economic transfers might be required to capture the full set of abatement options.

4. VARIATION IN REGIONAL ABATEMENT PROFILES

Each major geographic region has substantial abatement potential, although the cost and potential of individual options may vary by up to $50 per ton when pursued in different locations. Disparities reflect regional differences in population growth and/or density, carbon intensity of local power generation portfolios, energy productivity, climate, availability of renewable energy sources, forest cover, agricultural orientation, concentration of industrial activity, and other factors.

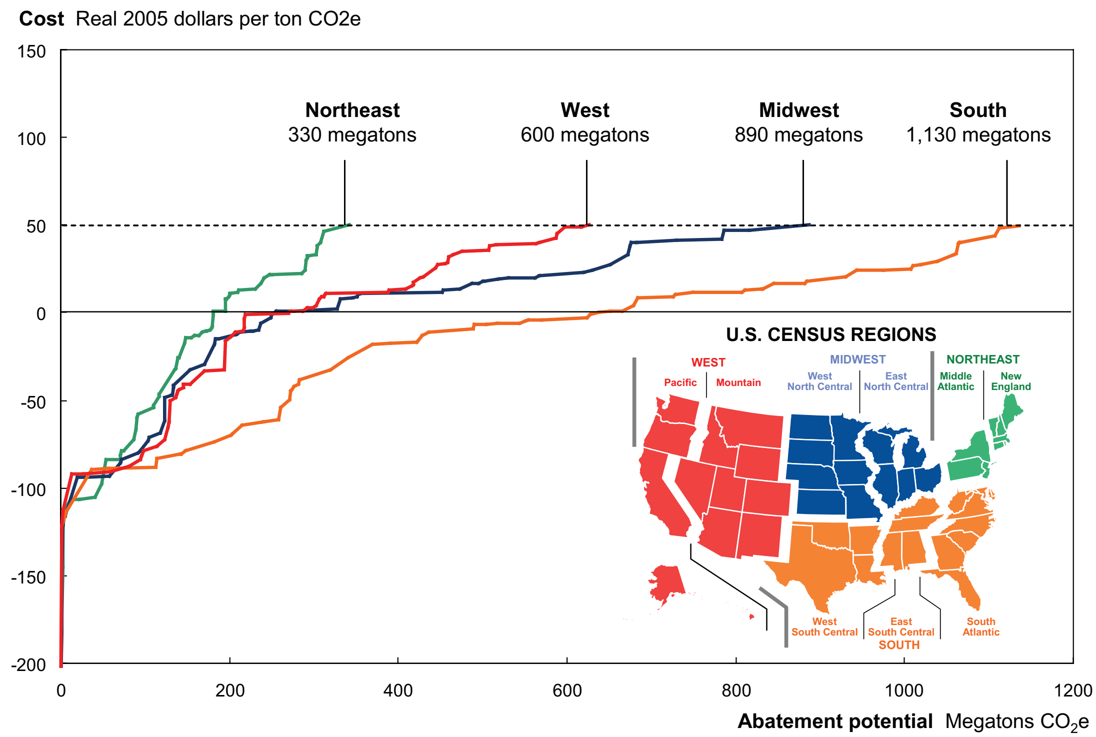
The regional curves show dramatic differences in the supply of abatement potential by geography (Exhibit 13). This variability ranges from roughly 330 megatons in the Northeast to 1,130 megatons in the South. These potentials are roughly proportional to total GHG emissions from the regions, though there are significant variations relative to GDP and population (Exhibit 14).

Not surprisingly, the underlying portfolios of low-cost abatement options differ substantially by region (Exhibit 15). Advantaged renewable sites in the West – particularly for solar – provide meaningful alternatives to fossil-based new-build power plants. Dense populations in the Northeast offer a disproportionate number of abatement opportunities in the buildings-and-appliances and transportation sectors. Availability of low-cost land in the Midwest opens up agricultural and forestry abatement potentials, while robust growth in the South provides significant opportunities in new-build construction.

Exhibit 13

GEOGRAPHIC DIFFERENCES IN ABATEMENT COST

MID-RANGE CASE – 2030



Source: McKinsey analysis

Any nationally oriented approach to managing GHG emissions will need to respect these industry sector and regional differences, if it is to efficiently stimulate emissions reductions and provide a least-cost abatement outcome.

5. SUBSTANTIAL IMPACT OF SEQUENCING AND INTERACTION EFFECTS

An abatement curve provides a static view of abatement outcomes. Abatement costs and potentials, however, are highly sensitive to a range of input assumptions, including sequencing, commodity prices, learning rates, and the time needed to capture the potential. We have drawn the following observations from the analysis:

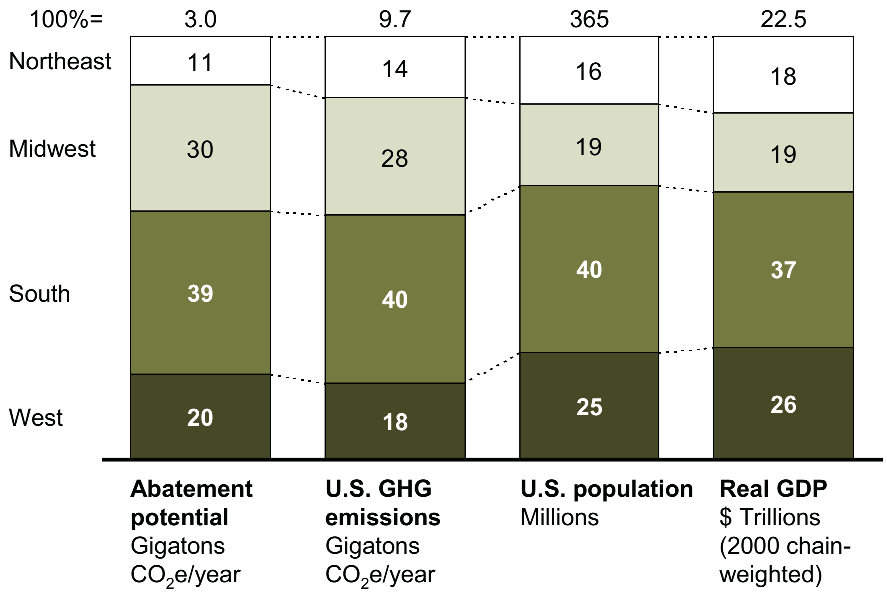
¶ **Sequencing of options affects potential.** Many technologies have competing or multiplicative (rather than additive) impact. The most compelling economics typically reside with the first abatement option in the analytical sequence. Pursuing energy efficiency in electric power, for example, has the potential to reduce the number of new coal-fired power plants needed (as projected by the Department of Energy) through 2030. Renewable energy sources that come after energy efficiency gains

Exhibit 14

GEOGRAPHIC DIFFERENCES IN ABATEMENT POTENTIAL, EMISSIONS, POPULATION AND GDP – 2030

MID-RANGE CASE – 2030

Percent



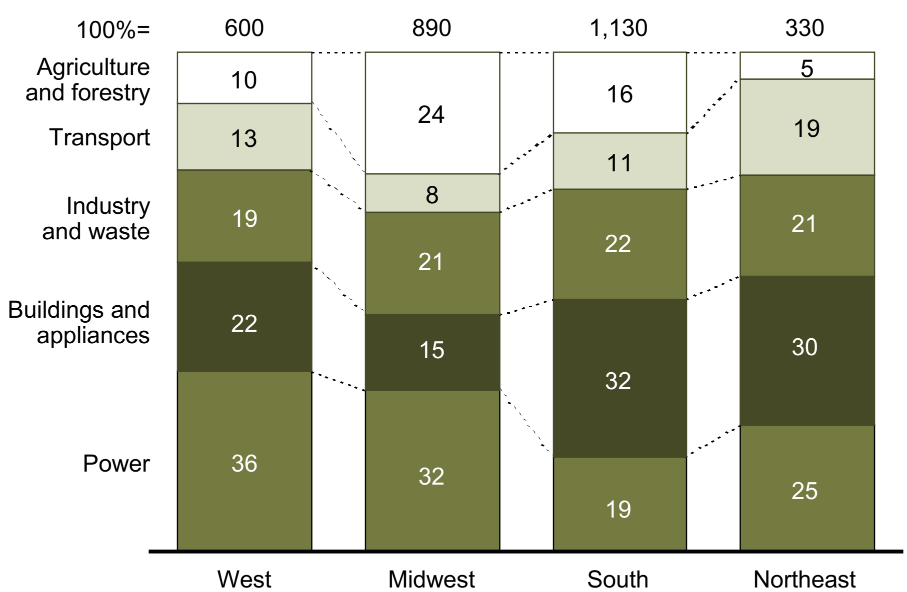
Source: U.S. EIA Annual Energy Outlook (2007) "Reference case," U.S. EPA; USDA; McKinsey analysis

Exhibit 15

GEOGRAPHIC DIFFERENCES IN ABATEMENT POTENTIAL BY SECTOR

Percent, Megatons CO_2e/year

MID-RANGE CASE – 2030



Source: McKinsey analysis

could enjoy the same comparative benefits – up to the point where the projected new-build plants are completely eliminated. From that point, the relative costs of additional GHG abatement must be compared to the shut-down economics for existing power plants. Changing this base of reference can add $5 to $20 per ton to the cost of an abatement option, depending on the region and the option. Similar sequencing effects occur throughout the power and transportation sectors in particular. Understanding how the carbon intensity of the regional electrical power grid and the transportation fuel supply will evolve is critically important in the estimation of the relative abatement potential for each succeeding option.

¶ **Options available over different time periods.** The ability to capture certain opportunities at the costs and volumes estimated here depends critically on when action begins. Some options, such as energy efficiency linked to new-build construction, are readily available yet imminently perishable. Abatement achieved by retrofitting a building shell with efficient insulation, windows, and roofing can cost as much as $80 per ton CO_2e more than installing these features during initial construction. Other options, such as CCS, depend upon significant near-term investment and progress on permitting and liability issues to ensure commercial viability by 2020. Some 25 percent of the options require additional investment and/or continued maturation with cost reductions to reach their full potential.

¶ **High sensitivity to oil/gas prices and commodity demand shifts.** The abatement analysis uses the Energy Information Administration's forward commodity price assumptions, which assume relatively stable oil and natural gas prices through 2030, with oil averaging approximately $60 per barrel and gas $6.00 per million BTUs (in 2005 dollars). If average energy prices move significantly higher, abatement options that compete with oil and natural gas, such as energy efficiency and fuel economy in vehicles, will become more economic at the margin. The abatement cost of biofuels, for example, depends on future petroleum prices. By contrast, options that depend on gas, such as switching from coal to gas for power generation, will become more expensive.

¶ **High sensitivities to learning rates.** Costs and/or yields for some technologies improve according to the scale at which they are pursued. Penetration levels tend to drive the learning rate and can determine whether the technology achieves sufficient scale to propel economic success. Solar photovoltaics, CCS, biofuels, and LED lighting exhibit a broad range of outcomes that depend on innovation and cost compression associated with reaching commercial scale.

With increasing penetration, the marginal cost of abatement for solar photovoltaics (solar PV), for example, is projected to decline from its 2005 level of $210 per ton. Depending on the level of cost improvements achieved throughout the production system – in module conversion efficiency, DC-AC conversion efficiency, inverter design, and installation – 2030 abatement costs for this option will fall to somewhere between $10 and $62 per ton. Initial cost reduction successes could create positive feedback and drive higher levels of penetration, accelerating a virtuous cycle of expansion; conversely, failure to achieve early cost reductions could inhibit the rate of penetration and reduce the potential of solar PV to provide large quantities of abatement before 2030.

6. SIGNIFICANT CHANGES IN INFRASTRUCTURE, INVESTMENT, AND COMMODITY PROFILES

Reducing greenhouse gas emissions would require increases in capital spending and a change in investment patterns relative to the government reference case. Fully abating 3.0 gigatons of GHG emissions in the mid-range case, for example, would noticeably change the composition of the U.S. power generation and transportation infrastructures by 2030, and it would require additional capital investment averaging approximately $50 billion annually through 2030. In the mid-range case, the cumulative net incremental investment through 2030 would total some $1.1 trillion – approximately 1.5 percent of the $77 trillion in real investment the U.S. economy is expected to make in this period.[9] This number would be higher if projected savings from energy efficiency gains do not materialize and/or the nation chooses to achieve emissions reductions by mandating higher cost options. This incremental spending would be highly concentrated in the power and transportation sectors. In the mid-range case, for example, the incremental capital outlay for the power sector (excluding potential capital savings from energy efficiency options) would total $560 billion, which is approximately 90 percent of the total market capitalization of the U.S. utility sector today. Consequently, policymakers and regulators would need to weigh the necessity of these investments against the likelihood of upward pressure on rates and vehicle prices.

Note that capital investment is one of the components of the abatement curves, along with operating and maintenance expenses. As a result, these levels of investment are reflected in the economics of the curves themselves: we refer to capital investment separately only to illustrate the relative scale of capital spending that would be required. The numbers would be larger under the high-range abatement curve – as would be the level of associated energy efficiency savings and abatement.

Infrastructure

Capturing mid-range abatement would have an appreciable impact on the nation's energy infrastructure, implying the following developments:

¶ **Significant slowing of new pulverized coal plant construction, with net coal-fired generation decreasing by 15 percent.** Where cost-competitive, CCS would be used for new-builds and selected retrofits, but it is not expected to be commercially viable for large-scale deployment until 2020, limiting its total contribution through 2030.

9 U.S. Energy Information Administration, *Annual Energy Outlook (2007),* reference case.

Under these circumstances, total coal-fired power generation in the U.S. (including coal-fired generation with CCS) would drop 15 percent from 1,990 terawatt-hours in 2005 to 1,700 terawatt-hours in 2030, as lower-carbon generation alternatives, including bio-mass co-firing, replace conventional coal.

¶ **Net increases in nuclear generation, totaling 29 gigawatts by 2030.** Continued permitting challenges, supply-chain bottlenecks, and issues with construction assurance suggest that the nuclear development cycle will be 9 to 11 years from conception to reactor start-up. A further delay could be caused by some investors waiting for a demonstration from the first wave of new reactors that expanded nuclear power is profitable. These and other factors would limit the number of new-build reactors to 25 prior to 2030 in the mid-range case.

¶ **Deep penetration of renewable technologies, creating an incremental 192 gigawatts of capacity.** Deployment of wind power in favorable, non-transmission-constrained sites would increase wind capacity 12-fold by 2030. Increased global demand for solar power in the mid-range case would foster important learning-rate improvements in solar photovoltaics, resulting in grid-parity cost in select regions by 2020. Development of concentrating solar power (CSP) would benefit from similar – though not as dramatic – cost compression. There would also be additional deployment of small-scale hydroelectric and geothermal power generation.

¶ **Expanded distribution network associated with energy production.** Integrating renewable energy sources (primarily wind and solar) into the nation's electricity supply would require an expansion of the central transmission and distribution grid. Deploying CCS on fossil-fired power plants would require development of CO_2 pipelines to transport some 1.6 to 2.5 gigatons (cumulative through 2030) of CO_2 once CCS becomes commercially viable.

¶ **Reduced carbon content of transportation fuel from increases in biofuels.** Producing 30 billion gallons of biofuels per year and delivering it to market would require additional refineries, pipelines, and other distribution infrastructure. In the mid-range case, biofuel volume would grow to 16 billion gallons of corn-based starch ethanol and 14 billion gallons of cellulosic biofuel per year. At this volume, biofuels would comprise 14 percent of the forecast gasoline pool by 2030.

¶ **Light-duty vehicle fleet with 60-percent improvement in fuel economy.** A suite of technology packages, including light-weighting, drive-train improvements, air conditioning and auxiliary power improvements, rolling resistance performance, turbocharging, as well as hybrids, plug-in electric hybrids, and diesel, would enable light-duty vehicles to improve their average fuel economy from 25 to 40 miles per gallon in the mid-range case.[10] Changing the composition of the vehicle fleet would

10 Average of new vehicle sales for four propulsion technologies – gasoline internal combustion engine, diesel, hybrid electric, and plug-in hybrid electric vehicles – including opportunities above $50 per ton.

imply significant modifications to automotive production lines and manufacturing processes, as well as to the refueling infrastructure for these vehicles. Some of these technologies are available at costs exceeding $50 per ton (e.g., hybrid electric vehicles).

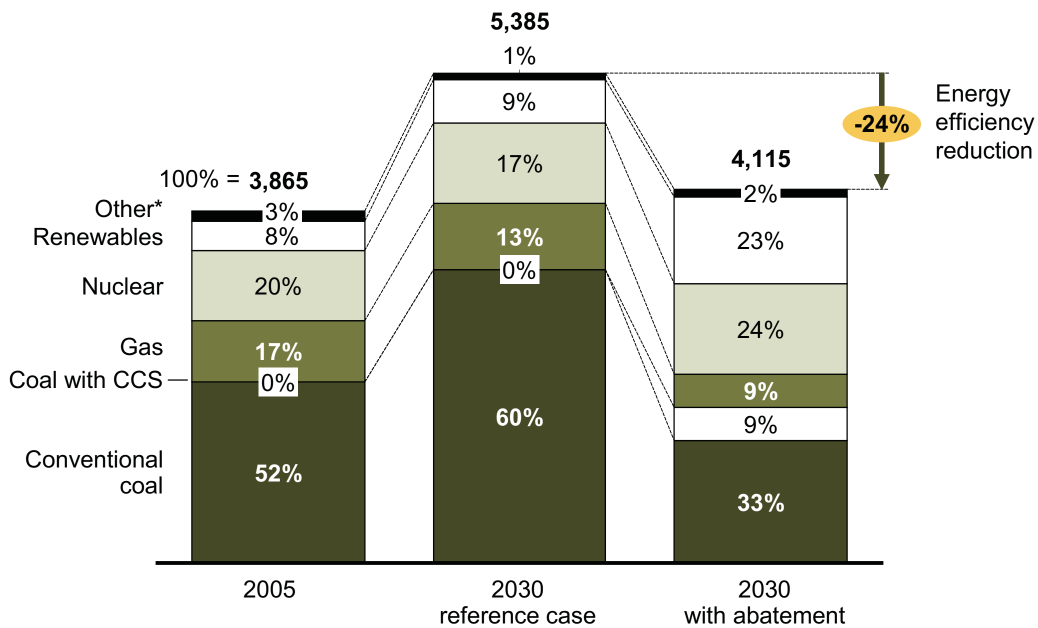
Mid-range abatement also has implications for the mix of energy production (Exhibit 16). Increased energy efficiency could reduce power load by some 24 percent. This shift, plus the expansion of renewable energy sources, would negate much of the coal-fired new-build generation assumed in the government reference case, and reduce the level of projected new gas-fired generation through 2030. A few new gas plants would be needed in sites with no suitable alternative fuel; some coal plants would be converted opportunistically to burn gas, and some generation would be needed to manage the intermittency effects of renewable energy. However, the increasing presence of low-carbon renewable generation capacity would likely force the least economic coal assets into retirement. Existing gas-fired capacity would likely stay on line, but at lower capacity factors.

Exhibit 16

CHANGES IN COMPOSITION OF U.S. POWER GENERATION

Terawatt-hours, Percent

MID-RANGE CASE – 2030



* Includes oil, geothermal, municipal solid waste, and pumped storage

Source: U.S. EIA Annual Energy Outlook (2007) "Reference case", McKinsey analysis

Investment requirements

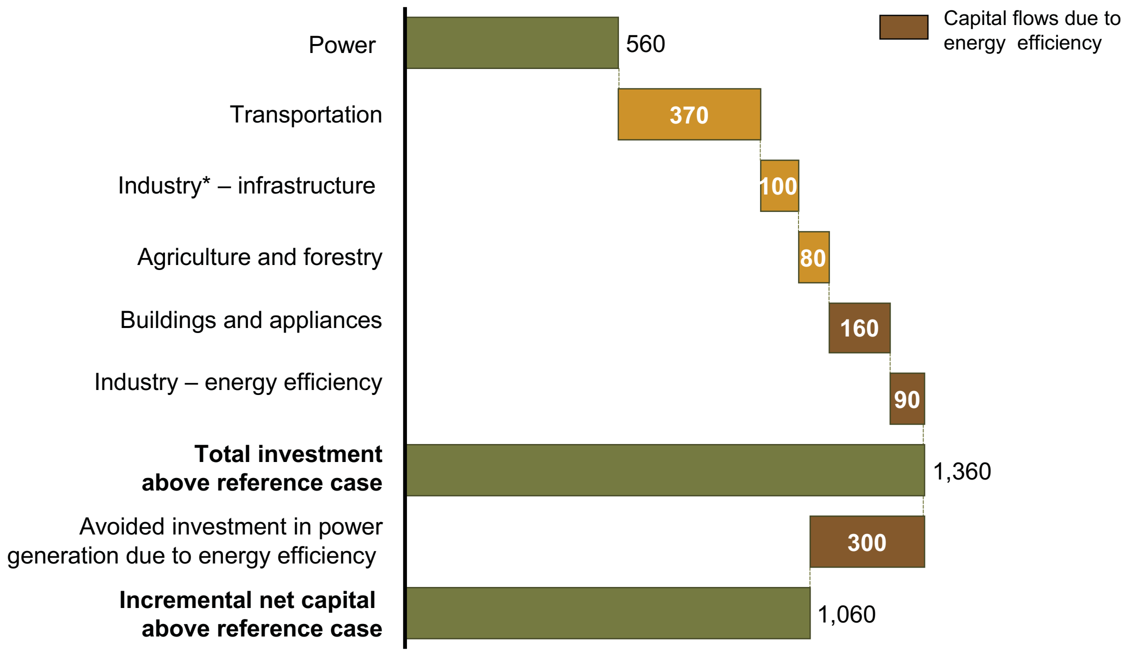
Creating the infrastructure and capturing the abatement potential associated with these trends will require changes in the nation's pattern of capital investment. Under the mid-range case, cumulative additional investment would total some $1.4 trillion through

2030,[11] prior to netting out avoided capital spending (Exhibit 17). Investment would include construction of new nuclear and biofuels plants, expansion in capacity for wind and solar energy, and the re-balancing and re-tooling of auto industry production lines. Much of the required expenditure would be above and beyond customary business cycle investments. Additional spending would also be needed to retrofit buildings with better insulation and improve their envelopes, replace water heaters and upgrade control systems, install CHP generation systems, replace electrical devices (e.g., motors, appliances), and pursue other abatement options.

Exhibit 17

INCREMENTAL CAPITAL INVESTMENT IN MID-RANGE CASE

Real 2005 $ billions, cumulative through 2030; options less than $50/ton CO_2e



* Including Waste industry
Source: McKinsey analysis

The cumulative potential from energy efficiency offers a significant opportunity to reduce energy demand, but without meaningful shifts in policy this potential most likely will not be realized. If agency issues and other barriers to market efficiency can be addressed, however, the massive deployment of energy efficiency practices and technologies assumed in the mid-range case would offset a substantial portion of the projected 40-percent increase in

11 The cost of an abatement option reflects its resource (or techno-engineering) costs – i.e., capital, operating, and maintenance costs – offset by any energy savings associated with abating 1 ton of CO_2e per year using this option, with the costs/savings levelized over the lifetime of the option using a 7-percent real discount rate. We excluded transaction costs, communication/information costs, taxes, tariffs, and/or subsidies. We also have not assumed a "price for carbon" (e.g., a carbon cap or tax) that might emerge as a result of legislation, nor any impact on the economy of such a carbon price. Hence, the per-ton abatement cost does not necessarily reflect the total cost of implementing that option.

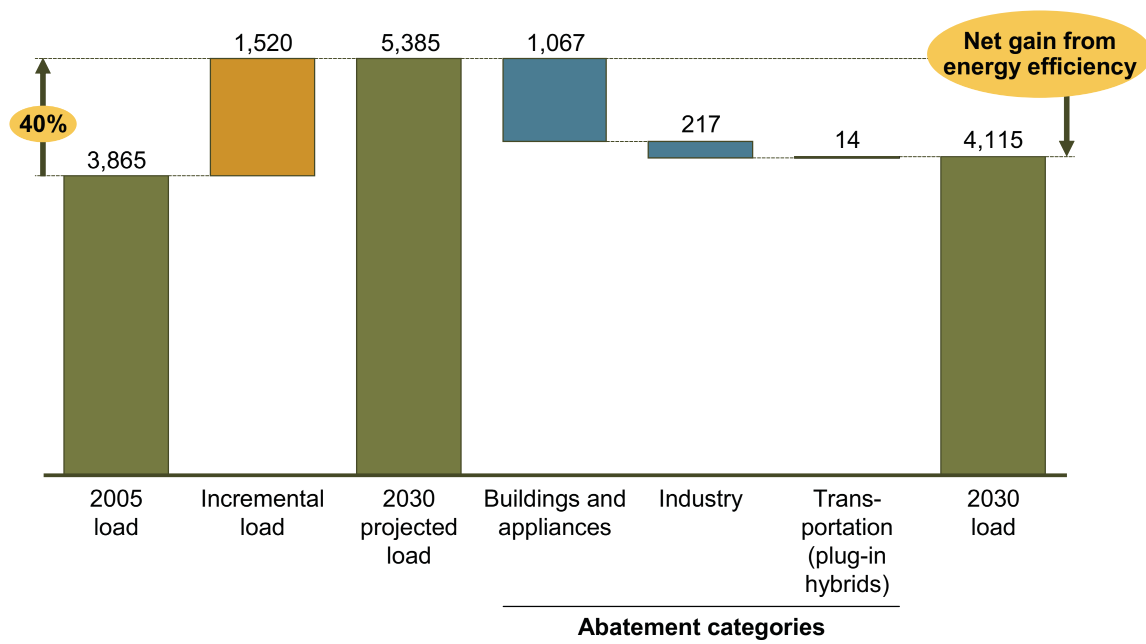
electricity demand between 2005 and 2030 (Exhibit 18). A parallel impact would be expected from new-build investment. Improved energy productivity could significantly reduce the need for new plant construction, eliminating more than $300 billion of the projected new-build investment through 2030. This reduction would offer additional savings from supporting infrastructure (e.g., transmission lines, rail, pipelines) that would have otherwise been built.

Exhibit 18

INCREMENTAL POWER LOAD vs. POTENTIAL ABATEMENT FROM ENERGY EFFICIENCY AND TRANSPORTATION

MID-RANGE CASE – 2030

Terawatt-hours



Source: U.S. EIA Annual Energy Outlook (2007) "Reference case;" McKinsey analysis

Commodity demand

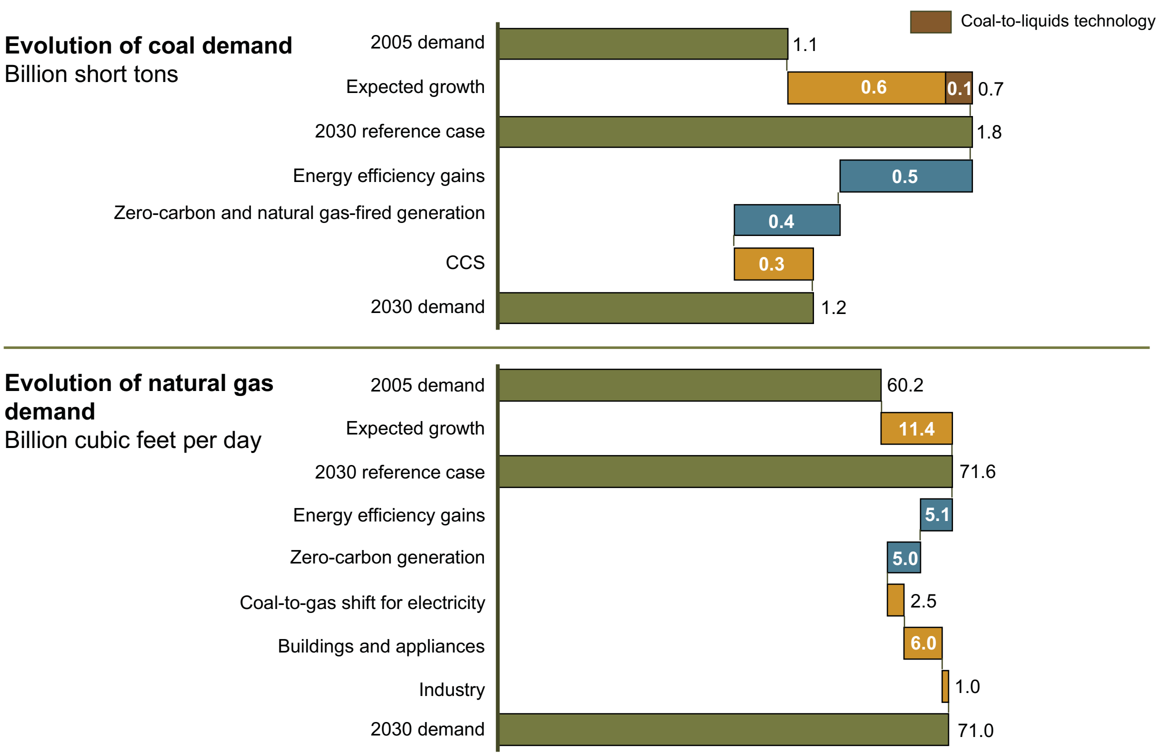
If the U.S. energy infrastructure were to develop in line with the mid-range abatement case, demand for certain energy commodities, such as coal and natural gas, would see some shifts in end-use application over this period. This project did not attempt to estimate the price impact of these potential demand changes, as these prices will be affected by many global forces outside the scope of this work.

If the U.S. economy captured the abatement opportunities in the mid-range case, coal consumption in 2030 would drop relative to the reference case projections and remain slightly above 2005 levels (Exhibit 19). The massive build-out in coal capacity (145 gigawatts) projected in the government reference case would be largely offset by gains in energy efficiency, plant retirements, heat rate improvements, and less frequent dispatch. Two factors would stimulate increased demand over this period: 55 gigawatts of CCS-fitted generation capacity would require a disproportionate incremental coal load (relative to 55 gigawatts of non-CCS-fitted supercritical pulverized coal plants), because of the inefficiencies introduced by the CO_2-separation process, and coal-to-liquids conversion for transportation fuel would increase demand by some 50 million tons.[12]

Exhibit 19

IMPACT ON U.S. COAL AND GAS DEMAND – 2005-2030

MID-RANGE CASE



Source: U.S. EIA Annual Energy Outlook (2007) "Reference case"; McKinsey analysis

Parallel analysis for gas in the mid-range case suggests approximately the same demand compared to the reference case forecast for 2030. Demand for gas in the power sector would fall: An increase in demand associated with shifting some load from coal to gas combustion of 3 billion cubic feet per day (bcfd) would be more than offset by a 5-bcfd reduction due to energy efficiency and a 5-bcfd reduction due to the substitution of nuclear power and renewable energy supply for gas-fired generation. Demand in the buildings-and-appliances and industrial sectors would rise by 7 bcfd primarily due to moves toward direct, on-site

12 Department of Energy estimates nearly 7 billion gallons of diesel production annually through new coal-to-liquids developments in the U.S. would be available in the 2020 time frame. This production capacity would require 52 million tons of additional coal annually. Our abatement scenarios assume this production capacity is developed with CCS technology to eliminate CO_2 emissions during the conversion process.

combustion for consumer and industrial purposes, notably commercial and industrial CHP applications and gas-fired furnaces, water heaters, and appliances in commercial and residential settings. The net result would be a 1-percent overall decrease in natural gas consumption in 2030 relative to demand projected in the reference case for 2030, essentially the same as what was projected in the reference case. If, however, the capture of energy efficiency options and the commissioning of incremental nuclear capacity are out of step with the growth in demand for electricity, building gas-fired generation capacity will be the most attractive alternative for many utilities.

* * *

In summary, the U.S. has the potential to abate 3.0 gigatons of greenhouse gas emissions (in the mid-range case) – and as much as 4.5 gigatons (in the high-range case) – at marginal costs below $50 per ton. This potential is distributed widely across economic sectors and geographic regions. Many of these opportunities have zero or negative costs, providing a net benefit over their lifecycle, though a number of barriers have historically prevented their capture. Pursuing mid-range abatement would require a substantial, sustained commitment and rapid progress toward commercial scale for a number of potentially important technologies. Developing this lower-carbon energy infrastructure would require approximately $50 billion per year in additional capital investment. These investments, in addition to lowering emissions in 2030, would position the U.S. economy more favorably to achieve steeper reductions in GHG emissions in the period from 2030 to 2050, should that be necessary.

Pursuing high-range abatement would place the U.S. in an even stronger position relative to proposed abatement levels for 2030 and even more aggressive reductions proposed for the 2030 to 2050 time period. The incremental investment needed would be higher and the degree of infrastructure change even more pronounced than what has been illustrated here. The abatement cases we have defined (low-range, mid-range, high-range), while instructive, are not meant to be recommended paths or a forecast of future outcomes. Ultimately, the degree of collective will – in the form of policy support, business and individual action, and technological innovation – will determine how far the nation gets with each individual abatement option and against any economy-wide abatement targets that the nation commits to pursue.

3 Five clusters of abatement potential

The main intent of this report is to help inform economically sensible strategies for reducing greenhouse gas emissions within the borders of the United States. The 250 abatement options we examined span every sector of the economy. They fall into five broad clusters (Exhibit 20). If pursued in unison, these clusters could abate 3.0 gigatons of emissions in 2030 in the mid-range case at marginal costs less than $50 per ton. With greater effort, these clusters could abate up to 4.5 gigatons (in the high-range case); however, the chances of capturing all opportunities in all clusters at this level would be considerably lower.

Ordered from lowest to highest average cost of abatement,[13] the five clusters of opportunity are:

1. **Improving the energy efficiency of buildings and appliances** – 710 megatons of abatement potential in the mid-range case to 870 megatons in the upper-range case.
2. **Encouraging higher energy efficiency in vehicles while reducing the carbon intensity of transportation fuels** – 340 megatons to 660 megatons.
3. **Pursuing a range of targeted measures across energy-intensive portions of the industrial sector** – 620 megatons to 770 megatons.
4. **Expanding and enhancing carbon sinks** – 440 megatons to 590 megatons.
5. **Reducing the carbon intensity of electric power production** – 800 megatons to 1,570 megatons.

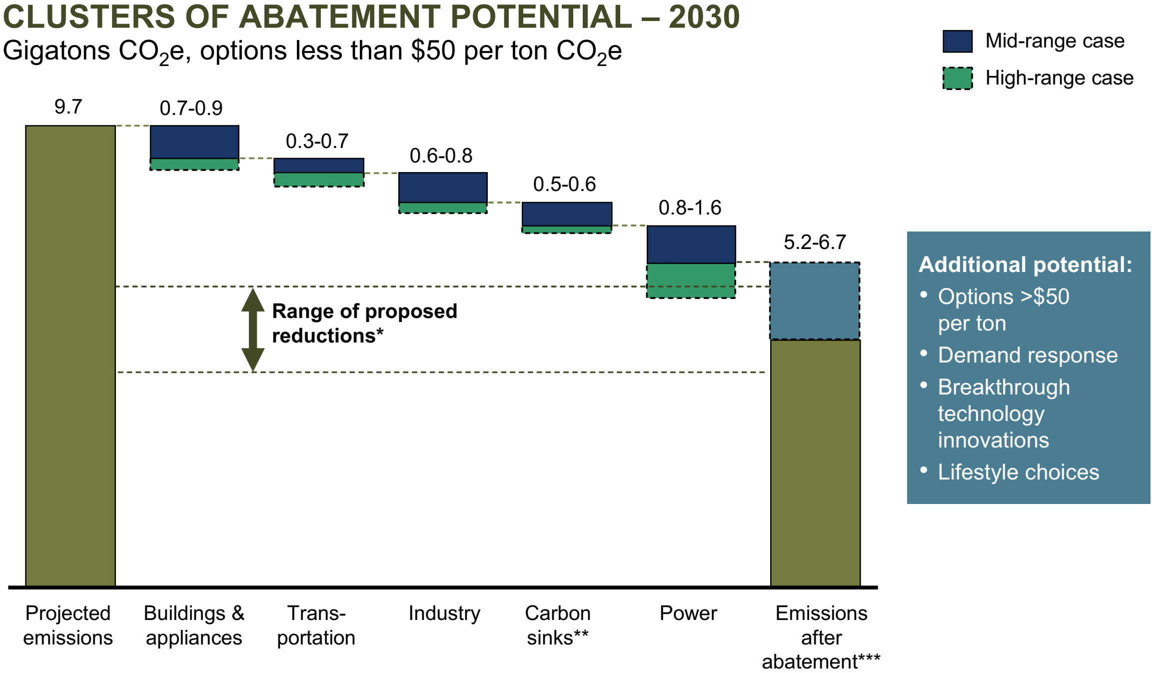
Unless otherwise noted, all figures cited through the remainder of this chapter refer to the mid-range abatement case.

13 The cost of an abatement option reflects its resource (or techno-engineering) costs – i.e., capital, operating, and maintenance costs – offset by any energy savings associated with abating 1 ton of CO_2e per year using this option, with the costs/savings levelized over the lifetime of the option using a 7-percent real discount rate. We excluded transaction costs, communication/information costs, taxes, tariffs, and/or subsidies. We also have not assumed a "price for carbon" (e.g., a carbon cap or tax) that might emerge as a result of legislation, nor any impact on the economy of such a carbon price. Hence, the per-ton abatement cost does not necessarily reflect the total cost of implementing that option.

Exhibit 20

CLUSTERS OF ABATEMENT POTENTIAL – 2030

Gigatons CO_2e, options less than \$50 per ton CO_2e



* Based on bills introduced in Congress that address climate change and/or GHG emissions on an economy-wide basis and have quantifiable targets; targets calculated off the 2030 U.S. GHG emissions of 9.7 gigatons CO_2e/year (reference case)

** Including abatement in the agriculture sector

*** Adjusted for cumulative rounding errors

Source: U.S. EIA; EPA; USDA; McKinsey analysis

1. IMPROVING THE ENERGY EFFICIENCY OF BUILDINGS AND APPLIANCES

At 710 megatons annually in the mid-range case, energy efficiency improvements in residential and commercial buildings (including the appliances inside) make up the largest cluster of negative-cost abatement opportunities. Many of these opportunities have strongly negative lifecycle costs, with the exception of upgrading select types of HVAC equipment, which is more capital intensive and may not generate enough savings to offset incremental costs. Most improvements use existing technology; 70 percent (500 megatons) are available before 2020. Together, they could offset 70 percent of incremental power load forecast in the reference case, forestalling the need to build many of the new power plants projected through 2030.

Emissions in the reference case

The reference case projects a 53-percent increase in GHG emissions – mostly CO_2 – associated with buildings by 2030. Emissions would rise from roughly 2.4 gigatons in 2005 to 3.6 gigatons in 2030. Indirect emission allocated from the power sector based on buildings usage represent 70 percent of this volume. The nation's commercial space would grow by 35 billion square feet (48 percent); housing stock would grow by 34 million homes (30 percent). There would be more homes, and they would be larger as well – 14 percent larger. The average home would expand from 1,755 square feet to approximately 2,000 square feet (roughly one additional room). Emissions per home in 2030 would remain virtually unchanged from 2005 levels – 11 tons CO_2e per year. In effect, gains from installing more efficient equipment would be offset by greater electricity demand from more appliances and the need to heat and cool more space.

Regional differences play a role as well. Accelerated growth in warmer regions (e.g., the South Atlantic and West South Central census divisions) will increase the number of homes and commercial buildings that need more electricity for cooling rather than more gas or oil for heating. The trend toward greater electricity consumption, combined with the projected carbon intensity of the national power supply, contributes to the 1.2-gigaton increase in emissions associated with buildings.

Important abatement opportunities

This sector offers significant low-cost abatement potential for two reasons: 1) residential and commercial buildings in the U.S. today are relatively energy and carbon inefficient; and 2) rapid projected growth in this sector would provide many opportunities to "build in" durable abatement options during initial construction, which is significantly less expensive than retrofitting them.

The cluster of energy efficiency opportunities associated with buildings includes lighting, improvements in HVAC equipment and building shells, electronic equipment, combined heat and power in commercial buildings, appliances and water heaters (Exhibit 21). The research team used stock-and-flow models to estimate the addressable market for these options, and calculated abatement potentials from the reference case stock and performance levels. Abatement costs reflect the combination of levelized capital costs and annual operating costs/savings.

Lighting. Lighting today accounts for 19 percent of the emissions associated with buildings. Lighting retrofits offer 240 megatons of annual abatement potential by 2030, making it one of the largest and most cost-effective ways to abate GHGs. The potential correlates with the size and expected growth rates of geographies within the U.S., with each region able to abate some 70 percent of lighting-related emissions relative to reference-case levels.

In general, commercial lighting is much more efficient than residential lighting. In the average household, for example, 92 percent of lighting comes from incandescent bulbs which are relatively inefficient. Within the lighting opportunity, residential general-use lighting could provide 130 megatons of abatement, while commercial applications, specifically light-emitting diode (LED) lights and super T8 fluorescents, offer 110 megatons.

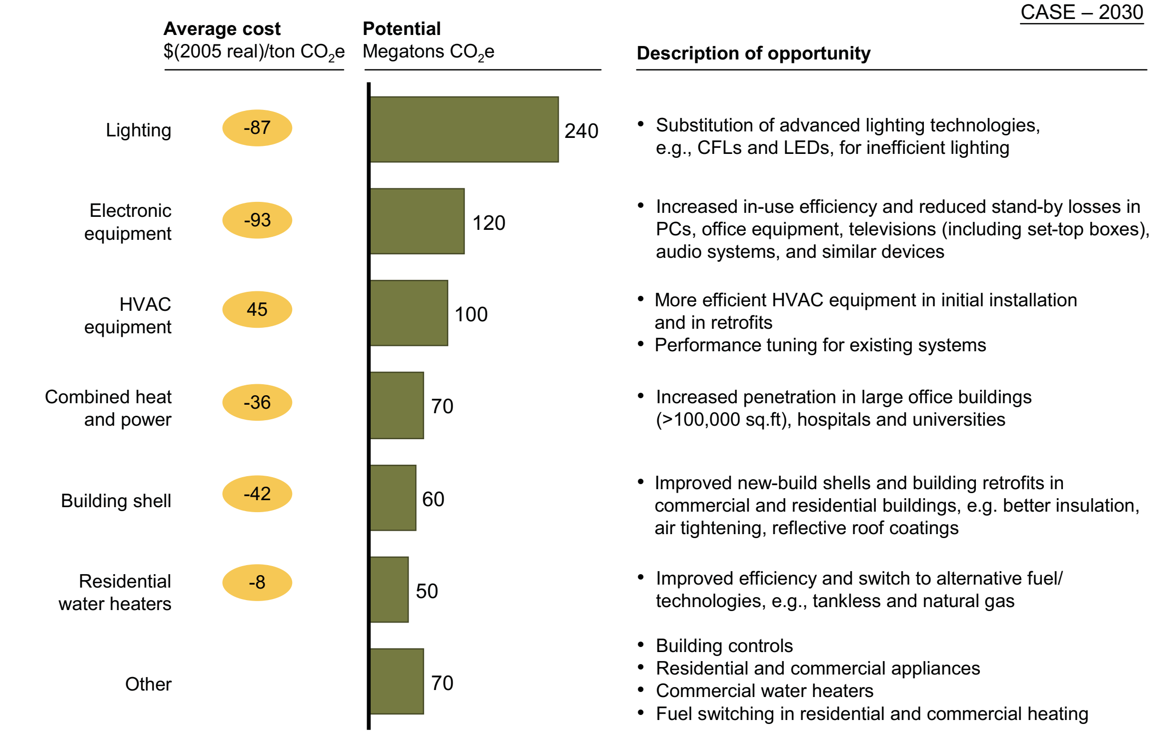
The opportunity comes from higher-efficiency lighting available now, such as compact fluorescent lights (CFLs), and technologies expected to be commercially available by 2015, such as LEDs. To produce the same amount of light, a CFL uses approximately 30 percent of the power an incandescent bulb requires and lasts almost eight times longer. An LED consumes about 12 percent of the energy an incandescent uses and lasts more than 40 times longer. Though CFLs today cost several times more than an equivalent incandescent bulb, long life and high efficiency make these lighting changes potentially very attractive abatement options.

Exhibit 21

ABATEMENT OPTIONS – BUILDINGS-AND-APPLIANCES CLUSTER

Options less than \$50/ton CO_2e

MID-RANGE CASE – 2030



Source: McKinsey analysis

The longer life of CFLs and LEDs will have a significant effect on stock flows in the lighting markets. The number of lamps sold per year could drop by 75 percent by 2030. Because CFLs will last years longer than incandescent bulbs, turnover in lighting stock will slow as CFLs penetrate the market. This slowing could have implications for the adoption of more efficient lighting technologies, such as LEDs, over the longer term.

A number of issues may impede capture of these opportunities, however, particularly in residential settings. Brightness levels for CFLs and LEDs can be matched to incandescent bulbs, but the color of the light has presented a barrier to adoption. CFLs contain mercury, a potential hazard if bulbs break. Furthermore, consumers typically expect payback for this class of household investment to come within the relatively short span of 2 or 3 years, making CFLs seem expensive for home use. As a consequence, commercial adoption has tended to precede residential use.

Electronic equipment. Electronic devices offer 120 megatons of abatement potential, with 70 megatons in commercial and 50 megatons in residential electronics. Strong expected growth in the number of devices and their energy intensity, plus significant potential to reduce per-unit energy consumption, make electronics a sizeable opportunity.

The Department of Energy projects that the nation will have 34 million additional computers and 213 million additional televisions in service by 2030, compared to 2005. It further projects that each PC and each television will consume 82 percent and 11 percent more energy, respectively, relative to 2005 levels. Some of this increase will be offset by slight improvements in per-unit consumption.

As a result, the reference case projects strong growth in electricity used by PCs, office equipment, televisions (including set-top boxes), audio systems, items using rechargeable batteries, and similar devices. While overall energy use in commercial settings would rise by 1.6 percent per year, energy consumed by office equipment and PCs would grow at more than twice that rate (3.2 and 3.9 percent, respectively). Similarly, in residential buildings, overall energy consumption is forecast to rise by 0.7 percent annually, with energy used by televisions and other electronics (including PCs) rising at three times that pace or more (2.5 percent for TVs and 2.1 percent for other electronics).

The primary abatement opportunity in electronics comes from reducing electricity used by each unit. Today consumers may have little knowledge about how much energy electronic devices consume. One model of a large-screen television, for example, may use up to one-third more power than another model of the same type and size. There may be opportunities to reduce energy consumption by establishing or raising performance standards for certain classes of devices, by providing additional information for consumers at the time of purchase, as well as other measures.

HVAC equipment. In the reference case, HVAC is expected to account for 34 percent (600 megatons) of residential GHG emissions annually and 19 percent (360 megatons) of the emissions associated with commercial buildings in 2030. For both residential and commercial buildings, the reference case assumes slight improvements in the average seasonal energy efficiency rating (SEER) for air conditioning equipment and sizeable growth in gas furnaces for heating.

Installing more efficient HVAC systems and improving building shells could abate 160 megatons per year by 2030, with changes in HVAC equipment providing 100 megatons of abatement and improvements to building shells providing 60 megatons. Issues of agency and duration of ownership have historically been a major barrier to capturing energy and carbon efficiency in this sector, as those who bear the initial cost of improvements are often not lifetime recipients of the benefits.

Although installing more efficient HVAC equipment (both residential and commercial) represents a significant abatement opportunity, unlocking the full potential requires that the equipment be installed properly. For example, an air conditioning system designed to perform at 13-SEER may be operating at 9-SEER due to a variety of installation issues. Systematic building audits coupled with selective upgrades and retrofits (i.e., retro-commissioning) have the potential to improve system performance significantly in these situations.

¶ **Residential HVAC equipment.** More efficient HVAC equipment for residential use could abate 55 megatons annually:

- **Air conditioning.** The principal opportunity in residential air conditioning consists of deploying units with higher SEER levels in new homes as they are built and in existing homes as cooling systems are replaced.[14] For central air conditioning 13-SEER units are prevalent today, but 15-SEER systems are readily available; similarly, room air conditioners are typically 10 SEER, but 12-SEER units are available. The higher-SEER units cost more initially, though they use substantially less electricity to provide an equivalent level of cooling.

- **Heating.** Gas-fired furnaces and radiators are expected to account for 76 percent of residential heating by 2030, up from 68 percent today, with their efficiency estimated at 80 to 82 percent. The opportunity in residential heating stems from improving efficiency of gas systems and in switching to gas beyond the level assumed in the reference case. Gas units available today average 86 percent efficiency and can approach 90 or even 92 percent (achieving efficiency beyond this level is less feasible). Switching fuel from LPG or fuel oil to natural gas, which burns more efficiently, could abate 12 megatons annually by 2030, with two-thirds of that amount in the Northeast.

¶ **Commercial HVAC equipment.** More efficient HVAC equipment in commercial buildings could abate 45 megatons annually.

- **Air conditioning.** The types of equipment used in commercial settings vary more widely than those used in residential applications, reflecting greater variation in building types. Electric roof-top units (RTUs) and reciprocating and centrifugal chillers are widely used, though more than 20 percent of the cooling is provided by residential-style equipment. Opportunities for upgrading the SEER level apply to RTUs and residential-style central air and room air conditioners. With chillers, the opportunity is in better design and load matching to the building and in better controls and operation (e.g., staging of compressors).

- **Heating.** Switching fuel for heating to natural gas in commercial buildings represents – beyond the level assumed in the reference case – a 7-megaton abatement opportunity, with the benefit concentrated in regions that rely on fuel oil for heating today.

Combined heat and power applications. The use of CHP applications in commercial (excluding industrial) settings could provide 70 megatons of abatement by 2030. These applications are typically most suited to hospitals, universities, and office buildings larger than 100,000 square feet, but may enjoy favorable economics in many other settings.

The abatement potential in CHP derives from the use of waste heat given off by on-site natural gas combustion. This waste heat displaces additional fuel needed for heating or cooling purposes. When transmission losses associated with electricity from the grid are included, a

14 In drier climates, EER (energy efficiency ratio) may be the more appropriate measure of equipment efficiency, but the general principle remains the same.

conventional approach to heat and power for a building would use significantly more energy than a properly sized CHP system. Proper sizing is critical to CHP effectiveness, because CHP typically draws electricity from the grid for peak loads and back-up needs. Balancing system utilization is engineering intensive, and often involves the development of customized solutions on a building-by-building basis.

CHP is projected to provide abatement at negative cost, but it faces significant implementation challenges, including costly interconnections with the power grid, lengthy processes for environmental approvals, local zoning restrictions, as well as site infrastructure, such as adequate space and compatible distribution systems.

Building shells. The reference case assumes most new homes through 2030 will be built to a minimal standard of energy efficiency; it also assumes no improvements to existing homes. Commercial buildings today are built more uniformly to a higher standard and will likely continue to be so. Improving building shells beyond the reference case offers 60 megatons of abatement annually by 2030. This potential is evenly split between residential and commercial buildings.

¶ **Residential buildings.** The nation's housing stock is forecast to grow from 113 million homes to 147 million by 2030, with most of these houses built to a minimum performance standard below desirable economic and efficiency levels. Tighter-fitting, better-insulated windows and doors, leak-proof ducting, additional attic and wall insulation and commercial grade housewrap would improve their efficiency. Because builders typically do not bear the ongoing operating and maintenance costs of a building (while homeowners do), they tend to focus on reducing first cost and have less of an incentive to install efficient building systems. The opportunity to improve the efficiency of new-build homes is concentrated in faster-growing regions, where adding less than $750 of materials and labor would improve cooling and heating performance by 6 to 20 percent over the reference case. As a consequence, any new-build home in the nation – regardless of region – represents an opportunity to create long-lasting abatement at negative cost.

In addition, roughly 20 million existing homes (by 2030) would be candidates for retrofit improvements to the building shell, particularly in areas where heating prevails and the building stock is older. In such regions as the Northeast, East North Central and West North Central census divisions, increased attic insulation would offer the biggest opportunity and could improve heating performance by nearly 30 percent from the reference case. Although retrofit improvements typically deliver substantial abatement, they cost much more than comparable improvements in new-build shells. Building shell retrofits may cost $80 per ton more than measures delivering similar impact on new-build construction.

¶ **Commercial buildings.** Similar growth is expected in commercial buildings. By 2030 total square footage of commercial buildings is forecast to increase from 73 billion to

108 billion. By 2030, more than 56 billion square feet of this commercial space will have been built new or rebuilt on site.[15]

Although the emissions reference case assumes modifications in commercial building shells will improve heating and cooling efficiency by some 5 to 7 percent, there is significant additional abatement potential. Use of programmable thermostats and energy management systems – reducing thermal shorts, installing reflective roof coatings, improving air tightness, and using advanced insulation types – may improve heating and cooling efficiency by an additional 15 to 20 percent.

Residential hot water. Water heating is projected to consume 13 percent of energy used in homes by 2030. Virtually all of this amount would be supplied by conventional units. Deploying higher-efficiency conventional natural gas water heaters and alternative designs, such as tankless and condensing models, could abate 50 megatons annually. Many factors limit the deployment of higher-efficiency models available today. Efficiency is not a top priority for most consumers; in fact, most water heaters purchased by consumers are rated only at the federal minimum efficiency standard. Purchase decisions are more typically driven by need and availability: homeowners buy a new unit when the existing unit breaks, with their choice about the replacement limited to what the plumber or local retail outlet has in stock. In addition, switching to alternative designs may incur added costs for retrofitting. Consumers tend to apply a high discount rate to these purchases, seeking to shorten their payback period. With water heaters installed in new-build homes, builders have an incentive to minimize first cost at the expense of operating cost or carbon efficiency.

Because pursuing a number of these opportunities, such as insulation and HVAC systems, during initial construction is more cost-effective than retrofitting buildings later and because buildings have a long economic life, the low-cost nature of some of these abatement opportunities has to be viewed as perishable. Every building constructed by 2030 without carbon emissions in mind increases the potential cost of abatement in the future.

Implementation barriers and implications

Despite the large abatement and economic savings associated with these energy efficiency opportunities, significant barriers have the potential to impede widespread adoption. Historically, understandable individual decisions have led to unfavorable emissions outcomes for society, suggesting that some form of policy intervention (e.g., standards, mandates, utility incentives, fee-bates) or innovative private sector initiatives may be necessary to unlock the abatement potential in this area:

¶ **Costs.** Consumers expect many household investments to have a short, 2- or 3-year payback period, which implies a discount rate of nearly 40 percent. In addition,

15 The 56 billion sq. ft. of commercial space new builds/rebuilds includes 35 billion sq. ft. of new floor space and 21 billion sq. ft. of floor space rebuilt on site.

affordability constraints may reduce the willingness of consumers to invest in measures offering greater efficiency, even if the financial benefits are satisfactory.

- **Visibility.** In many markets, electricity customers do not see the real cost of power, which limits the potential for price signals to encourage changes in behavior. Customers typically have no accurate information about the energy consumed by any particular application, such as the added cost of a spare refrigerator, or the relative benefit of having that refrigerator located in a cool basement versus a warm garage. Furthermore, based on the way electricity is priced, customers often do not receive accurate signals about the marginal cost of power, which, for example, can vary significantly throughout the course of a day.
- **Agency.** The owner, operator, occupant, and bill-payer (benefit capturer) associated with a building may be separate entities or may not be involved for the full relevant time period; as a result, their interests in supporting energy efficiency and GHG abatement are not aligned.
- **Education.** Consumers, architects, engineers, builders, contractors, installers, and building operators are often not aware of savings potential, or are poorly informed about performance benefits.
- **Quality.** Real or perceived quality differences can deter consumers. Slight perceived differences in color can affect purchase decisions for light bulbs, despite greater efficiency. In some cases, consumers worry that high-efficiency devices (such as some washing machines and dishwashers) will not perform as well as conventional models.
- **Availability.** Even when consumers intend to purchase energy efficient devices, they may have a hard time finding the item, due to a retailer's approach to inventory management and stock optimization.

Capturing energy efficiency opportunities in buildings would require that these persistent barriers be addressed, while tailoring the approach for variations in regional population and climate. Our ability to move from 710 megatons of abatement in the mid-range case to 870 megatons in the high-range case depends largely on expanding the efforts to remove these barriers across a broader range of independent consumer decisions.

2. ENCOURAGING HIGHER ENERGY EFFICIENCY IN VEHICLES AND REDUCING CARBON INTENSITY OF FUELS

The transportation cluster offers 340 megatons annual abatement in the mid-range case. Savings achieved over the lifetime of a vehicle from improvements in fuel economy (in all classes of vehicles: light-, medium-, and heavy-duty vehicles) and the commercialization of cellulosic biofuels may offset the incremental costs needed to unlock these opportunities. As a result, this cluster of opportunities has a net average cost that is moderately negative.

Emissions in the reference case

Annual emissions from the transportation sector are forecast to rise from nearly 2.1 gigatons in 2005 to more than 2.8 gigatons by 2030. This 37-percent increase is expected to come from significant growth in vehicle miles traveled (59 percent for light-duty vehicles, 73 percent for commercial freight vehicles), increased penetration of light trucks, and limited penetration of diesel, hybrid vehicles, and biofuels. Incremental fuel efficiency gains in the reference case will only partially offset the increase (e.g., light-duty vehicle fuel efficiency would rise from 25 to 29 miles per gallon by 2030).

Important abatement opportunities

In line with the team's analytical approach, we organized transportation-related abatement options into three groups: reducing the carbon intensity of the fuel supply, improving fuel efficiency of vehicles, and adopting alternative propulsion technologies.

Sequencing matters

To avoid counting abatement potential twice, the research team carefully sequenced opportunities associated with vehicles. Because of the sequencing, options that come earlier "look better" than options that come later. This is because fuel saved today contains more carbon than fuel saved in the future – once biofuels have substantially penetrated the national fuel supply, for example. The team created three tiers of abatement options starting with vehicles powered by contemporary internal combustion engines:

1. Reduce fuel carbon intensity
2. Deploy fuel economy packages for conventional vehicles to improve vehicle fuel efficiency (gasoline and diesel)
3. Adopt alternative propulsion technologies such as hybrids and plug-in hybrids.

Re-sequencing abatement options would change their relative size and cost (and location on the curve), but would not increase the total abatement potential from transportation, unless fundamental constraints, such as supply chain bottlenecks or technological uncertainties, were relaxed or removed.

Given our intent to hold consumer utility constant, we did not evaluate demand-management schemes, such as incentives for mass transit use, congestion pricing, or pay-as-you-go insurance. Nor did we assess the potential of urban designs that foster denser, more transport-efficient communities. Population growth, demographic changes, and shifts in consumer preferences may make investigation of these options necessary.

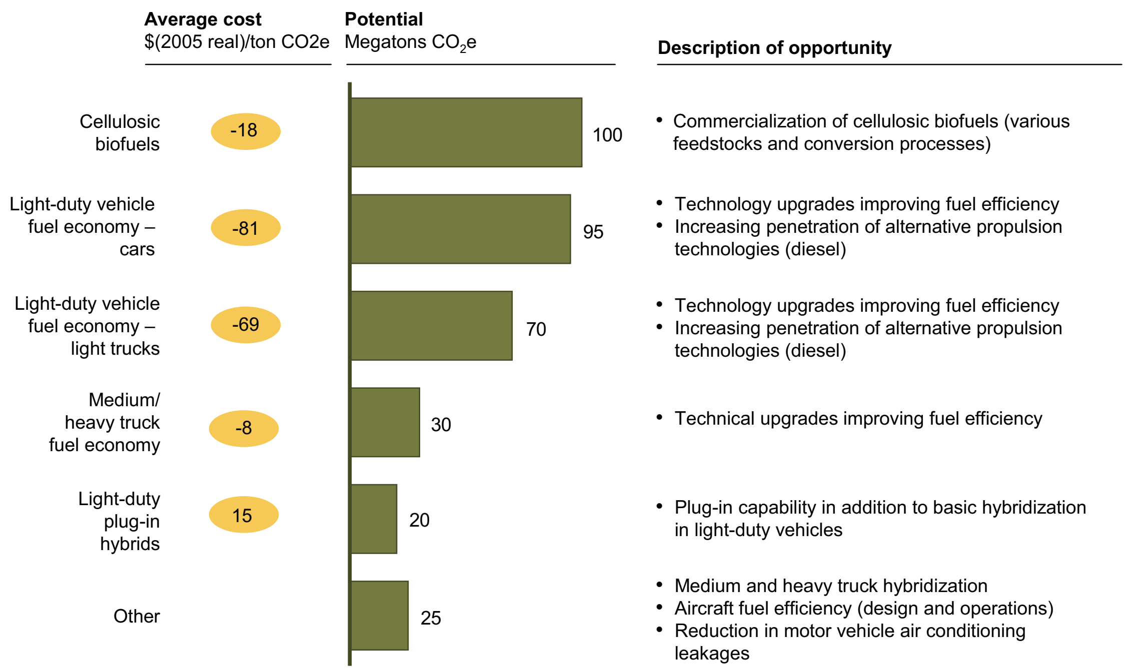
Transportation could provide some 340 megatons of annual abatement (mid-range case) below a marginal cost of $50 per ton. Improved fuel efficiency and/or dieselization in various classes of vehicles could provide 195 megatons of abatement, with lower-carbon fuels providing an additional 100 megatons. Smaller opportunities in alternative propulsion technologies (medium and heavy truck hybridization, plug-in hybrid light-duty vehicles), vehicle air conditioning systems, and air transportation could make up the remaining 45 megatons (Exhibit 22). Hybridization of cars and light trucks could abate an additional 70 megatons by 2030, but at marginal costs above $50 per ton. Because of the higher cost, we have not included them in the abatement ranges.

Exhibit 22

ABATEMENT OPTIONS – TRANSPORTATION CLUSTER

Options less than \$50/ton CO_2e

MID-RANGE CASE – 2030



Source: McKinsey analysis

Reducing carbon in the fuel supply through biofuels. In the mid-range case, the production of biofuels could reach 30 billion gallons per year – or 14 percent of gasoline consumption – by 2030. Cellulosic biofuels could supply up to 14 billion gallons of that total. Compression of cellulosic production costs would drive this market growth, with the cost declining from a projected \$1.83 per gallon in 2010 to \$1.28 per gallon in 2030, excluding distribution and marketing costs, taxes or subsidies. Cost reductions would come primarily from innovation in enzymes and through streamlined bio-refinery design, which would reduce up-front capital costs. At this level of production, biofuels would abate 100 megatons of GHG emissions.

Achieving large-scale production of cellulosic biofuels depends on many critical – and uncertain – developments. Considerable enzyme innovation remains necessary to improve yield rates and shorten process time. While still in the first generation of plants, capital costs appear high relative to similarly sourced starch ethanol systems. Design improvements will be needed to drive down costs, while bottlenecks in the plant delivery process (e.g., engineering, permitting, and procurement) must be addressed to establish competitiveness with fossil-based alternatives.

Depending on what biofuel blend (e.g., cellulosic ethanol, green diesel, cellulosic diesel/gasoline) wins out, developing an alternative distribution infrastructure for the new fuel base may incur additional costs. For instance, owing to its material properties, cellulosic ethanol is unsuitable for transport in the nation's pipeline network at levels beyond a 10-percent blend. The result is that large-scale penetration in the gasoline pool would require a parallel infrastructure, which could add as much as 10 percent to the delivered cost of fuel. Cellulosic fuels that have more compatible physical properties (e.g., cellulosic diesel/gasoline) would avoid this additional capital cost.

Cellulosic biofuels production is not likely to be constrained by the availability of biomass in the near term. Biomass feedstock for up to 86 billion gallons of biofuel is available without impacting current land-use patterns, though other environmental concerns may reduce that number somewhat.

Unlike cellulosic options, starch ethanol does not offer a significant abatement opportunity beyond the reference case. Although production is expected to reach 16 billion gallons by 2030, starch ethanol's lower level of lifecycle CO_2 abatement (18 percent versus 70 to 88 percent for cellulosic biofuels) and its higher per-gallon production costs make it relatively less attractive for GHG abatement.

Improving fuel efficiency of conventional vehicles. Although the reference case assumes that fuel efficiency for light-duty vehicles with internal combustion engines (ICEs) will improve some 18 percent by 2030, vehicle fuel efficiency offers significant additional abatement potential.[16] Opportunities with passenger cars and light, medium, and heavy trucks total 195 megatons in 2030.

The abatement cost of fuel efficiency improvements for conventional vehicles includes lifetime fuel savings. Given that vehicles typically have several owners over their 12- to 15-year lifetime, the fuel savings that individual owners receive depends on how long they own the vehicle and may be less than the incremental cost of abatement. As a result, for the individual owner the cost of abatement through fuel efficiency improvements may seem positive (i.e., an expense), though for society it would be negative (i.e., a savings).

¶ **Light-duty vehicles.** The research team identified many options for improving fuel economy with ICE-powered vehicles that burn gasoline or diesel. Altogether, these options could offer some 165 megatons of abatement.

Notable options include dual-cam phasing, improved alternators, weight reduction, lower rolling resistance tires, and turbocharging. Increasing the use of diesel engines is itself an additional option. Although each individual technology could help improve fuel economy, the options need to be analyzed in packages to avoid double-counting efficiency gains. Drawing on input from industry experts, the team bundled these options into suitable packages that would be used to balance performance and fuel economy against various vehicle design criteria.

16 To be consistent with the government reference case forecasts used for this analysis, values for fuel economy are presented here using the pre-2007 Environmental Protection Agency fuel economy rating system.

These fuel economy packages would add $700 to $1,400 to the cost of a light-duty vehicle and would improve miles-per-gallon beyond the level assumed in the emissions reference case by 15 percent for passenger cars and 8 percent for light trucks by 2030. For gasoline-powered vehicles, this improvement would correspond to fuel economy ratings of 38 miles-per-gallon for the average new car and 28 miles per gallon for the average new light truck in 2030. For diesel-powered vehicles, this improvement would correspond to fuel economy ratings of 48 miles per gallon for the average new car and 34 miles-per-gallon for the average new light truck in 2030.

Fuel savings, bolstered by the $59-per-barrel long-term oil price assumed in the reference case, offset incremental costs of fuel efficiency over the lifetime of a vehicle, making these abatement options available at negative cost. If the long-term price of oil were higher, these options would become even more attractive.

¶ **Medium and heavy trucks.** Greater fuel efficiency for medium and heavy trucks is available at relatively higher cost, although the expense may be offset by fuel savings over the lifetime of the vehicle. The team assessed such near-term improvements as improved aerodynamics and advanced (reduced friction) transmissions; it also reviewed such medium-term options as pneumatic blowing and fuel-cell operated auxiliaries, and improved thermal management.

Fuel economy packages for medium and heavy trucks would add $5,200 to $9,400 to the cost of a vehicle and would improve miles-per-gallon by 13 percent for medium trucks and 6 percent for heavy trucks by 2030, relative to improvements assumed in the emissions reference case. In total, the abatement potential of medium and heavy truck fuel efficiency would be some 30 megatons by 2030.

Adopting hybrid electric propulsion. Hybrid electric vehicles (HEVs) could provide nearly 90 megatons of abatement by 2030 (beyond growth projected in the emissions reference case). However, only 20 megatons would come at a marginal cost below $50 per ton (hybridization of medium and heavy trucks). Opportunities for abatement through hybridization of cars and light trucks are larger – in excess of 70 megatons, based on an assumed 24-percent penetration of new light-duty vehicle sales by HEVs in 2030 – but they are more expensive, with their abatement cost approximately $100 to $140 per ton. This is because hybridization becomes less "carbon cost effective" if the reference (pre-hybrid) vehicle is already highly carbon efficient. Greater penetration of biofuels and fuel efficient vehicles reduces the carbon intensity of the fleet. As a result, hybridization would deliver less incremental carbon abatement, and therefore becomes less cost effective as an abatement option.

There are significant uncertainties around the penetration of HEVs in new light-duty vehicle sales in 2030. Although HEVs are not a low-cost abatement option, they could occupy 24 percent of the market by 2030, driven by consumer preferences, bolstered by high oil prices, and supported by automakers' investments in HEV technology. For auto manufacturers, investments in HEVs can help accelerate commercialization and deployment of plug-in hybrids (PHEVs). Penetration of HEVs in 2030 could be considerably lower, however, if design innovations do not occur, battery costs are not compressed, and supply chain bottlenecks are not resolved.

Pursuing plug-in hybrid electric vehicles (PHEV). Plug-in hybrid technology is projected to enable passenger cars to travel 113 miles-per-gallon and light trucks 79 miles-per-gallon. Abatement due to PHEVs could total 20 megatons in 2030. Plug-in hybridization for light-duty vehicles is a positive-cost option, because the expected additional cost of a PHEV ($4,300 to $5,300) is not fully offset by fuel savings. The high cost and significant innovation required to improve battery performance (miles per kilowatt-hour), plus the uncertainty over which technology will prevail (lithium-ion versus nickel-metal hydride), slow the expected penetration of PHEVs. Our estimates suggest that they may grow to 6 percent of new light-duty vehicle sales by 2030.

The effectiveness of plug-in hybrids as an abatement option depends not only on battery performance, but also on carbon intensity of the regional electrical grid and the relative penetration of biofuels into the conventional motor fuel supply. In many regions, overnight charging of plug-in hybrids would draw additional electricity from baseload coal-fired power plants, which would increase incremental GHG emissions. Even under these circumstances, PHEVs could abate carbon emissions if their electric efficiency achieves the higher end of the performance range expected by the industry (approximately 3.5 miles per kilowatt-hour). In a world where biofuels – particularly cellulosic biofuel – penetrate the fuel supply beyond 10 percent, however, the attractiveness of PHEVs decreases substantially as an abatement option.

In certain geographies, creative solutions may support greater penetration of plug-in hybrids, given their potential to act as programmable energy storage. In a region where significant wind resources are available at night, for example, incremental demand from PHEVs could support the integration of additional volumes of zero-carbon power into the grid.

With improvements in fuel efficiency for ICE-powered light-duty vehicles and adoption of alternative propulsion technologies, the fuel economy rating of the average new passenger car in 2030 (weighted by penetration of all fuel types and propulsion technologies) would be 47 miles-per-gallon. The corresponding rating for light trucks would be 34 miles-per-gallon. This represents a 42-percent improvement for passenger cars and 31-percent improvement for light trucks, relative to the government reference case for 2030.[17]

Implementation barriers and implications

Increasing the GHG-reduction potential within the transportation sector from 340 megatons (mid-range case) to 660 megatons (high-range case) will require a substantial commitment to

17 Within the average miles-per-gallon performance improvements for new passenger cars, we include HEV technology, even though abatement costs for this category in isolation exceed $50 per ton. However, the associated levels of abatement were not included in our abatement ranges.

reducing carbon in the mobile vehicle fuel supply and improving vehicle fuel efficiency. An effective cluster strategy would need to take the following factors into account:

¶ **Near-term deployment of fuel-efficient technologies must overcome barriers associated with consumers' willingness to pay.** A variety of technological changes, already under way or possible in the near-term, could substantially improve fuel economy in the nation's fleet of new vehicles. Consumers' historical unwillingness to bear the full cost of each option presents a significant barrier to deployment of these improvements, placing the automotive manufacturers in a position of disproportionate responsibility for efficiency costs. There are many reasons for this consumer behavior. Ownership periods for automobiles are often too short to engender a long-term financial view; short personal payback requirements lead to the discounting of fuel savings that accrue over time; relatively low historical gas prices have undermined the perceived value of efficiency measures; and affordability limits adoption of these technologies, when trade-offs have to be made between competing features with wholly different utilities. The 12- to 15-year average lifetime of an automobile makes improving the fuel efficiency of new cars an urgent matter, because each individual purchase decision represents an enduring emissions commitment. The disconnect between initial costs and eventual fuel savings suggests that some form of intervention will be required (e.g., standards, fee-bates) for manufacturers to incorporate these features into their vehicles and for customers to pay higher up-front costs.

¶ **Reducing carbon in the fuel supply over the long term depends on the success of cellulosic biofuels.** The production of cellulosic biofuels offers a substantial reduction in net carbon emissions and represents a critical component of a low-carbon fuel pool. Commercial scale production of cellulosic technologies, however, faces a number of barriers: additional innovation in enzymes are needed; process design has to be developed and optimized at production scale; plant construction costs must be driven downward, as designs are standardized and supply chains develop. In addition, site permitting and environmental concerns about sourcing remain potential constraints. Each of these barriers could be addressed through traditional patterns of industry growth, although additional support in the form of standards or incentives could accelerate development. Sustained high oil prices would also serve as a powerful stimulus, and would accelerate development.

¶ **Technological innovation and lower-carbon electricity generation are needed for PHEVs.** Further innovation will be needed if electric-fueled vehicles, such as PHEVs, are to penetrate transportation markets with favorable economics. In particular, current battery capabilities are a barrier: ensuring that plug-in hybrid (or electric) vehicle ranges meet consumers' needs with reasonable conversion efficiencies will require further advances. In addition, abatement with vehicles powered by electricity from the grid depends on the relative carbon intensity of electricity production. The rollout of PHEVs in the absence of incremental lower-carbon generation capacity, or with lower-than-expected vehicle electrical efficiency, may inadvertently increase GHG emissions. If deployed in a specific region for the purpose of abating greenhouse gases, PHEVs would need to be integrated into a comprehensive plan that addresses the local supply of electric power, the evolution of peak and off-peak carbon intensity in the grid, vehicle battery performance, and motor fuel carbon intensity. With PHEV technology in an early stage of development, achieving its commercial and abatement potential will depend on adequate research and development support. The success of hybrid electric vehicles may provide some of the technological advances – though perhaps not all – that will be needed for PHEVs to succeed as an abatement option.

3. PURSUING A RANGE OF TARGETED MEASURES ACROSS ENERGY-INTENSIVE PORTIONS OF THE INDUSTRIAL SECTOR

Opportunities in the industrial sector (including waste) are highly fragmented across industries, processes, and energy-related applications. These options could provide 620 megatons of abatement annually in the mid-range case. Negative-cost opportunities slightly outweigh positive-cost options, giving this cluster a slightly negative average cost overall.

Emissions in the reference case

The U.S. industrial sector (including waste) produces approximately 2.2 gigatons of GHG emissions annually (Exhibit 23), representing 31 percent of U.S. annual emissions. Some 35 percent of this amount is indirect emissions associated with electricity consumed by the sector. The reference case projects a 24-percent increase in GHG emissions (to 2.7 gigatons) from the sector by 2030, growing at 0.9 percent per year. Industrial emissions are expected to rise more slowly than emissions from other sectors, such as power, transportation, and buildings-and-appliances. This slower-than-average growth would be due in part to a decrease in energy intensity in bulk chemicals, primary metals, pulp and paper, and the cement industries, and to the relatively faster growth of less energy-intensive industrial sub-sectors, such as computers, construction, and transportation equipment.

Important abatement opportunities

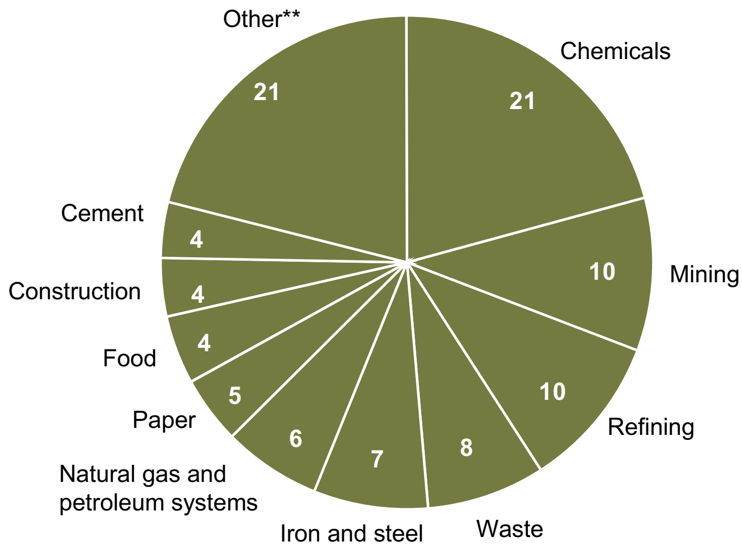
The team identified 620 megatons of abatement potential below $50 per ton, which could reduce the sector's projected emissions by 23 percent from the reference case. Important categories of abatement options include: 1) recovery and/or destruction of industrial non-CO_2 GHGs, 255 megatons; 2) carbon capture and storage, 95 megatons; 3) increased CHP generation, 80 megatons; 4) energy efficiency, 75 megatons, and 5) a switch to less energy-intensive processes and product innovation, 70 megatons (Exhibit 24). These five abatement categories cover 75 abatement options.

Recovering and/or destroying non-CO_2 GHGs. Recovering and/or destroying non-CO_2 greenhouse gas emissions across multiple industrial sectors could abate 255 megatons per year

Exhibit 23

GHG EMISSIONS IN INDUSTRIAL AND WASTE CLUSTER – 2005

100% = 2.2 gigatons*



* Including direct (from fuel/ feedstock fossil fuel combustion) and indirect emissions (from electricity usage)

** Including construction, cement, aluminum, transportation equipment, plastics, fabricated metal products, computers, machinery, wood products, electrical equipment, glass, other manufacturing, and health sub-sectors

Source: U.S. EPA; U.S. EIA Annual Energy Outlook (2007) "Reference case"

by 2030. The waste sub-sector plays a critical role in non-CO_2 GHG abatement, accounting for 25 percent of the potential. This potential comes from several gases: 70 percent is CH_4 (methane), 22 percent HFCs/PFCs, and 8 percent N_2O (nitrous oxide). The principal sources of methane-related abatement would be natural gas and petroleum systems (75 megatons), underground coal mining (35 megatons), and landfills (65 megatons). Abatement of HFCs and PFCs in semiconductor manufacturing could add another 55 megatons, and abatement of N_2O from nitric/adipic acid production could add a further 25 megatons.

The specific actions to abate non-CO_2 GHGs vary. Degasification (regular and enhanced) and catalytic oxidation would unlock the abatement potential in coal mining, possibly at negative cost. Abating HFCs/PFCs in manufacturing processes would involve repairing leaks, improving capture and recovery systems, eliminating thermal oxidation, and cleaning remotely. Methane-reduction measures in the waste industry would expand the number of landfills at which methane is recovered and improve the capture methods at others; once captured, the methane can be used in industrial processes or in electricity generation, or is flared rather than vented, converting the methane into carbon dioxide – which has considerably less warming potential.

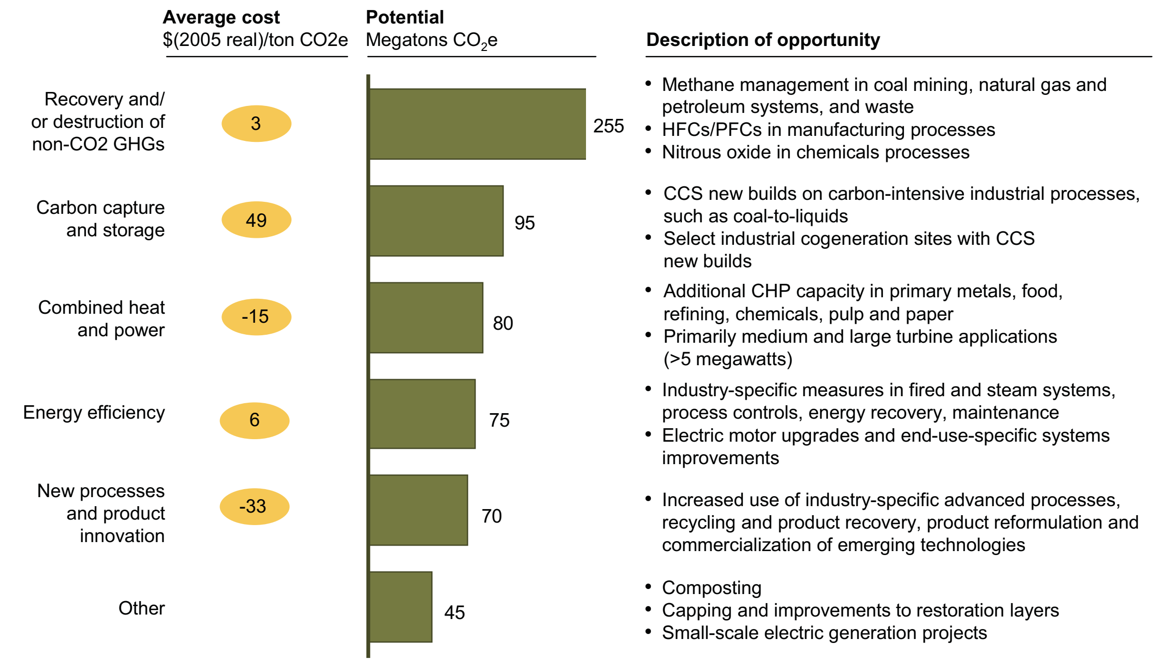
Although non-CO_2 GHG abatement options vary by sector, they share a number of common characteristics. These options are very fragmented and site specific, with varying costs and

Exhibit 24

ABATEMENT OPTIONS – INDUSTRIAL AND WASTE CLUSTER

Options less than $50/ton CO_2e

MID-RANGE CASE – 2030



Source: McKinsey analysis

volumes. Typically, they are available at negative or low incremental cost, but require additional capital that might otherwise be channeled to more attractive investment opportunities.

Capturing and storing carbon in industrial settings. CCS in industrial settings could provide 95 megatons of abatement. This option consists largely of adding CCS technology to coal-to-liquids (CTL) manufacturing sites projected (in the reference case) to come on line by 2020.

As in the power sector, CCS technology is expected to become commercially available by 2020. As a consequence, its potential is limited to 75 megatons at CTL facilities, plus 20 megatons at newly built CHP installations.

Increasing CHP capacity. Increasing CHP capacity could reduce CO_2 emissions by 80 megatons. About 65 percent of the potential incremental CHP capacity (23 gigawatts) is in medium (5 to 49 megawatts) or large (50 megawatts and larger) systems and may be achieved at near negative cost. The remainder is in smaller systems (less than 5 megawatts) and has less favorable economics. In fact, the difference between abatement costs of large and smaller CHP systems may be as much as $30 per ton. The economics of CHP are heavily region-specific, driven by local construction costs and electricity prices. Small CHP applications in the Northeast census region could potentially break even (from a cost-per-ton CO_2e perspective), for example, while in other regions they may be far less attractive economically.

Distribution of potential CHP capacity varies widely across industrial sub-sectors. About 90 percent of small CHP applications are in food and other smaller-site manufacturing sectors; 70 percent of large CHP applications would be concentrated in refining, chemicals, pulp and paper, primary metals, and cement.

Our analysis assumed natural gas would be the fuel of choice for additional CHP capacity. Abatement associated with switching fuels from coal to biomass or natural gas is limited by the share (7 percent) of coal-fired CHP that is projected for 2030 by the reference case.

The challenge of fragmentation

Greenhouse gas emissions and abatement options in the industrial sector are highly fragmented. More than 20 sub-sectors contribute to industrial emissions, with five accounting for 56 percent of emissions: chemicals, refining, mining, waste, and iron and steel. Much of the abatement potential is spread across more than 75 options: some opportunities will be unlocked through favorable economics, but others may require tailored regulatory support.

Although the reference case assumes that improvements in the energy intensity of processes in some sub-sectors (e.g., aluminum, food, cement) will avoid some 470 megatons of future emissions, these improvements are not assured and still must be captured. Without supportive regulatory structures, some of these improvements may not be made, or the emissions will be "off-shored" to other economies, with U.S. domestic GHG emissions decreasing and global emissions staying flat or rising.

Improving energy efficiency. Efficiency improvements could reduce emissions from the industrial sector by 75 megatons by 2030. Of this amount, 75 percent consists of direct emissions associated with reduced fuel and or feedstock consumption. The remaining 25 percent could come from efficiency measures related to electricity consumption.

Options for abating direct emissions include industry-specific energy efficiency measures, such as increasing the efficiency of fired and steam systems, using advanced process controls, pursuing energy recovery, and performing preventive maintenance within such energy-intensive sectors as bulk chemicals, refining, primary metals, pulp and paper, and cement.

Options for abating indirect emissions include upgrading electric motors and improving end-use-specific systems to increase efficiency. The latter includes improvements to system components, correct-sizing (load-size matching), preventive maintenance, and speed control; it accounts for 80 percent of the abatement potential associated with indirect emissions. In total, up to 30 terawatt-hours of electric power would be eliminated relative to the reference case. However, the total energy demand-management opportunity is nearly 130 terawatt-hours, if measured against current practices. The reference case assumes 100 terawatt-hours of this potential will be captured, making the incremental abatement opportunity 30 terawatt-hours.

Nearly 80 percent of the 75-megaton abatement potential in improved energy efficiency is concentrated in the Midwest and South census divisions of the U.S., in line with the distribution of energy-intensive industries, such as chemicals, refining, iron and steel, and pulp and paper.

Pursuing process and product innovations. A range of process and product improvements in the chemicals, pulp and paper, iron and steel, and cement industries could contribute up to 70 megatons of abatement potential by 2030.

The reference case projects significant reductions in energy intensity for iron and steel (28 percent), aluminum (32 percent), and cement (14 percent) production, with relatively smaller improvements in the pulp and paper and chemicals sub-sectors (8 percent each). The improvement in energy intensity includes shifts in processes and technologies (such as moving to electric arc furnaces for steel-making) that would effectively reduce the carbon intensity of the industrial sector.

We examined a wide array of process improvements and technologies that could make current and future technologies more efficient. This would include such abatement options as deploying advanced processes more widely, recycling and recovering products, reformulating products, and commercializing emerging technologies. There are multiple sector-specific abatement options within these four sub-groups, with more than 40 processes and technologies in total. These would include liquid membrane separation for chemicals; increased penetration of electric arc furnaces and thin slab casting in steel; black liquor gasification, new drying processes and paper recycling in pulp and paper; and conversion to multi-stage preheating and blended cement in the cement industry.

Like energy efficiency opportunities, abatement options in process and product innovation are concentrated in the Midwest and South census regions. Some 75 percent of this 70-megaton potential is located in these census areas, in line with distribution of the energy-intensive sectors noted above.

Implementation barriers and implications

Unlocking the abatement potential within the industrial cluster will require detailed consideration of each sub-sector. Nonetheless, a number of prevailing themes emerge when the cluster is considered as a whole. Achieving abatement between 620 megatons (mid-range case) and 770 megatons (high-range case) would require addressing the following challenges:

¶ **Composition and price volatility of the energy supply add risk.** Having pursued energy efficiency, the industrial sector has become – and is projected to remain – more natural-gas intensive. For many applications (e.g., CHP, heating furnaces), natural gas provides improved performance relative to alternatives. Nonetheless, this trend increases the industrial sector's exposure to volatile energy prices and makes the return on capital expenditures for energy efficiency improvements less certain. In an unstable environment and absent additional incentives, industrial companies may choose to pursue only a portion of the abatement potential embedded in the government reference case or otherwise discussed in this analysis.

- **Investment hurdles are high.** Typically, industrial companies require relatively rapid payback (in 1 to 2 years) on the types of investment projects covered in this chapter (e.g., investments in energy and process efficiencies). Compared to other potential capital projects, energy efficiency projects are frequently not pursued because of their lower expected rate of return and the capital constraints of companies. Finally, they also tend to be widely distributed, requiring disproportionate human resources and management attention to capture them.

- **Lack of focus on energy efficiency impedes pursuit of these opportunities.** "The more you look, the more you find" is a well-supported and repeated observation by business leaders who have experienced significant gains through energy and process efficiency improvements. Creating awareness and education programs to help industrial sector participants identify and capture efficiency opportunities across their facilities and manufacturing processes would facilitate the process of capturing abatement potential in this sector.

4. EXPANDING AND ENHANCING U.S. CARBON SINKS

Most opportunities to expand or enhance the carbon stored in U.S. agricultural lands and forests are positive cost, due to the expense of pursuing and maintaining these options. The abatement potential for this cluster totals 440 megatons in the mid-range case, with the average cost of abatement being moderately positive.

Emissions in the reference case

U.S. forests and agricultural lands absorb almost 1.1 gigatons of carbon each year. In contrast to some developing countries, where deforestation has increased GHG emissions, the U.S. has experienced the reverse. Land-based carbon sinks, specifically the carbon stored in U.S. lands and forests, have grown steadily over the past 50 years.[18] Purposeful management could enhance the ability of these sinks to absorb carbon by some 440 megatons by 2030. This represents a significant opportunity that could be used in the near-term to offset emissions until other sectors develop more cost-effective methods of abatement.

Net annual carbon absorption by U.S. lands and forests has risen by 25 percent since 1990, primarily due to greater accumulation of carbon in existing forests. Indeed, the period from 1990 to 2005 saw a 17-percent rise in the net amount of carbon stored in forests annually, due to increased stock in existing forests and some limited afforestation.

Despite recent growth, net annual carbon absorption is projected to slip by 7 percent between 2005 and 2030, due to slower expansion of forest lands and slower carbon uptake rates in maturing forests.

18 This project focused on terrestrial carbon sinks and did not address carbon absorption by oceans, lakes, and rivers.

The stock of harvested wood used for such products as lumber, paper goods, and firewood will continue to increase, due to the slowing rate of decay in landfills. This increase may partially offset the loss of absorption by forest stocks. At the same time, carbon absorption in the soil is projected to remain level at 35 megatons to 40 megatons per year.

Important abatement opportunities

Carbon sinks associated with forestry, land use, and soils could provide some 440 megatons of annual emissions offset by 2030. Within this total, forestry and land-use changes account for 320 megatons – enough to increase net carbon absorption by 30 percent over present levels; expanding agricultural sinks could provide the remaining 120 megatons.[19] We refer to these opportunities as offsets, because they absorb CO_2 emissions. They are, however, vulnerable to disruption and decay, making them less permanent than other forms of abatement.

The key areas of opportunity include afforestation of pastureland and cropland, conservation tillage, forest management, and usage of winter cover crops (Exhibit 25).

Afforestation of pastureland. This opportunity consists of afforesting marginal lands, where opportunity costs are low. Seventeen million hectares – 7 percent of U.S. pastureland – qualifies as marginal, based on unsustainable erosion or low productivity. This land could be converted to forest over the course of 15 years without significantly affecting livestock production. Indeed, 88 percent of beef production in the U.S. occurs in feedlots, which comprise less than 0.1 percent of pastureland; eliminating less than 10 percent of U.S. pastureland would affect only a small fraction of the U.S. meat supply. Converting this land to forest could create an incremental carbon sink of some 130 megatons per year.

The total cost of afforesting pastureland depends on three factors: opportunity costs, conversion costs, and maintenance costs, each of which make up roughly one-third of the total. The opportunity cost derives from lost potential production, for which land-owners would likely seek compensation before they commit to afforesting their land. Conversion includes the cost of establishing a forest, such as seed, labor, and equipment costs; maintenance includes annual upkeep, such as fertilizers, herbicides, and labor, as well as the cost of measuring and monitoring to track carbon accumulation over time.

The viability of afforestation varies by region, with offsets being more cost-effective where opportunity and conversion costs are lower and carbon-uptake rates are high. Given these factors, it is not surprising that the southern U.S. could be a major provider of abatement through afforestation, contributing some 50 percent of the incremental offset from

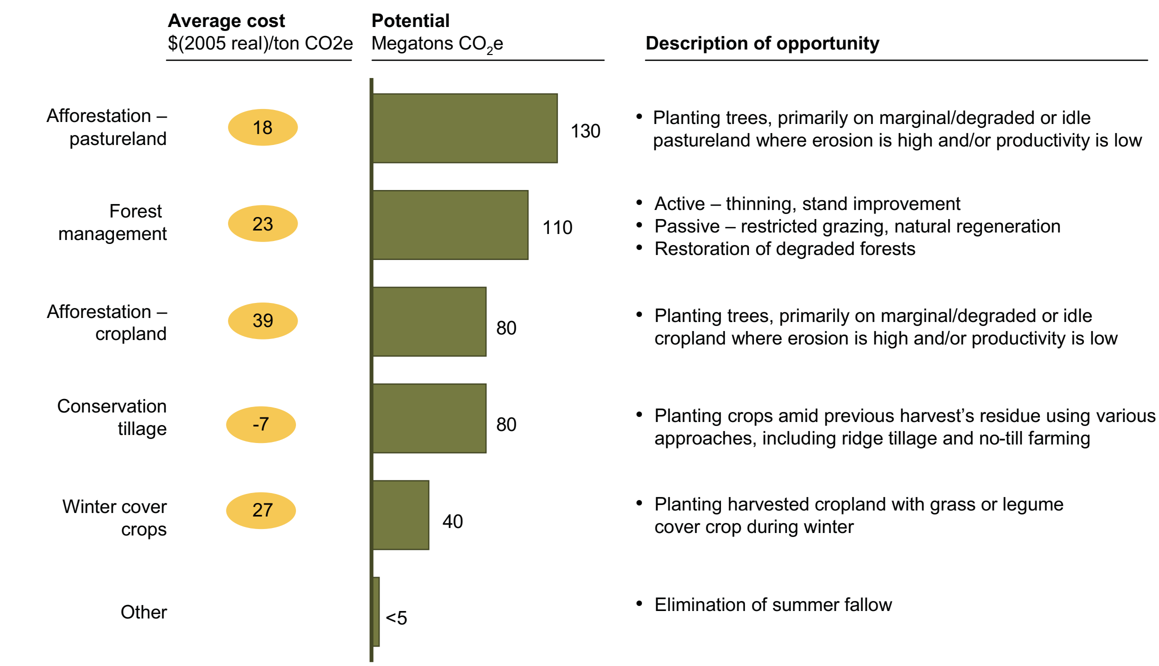
19 The team identified an additional 40 megatons of abatement potential (beyond the expansion of sinks) in the agriculture sector, with an average cost of $17 per ton. Options analyzed included improved manure management practices (for dairy cattle and swine); grazing management; reductions in enteric fermentation emissions through intensive grazing, dietary supplements, and injections; split fertilizer application; and nitrification inhibitors. Some of these opportunities, however, provide abatement only at costs considerably above $50 per ton and therefore were not included in our analysis.

Exhibit 25

ABATEMENT OPTIONS – TERRESTRIAL CARBON SINKS

Options less than \$50/ton CO_2e

MID-RANGE CASE – 2030



Source: McKinsey analysis

afforestation of pastureland. Rapid carbon uptake and low conversion costs due to a warm, moist climate make afforestation in the South the forestry and land-use management option of lowest cost.

Afforestation of cropland. Afforestation of 13 million hectares of cropland could provide 80 megatons of emissions offset. Afforesting cropland costs more than afforesting pastureland, because of the substantially higher opportunity cost. Of the 179 million hectares of cropland in the U.S., 13 million (7 percent) could be afforested. These 13 million hectares constitute some 80 percent of the land in the federal government's Conservation Reserve Program (CRP). This program, begun in the 1990s, encourages land-owners to take marginal cropland out of production. Sitting fallow now, this land could be afforested without affecting crop production.

Cropland and pastureland have similar conversion and annual maintenance costs, and they have a similar expected carbon uptake rate of around 7.4 tons CO_2e per hectare per year. As with pastureland afforestation, the most cost-effective opportunities for cropland conversion are found in the South, due to high carbon-uptake rates and low conversion costs.

Conservation tillage. Adopting conservation tillage practices, such as reduced-till and no-till, could offset 80 megatons per year. Nearly half of this potential is located in prairie states. These practices store carbon by preventing the disruption of organic matter in the soil, allowing the organic matter to accumulate in the ground rather than be released as carbon dioxide, as occurs through intensive tilling practices. With conservation tillage, carbon would continue to build up in the soil for 20 to 25 years – so long as the soil was not disturbed – until the soil reaches its saturation point.

The shift to conservation tillage may come at a net savings for soy and wheat farmers. The practice is more difficult with corn, however, because corn requires more intensive tilling: residue tends to build up in corn fields, and corn's longer growing season requires earlier planting, when the ground is harder – both factors necessitate the use of row planters. In addition, the 5-percent projected yield loss that typically occurs during the first 3 to 5 years of conservation tillage of corn would result in a high opportunity cost, given the current high price of corn.

Forest management practices. These practices would provide the lowest-cost offset option in most regions. They fall into three categories, which together could offset some 110 megatons by 2030:

- **Active forest management** involves improving timber stands on some 10 million hectares of privately held lands across the nation. This is by far the least costly of the forest management practices, with total levelized costs of $45 per hectare per year. Active management could provide 30 megatons of offset.
- **Passive forest management** allows natural regeneration by measures such as restricted grazing. Though less expensive in absolute terms ($27 per hectare per year), because less labor is required, the expected per-hectare carbon-uptake gains from passive management are lower than those of active management, resulting in a slightly higher cost

Storing carbon

Even with substantial afforestation over the past 50 years and gradual changes in soil management practices, the carbon stored in U.S. lands and forests is far less than it once was. The nation has a significant opportunity to cultivate new forests, increase the carbon in existing ones, and increase the carbon stored in the soil.

The gradual saturation of forests and soils and the risk of impermanence remain key challenges in the use of forests as offsets for carbon emissions. The annual gains, particularly in forests, cannot be maintained indefinitely. As a forest approaches maturity (the point at which annual growth is balanced by annual decay), the annual absorption potential declines, eventually reaching zero. In most regions, maturity arrives after 150 to 200 years, though in fast-growth regions like the Southeast, carbon uptake can begin leveling off as early as 50 years after planting.

The increased carbon uptake from afforestation, forest management, and conservation tillage may be reversed if the forests are ever disturbed or farmers switch back to conventional tilling. A forest fire, for instance, would release much of the carbon stored in the trees, counter-balancing the years of incremental offsets gained through afforestation. For an offset to be equivalent to a reduction in emissions, the offset would have to be managed as an ongoing concern.

per ton of abatement. Some 8 million hectares of forests would benefit from passive management practices (mostly at the edges of pastureland, where grazing disturbs tree growth), yielding an additional offset of 10 megatons per year.

¶ **Reforestation** involves planting additional trees in low-density or recently harvested forests. Reforestation is the most costly of these practices. Unlike crop or pasturelands, forests suitable for restocking are typically filled with obstacles (such as uprooted trees and stumps) that make hand planting necessary, which is more expensive than mechanical planting. While reforestation is the most significant source of incremental offset among the viable forest management practices, lack of safeguards could allow conversion of natural forests to plantations, with attendant adverse impact on climate and other environmental considerations. Some 14 million hectares of forest, 60 percent of which is in faster-growth southern regions, would benefit from restocking, providing 70 megatons of additional carbon absorption.

Winter cover crops. Planting harvested land with a legume or grass cover during the winter to preserve residue in the soil has the potential to store an additional 40 megatons of carbon per year at relatively low cost. Nearly 25 megatons of abatement potential is concentrated in the prairie states. Up to 59 million hectares of moist cropland would benefit from cultivation of winter cover crops. In addition to enabling incremental annual carbon uptake of 0.3 tons CO_2 per acre of soil, planting winter cover crops reduces the amount of fertilizer needed during the summer growing season by some 30 percent, making this a relatively cost-effective option, despite the additional labor required to plant the cover crop. It also reduces erosion and nitrate leaching.

Implementation barriers and implications

The mid-range case suggests that 440 megatons of annual CO_2e reductions are possible within the carbon-sink cluster. Achieving the high-range potential of 590 megatons would require commensurate discipline to alter, improve and sustain more carbon-beneficial land-use practices. Several important implications follow from this discussion:

¶ **Opportunities are widely distributed across a broad range of stakeholders.** Carbon sinks are distributed across a diverse population with widely divergent motives, making them inherently hard to access and manage. Given the many alternatives for using land, it is particularly important that incentives be available to compensate farmers and other landowners for managing the carbon in lands under their control. These incentives could take many forms (e.g., tradable offset credits, tax credits).

¶ **Monitoring and verification will require special attention.** An overarching monitoring and verification program for carbon sinks would need to address three issues: the risk of impermanence, leakage, and varying carbon uptake rates. Storing carbon through forestry and land-use techniques depends on the long-term management of natural resources. Sustained accounting and verification processes will be needed to ensure the integrity of and future investment in carbon storage programs. A sink management system would need to address carbon stocks holistically and manage linked activities wherever possible. Finally, the differences in carbon uptake rates between and within regions and among forest, soil, and crop types, as well as the gradual reduction in uptake that occurs as the soil and forests approach saturation, demand additional verification. Systems must be developed to effectively survey and account for such variations.

¶ **The offset potential associated with forests and agricultural lands could serve as a "bridge" until emissions can be reduced elsewhere in a more cost-effective manner.** As participants in other sectors seek more efficient methods for decreasing emissions, the offset opportunities from forest and soil management and land-use would likely be an attractive option in the near-term. Interest in offsets, particularly low-cost forestry management offsets, might flourish in the near-term to respond to demand from high-emitting sectors where abatement of commensurate volumes of carbon is possible only at higher costs.

5. REDUCING THE CARBON INTENSITY OF ELECTRIC POWER

At 800 megatons annually in the mid-range case, options that reduce the carbon intensity of electric power form the largest cluster of abatement potential that we analyzed. This cluster also has the highest average cost, due to the capital intensity of many options.

Emissions in the reference case

In the emissions reference case, power generation in the U.S. is projected to increase by 1,520 terawatt-hours: from 3,865 terawatt-hours in 2005 to 5,385 terawatt-hours in 2030. Increased demand for power would be met largely through the construction of new coal-fired plants utilizing either pulverized coal or IGCC to produce 145 gigawatts of capacity, and gas-fired plants yielding 80 gigawatts of capacity. A modest build-up of renewables would yield 17 gigawatts, and nuclear power would account for 13 gigawatts. As a result, the carbon intensity of the U.S. electric grid would remain near its current level, rising slightly from 0.61 to 0.62 tons CO_2e per megawatt-hour by 2030.

The sustained use of carbon-based generation capacity – coupled with growing demand for electricity – would result in an increase in GHG emissions from the power sector. Direct emissions from the power sector are projected to rise from 2.4 gigatons in 2005 to 3.4 gigatons in 2030.

The reference case assumes certain performance improvements at power plants, such as the heat rate of a new supercritical pulverized coal plant, which is projected to be 15 percent better in 2030 than the average for the U.S. coal-fired fleet in 2005. It does not assume, however, that some of the important GHG-abating technologies, such as CCS technology, will be available by 2030.

Important abatement opportunities

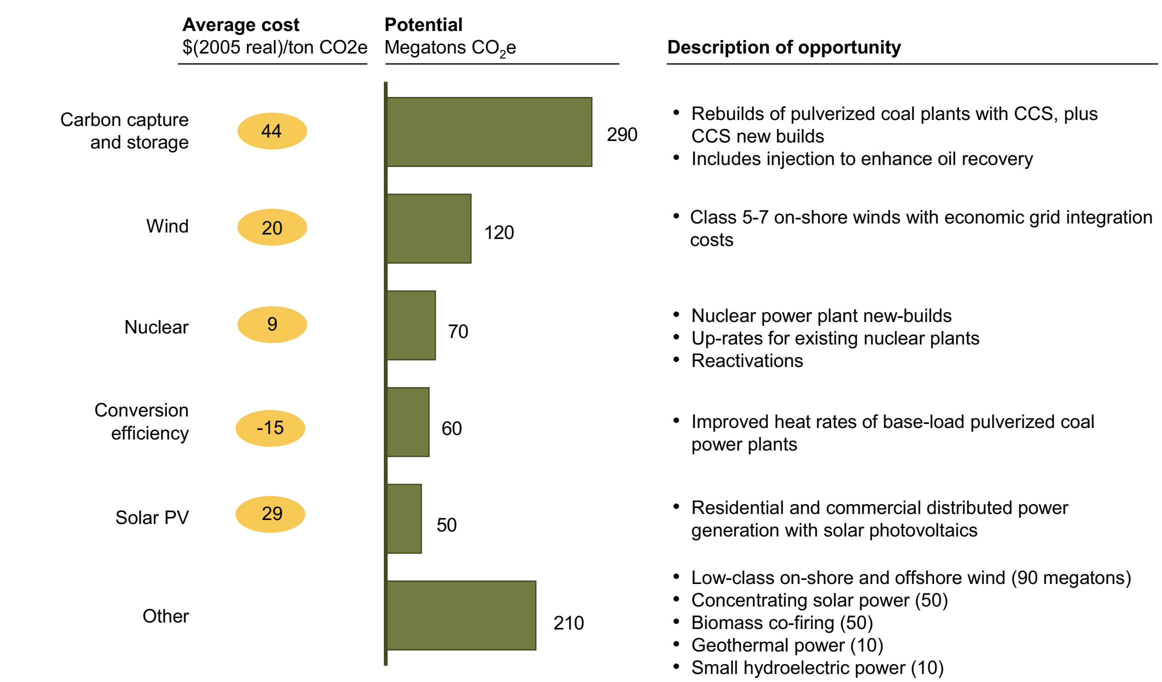
The power sector offers nearly 900 megatons of GHG abatement. Approximately 800 megatons could be abated at marginal costs less than $50 per ton. This potential would be in excess of totals achieved through energy efficiency measures in the buildings-and-appliances and industrial sectors. The key areas of opportunity within this cluster include: carbon capture and storage; wind, nuclear, and solar power generation; and improvements in power plant conversion efficiencies (Exhibit 26).

Exhibit 26

ABATEMENT OPTIONS – POWER CLUSTER

Options less than $50/ton CO_2e

MID-RANGE CASE – 2030



Source: McKinsey analysis

The interplay between energy efficiency and additions of zero-carbon energy sources has a noteworthy impact on the cost of abatement. Assuming energy efficiency measures take effect within the next few years, they would “abate” the construction of coal- or gas-fired power capacity that would have otherwise been built to meet incremental demand for electricity. In most service regions, zero-carbon power generation (e.g., renewables, nuclear) will come on line over the next 5 to 15 years, abating the remaining expected new-build fossil-fired capacity and eventually displacing and retiring some base-load fossil-fired power plants. At this point, additional renewable energy sources will incur the expense associated with retiring productive (though aging) assets. As a consequence, the cost of abatement through renewables will rise as their growing presence leads to the retirement of fossil-fired generation capacity.

We will examine the key opportunities in this sector in order, starting with the largest:

Carbon capture and storage. CCS captures concentrated carbon dioxide emissions at the point of generation and stores them. CCS can be used with any fossil fuel, but enjoys more favorable economics when coupled with coal-fired power plants, because of the higher carbon concentration of the exhaust gases. This technology is particularly important because of its potential role in neutralizing the GHG emissions associated with the nation's most plentiful fuel source.

At the moment, CCS is an expensive, early-stage technology that has yet to be proven at commercial scale for base-load power generation. A number of emerging approaches are expected to enable carbon capture. Each of these technologies – IGCC, post-combustion, oxyfuel – may provide tangible benefits and be better suited for specific coal types or installations.

Based on interviews with industry experts and a bottom-up assessment of system costs, the research team estimated the generic cost of building a CCS-equipped coal power plant at approximately $2,800 per kilowatt of capacity (excluding financing costs).[20] This figure, with associated operating costs, was adjusted to reflect local considerations when determining likely penetration by region. We calculated the cost of abatement based on the least-cost solution available today for the specific application. While there is no clear technological winner at present, we would expect a successful future technology to be available at or below the current lowest-cost CCS option.

Based on the projected timeline for commercialization, we do not expect that CCS would provide substantial abatement until after 2020. This expectation is due in part to likely delays in the progress of the first pilot plants, as they are developed and tested to prove the economics of the technology. There are also difficult permitting and liability issues (e.g., regarding underground storage of CO_2) that must be resolved which will lengthen the time to large-scale rollout.

Within the decade of the 2020s, however, CCS has an abatement potential of more than 290 megatons. The potential is split between new-build and rebuild coal-fired power plants. If this potential were fully captured, by 2030 nearly 9 percent of U.S. electricity would come from CCS-equipped coal plants.

Full commercialization would bring many challenges. Even when carbon-capture technology is proven and available, there would be concerns about its reliability and operational performance. The carbon capture process would also have to be integrated with transportation, injection, storage, and verification systems. These issues, as well as legal and regulatory risks (including permitting for storage facilities and CO_2 pipelines), may slow the realization of this opportunity. If proven commercially viable, CCS has the potential to provide even greater GHG reductions beyond 2030.

20 We have recently observed significant run-ups in capital costs for new-build power plants, in the range of 30 to 50 percent, with greater increases in some regions. The research team has modeled capital costs (net of financing costs) in steady state terms, which do exceed historical levels due to fundamental shifts in the economics of construction, equipment, and materials markets.

CCS retrofits have lower potential and are more expensive than rebuilds. Although they use the same basic technologies as re-builds (e.g. oxyfuel, post-combustion) to enable carbon capture, retrofits incur significant additional costs due to space limitations and plant-tuning requirements. With these added expenses, the cost of abatement with a CCS retrofit is $10 to $15 per ton higher than with a CCS re-build.

Some of the cost associated with CCS abatement may be offset by pairing CCS with some other industrial application, such as oil extraction, where injecting CO_2 into oil wells enhances oil recovery. Depending upon oil well characteristics and geographic considerations, enhanced oil recovery (EOR) could offset between $15 and $25 of the per-ton cost of captured and injected CO_2. The incremental size of the EOR market for CO_2 has been estimated at 100 to 200 megatons CO_2 per year by 2030. Beyond well and geographic constraints, EOR appears to be limited also by the availability of purer sources of CO_2 gas available elsewhere, which may capture a large fraction of this market.

Wind power. Wind power could provide 120 megatons of annual abatement by 2030. This potential derives from Class-5, Class-6, and Class-7 wind locations with moderate costs for grid integration. Capturing this abatement potential would require 116 gigawatts of installed capacity in 2030 (versus 10 gigawatts available in 2005). An additional 90 megatons of abatement may be available if the potential of sites with lower wind classes, off-shore locations, and/or high connection costs can be unlocked. However, these opportunities would have considerably higher costs.

As penetration increases and progressively fewer attractive wind resources are unlocked, the abatement cost for wind power will rise. This trend is in sharp contrast to solar PV, where learning and innovation make abatement cheaper over time. Three factors drive the rise in cost for wind: the lower quality of incremental wind resources, higher relative costs for grid integration, and an increased service penalty for intermittency due to the burden this cycling capacity places on the grid.

Wind also suffers additional challenges related to permitting and public acceptance, which create policy and social barriers to full capture of the resource's potential.

Nuclear power. Nuclear power has the potential to provide some 70 megatons of abatement annually by 2030. The team looked at three options: new-build plants, up-rates, and reactivations. For the mid-range case, we assumed no license extensions beyond those forecast in the reference case would be granted. Of these options, new-build plants and up-rates warrant discussion:

¶ **New build plants.** In the mid-range case, we estimate the potential for new-build nuclear power capacity in 2030 at nearly 25 gigawatts above 2005 levels. Expanding capacity depends on successful construction and commencement of early nuclear plants, particularly as measured by cost and time of construction. Should overruns for construction costs and schedules occur, the expansion of nuclear power would likely be limited. Long construction lead times and severe bottlenecks in permitting, engineering, materials (e.g., nuclear-grade nickel alloys), equipment (e.g., nuclear-grade large-ring forgings), and construction have driven up the cost of nuclear plant long-term construction cost to $3,500 to $4,000 per kilowatt of capacity (net of financing cost) and may impede the build-up of this sub-sector in the future.

¶ **Up-rates.** The team looked at three types of up-rates: measurement-uncertainty-recapture-power up-rates, stretch-power up-rates, and extended-power up-rates. These are typically available at negative cost, due to the low operational and maintenance costs of depreciated nuclear power plants.

Many of the 104 operating reactors in the nation's existing nuclear fleet will approach the end of their 60-year service lives between 2030 and 2050. Assuming they are replaced with new nuclear plants, a wave of additional construction and commissioning would follow. An expansion of that magnitude would require many additional qualified operations, maintenance, and construction personnel to build and operate the new nuclear sites.

Conversion efficiency improvements. Improving conversion efficiency of power plants – particularly coal-fired units – could provide 60 megatons of abatement potential by 2030. The team screened the nation's fossil fleet, focusing on heat rate improvements in high-capacity base-load power plants (larger than 250 megawatts with a capacity factor greater than 50 percent). We evaluated an array of options in key areas of efficiency loss: boiler air-in leakages, turbine seals, condenser fouling, turbine blades, boiler cleanliness, and feed pump efficiency. We also evaluated the potential for operational changes, such as the elimination of variability in operator performance.

Costs for improving heat rates are frequently negative, because the fuel savings offset the capital investments. Some plants may be unwilling to make these capital investments, however, because the investments could trigger a requirement to install the best available environmental control technology (e.g., New Source Review), leading to additional – and potentially unrecoverable – investments. Furthermore, fuel costs are often passed through directly to rate payers, though capital investments must be recovered through base-rate increases.

Distributed solar photovoltaics (PV). Solar power and distributed generation with solar photovoltaics represent considerable abatement potential. In total, distributed solar PV could achieve nearly 50 gigawatts of capacity by 2030, yielding some 50 megatons of abatement. At this level of penetration, nearly 5 million residences would have solar panels on their roofs (~3 percent of houses nationwide) and 150,000 businesses would have commercial systems installed. Unlike other solar technologies, solar PV relies only on ambient solar radiation, which allows it to be used in regions with less direct solar exposure.

Our estimate of solar PV penetration anticipates cost reductions due to improvements in module conversion efficiency, DC-AC conversion efficiency, inverter design, and the installation process. Additional improvements in manufacturing processes, plus innovation and the removal of bottlenecks in the materials and construction markets, would enable solar PV to achieve cost parity with a region-specific combination of natural gas-fired baseload and conventional peaking generation sources in the grid near 2020. In the past, cost improvements in solar PV have been as high as 20 to 25 percent with each doubling of installed capacity. The research team applied various learning rates to system components, depending on the potential for innovation in those areas. On average, the full levelized cost for electricity from solar PV (including module and installation costs, plus continuing transmission and distribution charges) would be compressed from the range of $300 to $350 per megawatt-hour in 2005 to $90 per megawatt-hour by 2030. In the most attractive regions with the highest level of solar radiation, the cost could fall as low as $70 per megawatt-hour.

Despite significant cost compression, regional differences remain important. Abatement costs vary by as much as $30 per ton across regions. The variation stems primarily from differences in the intensity of solar radiation, which affects capacity factors, though installation costs are also a significant contributor. If costs do not decline as expected, whether due to technology barriers or lack of up-front investment to generate learning, the abatement cost for solar PV may remain at the current level (~$210 per ton), and the corresponding abatement potential would be forfeit. The technology faces additional challenges as well, including high up-front system costs, near-term bottlenecks in the silicon market, aesthetics and zoning concerns, interconnection compatibility, and poor conversion efficiency (especially for thin film in residential settings).

Solar uncertainty

Among the options discussed in this report, abatement from solar power exhibits the widest range of potential outcomes. In 2005, the U.S. had less than 0.5 gigawatts of installed solar PV capacity. By 2030, the U.S. could have somewhere between 28 gigawatts (low-range case) and 148 gigawatts (high-range case) of solar PV capacity, depending largely on the degree of cost compression and learning rates achieved for production and installation.

Solar PV could achieve growth akin to that of the semi-conductor industry over the past 25 years, if conditions are favorable. Specifically, if solar power reaches cost parity relative to a region-specific combination of natural gas-fired baseload and conventional peaking generation sources – absent subsidies or other distorting mechanisms – capital would likely flow in quickly to meet demand and develop the industry scale required for further rapid deployment. Global investment rates, production capacity increases, and technological improvements suggest grid parity in large areas of the U.S. may be possible by 2020.

Should learning rates and cost compression slow, due to significant technology challenges or the pursuit of other renewable energy sources at the expense of solar applications, the growth of solar capacity over the next two decades will be stunted.

Natural gas-fired power. The research team assessed the abatement potential of natural gas-fired power generation, looking at construction of natural gas-fired assets instead of more carbon-intensive coal assets and more frequent dispatch of existing natural gas-fired plants.

Gas-fired generation may serve as a tactical solution in the short term, but it does not appear to be an economically efficient option for sustainable long-term abatement, given the likely sources of incremental gas supply (new well development, liquefied natural gas imports, and unconventional gas resources) and the corresponding implications for the price of gas. Consequently, we estimated nearly 60 megatons of abatement potential for natural gas-fired power at a marginal abatement cost of $64 per ton, which, because of its high cost, we did not include in our abatement ranges.

Implementation barriers and implications

Moving from 800 megatons (mid-range case) to 1,570 megatons (high-range case) of annual CO_2e reduction in the electric power sector would be difficult: it would require simultaneous success delivering risk-laden, large-scale power plant projects (e.g., nuclear, CCS), while harnessing a new set of renewable resources that will challenge the distribution model of the electricity grid today (e.g., solar, wind). An effective power sector abatement strategy should take the following factors into account:

¶ **Advances in several areas will be needed to realize the potential of CCS.** CCS would enable the U.S. to continue taking advantage of its plentiful coal reserves, even in a carbon-constrained world. Unlocking the potential of CCS, however, will require innovation to ensure commercial scalability of the technology, component advances to improve system reliability, enhancements in verification and monitoring processes to validate storage, and possibly financial support to reduce initial capital risks during early-stage development. In addition, significant liability issues will have to be overcome to provide legal protection against the uncertainties associated with the management of underground CO_2 reservoirs. Given the broad range of unknowns, large-scale pilots will be essential to validating the technology and demonstrating its reliability. Initial policy support should enable integration of the technologies at scale in demonstration units. Once performance expectations are known, a broader plan to support deployment can then be defined. Not only does CCS offer significant abatement potential for the period from 2020 to 2030, but if proven at scale, it will likely become important in the development of infrastructure capable of making deep cuts in the carbon intensity of the power sector from 2030 through 2050.

¶ **Renewables offer significant potential and substantial challenges.** The U.S. is rich in the conditions favorable for renewable power production. Harvesting renewable energy resources will require overcoming a number of barriers. Intermittent availability and the need for back-up power present challenges for solar and wind power alike. Both technologies would require investments in the transmission and distribution grid at a time when broader network upgrades are needed; consequently, solar and wind will be competing for capital and other resources. In addition, both technologies are facing supply chain bottlenecks, with constrained production generating significant margin inflation due to short-term supply-demand imbalances. Solar will further require additional innovation in production and installation, if it is to achieve long-term cost parity with alternative generation. Some of the potential from wind and solar power may be unlocked through provisions in current policies. Capturing further abatement potential, however, will likely require significant innovation and support from carefully crafted region- and technology-specific measures. These measures might include tax credits and exemptions, performance-based incentives, payment to distributed generators for electricity produced, regional Renewable Portfolio Standards (RPS) with set-asides for specific technologies, simplified interconnection standards, and peak pricing, to name a few options.

¶ **Barriers to the rapid ramp-up of nuclear power are significant.** Lengthy permitting processes, bottlenecks in the value chain, limited site availability, and shortages of engineering and operational talent are the formidable challenges facing nuclear power. Engineering, procurement and construction capabilities will remain a bottleneck for any abatement opportunity that requires large-scale plant development. Ongoing political concerns about nuclear waste and the proliferation of nuclear technology remain relevant and have the potential to present unforeseen challenges as incidents occur around the globe. Addressing the barriers associated with increasing nuclear power generation capacity must begin with reasonable assurances against schedule overruns. Streamlined permitting procedures and safeguards against unnecessary delay will be required to prevent burdensome finance charges from undermining overall project economics.

¶ **Aggressively pursuing natural gas-fired generation may provide a near-term safety valve, but it will not likely be the most cost-effective abatement option in the long-run.** The inherent carbon-efficiency of gas and the comparatively low capital costs for gas-fired power plants favor this technology as a stopgap measure in areas requiring near-term generation capacity. Depending on where the natural gas is sourced, however, this option could increase the nation's dependence on foreign fossil reserves.

¶ **Utilities may be reluctant to support the changes anticipated in the power generation sector.** New electricity generation technologies investigated for this report are capital intensive and would require utilities to recover their investments. In regulated markets, regulators (and customers) would need to understand the potential impact on rates. In deregulated markets, regulators and system operators would need to ensure that low-carbon generation sources are made available and find ways to compensate providers for low-carbon service. Overall, motivating utilities to pursue abatement options in energy efficiency and energy production will require that utilities receive benefit from both reducing demand and developing higher-cost generation capacity.

* * *

The five clusters of opportunities discussed here could provide the U.S. with 3.0 gigatons (mid-range case) to 4.5 gigatons (high-range case) of abatement, using existing or high-potential emerging technologies while maintaining relatively constant consumer utility. Clearly, a number of additional abatement approaches fall outside this array of options (e.g., incentives to change consumer behavior, public education and awareness campaigns). Even within individual clusters, we expect additional approaches and innovations to emerge over time. That said -- given the abatement potentials contained in each cluster -- we believe they provide a useful framework and set of tools for shaping a coordinated economy-wide response to rising emissions.

4 Project conclusions

The intent of the U.S. Greenhouse Gas Abatement Mapping Initiative is to establish a rigorous and consistent fact base covering costs and feasible potentials for greenhouse gas abatement opportunities available in the United States. This report does not advocate a specific strategy or set of policies for reducing GHGs, and (as noted) the analysis was intentionally constrained in several ways. The resulting fact base, however, may provide a foundation for policymakers, business leaders, academics, and other interested parties in considering economically sensible strategies for curbing GHG emissions in the U.S.

The central conclusion of this project: *The United States could reduce greenhouse gas emissions in 2030 by 3.0 to 4.5 gigatons of CO_2e using tested approaches and high-potential emerging technologies. These reductions would involve pursuing a wide array of abatement options available at marginal costs less than $50 per ton, with the average net cost to the economy being far lower if the nation can capture sizable gains in energy efficiency. Achieving these reductions at the lowest cost to the economy, however, will require strong, coordinated, economy-wide action that begins in the near future.*

Abatement opportunities are highly fragmented and widely distributed across industry sectors and geographic regions in the U.S. No single abatement option accounts for more than 11 percent of the total opportunity. The sector with the largest emissions (power generation) only accounts for approximately one-third of the abatement potential we analyzed.

Each of the four major aggregated regions analyzed have abatement potential in excess of 330 megatons with marginal costs less than $50 per ton, but the mix varies significantly. The cost and potential for abatement in the power sector differs from region to region with the carbon intensity of the existing generation portfolio and expected growth of electricity demand: average carbon intensity of power generation varies by more than 50 percent per megawatt-hour, and expected growth for power through 2030 ranges from 22 to 54 percent across the regions. Solar photovoltaics are far more economical in the Southwest (given solar intensity) and the Northeast (given high electricity prices); wind energy has the greatest potential in the upper Midwest; and the Southeast offers the largest growth in new building stock but has limited potential in renewables.

Economic sectors and geographic regions that can quickly and cheaply adopt clean energy supplies will gain relatively less in abatement benefits from energy efficiency improvements compared to sectors and regions that have a high-carbon generation portfolio. In regions with high-carbon grids, energy efficiency improvements, typically through upgrades to building standards, HVAC equipment, and appliances, are likely to be the most effective and lowest-cost strategies. Conversely, sectors and regions with access to low-carbon grid infrastructure offer more compelling applications of such emerging technologies as PHEVs.

Any national strategy for reducing GHGs that does not unlock a broad range of options – including buildings, appliances, vehicles, industrial processes, forestry and agriculture management – will fall well short of the abatement reductions for 2030 contained in the economy-wide climate-change bills currently before Congress. By the same token, deemphasizing sectors or regions that are rich in low-cost or "negative cost" abatement would significantly drive up the aggregate costs of achieving any abatement target.

Consequently, we believe a comprehensive abatement program for the U.S. should be built on three principal actions:

1. **Stimulate action through a portfolio of strong, coordinated policies to capture GHG reductions efficiently across industry sectors and geographies.** These policies would need to support the following developments:

   ¶ **Visible, sustained signals to create certainty about the price of carbon and/or required emissions reductions.** This will help encourage investment in options with long lead times and/or lifecycles. Lack of investment certainty is a major reason that many important investments are not being made today.

   ¶ **A coordinated economy-wide set of abatement policies and initiatives.** Low-cost abatement options are widely distributed across sectors and geographies. Any policy approach that does not unleash a full range of these options risks missing proposed 2030 reduction targets and/or driving up total costs to the economy. A piecemeal approach to carbon GHG regulation may drive up total compliance costs, create market distortions (e.g., by encouraging companies to locate carbon-intensive activities in states with less stringent environmental policies), and create an uneven playing field for U.S. businesses. Furthermore, many of the early-stage technologies featured in our analysis will achieve economic viability more effectively if pursued on a national scale.

   ¶ **Exchange mechanisms (e.g., trading schemes, offsets, tax credits) to create fungibility across fragmented markets, create greater market transparency, and drive least-cost solutions.** Linking GHG-reduction opportunities across sectors and regions within the U.S. would facilitate the capture of many lower-cost abatement opportunities. The capture of forestry sector opportunities, for example, would likely be accelerated by an offset mechanism. Similarly, an international mechanism could give the U.S. access to lower-cost abatement opportunities abroad, assuming steps are taken to link carbon costs across economies, though this form of abatement was outside the scope of this report.

- ¶ **Verification, monitoring, management, and enforcement systems to ensure sustained abatement impact.** The ability to monitor the sustained impact of abatement options will be an essential element of any cost-effective program. The absence of such systems could bias the design of policy toward easily measured point sources, which may not always offer the most cost-effective solutions. As much as 40 percent of low-cost abatement potential is in distributed opportunities, such as end-user energy efficiency, forestry, and improved soil management practices. Ensuring sustained capture of these opportunities would require the development of new systems to verify, monitor, manage, and enforce the emissions abatement.

- ¶ **Safeguards against "leakage" and transfer of GHG-emitting activities internationally.** A counterproductive consequence of strong U.S. actions to abate emissions could be an unintended incentive for U.S. industry to off-shore the production of carbon (through relocation of industry and/or increasing imports from countries that do not have similarly stringent GHG policies). Consequently, policymakers should consider creating a consistent framework and strong enforcement approaches in concert with the international community to prevent emissions off-shoring.

2. **Pursue energy efficiency and negative-cost options quickly.** Many of the most economically attractive abatement options we analyzed are "time perishable": every year we delay producing energy-efficient commercial buildings, houses, vehicles, electric motors, and the like, the more negative-cost options we lose. The cost of building energy efficiency into an asset when it is created is typically a fraction of the cost of retrofitting it later or retiring an asset before its useful life is over. In addition, an aggressive energy efficiency program would reduce demand for fossil fuels and the need for new power plants.

   Energy efficiency options we analyzed would provide substantial lifecycle savings that exceed their incremental cost, abating 1.1 gigatons (mid-range case) to 1.4 gigatons (high-range case) of emissions. Other negative-cost options, such as conservation tillage and fuel economy packages, would increase this pool of economically beneficial abatement to 1.3 gigatons in the mid-range case and 2.0 gigatons in the high-range case. Pursuing these options would effectively "buy time" for the nation to develop and deploy the technologies for future low-carbon power production and transport. Furthermore, savings associated with negative-cost options – if fully captured – could (on a societal basis) substantially offset the remaining cost to reach 3.0 gigatons in the mid-range case and 4.5 gigatons in the high-range case.

   These economically beneficial options are not, however, being captured today, highlighting the need for policy support and industry innovation to overcome fundamental barriers to market efficiency. These inefficiencies in the market arise from many factors, including low visibility and lack of information (i.e., "how much would extra insulation save?"), agency issues (e.g., builders focus more on first cost than lifecycle savings), day-to-day "inertia" (e.g., individual decisions too small to bother with, though collectively they have material consequences), and high consumer discount rates (e.g., expectations that an investment should pay for itself within 2 or 3 years).

Given consumers' historically inelastic response to variations in energy prices, motivating end users to act based on price signals alone would likely require price stimuli well beyond what may be politically feasible. Further, simply imposing "carbon caps" on point-source emitters might provide the incentive – but not the means – to extract the energy efficiency potential that is distributed across millions of energy users. Policy support might consist of standards, mandates and/or incentives to promote carbon-efficient buildings, appliances, and vehicles.

Misaligned incentives among various stakeholders – end users, manufacturers, utilities, and supporting businesses – present a further challenge to accelerating the capture of energy efficiency options. The public and private sectors will need to explore and promote regulatory initiatives (e.g., innovative utility rate designs) and other initiatives (e.g., creative financing for energy efficiency) aimed at eliminating or at least reducing fundamental agency and lifecycle-ownership barriers to energy efficiency.

3. **Accelerate development of low-carbon energy infrastructure.** Moving to a lower-carbon economy will require significant changes in the country's energy infrastructure. The investment needed to deliver the abatement potential identified in the mid-range case would increase net capital spending by approximately 1.5 percent relative to total real investment projected for the U.S. through 2030 in the emissions reference case. The investment would average approximately $50 billion per year, totaling $1.1 trillion through 2030. The number would be higher if our projected savings from energy efficiency gains do not materialize and/or if the nation chooses to achieve emissions reductions by mandating higher cost options. These incremental investments would be highly concentrated in the power and transportation sectors; if pursued, they would likely put upward pressure on electricity prices and vehicle costs. Policymakers and legislators would need to weigh these added costs against the energy efficiency savings, opportunities for technological advances, and other societal benefits. Failure to invest, however, would not only limit near-term abatement, but would erode the nation's ability to create the new energy infrastructure required to achieve greater GHG reductions beyond 2030. To accelerate development of a lower carbon energy infrastructure, the U.S. would need to:

- **Encourage research and development for promising technologies and stimulate deployment.** Of the options that we analyzed, some 25 percent (e.g., solar photovoltaics, plug-in hybrid electric vehicles, cellulosic biofuels) would require investment and/or cost compression to become economically competitive and achieve their full abatement potential. Additional R&D investment and targeted deployment support may be needed to ensure that high-potential technologies not commercially available today – such as solar power and CCS – achieve the learning rates and scale required to accelerate widespread adoption. The primary source of investment will continue to be the private sector; however, targeted government support may be necessary. This support might include gap-closing financial incentives (e.g., investment tax credits, feed-in tariffs, or direct subsidies) and/or industry or regulatory standards to help achieve scale economies as soon as possible.

¶ **Streamline approval and permitting procedures.** Many energy infrastructure investments (e.g., nuclear power, transmission lines, and pipelines) have long lead times and can face substantial delays in getting necessary approvals. Permitting and approval delays can substantially increase the risk and cost to investors and, if not specifically addressed, may inhibit pursuit of these capital-intensive abatement options. Permitting and licensing for new nuclear power plants, for example, face possible shortages due to insufficient staff, as well as delays associated with certification of new designs (e.g., digital controls), construction processes (e.g., modular assembly), and field-testing of previously streamlined review processes. Some emerging technologies, such as geologic storage of CO_2, currently have no defined approval and permitting process. Anticipating and addressing potential regulatory hurdles – e.g., siting, liability, and monitoring issues associated with permanently storing large amounts of CO_2 – and developing public and technical review processes to address those issues will be essential to the speedy pursuit of these capital-intensive abatement options.

To address emissions comprehensively, the nation would also need to consider abatement options outside the scope of this project. Our analysis focused on one portion of the solution – namely proven techniques and high-potential emerging technologies with marginal abatement costs below $50 per ton. We fully expect that additional reductions could and will be achieved through some combination of further innovation in products, processes, and methods; changes in consumer lifestyle and behavior; and abatement options with marginal costs greater than $50 per ton.

Through 2030, innovation will doubtless produce additional low-cost abatement opportunities not factored into our analysis. Examples of technologies that we examined but decided not to model include biokerosene, biodiesel from algae, homogeneous charge compression ignition engines, and fuel cells. These and other known and not yet known technologies will advance on an accelerated basis as the nation devotes more attention and resources to developing GHG abatement solutions.

We held consumer lifestyle preferences constant in our analysis, but in reality some changes in consumer behavior could well occur. For example, in response to growing awareness and concern about global warming coupled with some form of "carbon price signals," some consumers may turn down thermostats, switch off lights, or shift to smaller, lighter or less powerful vehicles. Policy approaches could also induce lifestyle changes. "Smart growth" zoning policies may, for example, motivate people to live in more compact communities near mass transit, substantially reducing driving and public infrastructure expenditures. A broad public education program around wasteful energy consumption could be mounted. Modeled on the "Keep America Beautiful" campaign of the 1960s, it could promote reduction in "carbon littering" by building an increased social consciousness.

A range of higher-cost options are also available, if needed, to close any remaining gaps. These might include, for example, upgrading electricity transmission and distribution infrastructure to reduce power losses, generating power at dedicated biomass power plants, and shifting from coal to natural gas in electric power generation.

* * *

In the years ahead, the United States will likely face heightened pressure – at home and abroad – to reduce its overall "carbon footprint." Our project evaluated costs and potentials of more than 250 abatement options available in the U.S. We did not examine economy-wide effects associated with abating greenhouse gases, such as shifts in employment, impact on existing or new industries, or changes in the global competitiveness of U.S. businesses. The project did not attempt to assess the benefits to society from reducing global warming. The report also did not attempt to address other societal benefits from abatement efforts, such as improved public health from reducing atmospheric pollution or improving national energy security. Policymakers will undoubtedly want to weigh these factors – and others – when developing a comprehensive approach for reducing GHG emissions in the U.S.

Throughout our research, we have been struck by the practical challenges of reducing carbon in the economy, and we have tried to ground our projections in economic realities as of 2007. We frequently encountered others who see far greater potential than we have called out; they cite numerous historical examples of innovation (e.g., reducing CFCs through the Montreal Protocol) and portray an energy future far more promising in terms of what could be achieved through U.S. ingenuity. In the end, we have opted to focus on reasonably well-known options that do not require unheralded breakthroughs.

At the same time, we are encouraged by the breadth of abatement opportunities available in the U.S., the potential for energy savings to help minimize costs to society of beginning GHG abatement, and the range of ancillary benefits that could accrue with thoughtful approaches. Creating these approaches will be challenging: they will need to combine durable policies and a slate of strong near-term actions that mobilize economic sectors and geographies across the U.S. We hope that this report will help policymakers, business leaders, academics, and concerned citizens position the nation for continued prosperity as it addresses the challenge of reducing greenhouse gas emissions.

Glossary

Abatement. The purposeful reduction of greenhouse gas emissions or their rate of growth.

Abatement cost. The engineering and resource costs required to capture a specified abatement option. These costs include all capital, operations and maintenance costs, but exclude all social, welfare, and regulatory costs associated with realizing an opportunity. Where expressed as per-ton cost, the net discounted cost (including benefits) is divided by the total emissions reduction. Both are calculated over the lifetime of the measure.

Afforestation. The natural or human-induced spread of forest to previously unforested land, such as fields and pastures; contrasted with replantation of forest land after trees have been harvested, which is usually called "reforestation."

Carbon sink. The process by which more carbon is absorbed than is released into the atmosphere. Land-based organic matter – mainly forests, but also agricultural lands and crops – constitute a significant carbon sink. (Oceans and other bodies of water can also serve as carbon sinks, but are not discussed as such in this report.)

Carbon stock. A pool of stored carbon. Land-based carbon stocks include forest stocks containing living and standing dead vegetation, woody debris and litter, and organic material in the soil, and harvested stocks consisting of wood for fuel and wood products, such as lumber and paper.

CCS. Carbon capture and storage, the processes by which carbon dioxide is captured from the combustion of fossil fuels, prepared for transportation, moved and delivered to a storage site, and permanently stored to prevent its release into the atmosphere.

CHP. Combined heat and power, also known as "co-generation," the use of a heat engine or a power station to generate electricity and steam from a single fuel at a facility near the consumer.

CO_2e. Carbon-dioxide equivalent, a standardized measure of greenhouse gas emissions developed to account accurately for the differing global warming potentials of the various gases. Emissions are measured in metric tons of CO_2e per year, usually in millions of tons (megatons) or billions of tons (gigatons).

Carbon conversions

The relative carbon content of fossil fuels and the emissions that result from their combustion is an important benchmark for assessing carbon costs. The voluntary reporting program supported by the US Energy Information Administration recommends the following conversions for carbon. The actual carbon content of a fuel varies according to the fuel's exact composition. These values are converted to represent the added cost incurred with each $10 per metric ton increase in carbon cost.

Fuel	**CO_2e produced** Kilograms	**CO_2e cost** Per $10 per metric ton CO_2e price
1 gallon gasoline	8.9	$0.089
1 gallon diesel	10.2	$0.102
1 short ton bituminous coal	2,237	$22.37
1 short ton subbituminous coal	1,685	$16.85
1 short ton lignite coal	1,266	$12.66
1,000 ft^3 natural gas	54.7	$0.55
1 kilowatt-hour of electricity	0.61*	$0.0061

* Based upon average carbon intensity of U.S. national power grid in 2005. Note that for electricity, the actual cost would vary according to the carbon content of the marginal generating source, and hence requires market-specific information to calculate.

Consumer utility. Functionality or usefulness for people, such as level of comfort. Adjusting a thermostat, moving to a smaller house, driving a smaller vehicle, or driving fewer miles annually represent changes in consumer utility. In a strict economic sense, maintaining constant consumer utility assumes a constant economic surplus for the consumer while delivering against a common benefit.

CTL. Coal-to-liquids, the chain of chemical processes for converting coal to liquid hydrocarbons for transportation fuels, usually diesel fuel.

EOR. Enhanced oil recovery, the process of improving the productivity of oil wells by injecting CO_2 into the well.

GHG. Greenhouse gases, the major ones being:

- **CO_2** – carbon dioxide
- **CH_4** – methane
- **N_2O** – nitrous oxide
- **CFCs** – chlorofluorocarbons
- **HFCs** – hydrofluorocarbons
- **PFCs** – perfluorocarbons
- **SF_6** – sulfur hexafluoride.

Gigaton. 1 billion metric tons.

HVAC. Heating, ventilation, and air conditioning: climate-control systems for commercial and residential buildings.

IGCC. Integrated Gasification Combined Cycle, an advanced design for higher-efficiency power plants that generate and burn synthetic gas from coal, heavy petroleum residues, or biomass.

Megaton. 1 million metric tons.

Reference case. The projection of U.S. greenhouse gas emissions for 2005 through 2030, which was constructed from U.S. government sources and serves as the baseline against which abatement volumes are measured. This report uses the "reference" scenario in the U.S. Energy Information Administration's *Annual Energy Outlook* 2007 report as the foundation of the reference case for emissions through 2030. That scenario has been supplemented with data from Environmental Protection Agency and Department of Agriculture sources, as referenced in the report. Our analyses excluded HCFCs, which are being retired under the Montreal Protocol.

SEER. Seasonal energy efficiency ratio, the rating system for air conditioners: higher SEER numbers indicate greater efficiency. The federal minimum standard for residential air conditioners (except window units) is 13 SEER.

Wind class. The 1-to-7 scale (low to high) developed by National Renewable Energy Laboratory to describe power contained in wind. Class 5 to 7 winds represent reasonably gusty areas with mean wind speeds between 13.4 and 21.1 mph at 33 feet above the ground.

Methodology

This appendix describes the research team's methodological approach to the emissions and abatement analyses, by giving an overview of the methodology and critical assumptions.

CREATING THE REFERENCE CASE FOR EMISSIONS IN 2030

The reference case projection of U.S. greenhouse gas emissions for 2005 through 2030 derives from publicly available U.S. government data. The emissions projection is in no way intended to represent McKinsey & Company's forecast of expected emissions and economic activity for the U.S. Rather, the forecasts serve as a comprehensive, detailed, and internally consistent *baseline* from which to calculate the relative costs of various abatement initiatives. The reader should view these baseline projections as a forecast assuming business-as-usual conditions in which there are no drastic changes in consumption patterns and no major legislative initiatives to change the fundamental conditions (e.g., none of projections in the business-as-usual baseline assumes any price of carbon).

To create the reference case forecast, the research team reconciled data from Environmental Protection Agency, Department of Agriculture, and Department of Energy sources, with the "reference" scenario in the *2007 U.S. Energy Information Agency Annual Energy Outlook* report as the foundation. Additional sources include: *Inventory of U.S. Greenhouse Gas Emissions and Sinks 2005: 1990-2005; Global Anthropogenic non-CO_2 Greenhouse Gas Emissions: 1990-2020; Global Mitigation of non-CO_2 Greenhouse Gases;* and *Forest Service (2000).*

The reference case forecast integrates emissions and absorption of greenhouse gases across seven sectors of the U.S. economy: power generation, buildings, industry, transportation, forestry, agriculture, and waste. It includes emissions of six greenhouse gases: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulfur hexafluoride (SF_6), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs); the team excluded chlorofluorocarbons (CFCs) from the analysis because they are being retired from use under the Montreal Protocol. The forecast does account for terrestrial carbon "sinks," which absorb carbon. These sinks include changes in forest stocks, land use, and agricultural practices. To ensure comparability across sectors and sources, we converted all emissions and sinks to a common metric – CO_2 equivalents (CO_2e) measured in metric tons.

We constructed emissions estimates in a bottom-up manner, assessing demand growth regionally through census divisions, for example. This approach allowed us to account for regional variations in such factors as climate, population growth, and carbon intensity of electric power generation portfolios. It also allowed us to estimate more accurately the costs of abatement alternatives.

In calculating emissions from the electric power sector, we took the additional step of estimating power usage for end-user segments (e.g., buildings) and allocating the associated emissions (with transmission and distribution losses) to those segments. This approach allowed us to examine the power sector on a stand-alone basis and better understand what drives changes in power usage.

The assumptions embedded in the Department of Energy, Environmental Protection Agency, and Department of Agriculture data sets are too numerous to review in detail. A few critical assumptions and methodological considerations are worth highlighting, however:

1. The analysis assumes that the price of imported low-sulfur crude oil varies between $50 and $69 per barrel from 2005 to 2030, and is $59 in 2030. It also assumes that natural gas moves between $5.46 and $8.60 per million BTU at Henry Hub, stabilizing at $6.52 in 2030. Annual growth of the economy is assumed to be 2.9 percent.

2. The sources do not assume major technological breakthroughs or transformation of underlying energy infrastructures. Instead, they rely on the evolution of existing technologies, typically with moderate assumptions around learning and penetration rates.

3. The emission baseline was created using the macroeconomic general equilibrium model that selects most economical choices to meet the nation's energy demands. This approach does not take into account such non-economic factors as, for example, public opposition to building certain types of electric power generation.

4. No changes in the legislative policy regimes that were largely in place in 2005 have been assumed. The projections do not, for example, include the impact of AB32 in California or the Northeast Regional Greenhouse Gas Initiative (RGGI). Nor do they assume the adoption of higher appliance efficiency or fuel economy standards (as have recently been proposed by the Congress). Similarly, these cost estimates have not incorporated any carbon price or tax.

5. Our analysis considers only emissions and sinks generated within the borders of the 50 United States, and does not estimate a broader global carbon footprint associated with U.S. companies, individuals, and their economic activities. We do not, for example, estimate "imported" carbon in industry supply chains, nor do we include emissions produced by overseas subsidiaries of U.S. companies. Also, we have considered only terrestrial carbon sinks (forests, agricultural lands) and have not included oceans or bodies of water as specifically controllable abatement options.

6. We have looked at greenhouse gas emissions on an annual basis only, and have not attempted to estimate the build-up of greenhouse gases in the atmosphere over time. Clearly, given the magnitude of U.S. greenhouse gas emissions, the timing of any major increases or reductions in emissions – whether they occur closer to 2005 or to 2030 – would have a material impact on the build-up of atmospheric greenhouse gas levels, as would a change in the mix among types of greenhouse gases.

7. The reference case assumes the same consumption patterns for energy and goods as we have seen in the past, with no major shift to conservation and efficiency expected.

Despite these caveats, we believe the analysis provides a useful, integrated, and internally consistent picture of how emissions and energy infrastructure might evolve if the U.S. economy continues to operate with the same decision frameworks and pricing assumptions that were in place in the period leading up to 2005.

CALCULATING ABATEMENT POTENTIALS

We took a bottom-up approach to calculating the abatement potential of individual opportunities and to building abatement curves containing sets of opportunities. In essence, we calculated the value of specific opportunities, like switching from incandescent to compact fluorescent light bulbs, then arrayed all the opportunities from lowest to highest cost to determine how much abatement was available at what cost.

To identify realistic abatement potentials and accurately quantify benefits and costs, the research team first screened more than 250 abatement opportunities using four criteria:

1. **Stage of development.** The technology had to be at least in the pilot stage.

2. **Feasibility.** There had to be consensus among experts on it technological and commercial feasibility.

3. **Quantifiable value.** The technical and economic challenges had to be well understood, such that they could be modeled appropriately.

4. **Supportive positioning.** Compelling forces at work had to support its development, including policy and/or industry support, favorable economics, or other strong benefits, such as energy security.

The team then assessed each abatement opportunity that met these criteria to determine its realistic abatement potential by 2030, given known economic, technical, and regulatory constraints. Abatement potential is a function of the average net cost associated with the opportunity and the amount of greenhouse gases, measured in tons CO_2e, that can be abated in this manner during the course of a year, above and beyond the levels projected in the reference emissions case for 2030.

To improve the accuracy of the estimates, we developed a reference technology for each opportunity to properly estimate costs and carbon intensity of abatement: for a reference power plant for nuclear power generation, for example, a mix of new fossil baseload plants using pulverized coal and CCGT was used.

The team assumed no change in consumer utility or lifestyle, such as a shift to denser urban housing or mass adjustment of thermostats. We did not model measures aimed at reducing demand for goods and services, such as a tax on vehicle-miles traveled.

We applied no CO_2e discounting: we assumed 1 ton of greenhouse gas abated in 2029 would be as valuable as 1 ton abated in 2009.

A few other points about calculating abatement costs and amounts bear mentioning:

¶ **Abatement cost.** We assigned costs through a detailed construction of economics. For example, substituting a more efficient fluorescent bulb for a new incandescent lamp involves an up-front investment but also a reduction of the electrical and maintenance costs associated with incandescent usage. A hidden long-term benefit associated with the energy savings from fluorescent usage is a reduced need for construction of new power generation capacity. These net costs have to be factored into every abatement option considered. More specifically,

- We calculated the abatement cost for each opportunity from a techno-engineering perspective, combining initial investment and ongoing net operating costs over the lifetime of the opportunity, regardless of who (producer or consumer) would bear those costs. For example, the agent making an investment in a building and the benefactor who will own or occupy the building may be separate and have different incentives (minimizing first cost versus minimizing operating or lifecycle cost); abatement opportunities have been calculated for the economy as a whole (e.g., netting out total costs versus savings).

- We did not attempt to include transaction costs, communication/information costs, taxes, tariffs, and/or subsidies, existing today and possible in the future, any price for CO_2 (i.e., a carbon cap or tax), or any resulting impact on the economy (e.g., advantages from technology leadership, impact on GDP growth).

- Abatement costs were levelized to account for the time-value of money using a 7-percent social discount rate. The cost shown on the abatement cost curve is the weighted average abatement cost of that technology between the relevant time period (2010, 2020 and 2030), not the cost of the last period.

- Furthermore, the cost shown is typically a weighted average cost for several related, smaller opportunities, with those costs spread over the 25-year forecast period. For example, “optimizing refinery process” involves many smaller steps that are individually too small to put on the curve; in a similar way, “increase attic insulation" averages the costs from multiple regions, because the economics of adding attic insulation varies significantly between regions in the U.S.

- We did not model demand feedback for such things as gasoline prices. To estimate costs for different abatement options, we held fuel prices constant, despite a potentially substantial decrease in demand for gasoline.
- Throughout this report, all costs are presented in 2005 real terms.

¶ **Abatement amount.** We calculated abatement amounts by determining the potential impact of capturing that action on one occasion and multiplying that by the number of similar occasions available. For example, the amount of greenhouse gases that could be abated by increasing attic insulation in the East North Central census region of the United States is a function of several factors: the gap between the typical insulation level and the recommended level, the amount of fuel that a homeowner would not burn to keep the thermostat at current levels if they had the recommended insulation, the global warming potential of emissions from the fuel not burned as a result of the improved insulation, and the number of houses in that census region.

- We attempted accurately to capture the dynamic interplay between the nation's energy infrastructure and the carbon reduction attached to any incremental change. Frequently, calculating a reduction requires determining the carbon intensity of the fuel source implicated in the reduction. In the example of an incandescent-fluorescent lighting change-out, the energy savings (measured in kilowatt-hours) must be multiplied by a known electric power carbon intensity that is matched to the specific action by region, over time.
- We used a lifecycle approach where the abatement option creates additional emissions not captured in the existing baseline or where carbon abatement is happening not at the end-user level but over the value chain (e.g., biofuels).

Having calculated as realistic a cost as possible, given known economic, technical, and regulatory constraints, we tightened or loosened the constraints to define low and high levels of penetration for each opportunity. We linked the opportunities in internally consistent low, medium, and high abatement scenarios that capture the interplay between costs and volumes. Together, these low, medium, and high scenarios represent an envelope of abatement solutions available to the U.S.

To eliminate double-counting, we sequenced analysis of abatement options within sectors wherever relevant and checked for cross-sector linkages. Sequencing the options changes the abatement potential for some: those that come earlier in a sequence "look better" than those that come later. For example, a gallon of gasoline saved by use of a hybrid-electric vehicle today would abate more carbon than it would years from now after biofuels have substantially penetrated the national fuel supply, at which time a gallon of gasoline would contain less carbon overall. Similar cross-checks were applied to cross-sectoral interdependencies (e.g., energy efficiency in commercial and residential buildings and abatement analysis in the power sector).

Together, the combined axes of an abatement curve depict the available tools, their efficiency, and their relative impact when emissions reductions are being pursued. Each bar needs to be examined independently to understand the real barriers to capture. The value of the abatement curve lies in focusing on those opportunities that produce the greatest impact for the investment.

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This report is the product of a year-long effort by McKinsey & Company in close collaboration with seven leading U.S.-based companies and environmental NGOs. We hope that the fact base provided here will enable better informed decisions and the development of economically sensible strategies to address the nation's rising GHG emissions.

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We would like to emphasize that, as with all McKinsey research, the perspectives, views, and analyses expressed herein are the sole responsibility of McKinsey & Company.

We welcome the opportunity to engage in a constructive dialogue on the content of this report and its implications for businesses, the public sector, NGOs and policymakers.

Jon Creyts – Principal, Chicago
Scott Nyquist – Director, Houston
Ken Ostrowski – Director, Atlanta
Jack Stephenson – Director, New York

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