Fall 2010

CLIMATE CHANGE

The BRIDGE

LINKING ENGINEERING AND SOCIETY

NATIONAL ACADEMY OF ENGINEERING
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Promoting the technological welfare of the nation by marshalling the knowledge and insights of eminent members of the engineering profession.

The
BRIDGE

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Erratum

The following is the correct text for the last paragraph of the article by Richard Garwin in the June issue:

Although not everyone in such an attack can be saved, it is the federal government's responsibility to do the analysis, planning, simulation, and communication that might be needed for an attack on any one of 20 or more target cities. It would fall to local governments to prepare regulations that would facilitate the temporary sheltering of people, within tens of minutes, in office space to which they do not normally have access.

A complete copy of *The Bridge* is available in PDF format at *http://www.nae.edu/TheBridge*. Some of the articles in this issue are also available as HTML documents and may contain links to related sources of information, multimedia files, or other content.

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Editor's Note

Features

NAE News and Notes

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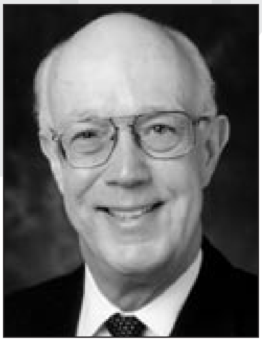
Editor's Note



Robert W. Fri

Bringing Climate Down to Earth

In May 2010, the National Research Council (NRC) simultaneously released three reports on climate change, part of a major project called America's Climate Choices (ACC).[1] The headline on the summary of the three reports stated that strong evidence of climate change underscores the need to limit emissions and adapt to inevitable impacts. Somewhat more expansively, the reports concluded that:

- A strong, credible body of scientific evidence shows that climate change is occurring, is caused largely by human activities, and poses significant risks for a wide range of human and natural systems (NRC, 2010a).
- Meeting internationally discussed targets for limiting atmospheric greenhouse gas concentrations will require a major departure from business as usual in how the world uses and produces energy (NRC, 2010b).
- Adaptation to climate change calls for a new paradigm—one that considers a variety of possible future climate conditions, some well outside the realm of past experience (NRC, 2010c).

Taken together, these reports address numerous complex issues that continue to arise in dealing with the climate problem over many decades. The scope of this issue of *The Bridge* is more modest, but I think important nonetheless. In it, five authors—all participants in the ACC project—look at the way industry, public officials, and households must begin now to incorporate climate change into their planning and decision making.

Henry G. Schwartz Jr. examines the likely effects of climate change on the transportation infrastructure. The extent of the possible impacts is impressive and, for me at least, unexpected. Schwartz points out that the ports of New York, Boston, and New Orleans are all in coastal, flood-prone zones at risk from rising ocean levels and stronger storm surges due to climate change. Many of the nation's highways and rail lines are similarly exposed. Other impacts on the built infrastructure are less direct but equally important; for example, rising temperatures could affect thermal expansion joints on bridges, buckle rail tracks, and degrade pavements. Schwartz concludes that engineers should be thinking about these matters now in their design decisions.

Gary Yohe explores how this thinking might be structured. The problem is uncertainty. Even as climate science makes a clear case for action, it cannot tell designers the specific impacts to expect at the local level. As a result, Yohe says, decisions about adapting to climate change are best considered in a risk-management framework. He explores the issue at both theoretical and practical levels. Of special interest is his review of the process developed in New York City to incorporate adaptation into the city's planning for infrastructure investment. A key observation from this experience is that adaptation decisions are driven more by the frequency of extreme events caused by climate change than by broad indicators of change.

The remaining articles turn to the transformations climate change will require in the nation's energy system. The U.S. energy system is more than 80 percent dependent on fossil fuels—coal, oil, and natural gas—and produces 85 percent of the nation's greenhouse gas emissions. Since limiting future climate change will require a reduction in these emissions by around 80 percent by 2050, the future energy system will necessarily look very different from the current system. And 40 years is not a long time to transform a massive system that is deeply embedded in the nation's infrastructure. Nevertheless, it is both necessary and possible to start

[1] A fourth report on providing information to support decisions was released in July 2010, and a synthesis report is forthcoming. Neither is included in this issue of *The Bridge*. Dr. Fri was chair of America's Climate Choices Panel on Limiting the Magnitude of Future Climate Change.

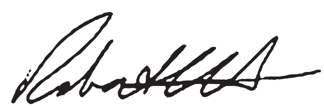
the transformation now, and two authors suggest how we might begin.

Marilyn A. Brown and her colleagues take on the problem of energy efficiency in industry. Improving energy efficiency is important in all sectors, of course, but as Brown points out, industry has special opportunities. For example, some industries can use waste heat profitably and with substantial effect in reducing carbon dioxide emissions. And in many cases, technology that uses less energy is also more productive in other ways. Then, expanding her focus beyond the United States, Brown also argues that energy efficiency is becoming a decisive strategy for maintaining U.S. competitiveness in the global economy.

Increasing electricity production from renewable energy sources, such as wind, is another step toward transforming our energy system that can begin now. Douglas J. Arent reviews the current state of our rapidly growing renewable energy production and makes a crucially important point about the future of these sources. Some energy industry analysts assign demerits to wind and solar energy because of their variable availability. It's true, of course, that the wind doesn't blow and the sun doesn't shine uniformly throughout the day. But Arent points out several practical steps that could be taken to integrate these variable sources into the electric system. These ideas are just beginning to take hold, and more experience with them could have important benefits for the potential of renewable energy.

In the final article, I look at the energy system as a whole and ask whether technology is available to transform it to the necessary extent. By estimating a greenhouse gas emissions budget for the United States, it is possible to make a quantitative, but rough comparison of the need for technology and its availability. This analysis suggests that we could go a long way toward meeting the emissions budget with existing technological know-how but cautions against being overly optimistic. Substantial barriers to the diffusion of known technology will have to be overcome, and we need more research to produce new technologies that can do the job at lower cost.

These five articles obviously cannot cover the full range of steps we must take to manage climate change. But they do share a common theme—that engineers and scientists should lead the way. Getting technology actually working in place and learning from experience with it are essential first steps in transforming the energy system. Similarly, as New York City and other jurisdictions have learned, assessing the impact of climate change on the built infrastructure can have real consequences for infrastructure planning. In short, there is plenty of work to be done, and it should begin now.



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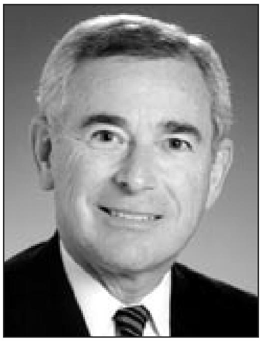
NRC. 2010c. Adapting to the Impacts of Climate Change. Prepublication. Washington, D.C.: National Academies Press. Available online at *http://www.nap.edu/catalog.php?record_id=12783*.

Nowhere will the impacts of climate change and the need for adaptive responses be more apparent than in our vast, complex transportation system.

Adaptation to the Impacts of Climate Change on Transportation



Henry G. Schwartz Jr. is a consultant and an NAE member.

Henry G. Schwartz Jr.

The great preponderance of scientific evidence suggests that the planet is warming at an accelerating rate due in large measure to the use of fossil fuels. Heretofore, most of the discussion about global warming has focused on limiting or mitigating climate change by reducing emissions of greenhouse gases (GHGs), most notably carbon dioxide, but also methane, nitrous oxides, and other gases.

No matter what policies are eventually adopted and implemented by the world community, however, the impacts of increasing levels of GHGs will continue to be felt for decades to come. These include the northward migration of pests and disease vectors; changes in local and regional weather patterns, such as decreasing precipitation in the already arid Southwest and increasingly intense storms in the Midwest and Northeast; extended heat waves with concomitant effects on air quality, health, and material longevity; and sea level rise that will impact coastal communities and ecosystems.

Nowhere will the impacts of climate change be greater and the need for adaptive responses more apparent than in the built infrastructure, especially the vast network of highways, bridges, tunnels, railroads, transit systems, airports, ports and harbors, and pipelines. Although the focus of this paper is on transportation, most of these concerns will also affect other infrastructure segments, such as power generation and transmission facilities and water and wastewater distribution and treatment systems.

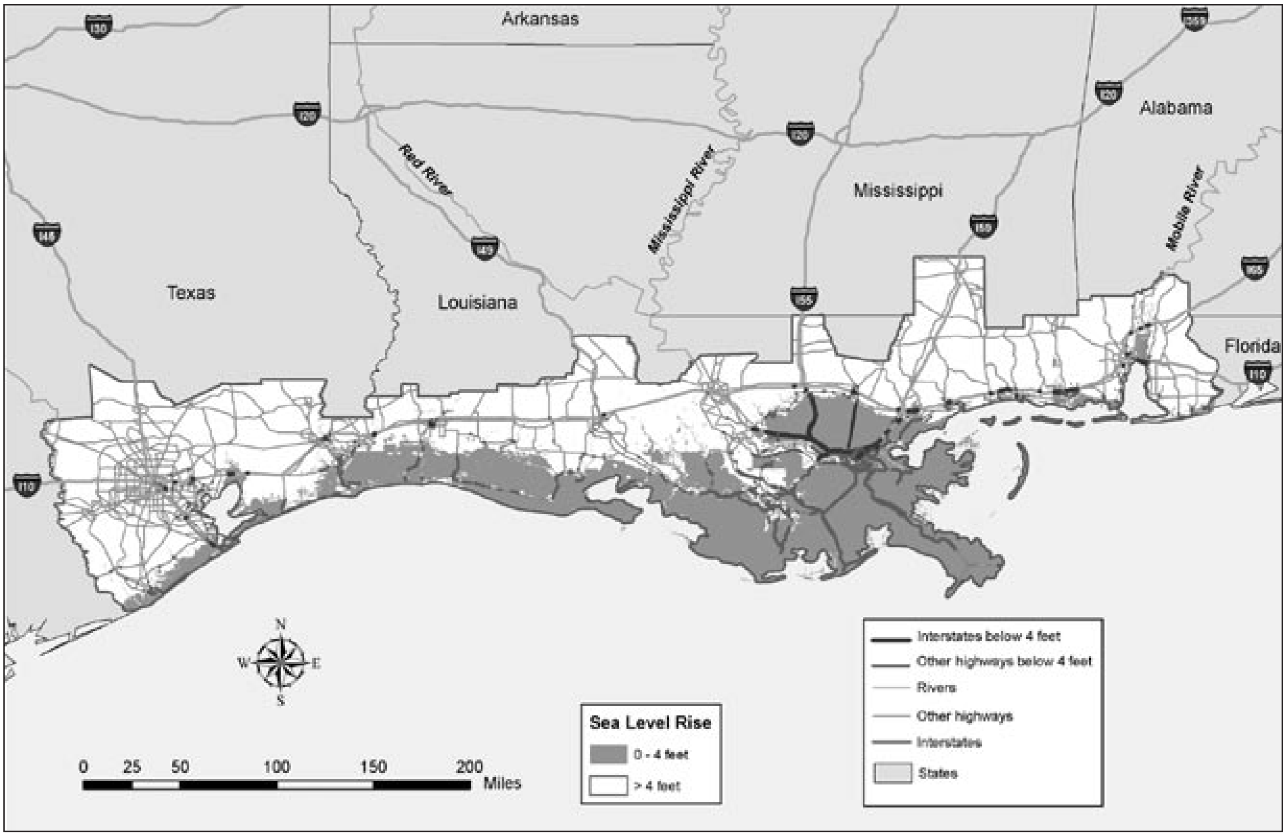


FIGURE 1 Highways vulnerable to relative sea level rise (4 feet of sea level rise). Source: Cambridge Systematics analysis of U.S. Department of Transportation data.

Impacts of Climate Change

Based on the climate-science literature, one can conclude that in the next 50 to 100 years five specific impacts of global warming will have potentially serious implications for the built infrastructure: sea level rise (virtually certain, > 99 percent probability); heat waves (very likely, > 90 percent); rising Arctic temperatures (virtually certain, > 99 percent); changes in precipitation patterns (very likely, > 90 percent); and increasingly intense, strong hurricanes (likely, > 66 percent) (IPCC, 2007; NRC, 2008).

Sea Level Rise

As a result of melting glaciers and the expansion of the ocean as water temperatures rise, sea levels will continue to rise throughout this century. Globally, the sea level is projected to rise 7 to 23 inches. However, in some regions, such as the U.S. Gulf Coast, the relative sea level rise will be exacerbated by land subsidence.

A sea level rise of 2 to 4 feet along the Gulf Coast, which is well within the range of possibility over the next century, would inundate major portions of the coastline from Mobile to Houston, particularly in Louisiana and East Texas (Figure 1). To put this in perspective, a 4-foot rise would inundate 2,400 miles of roadway, 9 percent of rail lines, and 72 percent of ports in the region

If storm surges are combined with higher sea levels, the damage can be much more severe and extend much farther inland. The 25-foot storm surge during Hurricane Katrina literally lifted the deck of the Bay St. Louis Bridge off its piers (Figure 2). Figure 3 shows the impact of a 23-foot storm surge on the region: 64 percent of Interstates, 57 percent of arterial roads, 41 percent of freight rail lines, 99 percent of ports, and 29 airports could be affected.

Even though it is highly unlikely that a single storm surge will flood the entire area, it is important that we understand the risks to the Gulf Coast and to the nation. Seven of the 10 largest freight ports in the United States are located on the Gulf Coast, and approximately two-thirds of the nation's oil imports pass through Gulf Coast facilities. Adaptation to the rise in sea level will require that those ports and harbors be reconfigured or reconstructed to accommodate higher seas.

FIGURE 2 Damage from Hurricane Katrina to the Bay St. Louis Bridge in Mississippi. Source: NASA Remote Sensing Tutorial.

But the danger would go beyond transportation systems and affect much of the built infrastructure. Water and wastewater treatment facilities and distribution and collection systems could be out of service for weeks, or even months, as they were in 2005 after Hurricanes Rita and Katrina. Electric power generation and distribution systems and critical service facilities such as hospitals will also be threatened. In addition, higher sea level and storm surges will accelerate the destruction of the barrier islands that protect the mainland. Without them, sections of the Inland Waterway will become unprotected ocean and unsuitable for barge traffic.

Although the Gulf Coast is the "poster child" for the impact of rising seas and storm surges, many other coastal areas are just as vulnerable. More frequent disruptions and damage to much of the infrastructure near all of our coasts can be expected. Many of the nation's busiest airports—(e.g., in Fort Lauderdale, New Orleans, Boston, and New York)—are in coastal, flood-prone zones. Tunnels and other low-lying infrastructure will also come under assault. Studies in New York have shown that heavy storm surges could inundate major portions of the lower Manhattan subway system.

Heat Waves

High temperatures and heat waves are very likely to become more intense and more frequent and to last

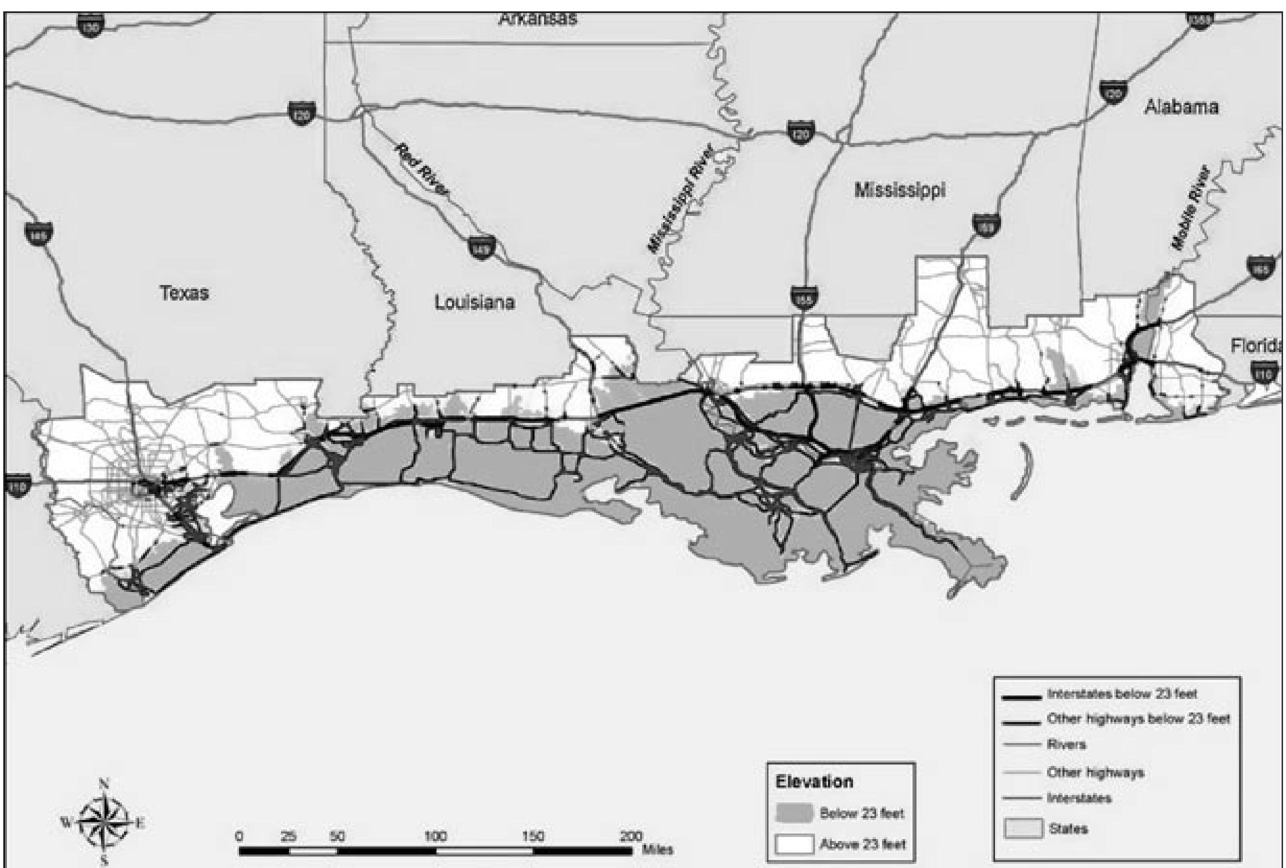


FIGURE 3 Highways vulnerable to relative sea level rise (23 feet of sea level rise). Source: Cambridge Systematics analysis of U.S. Department of Transportation data.

longer than they do today. Climate scientists have developed numerous models that forecast future temperature levels. Absent effective reductions in GHG emissions, projected temperature rise by the end of this century ranges from a low of 4 to 7°F to a high of 7 to 11°F.

These are enormous increases! Currently, for example, Dallas has a 30-percent probability of having one day per year with a temperature higher than 110°F. By 2100, the 30-percent probability rises to 19 days with temperatures of 110°F and an 80 percent chance of at least 8 days of 110°F.

These temperature increases will affect thermal expansion joints on bridges, increase stresses and buckling on rail tracks, and cause more rapid degradation of pavements, especially asphalt. In addition, construction workers will have to operate on reduced schedules or at night as summer temperatures consistently rise above 90°F in much of the country.

The 1:100 year storm event of yesterday may now be a 1:20 year event.

Higher temperatures, decreases in ice cover, and increases in evaporation are forecast to lower water levels in the Great Lakes and the Saint Lawrence Seaway thereby necessitating reductions in the cargo-carrying capacity of freighters on the Great Lakes and oceans. Similarly, elevated temperatures will lead to more severe droughts, especially in the Southwest and perhaps in the Southeast. Water shortages, which are already a critical problem in the Southwest, will become even more acute, leading to feuds between agricultural interests and municipal and industrial users and fighting among neighboring states over a diminishing water supply.

Pests, such as the pine bark beetle in Colorado and the spruce bark beetle in Alaska, are already decimating lodgepole pines and spruces and creating a tinder box for forest fires. These insects are spreading because winter temperatures no longer stay cold long enough to kill the beetle larvae. Large forest fires seem to be breaking out more frequently causing disruptions to air and ground traffic and damage to infrastructure of all types, as well as to residential buildings. Fires are often followed by landslides on denuded slopes.

Increasingly Intense Precipitation

Over the past 50 years, there has been a significant increase in the frequency and intensity of heavy precipitation events across the country. The small increase in total precipitation over this time period is the result of these more frequent, heavier downpours.

In simple terms, warmer temperatures lead to more evaporation, hence drought in the Southwest, lower water levels in the Great Lakes, and greater moisture-carrying capacity in the atmosphere, which leads to more intense storms in the Midwest and Northeast. Severe storms create delays and disruptions to almost all types of transportation, and overwhelmed drainage systems for roads, airports, tunnels, and neighborhoods cause localized flooding. Generally, the intensity of precipitation is expected to increase in northern latitudes, such as Alaska and the Northeast, while the West and Southwest become drier (Figure 4).

The probability of a particular storm event is called the return frequency. A one in twenty (1:20) year event equals a 5 percent probability of a storm of a specified intensity occurring in a given year. Return frequencies are based on historical weather data going back 100 years or more. However, because the climate is changing relatively rapidly, historical statistical computations do not reflect the upturn in precipitation events. In other words, the 1:100 year storm of yesterday may now be a 1:20 year event.

Inland waterways may experience higher and perhaps more frequent floods. Over the past 17 years, there have been two major floods in the upper Mississippi, both of them 1:300 to 1:500 year return frequency events. Is this just statistical probability at work, or are our return frequency curves hopelessly out of date because of the effects of climate change?

Hydrologic models and computations must be revised to reflect tomorrow's precipitation intensities. Updated models would immediately alter the designation of flood plains and the design of virtually all hydraulic structures, including storm drains.

Increasingly Intense Hurricanes

Some evidence shows that rising temperatures in the ocean, notably in the Gulf of Mexico, fuel stronger hurricanes—not necessarily more frequent storms, but deadlier storms with higher wind speeds and heavier precipitation. The science of hurricanes leaves many unanswered questions, but storms packing higher winds

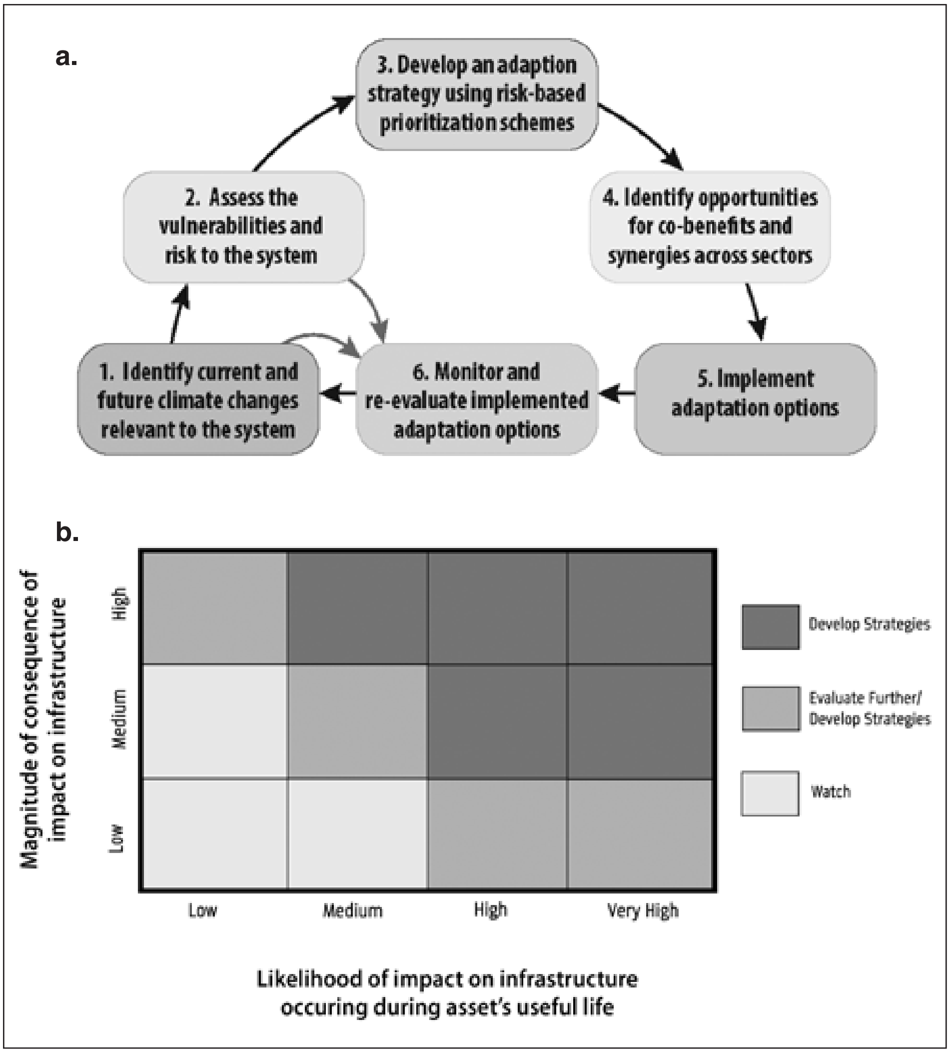


FIGURE 4 4a. Classic risk management approach. 4b. Risk matrix showing the likelihood of impact on infrastructure assets.

and coming further inland on higher sea levels will be a recipe for disaster.

The damage to oil and gas facilities from Hurricanes Katrina and Rita exemplifies the impact of major storms on the nation's economy of shutting down off-shore production, refineries, and pipelines. Reportedly, 15 percent of U.S. refining capacity was shut down in anticipation of Hurricane Gustav in 2008, and virtually all off-shore oil and gas production was halted in the Gulf. In an attempt to avoid the evacuation tragedies of 2005, more than three million people fled the coast ahead of Hurricane Gustav.

Arctic Warming

Global warming is most apparent at high northern latitudes, that is, in the Arctic. Temperatures in Alaska have already risen 3 to 5°F, twice as much as in the contiguous 48 states. We anticipate thawing of as much as 90 percent of the permafrost, which will result in the displacement of pavements, runways, rail lines, pipelines, and buildings. Bridges and pipelines, which are especially vulnerable to the heaving of permafrost, are typically difficult to protect and repair.

Satellite photography clearly shows that the sea ice is retreating above the Alaskan North Slope, and as it does, the protection afforded by the ice sheet is being lost. Strong winds, which are prevalent in the Arctic, are creating waves that erode coastlines endangering whole villages and transportation systems. Alaska projects that the cost of maintaining public infrastructure will increase by \$4 to \$6 billion by 2030 as a result of addressing the effects of climate change.

A positive consequence of Arctic warming is the possible opening of the Northwest Passage, which would permit shipping and tourism (cruise ships) above the Arctic Circle. Last summer, two German freighters accompanied by a Russian icebreaker navigated the northern sea route off the coast of Siberia, shortening the shipping journey by thousands of miles (Box 1).

Adaptation: Engineering Challenges and Opportunities

The best scientific studies clearly indicate that threats from global warming are real, not illusory. Moreover, we can no longer use historical weather analyses to predict the future environment in which we will have to function. Indeed, climate data collected by the National Oceanic and Atmospheric Administration shows that

BOX 1
Climate vs. Weather

Climate is often defined as long-term average weather. ***Weather*** is defined as the conditions one experiences at any moment in time. Often we are not overly concerned about gradual changes in average conditions, such as temperature or precipitation (i.e., in the climate). We are, however, concerned about changes in weather, such as increased frequency of extreme weather events (e.g., Category 4 and 5 hurricanes, greater storm surges, heavier downpours, higher flooding, and longer heat waves).

global temperatures from January through June 2010 were the warmest on record (NOAA, 2010). Weather extremes will become increasingly severe and destructive to infrastructure, and mitigation measures, however effective, will not appreciably change the trajectory of global warming for decades (Box 2).

How should we respond or adapt to the anticipated impacts of global warming, especially as they impinge on infrastructure? Note that the question is not whether we should adapt to climate change, because we necessarily will adapt. The question facing the engineering profession is whether adaptation will be a planned, studied response or a haphazard reaction to events as they unfold.

In many ways, adaptation is classic risk management, but it is complicated by the inherent uncertainties associated with climate change. The terms of the risk analysis include: the hazards of concern (sea level rise, stronger storms, and heat waves); vulnerable assets (transportation infrastructure and its value to the economy); potential consequences (direct and indirect); and the likelihood or probability that a hazard will occur.

BOX 2
Mitigation and Adaptation

Mitigation measures to reduce GHG emissions could include: underground carbon sequestration, increased biomass uptake, and geo-engineering to limit the amount of incoming solar radiation. Legislative actions to encourage mitigation measures could include: carbon taxes; cap and trade markets; and new CAFÉ (corporate average fuel economy) standards for vehicles.

Adaptation measures are natural or man-made adjustments or actions to accommodate or reduce the adverse consequences of climate change.

These are the questions engineers must address to balance risk and benefits. The answers will range from very low-probability, high-consequence events (e.g., Hurricane Katrina's impact on New Orleans) to high-probability, low-consequence events (e.g., annual flooding of agricultural flood plains). The focus then is on the direct and indirect cost implications within the range of probabilities (Figure 4).

The Special Challenge of Uncertainty

The very words "climate change" and "global warming" immediately raise questions about the certainty of science and the actions to be taken. Indeed, there are three broad areas of uncertainty in addressing climate projections. First, natural variations occur in climate systems even when there are no external forcing factors, such as GHG emissions or major volcanic eruptions. Natural variations include large-scale phenomena, such as the El Niño/La Niña-Southern Oscillation.

Second, there is uncertainty about the level of GHG emissions, which may change with technological breakthroughs (e.g., carbon sequestration), political agreements, and social and economic drivers. However, given the level of geopolitical disagreement between industrialized and developing nations and internal debate in the United States and elsewhere about the risks of climate change, it seems unlikely that this kind of uncertainty can be reduced.

Finally, there is uncertainty about the response of the climate to various perturbations, especially increasing levels of GHGs. Most global climate models are based on radiative forcing mechanisms, and virtually all of them predict increased warming of the globe, albeit at different rates. Models based on lower GHG emissions predict temperature rises of 4 to 6°F by the end of this century in the United States. Models based on higher emissions predict rises of 7 to 11°F.

The Issue of Scale

These complex analytical challenges go beyond the uncertainties surrounding basic climate science. Consider the issue of scale, for example. Virtually all current climate change models are created at the global scale (i.e., the global temperature will rise by some amount over a set period of time). As the spatial scale is reduced, however, confidence in the predictions decreases.

Unfortunately, engineers can do little with data on temperature change on a global level. For the information to be useful, it must be on the regional or local level.

Even though confidence in our understanding of the changes in climate increases as the spatial scale increases, the practical value of the information to owners and operators of the nation's infrastructure diminishes as the scale increases. This means that developing a finer-scale understanding of climate change will be essential to developing a better understanding of the risks and, hence, the adoption of better, more cost-effective adaptation measures. Fortunately, climate scientists are becoming more confident in down-scaling their models to regional levels.

As we look more closely at the five impact areas identified above, it becomes apparent that some relate to gradual changes, such as sea level rise, while others relate to extreme events. For example, the gradual increase in total precipitation in the Midwest is of far less concern than the projected increase in the return frequency of heavy storms and flooding. Analytical data on the size and frequency of extreme events will be necessary for the development of effective response mechanisms.

Stresses That Influence Decisions

Global warming is an important part of the changes we are experiencing, but we must consider climate change in a context that includes other stress factors that threaten the human experience and the ecosystem in which we live. These stress factors include worldwide population growth, environmental degradation, wars and political unrest, and economic turmoil. Climate change, added to these stresses, can be the tipping point that moves an ecosystem beyond recovery, such as the loss of biological species.

Similarly, climate change is one of many concerns that must be addressed in planning for improvements in transportation and the built infrastructure. Continued coastal development, for example, brings with it serious risks to transportation and other infrastructure, as well as to the homes, businesses, and economy that may flourish there for a limited time. Land use and development are traditionally jurisdictional matters for local and regional authorities, but their decisions may have cost implications for a large segment of society and the ecology. For example, insurance costs for coastal communities are likely to be spread to individuals and businesses that are far from the danger zones.

Interactions and relationships among geographical regions and social sectors cannot be ignored. Drought in the Southwest and/or increases in water and air temperatures may reduce the efficiencies of power plants, just when more power is needed for air conditioning. Intense storms and floods can impact commerce, as they did following Katrina and the great floods of 1993 on the upper Mississippi River.

Conflicts inevitably arise between the needs of people and the needs of the ecosystem in which they live, and adaptation measures to manage the risks of climate change must incorporate sound sustainability principles. If we plan and act responsibly, we may be able to "have our cake and eat it too."

Sound Solutions for the 21st Century Transportation System

We must not use the uncertainties and challenges of adapting to climate change as an excuse for inaction. The challenge to the engineering profession is to take into account the inherent uncertainties of climate science, as well as complex technological, social, economic, and environmental interrelationships, and develop sound solutions for transportation systems that will serve us until the end of the century. A large body of work has been done on making decisions on issues that include great uncertainties. Scenario analyses, for example, can provide "envelopes" of possible outcomes (e.g., best case/worst case scenarios and respective probabilities).

Climate change must be considered in the context of other stress factors that threaten humans and ecosystems.

To many, climate change is a distant worry, but developers of transportation systems work on a time horizon of 50 to 100 years for new and rehabilitated facilities. Thus they have no choice but to take into account the impacts of climate change. The marginal costs of accommodating climate change impacts in major systems will be dwarfed by the cost of retrofitting systems to meet these same needs decades hence. To engineers, many of the solutions for adaptation are fairly obvious—build robust, resilient systems, protect or move existing assets, and, when necessary, abandon indefensible facilities.

Some adaptations to climate change are listed below:

Sea Level Rise

- Build or enhance levees and dikes to resist higher sea levels and storm surges.
- Elevate critical infrastructure.
- Abandon or relocate coastal highways, rail lines, and bridges.
- Provide good evacuation routes and operational plans.
- Provide federal incentives to reduce the amount of development in at-risk coastal regions.

Heat Waves

- Support research on new, more heat-resistant materials for paving and bridge decks.
- Replace and/or reconstruct highway and bridge expansion joints.
- Increase the length of airport runways to compensate for lower air densities.
- Revisit standards for construction workers exposed to high temperatures.

Increased Storm Intensity

- Revise hydrologic storm and flood frequency maps.
- Develop new design standards for hydraulic structures.
- Reinforce at-risk structures, particularly to protect against scouring of bridge piers.
- Encourage better land-use planning for flood plains.

Stronger Hurricanes

- Move critical infrastructure inland.
- Reinforce and/or build more robust, resilient structures.
- Design for greater storm surges.
- Strengthen and elevate port facilities.

Arctic Warming

- Identify areas and infrastructure that will be damaged by thawing permafrost.
- Develop new approaches to foundation design.
- Reinforce, protect, or move seaside villages.

Conclusions

We can continue to debate the validity of climate science, but waiting for decades or longer for final "proof" would be foolhardy at best. Fifty or 100 years from now the impact of increasing emissions of GHGs will be firmly established. If the projections of today's climate scientists are correct and we have failed to take both mitigating and adaptive actions, then much damage will already have been done.

The potential impacts of climate change on the built environment and the implications for transportation infrastructure are sufficiently well defined for us to take action now. If this generation of engineers fails to act, coastal highways and railroads will be under water, bridges will be unusable, tunnels will be periodically flooded, communities in the Midwest, Northeast, and Southeast will be threatened by river flooding, people in the Southwest will face increasing water shortages, and entire villages along the North Slope of Alaska will be swallowed by the sea.

However, if we incorporate climate change into the regular planning processes for transportation and other infrastructure, the marginal costs of building more robust, resilient systems can be readily accommodated. And we will have met our obligations to future generations.

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Managing risks associated with climate change is essential for planning and policy decisions.

Risk Assessment and Risk Management for Infrastructure Planning and Investment[1]

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In *Climate Change 2007: Impacts, Adaptation and Vulnerability*, the contribution of Working Group II to the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC, 2007a), authors from around the world focused attention on the impacts of climate change that we either cannot avoid or choose not to avoid. In other words, IPCC made the case that adaptation to climate change should no longer be considered as giving up on the problem. This message is reinforced in the panel report on adaptation to climate change released in May by the National Research Council (NRC, 2010a).

Many impacts of climate change become apparent through increasingly intense and/or more frequent extreme weather events (e.g., heavier precipitation, more intense coastal storms, and severe droughts, floods, wildfires, and heat waves). Both the IPPC and NRC reports describe changes attributed to anthropogenic sources that have already been observed and are threatening some unique social and natural systems. The magnitude of these changes will very likely be exacerbated over the near and more distant future as natural climate variability is distributed around increasingly worrisome central tendencies. Indeed, because temperature increases driven by higher

[1] This article relies heavily on material in Chapter 2 of NPCC (2010b) and the section on the New York City approach in Chapter 5 of NRC (2010b).

greenhouse-gas concentrations reflect only 50 percent of the corresponding equilibrium warming, near-term decisions to mitigate climate change modestly (or not at all) may actually commit the planet to sudden, irreversible changes by the end of the century (NRC, 2010d; Solomon et al., 2009).

Given the evidence, climate *is* changing, and absent significant reductions in emissions of greenhouse gases, it will continue to do so at an accelerating pace. IPCC, its client governments, the New York Panel on Climate Change (NPCC, 2010b), the National Academies (NRC, 2010a,b,c,d), and many other international assessments have all turned to *risk management* as a framework for constructing responses to climate challenges. Indeed, the unanimously approved "Summary for Policymakers" in the IPCC Synthesis Report closed with a statement on the importance of considering risk in all deliberations: "Responding to climate change involves an *iterative risk management process that includes both adaptation and mitigation* and takes into account climate change damages, co-benefits, sustainability, equity and attitudes to risk" (IPCC, 2007b, emphasis added).

Governments throughout the world have thereby clearly stated their understanding that managing risks associated with climate change must be the central theme in present and future planning and policy decisions. Moreover, now that all four NRC panels of the America's Climate Choices initiative have accepted this tenet, we can count the United States among those governments.

This article begins by covering some critical definitions and fundamental insights about applying the risk-management paradigm to climate adaptation and mitigation and a brief description of a specific application for infrastructure investment in urban Boston designed explicitly to respond to potential changes in climate driven by natural cycles. This is followed by a description of New York City's decision to include climate change in its planning processes to protect both public and private infrastructure. The article ends with some observations about the context and applicability of risk management approaches to adaptations to climate change.

Definitions and Fundamentals

Our understanding of some of the aspects of climate change is well established. For example, IPCC (2007b) concluded that it is "virtually certain" that global mean temperatures are rising, and NRC (2010a) confirmed this conclusion. Both assessments also concluded that we know with "very high confidence" that anthropogenic emissions are the cause of this temperature rise.

Thus, even though substantial uncertainties persist about specific sources of risk from specific manifestations of climate change at specific locations, IPCC and NRC agree that near-term action, including adaptation, should be taken immediately to minimize the costs of reducing the rate and magnitude of climate change impacts driven largely by increases in global mean temperature. This means that local decision makers must take action in the face of substantial uncertainties and associated risks, particularly when making decisions about major investments in infrastructure.

The IPCC and NRC agree that near-term action, including adaptation measures, should be taken immediately.

All risk management techniques are based on the same statistical definition of risk—the probability that an event will occur multiplied by a measure of its consequences (e.g., Raiffa and Schlaiffer, 2000). Many decision makers favor risk-based approaches because they are based on the same theoretical underpinnings that support other kinds of economic analyses *and* because they can be applied to situations characterized by significant uncertainty.

Finance directors, government officials, and infrastructure managers, all of whom deal with risk and associated best practices on a daily basis, understand that spreading risk can improve social and/or private welfare. Even though risk diversification does not eliminate risk in most cases, spreading risk does lower net exposure for all participants.

On a fundamental level, first principles of economic efficiency in an uncertain world lead to robust

[2] Risk analyses have demonstrated that decisions are critically dependent on subjective prior distributions with which we weight the relative likelihoods of future outcomes, thereby demonstrating how aversion to risk influences the value of information. Economic efficiency establishes criteria by which maximal welfare could be achieved with limited resources by allocating them effectively to meet a wide range of competing demands.

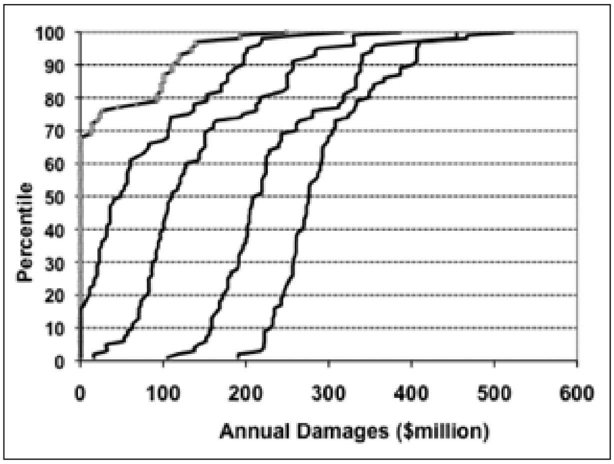

FIGURE 1 Distributions showing economic damage from coastal flooding in selected years for an urban area in Boston for a 1.0 meter rise in sea level (from left to right, 2010, 2030, 2050, 2070 and 2090). Source: Panel A of Figure 4 in Yohe et al., forthcoming.

responses that work reasonably well for a wide range of possible outcomes even though they may not be optimal for any particular outcome.[2] Because uncertainty is inherent in our understanding of climate change and climate impacts, particularly impacts driven by changes in the distributions of climate variability, it is entirely appropriate that risk has become the "currency of the realm."

Take, for example, a recent analysis of a large public investment to provide substantial protection along a developed coastline in an urban area of Boston; the area is subject to future coastal storms whose intensities will be amplified by sea level rise (Yohe et al., forthcoming). Figure 1 shows distributions of underlying damages that could be suffered for selected times for a 1.0 meter sea level rise by the end of the century.

Decisions about whether and when to make this investment (and thereby commit to ongoing maintenance expenditures that will last for decades) involved determining when the present value of benefits (i.e., reductions in damages calibrated to include attitudes toward risk) would exceed the present costs. Specifically, the analysis confirmed that damages attributed to sea level rise—the source of value for this adaptation—would increase as risk aversion increased. This is illustrated in Figure 2, which shows the internal rates of return (IRRs) for undertaking the Boston investment at various times between now and 2040 as aversion to risk increases.

To understand Figure 2, relative risk aversion (RRA) must be set at 0 to indicate complete risk neutrality. In other words, RRA = 0 means that decision makers are agreed that a dollar of damage is the same regardless of whether it is the result of a catastrophically large storm or an unusually small storm that might be inconsequential from a societal perspective. Allowing the RRA value to rise above zero indicates that decision makers feel that the consequences of coastal storms increase with their intensities, and at an increasing rate (because simple dollar metrics do not reflect the magnitude of social disruption and human pain caused by larger storms).

For reference, the IRR of an investment indicates the discount rate for which the present value of net benefits is zero. Investments may be made with IRR values greater than the going rate of interest (i.e., the rate by which decision makers discount future costs and benefits), but investments with IRR values below the applicable interest rate are either deferred or discarded entirely.

Therefore, because the IRR increases with risk aversion, investments that reduce risk become increasingly appealing as decision makers become increasingly averse to risk. Because the IRR increases over time, the adaptation investment has a predictably greater chance of being above the implementation threshold with the passage of time.

Several general hypotheses can be derived from this analysis for cases in which the manifestations of climate change cause economic damage stochastically correlated

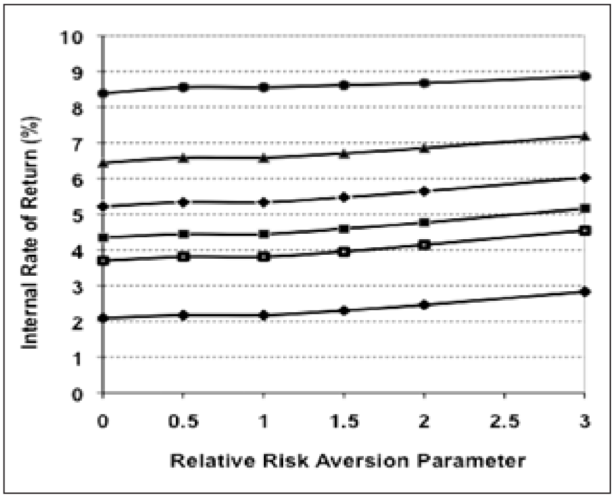

FIGURE 2 Internal rates of return for infrastructure investment designed to protect an urban area in Boston with a sea level rise that reaches 1.0 meter by 2100. Rates are evaluated at five-year intervals for different levels of risk aversion (2010, 2015, 2020, 2025, 2030, and 2035 from bottom to top). Source: Figure 6 in Yohe et al., forthcoming.

with long-term trends. First, the choice of a baseline against which to gauge the values of various responses to external stress is not just an academic exercise. Differences in baselines, which can be framed in terms of the degree to which economic risk can be spread across a population, and therefore the degree to which RRA approaches zero, can easily change the value of an adaptation and influence its optimal timing.

Second, the economic value of an adaptation should be expressed in terms of differences in expected outcomes (damages with and without the adaptation) only if the affected community has access to efficient risk-spreading mechanisms or reflects risk neutrality in its decision making procedures. Otherwise, increases in decision makers' aversion to risk will increase the economic value of adaptations that reduce expected damages and diminish the variance of their inter-annual variability.

Finally, for engineering and other adaptations that involve significant up-front expenses followed by annual operational costs for the foreseeable future, increases in decision makers' aversion will increase the value of that adaptation and, therefore, move the date of economically efficient implementation closer to the present.

The New York City Approach to Adapting Infrastructure

Although in theory a risk-based approach can be applied to many types of adaptation decisions (e.g., retrofitting existing infrastructure, changing the design of new infrastructure, or initiating new infrastructure projects), the requisite data may not always be available. Thus the need to identify information requirements and gaps in knowledge is one reason to begin planning for and prioritizing adaptation options as soon as possible.

New York City adopted a risk-based approach of the kind described above to protect its enormous private and public infrastructure from increasing vulnerability to climate change and associated climate variability. The city was motivated by abstract, sometimes academic constructions of risk which were turned into practical, transferable decision-support tools that could be applied in situations where information was scarce.

From the beginning, the research and policy communities understood that setting climate policy for an entire century would not be possible. For example, based on our current understanding of climate sensitivity, the likely range of temperature rise is from 2°C to more than 4.5°C, but it could also be much higher

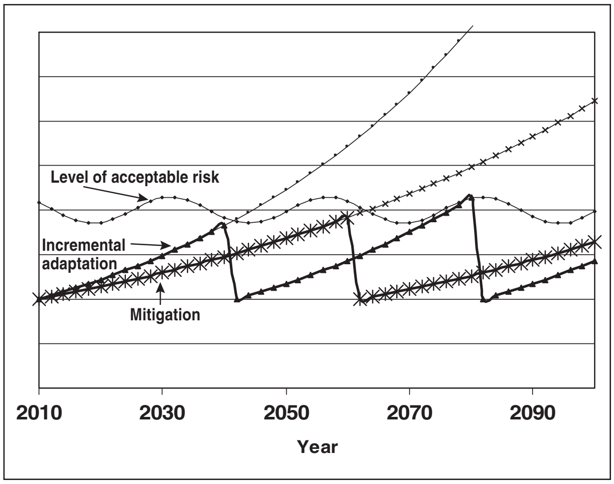

FIGURE 3 In this schematic illustration of iterative adaptation born of a risk management perspective, the wavy but roughly horizontal line shows the evolving threshold of acceptable risk. If greenhouse gas emissions were to continue unabated, then risk would climb exponentially along the higher exponential curve, and the risk threshold would be crossed about 2040. Iterative adaptation against this trajectory (the darker saw-toothed line that tracks unabated risk through 2035 or so) could maintain acceptable levels of risk over time in two steps (one investment in the 2030s and another around 2080). A lower exponential risk trajectory crosses the acceptable risk threshold about 2060 or so; it illustrates the value of mitigation. Iterative adaptation would still be warranted (results are portrayed by the lower saw-toothed line that shows an investment in adaptation sometime in the 2050s). The slower pace of warming (the result of investment in mitigation) allows later and ultimately less frequent investments in adaptation throughout the century and perhaps beyond. Source: The antecedent of Figure 2.1 in NPCC (2010b).

(IPCC, 2007b). In addition, it is now widely accepted that even advances in fundamental scientific understanding are not likely to lead to substantial decreases in this temperature range.[3] Roe and Baker (2007) showed, for example, that "the probability of large temperature increases" is "relatively insensitive to decreases in uncertainties associated with the underlying climate processes." Allen and Frame (2007) further argued that it is pointless for policy makers to count on narrowing this fundamental uncertainty.

Thus decision makers and resource managers must

[3] Climate sensitivity is the increase in equilibrium global mean temperature associated with a doubling of atmospheric concentrations of greenhouse gases from pre-industrial levels. IPCC (2007a) reports, for example, that "the equilibrium climate sensitivity is a measure of the climate system response to sustained radiative forcing. It is not a projection but is defined as the global average surface warming following a doubling of carbon dioxide concentrations. It is *likely* to be in the range 2°C to 4.5°C with a best estimate of about 3°C, and is *very unlikely* to be less than 1.5°C. Values substantially higher than 4.5°C cannot be excluded, but agreement of models with observations is not as good for those values."

accept that inflexible, long-term, climate-change policies that can predictably limit greenhouse gas emissions and associated risks will not be put into place in the near future. Therefore, there must be a *process* by which interim targets and objectives for both mitigation and adaptation can be informed by long-term goals to enable appropriate adjustments to be made as efficiently and transparently as possible (Yohe et al., 2004).

Although this simple conclusion makes sense, problems arise as soon as one begins thinking about how to make it operational, especially for infrastructure investments with lifetimes that can last for many decades or longer. Figure 3 is a schematic portrait of one approach showing a threshold level of acceptable risk (represented by a horizontal wave) that would be breached around 2035 if climate change continues unabated. Incremental adaptation alone, reflected by a "saw-toothed" trajectory, would involve a sequence of responses for keeping risk below the acceptable limit. Since this trajectory approaches the threshold of tolerable risk more quickly and more frequently with the passage of time, Figure 3 illustrates why IPCC (2007a,b) concluded that unabated climate change could easily overwhelm the capacity to adapt by 2100 even in developed countries.

Figure 3 also suggests that mitigation could slow this process—producing a lower risk profile that would not cross the acceptable-risk threshold until 2065. Even though mitigation would provide a delay of only 15 years, this would mean that adaptation responses could be pursued with a more leisurely and presumably less expensive investment program. Schematically, then, it is not difficult to see how mitigation and adaptation might complement each other.

Based on this context, New York City planners worked with the New York Panel on Climate Change

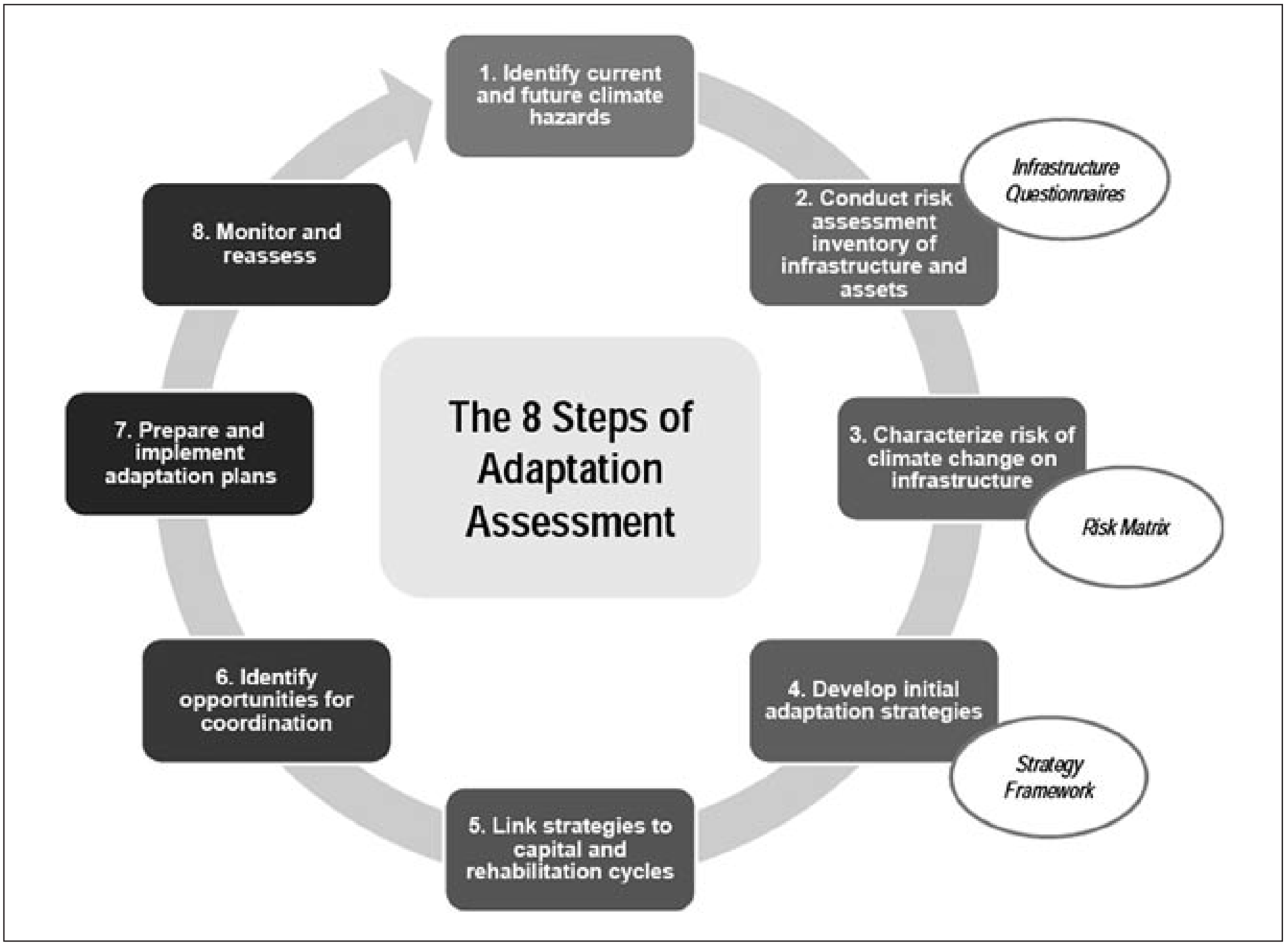

FIGURE 4 The iterative process based on the adaptation assessment and supplemental tools used by New York City. The process included Infrastructure Questionnaires, Risk Matrices, and a Strategy Framework that were general enough to be used for a variety of jurisdictions and infrastructure sectors but specific enough to be used as a template for the development and implementation of an adaptation plan for each sector. Source: Figure 1.5 in NPCC (2010b).

(NPCC) to develop a multi-step process to help stakeholders create an inventory of their at-risk infrastructure and develop adaptation strategies to address the risks. Each step, illustrated schematically in Figure 4, became an integral part of ongoing infrastructure maintenance and operation programs, as well as part of a priority-setting planning process for the city agencies and private actors who manage and operate critical infrastructure.

At the start of the project, NPCC (2010b) reported ranges of possible futures (Step 1 at top of the circle). The task force was also provided with tables and other materials showing ranges of broad indicators of climate change through the turn of the century. Perhaps most important to decision makers was a table (Table 1) showing the frequency of extreme weather events that would create risks to particular infrastructure sectors.

Building on this and other information reported by NPCC, the city authorized the newly created Climate Change Adaptation Task Force to apply three risk-based decision-support tools that had been designed in consultation with NPCC (2010b): (1) sector-specific *infrastructure questionnaires* to help stakeholders create inventories of infrastructure vulnerable to the impacts of climate change, especially impacts driven by dynamic climate variability (Step 2 in Figure 4); (2) *risk matrices* to help stakeholders categorize at-risk infrastructure based on the likelihood of impact and the magnitude of consequences as the climate changes and the parameters of variability mutate (Step 3 in Figure 4); and (3) *strategy frameworks* to assist stakeholders in developing and prioritizing adaptation strategies based on criteria related to effectiveness, cost, timing, feasibility, co-benefits, and other factors (Step 4 in Figure 4).

These process-based tools ultimately provided a foundation for the development of climate-change adaptation plans for critical infrastructure in the New York City region as part of an overall planning process described in *Adaptation Assessment Guidebook* (NPCC, 2010a).

TABLE 1 Information about Climate Change (manifestations of climate change in terms of extreme events that produce infrastructure risk for three time slices in the 21st century).

	Extreme Event	*Baseline (1971-2000)*	2020s	2050s	2080s
Heatwaves & Cold Events	# of days/year with maximum temperature exceeding:				
	90°F	*14*	23 to 29	29 to 45	37 to 64
	100°F	*0.4*	0.6 to 1	1 to 4	2 to 9
	# of heat waves/year	*2*	3 to 4	4 to 6	5 to 8
	Average duration (in days)	*4*	4 to 5	5	5 to 7
	# of days/year with minimum temperature below 32°F	*72*	53 to 61	45 to 54	36 to 49
Intense Precipitation & Droughts	# of days per year with rainfall exceeding:				
	1 inch	*13*	13 to 14	13 to 15	14 to 16
	2 inches	*3*	3 to 4	3 to 4	4
	4 inches	*0.3*	0.2 to 0.4	0.3 to 0.4	0.3 to 0.5
	Drought to occur, on average	*~once every 100 yrs*	~once every 100 yrs	~once every 50 to 100 yrs	~once every 8 to 100 yrs
Coastal Floods & Storms	1-in-10 yr flood to reoccur, on average	*~once every 10 yrs*	~once every 8 to 10 yrs	~once every 3 to 6 yrs	~once every 1 to 3 yrs
	Flood heights (in ft) associated with 1-in-10 yr flood	*6.3*	6.5 to 6.8	7.0 to 7.3	7.4 to 8.2
	1-in-100 yr flood to reoccur, on average	*~once every 100 yrs*	~once every 65 to 80 yrs	~once every 35 to 55 yrs	~once every 15 to 35 yrs
	Flood heights (in ft) associated with 1-in-100 yr flood	*8.6*	8.8 to 9.0	9.2 to 9.6	9.6 to 10.5
	1-in-500 yr flood to reoccur, on average	*~once every 500 yrs*	~once every 380 to 450 yrs	~once every 250 to 330 yrs	~once every 120 to 250 yrs
	Flood heights (in ft) associated with 1-in-500 yr flood	*10.7*	10.9 to 11.2	11.4 to 11.7	11.8 to 12.6

Note: This table records details about extreme events elicited from the science panel to inform evaluations of risk to critical public and private infrastructure. Source: Table 2 in Appendix C in NPCC (2010b).

Likelihood of exposure / Magnitude of consequences	Low	Medium	High	Virtually certain/ Already occurring
High				
Medium				
Low				

FIGURE 5 The risk matrix. This two-dimensional risk matrix, with qualitative judgments about both the magnitude of vulnerability and the likelihood of exposure at specific points in time, relates the fundamental nature of the risk (the product of likelihood and consequence) to specific types of infrastructure, which were placed in the matrix for specific points in the future. The darker the shading in the box, the higher the qualitative and functional levels of risk. Source: Figure 5 in Appendix B of NPCC (2010b).

The task force was divided into four working groups representing categories of infrastructure important to the city: communications, energy, transportation, and water/waste.[4] In addition, a policy group was convened to review the codes, rules, and regulations governing infrastructure in New York City and to identify historical standards that might have to be altered in the future to maintain the current level of acceptable risk. Each group provided participants interested in a particular critical sector of city infrastructure (either public or private) a context within which they could identify common vulnerabilities, share best practices, take advantage of potential synergies, and develop coordinated adaptation plans.

The working groups met from time to time as necessary to ensure consistency, identify opportunities for coordination, investigate impacts of adaptation strategies on other sectors, and develop cross-sector adaptation strategies. In addition, the policy group led reviews for each working group of regulations that embodied common attitudes toward tolerable risk and searched for synergies and inconsistencies across sectors. Informed by these interactions, working groups put forward adaptation strategies that went beyond the scope of their specific interests and could become part of city-wide initiatives.

NPCC's (2010b) projections of climate change were essential to the process. The projections (reflected in Table 1) provided all stakeholders with a common understanding of climate science, initial potential impacts, and uncertainties. As a result, the inventories and adaptation alternatives developed by stakeholders and proposed to wider audiences were based on the same state-of-the-art climate-change projections. In addition, decisions about allocations of scarce resources were more productive and less contentious than they might have been otherwise.

New York City stakeholders then completed automated templates in which risks for particular "pieces" of infrastructure were determined to be the product of the likelihood an impact would occur and the magnitude of the consequences. Because both terms were described qualitatively, the lack of precise information about distributions and consequences did not impede the process. The risks were then placed in a matrix (see Figure 5).

Perhaps most important, the risk-management process included monitoring and assessment exercises (Step 8 in Figure 4) designed to feed directly into subsequent iterations of the same process. In other words, the city envisioned a dynamic cycle of analysis and action, followed by re-analysis and possible adjustments to or continuations of previous actions (i.e., learn, then act, then learn some more). Thus, the approach was based on an understanding of the need for flexible adaptation pathways of the sort shown schematically in Figure 3 that would evolve over time as knowledge about the climate and local, national, and global economies improved. Indeed, as of summer 2009, the Bloomberg administration intended to push the City Council to pass a law requiring subsequent administrations to submit progress reports and revised climate adaptation plans, just as they are now required to submit updates on progress toward achieving sustainability goals.

Figure 4 also shows that no part of an adaptation plan can be considered in isolation (Step 7). Investments in adaptation programs must be integrated into budget decisions based on a myriad of competing demands for scarce resources (Step 5). New York City has concluded that the urgency and cost of any proposed adaptation

[4] The Waste and Water Working Group includes agencies that handle the city's solid waste and wastewater as well as entities responsible for the natural environment and a significant portion of waterfront properties.

response must be compared with other options so its place in the long-term sustainability planning of the city can be determined and supported (Step 6).

Notice that the monitoring function in Step 8 of Figure 4 must include not only adaptations that have been implemented, but also adaptations that have been deferred. In that way, the flexible, iterative program can adjust the urgency of options for the next round of decisions. In summary, New York City's planning for climate change is a fully integrated component of its ongoing plans for managing growth, infrastructure, and environmental sustainability.

Concluding Remarks

Major conclusions that can be drawn from this brief review of current thinking about addressing risks associated with climate change have been succinctly summarized by the IPCC (2007b). To paraphrase, responding to climate change *requires* a *risk-management approach* by which adaptation and mitigation are understood as part of an *iterative process* that explicitly takes into consideration changes over time and the need for mid-course corrections as knowledge of the underlying science of climate and its translation into climate variability evolves. It follows, then, that governments and other institutions must establish cooperative mechanisms by which they can track, analyze, and project key manifestations of climate change, their associated impacts, the degree to which responses might reduce both exposure and sensitivity to those impacts, and the inevitable interactions of these responses with other private and public initiatives.

It is important to emphasize in closing, however, that the decision to base targeted climate-protection levels over time on socially tolerable levels of risk inferred from existing design standards and codes involves informed, precautionary value judgments that other jurisdictions, with different values and resources, may not find acceptable. Although different values may therefore be adopted in different locations, IPCC (2007b) and NRC (2010a,b,c,d) agree that the risk-management approach to coping with climate change can accommodate this diversity.

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Energy-efficient industry will contribute to a cleaner environment, U.S. competitiveness and security, business profitability, and the quality of the workforce.

Transforming Industrial Energy Efficiency

Marilyn A. Brown, Matt Cox, and Rodrigo Cortes

Marilyn A. Brown

Matt Cox

Rodrigo Cortes

Meeting the energy needs of future generations without overheating the planet is one of the most vexing challenges of our time. In an increasingly resource-constrained world, improving the energy efficiency of industry must be part of the climate solution. In addition to environmental, security, and competitiveness benefits, improving industrial energy efficiency will deliver a return on investment that contributes to the profitability of enterprises and strengthens the nation's employment base.

Industrial energy efficiency has improved over the past several decades in response to volatile fossil-fuel prices, global and domestic competition, and technological advances. U.S. manufacturing has undergone significant changes to improve market competitiveness and increase profits, including reductions in the energy intensity of manufacturing following the oil crises in the 1970s. Over the past several decades, however, the pace of

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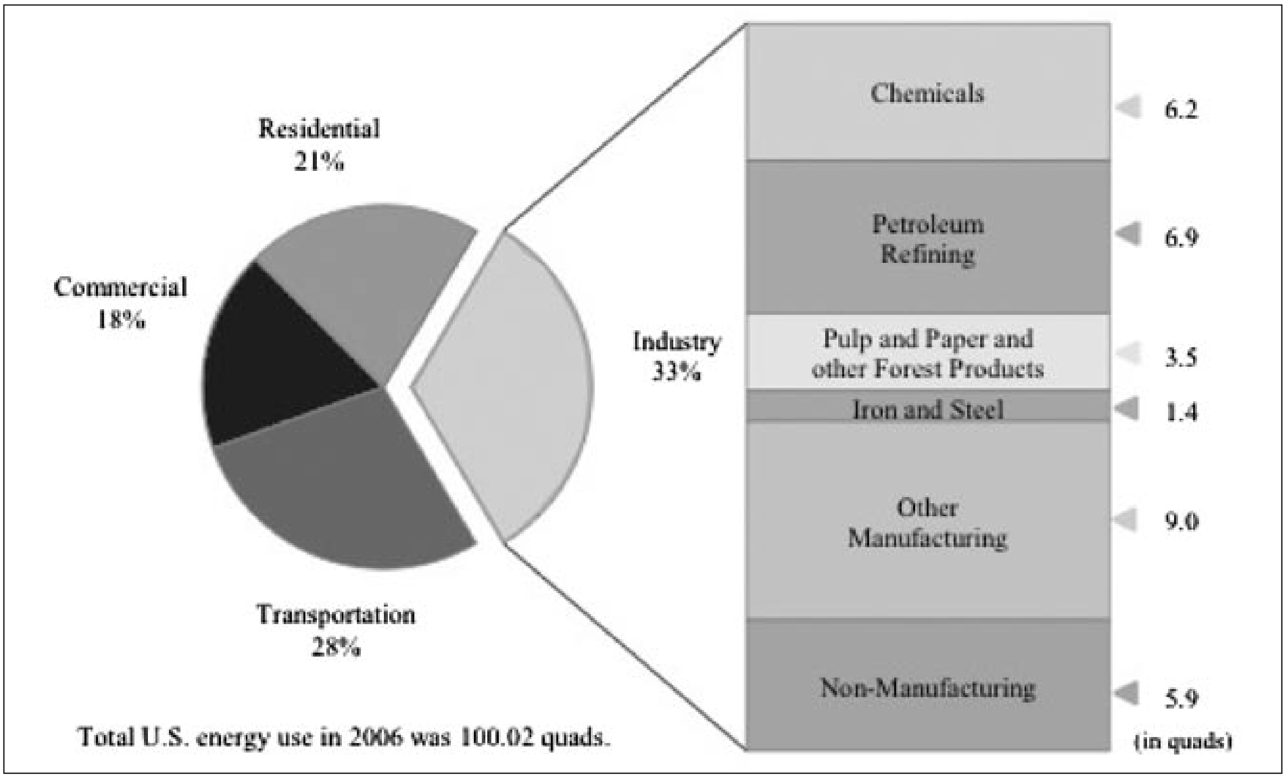

FIGURE 1 U.S. energy consumption in 2006.

investment in industrial efficiency has slowed, even though technological opportunities for clean energy transformations of industrial systems have increased. After a decade of stagnation, federal policy makers are finally considering options for accelerating clean-energy industrial transformation.

Technology Options

Industry, the largest energy-consuming sector in most countries of the world, accounts for 37 percent of primary energy use worldwide (IPCC, 2007) and approximately one-third of total U.S. energy consumption, mostly by four energy-intensive industries: chemicals, petroleum refining, pulp and paper, and iron and steel (Figure 1). Less energy-intensive industries include the manufacture and assembly of automobiles, appliances, electronics, textiles, food, beverages, and other products. Since energy is a smaller portion of their overall costs, these industries have tended to pay less attention to finding ways to cut energy use. However, current evidence shows that this may be changing as the result of an increased focus on reducing carbon footprints (Prindle, 2010).

As populations grow and standards of living rise, the production of energy-intensive goods is likely to continue to increase worldwide. An increasing proportion of this production is moving to China, Korea, India, and other rapidly industrializing countries. For example, although the United States remains the world's largest producer of bulk chemicals and refined petroleum products, China has become the world's largest producer of steel, aluminum, and cement (IPCC, 2007). Global competition for export markets, foreign investments, and raw materials is intensifying, which will reward industries that can cut costs by reducing their resource requirements.

As the era of cheap energy comes to an end, successful manufacturers will increasingly focus on technological innovations that enable order-of-magnitude reductions in energy consumption and on substituting renewables for fossil fuels and using other low-carbon energy resources. Advances in engineering, materials, thermodynamics, sensors and controls, and information technologies (among others) have the potential to transform industrial processes.

The America's Energy Future (AEF) Committee of the National Academies concluded that investments in available efficiency technologies could reduce U.S. energy consumption in the industrial sector by 14 to 22 percent over the next decade (National Academies,

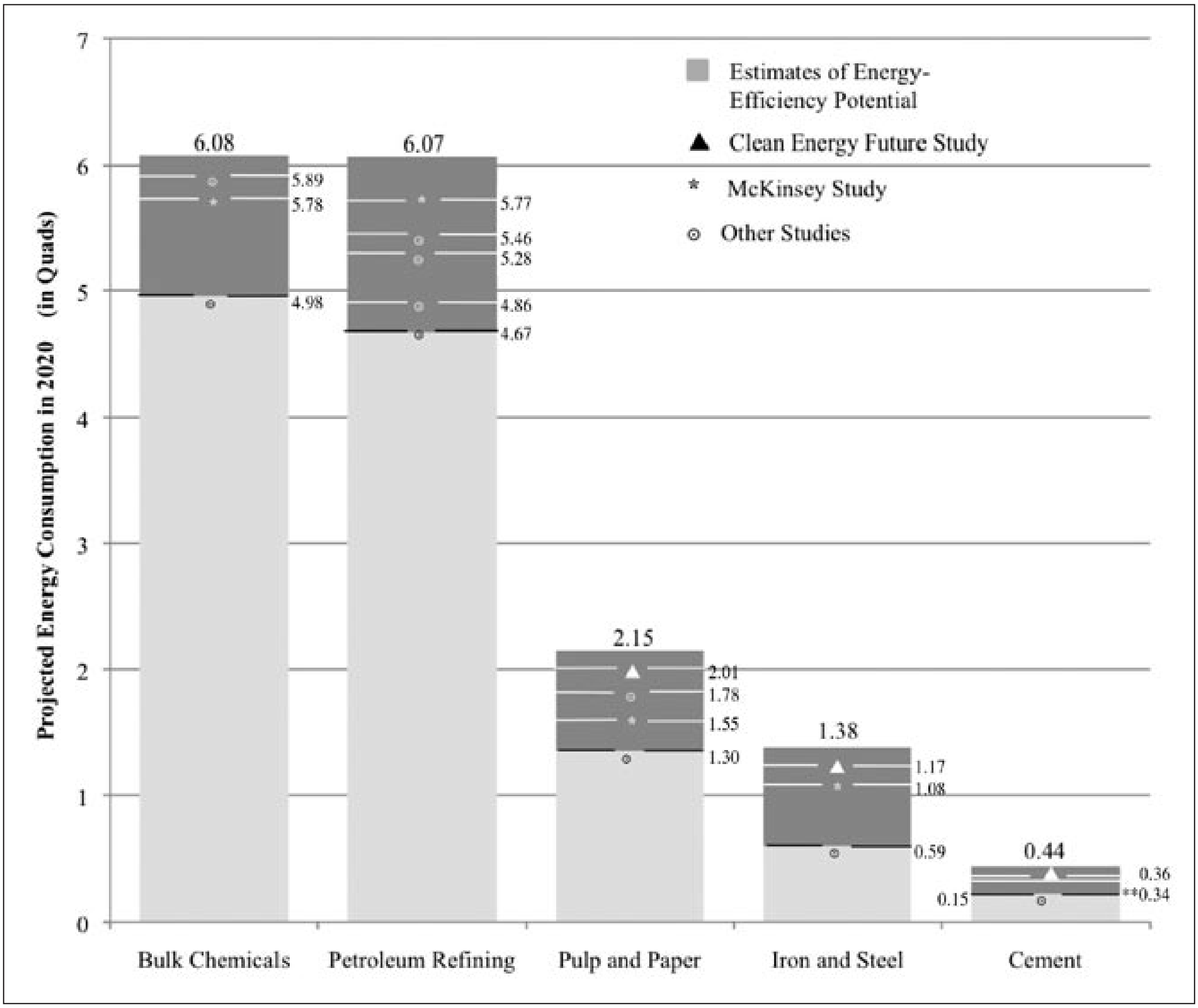

FIGURE 2 Potential for improving energy efficiency in key industries by 2020. Source: Compiled from National Academies (2009).

2009). At the current average rate of industry carbon dioxide (CO_2) emissions per Btu of consumption, this would reduce emissions by 434 million metric tons of CO_2 annually by 2020.[1]

There are numerous examples of technological innovations with the potential for industry-wide energy savings:

- In today's power generation and utilization infrastructure, with large-scale centralized power plants and dispersed end-use locations, there are large mismatches between thermal needs and waste heat streams. Tremendous overall energy savings could be achieved if systems were optimized so that wasted energy was recycled into productive uses. This can be done by cascading and recycling the waste heat and hot exhaust gases that are vented to the atmosphere, low-grade fuels that are typically flared off, and high-pressure steam and gas. Such combined heat and power (CHP) opportunities exist in many industries, including bulk chemicals, food processing, and pulp and paper production (Shipley et al., 2008).
- Opportunities to improve petroleum refining include high-temperature reactors, distillation columns for separating liquids, gas separation technologies, corrosion-resistant metal- and ceramic-lined reactors, sophisticated process-control hardware and software, pumps of all types and sizes, and more efficient steam generation (DOE, 2006; LBNL, 2005).

[1] Author's calculation.

- In the papermaking industry, fiber optic and laser sensors can monitor water content, sheer strength, and the bending stiffness of paper, thus saving energy and improving paper quality.[2]
- Blending fly ash, steel slag, and other recycled materials with cement could cut energy consumption in the cement industry by 20 percent (Worrell and Galitsky, 2004).
- Motors, the largest single category of electricity end use in the U.S. economy, offer considerable opportunities for saving electricity through technology upgrades and improvements in system efficiency achieved by selecting appropriately sized and the most efficient available motor for the application at hand. Next-generation motor and drive improvements, including superconducting materials, are currently under development (National Academies, 2009).

A recent study by the McKinsey Group (Granade et al., 2009) and numerous other studies have documented the great potential for energy savings in energy-intensive U.S. industries. The National Academies (2009) reviewed the literature on five energy-intensive industries to evaluate their potential for cost-effective improvements by 2020 (Figure 2). In the chemicals industry, potential cost-effective energy savings are estimated to reduce energy consumption from 6.08 to 5.89 or even 4.98 quads (savings of 3 to 18 percent) by 2020. Larger potential savings could be made in the petroleum refining industry, ranging from 5 to 23 percent of energy consumption by 2020. Estimates for the pulp and paper industry range from 6 to 37 percent reductions by 2020. The broad range of these estimates highlights the lack of consensus about the magnitude of the opportunity. Nevertheless, all of the studies show that sizeable energy savings can be made while providing positive cash flows for investors.

Reasons for the Efficiency Gap

Some of the barriers that have impeded the transformation of industrial energy systems are described below:

- Technical risks. Uncertainties about the benefits and risks of new technologies is a major barrier in the current manufacturing environment, which requires 24/7 operation. Reliability and operational risks are major concerns for industries adopting new technologies.
- High costs. New energy-efficient technologies often have longer payback periods than traditional equipment and entail more financial risk because of uncertain future energy prices. New technologies must compete for financial and technical resources against projects that achieve other company goals.
- External benefits and costs. External environmental benefits—including reductions in greenhouse gas (GHG) emissions—are not usually considered by potential investors in energy-efficiency technologies.
- Lack of specialized knowledge. Industrial managers can be overwhelmed by the number of energy-efficiency products and programs, which can be difficult to evaluate unless a company has in-house energy expertise.
- Incomplete and imperfect information. Researching a new technology takes time and resources, especially for small firms, and many industries prefer to spend their human and financial capital on other priorities.
- Market risks caused by uncertainty. Uncertainties about future electricity and natural gas prices and long-term product demand can present a powerful barrier.

Sizeable energy savings can be made while cash flows for investors remain positive.

Existing regulations can also impede efforts to improve energy efficiency. For example, the Environmental Protection Administration (EPA) New Source Review (NSR) Program can discourage improvements in energy efficiency at industrial facilities (EPA, 2002). As part of the 1977 Clean Air Act Amendments, Congress established the NSR Program and modified it in the 1990 Amendments, but old coal plants and industrial facilities were exempted from the New Source Performance Standards (NSPS). NSPS standards are intended to promote the adoption of the best available air pollution control technologies, taking into account

[2] See *http://www.physorg.com/news4221.html.*

technology costs and other non-air quality, health, and environmental impacts and energy requirements.

However, investing in an upgrade could trigger an NSR, and the threat of such a review has discouraged companies from investing in upgrades. NSR thus imposes pollution controls where they are least needed and artificially inflates the value of the dirtiest plants. Overall, these effects have led some critics to question whether the NSR Program and NSPS have resulted in higher levels of pollution than there might have been without the regulation (Brown and Chandler, 2008; List et al., 2004).

The barriers described above have caused many firms to defer decisions on investing in energy efficiency. Unfortunately, once an asset is installed, it becomes difficult to change, thus locking in a level of energy efficiency that will last for years or even decades (IEA, 2008). This is another reason to aggressively pursue "windows of opportunity" for putting energy-efficient technologies and systems in place.

Combined Heat and Power: A Case Study

Combined heat and power (CHP) is a suite of technologies that couples thermal systems with electricity production that can boost overall efficiencies from the 35 to 50 percent range to the 70 to 80 percent range and sometimes higher (Shipley et al., 2008). Numerous barriers to deploying CHP technologies include the way states implement the Clean Air Act. Most of them use an input-based emissions standard, thereby ignoring the efficiency of the industrial system. Switching to an output-based emissions standard measured in emissions per unit of useful energy output would reflect the efficiency of the industrial system and enable the installation of more efficient technologies, without threatening the legality of the current environmental permits for the facility. Although EPA supports the adoption of output-based emissions standards, only 17 states have done so.

A recent analysis by the Georgia Tech version of the National Energy Modeling System (GT-NEMS)

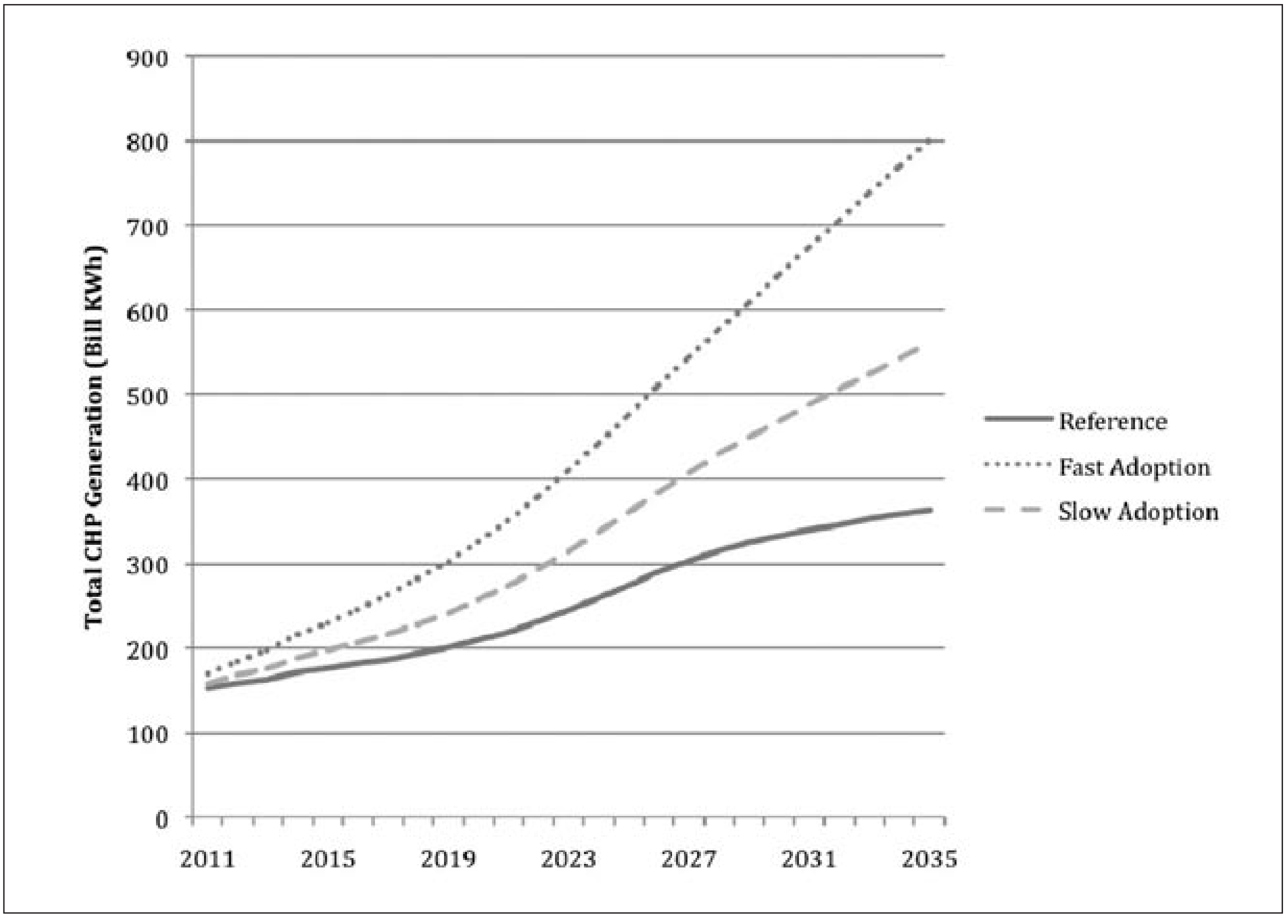

FIGURE 3 Total industrial CHP generation based on output-based emissions standards.

TABLE 1 Total Resource Test for the Fast Adoption of Output-Based Emissions Standards

Year	(Million $2008)					B/C Ratio
	Public Costs		Private Costs	Total Cumulative Costs	Total Cumulative Savings	
	Annual Administration Cost	Annual Investment Cost	Annual (Investment & Other)			
2020	0.09	7.87	805	8,850	31,700	—
2035	0.013	0	329	16,900	95,000	—
2055	—	—	—	16,900	138,000	8.17

Note: Costs and savings are in "present values" using a 2.7 percent public discount rate and a 10 percent private discount rate.

assessed the potential impact of a nationwide output-based emissions standard on CHP installations. GT-NEMS modeled a fast scenario (5 years) and a slow scenario (10 years) for the entire nation to adopt the new standards. The results suggest that if all states adopted output-based standards over the next five years, CHP electricity generation would increase twice as fast as the official "reference" forecast by the Energy Information Administration. Overall, the installed capacity of CHP systems could increase by 450 percent—from 26 GW in 2010 to almost 120 GW in 2035 (Figure 3).

Because CHP systems are ultra-efficient, industrial energy consumption would shrink relative to the forecasted growth, as would CO_2 emissions and criteria pollutants. If the change were evaluated based strictly on energy savings, the policy would have a benefit:cost ratio of approximately 8:1; this includes a 10-year/$100 million R&D effort to increase the efficiency of CHP systems (see Brown et al., 2010, for a thorough discussion). Table 1 summarizes the energy savings and costs.

A recent report by the National Research Council (NRC) examined the damage caused by pollution from energy production and consumption in the United States (NRC, 2010). The study committee concluded that these damages totaled $120 billion in 2005, excluding any costs of climate change, the effects of mercury, the impacts on ecosystems, and other damage that is difficult to monetize. The total costs were dominated by damage to human health from air pollution associated with electricity generation and vehicle transportation.

We used the NRC damage estimates to evaluate the benefits of expanding CHP systems over the next two decades; in addition, we included an estimate of the value of reductions in CO_2 emissions. After examining the allowance price projections estimated by the Energy Information Administration (EIA, 2009), Congressional Budget Office, EPA, and the Natural Resources Defense Council, we estimated a carbon price starting at $17 per ton of CO_2 (2008 dollars) in 2011, increasing at a rate of 7 percent annually, and reaching $78 per ton in 2030. When these estimates of avoided damages from criteria pollutants and CO_2 emissions are included in the analysis of an output-based emissions standard, the benefit/cost ratio more than doubles (Table 2).

Industrial Energy Policies in the United States and Around the World

Much can be learned by looking into approaches to improving industrial energy efficiency used around the world. Since 1992, when the **Netherlands** entered into "Long-Term Agreements" with industry, the country has maintained a proactive stance on industrial energy efficiency. These agreements are based on industry's understanding that the government closely observes energy consumption but will not initiate strong regulations or energy price penalties as long as industry meets its targets (Nuijen and Booij, 2002). A second phase of Long-Term Agreements was initiated after the phase-one target goal of a 20-percent saving by 2000 was exceeded.

India has recently adopted an innovative approach to the problem. The country introduced an energy-efficiency trading program designed to reduce energy intensity by 5 percent a year through certificate trading. This energy-trading market is expected to grow to $15 billion and cover nine sectors by 2015 (Lamont, 2009).

TABLE 2 Benefit-Cost Ratio of a National Output-Based Emissions Standard (5 Year Adoption) (in $ billions 2008)

	Benefits				Costs	
Year	Value of Avoided Criteria Pollutants (cumulative)	Value of Avoided CO_2 (cumulative)	Cumulative Energy Savings	Social Cumulative Benefits	Social Cumulative Costs	B/C Ratio
2020	8.90	6.70	31.7	47.3	8.85	—
2035	40.7	54.4	95.0	190	16.9	—
2055	62.2	110	138	311	16.9	18.4

Note: Costs and savings are in "present values" using a 2.7 percent public discount rate and a 10 percent private discount rate.

The goal of **Japan's** Energy Conservation Plan is to improve energy efficiency by 30 percent by 2030. To achieve this ambitious goal, the Ministry of Economy, Trade and Industry mandates energy-management plans for industry, the appointment of a certified energy manager for each business, and the introduction of benchmarking for industrial sectors (Energy Conservation Center, Japan, 2009).

Just before the December 2009 Copenhagen Summit began, **China** announced a commitment to reducing the carbon intensity of its economy to 40 to 45 percent below its 2005 level by 2020. This will require a 4-percent reduction in projected increases in GHG emissions every year. At the same time, China's economy could grow at an annual rate of 8 percent or more. Achieving this goal is likely to require expanding the scope of major efficiency improvements to China's smaller industrial facilities, as well as imposing new regulations and continuing to close inefficient plants (Friedman, 2009). China has taken steps toward meeting its carbon-intensity goal through tax credits, the adoption of building and appliance standards, programs focused on high energy-consuming firms, modifications of the Energy Conservation Law of 1997, and other actions.

In the United States, the implementation of federal efforts is distributed among federal agencies, with more than a dozen currently administering 72 deployment programs working on energy efficiency in industry (CCCSTI, 2009). Compared with many other nations, U.S. programs and policies have focused less on regulation and more on the promotion of voluntary action. Reflecting the importance of informed decision making in industry, about half of these federal policies and programs involve the dissemination of information about energy-efficient technologies currently available to industry.

For example, EPA's VendInfo database helps industrial clients find providers of industrial energy-efficiency services. Other policies involve public-private partnerships with industry to encourage efficiency improvements. For example, Save Energy Now, administered by the U.S. Department of Energy Industrial Technologies Program (ITP), works with large industry partners in energy-intensive industries to identify opportunities for significant improvements in efficiency. ITP also works with small and medium-sized firms through audits performed by Industrial Assessment Centers located at universities throughout the country.

Based on international policy benchmarking, today's U.S. policies are lagging. Scaling up energy efficiency will require more stringent voluntary and mandated standards supported by stronger and sustained government support.

Spawning Green Industries

The role of industry in the development of emerging technologies will lead to even greater energy savings than might be apparent from industry's energy-use patterns. For example, developing a new generation of fuel cells may lead to greater savings in motor vehicles. Other possibilities include using ink-jet printing systems to manufacture complex three-dimensional devices with minimal thermal losses and fabricating new plastics that double as integrated photovoltaic systems (Laitner and Brown, 2005). As corporate sustainability has become better understood, industry has taken a much broader view of its energy and environmental responsibilities, extending its concerns to the sustainability of the products and services it offers, as well as the sustainability of its chain of suppliers. Walmart, for example, has included indicators of energy sustainability in its metrics for selecting products and service providers.[3]

Imagine a future in which the concepts of industrial ecology are taken to an extreme, manufacturers rely principally on renewable resources, and production systems clean up our ecosystems. Today industries are often seen as necessary evils that must be exiled to remote locations to avoid contamination. Yet the public imagination is captivated by buildings that might generate more energy than they use and cars that operate like pollution vacuum cleaners. Now we need a similar vision for industries-of-the-future.

Acknowledgments

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Renewable technologies are strategically important for limiting climate change.

The Role of Renewable Energy Technologies in Limiting Climate Change

Douglas J. Arent

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The recent National Academies (NRC, 2010) report *Limiting the Magnitude of Future Climate Change* concluded that ". . . renewable energy technologies that do not emit GHGs [greenhouse gases] are an important and viable part of a near-term strategy for limiting climate change, and they could potentially play a dominant role in global energy supply over longer time scales."

Renewable energy is potentially a very large energy resource for the United States, and the use of renewables has increased rapidly over the past decade as technology has improved and costs have come down. To realize its full potential, however, renewable technology must continue to improve and users must learn how to integrate renewables into the electricity and transportation fuel systems. In addition, the policy and market forces driving the adoption of renewables must stabilize to provide financial predictability for investors.

This article provides a summary of renewable energy technologies (RETs),[1] including resource potentials in the United States, recent increases in the use of these technologies, technology advancements and cost trends, investment trends, and the policy landscape for renewables. The discussion then

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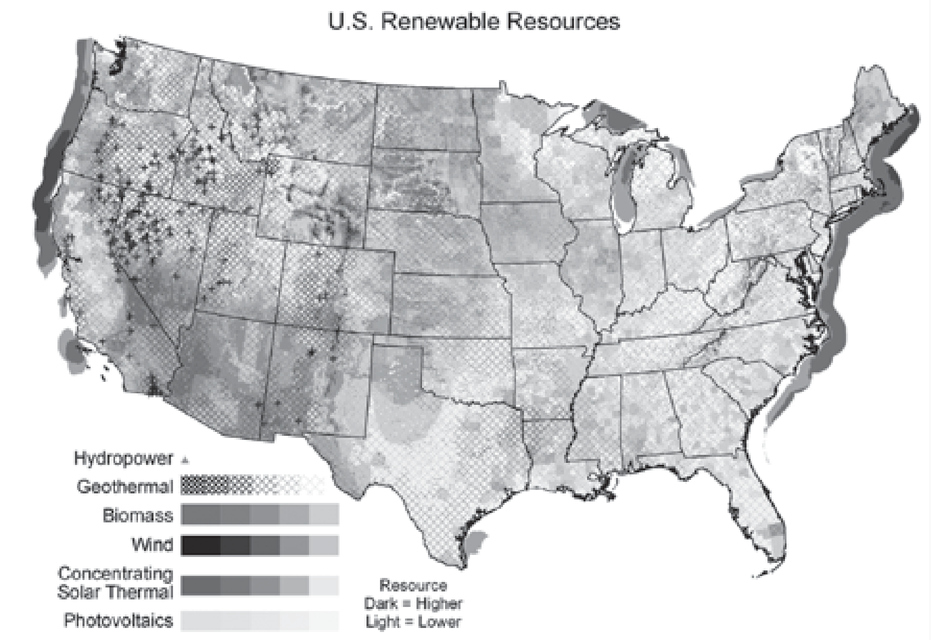
[1] In this article, renewable energy technologies are defined to include wind, solar, biomass, hydropower, ocean energy, hydrokinetic, and geothermal energy sources. Pathways to providing thermal, electrical. or mechanical power from these resources include thermal, chemical, and direct conversion (e.g., photovoltaics or solar cells).

turns to how RETs could help limit the impacts of future climate change.

Resource Potentials

The United States is endowed with significant—some say enormous—amounts of renewable resources. Figure 1 provides an overview of the geographic distributions of solar, geothermal, wind, biomass, and hydro resources in the 48 contiguous states. The theoretical potentials summarized below the map indicate potential electricity-generating capacity of more than 228,000 gigawatts (GW)—that is, more than 200 times the current installed capacity of 1,105 GW (EIA, 2010). The map provides a visual overview of the breadth and diversity of the resource base across the country. In addition, Alaska and Hawaii also have considerable local renewable resources.[2]



Resource	Solar PV/CSP	Wind	Geothermal	Water Power	Biopower
Theoretical Potential	206,000 GW (PV) 11,100GW (CSP)	8,000 GW (onshore) 2,200 GW (offshore to 50 nm)	39 GW (conventional) 520 GW (EGS) 4 GW (co-produced)	140 GW	78 GW

FIGURE 1 Renewable resources in the contiguous United States. Source: National Renewable Energy Laboratory. Available online at *http://www.nrel.gov/gis/docs/resource_maps_200905.ppt*.

Despite their great quantities, renewable resources are widely dispersed and are found in relatively low concentrations compared to energy demand, which is highly concentrated in and near major citites. Thus there is a significant challenge in matching resources with energy demand. Even though a vast amount of energy can be supplied by renewables, it will require careful technology development, policy planning, and market adoption measures to meet the challenges of integrating renewables into the current energy system.

Renewable Energy Use in the United States

In the past 150 years, the U.S. energy supply has evolved from 2.5 Quads to about 100 Quads. Today our energy supply is dominated by fossil fuels, but the market penetration of RETs has increased rapidly in the past few decades (Figures 2 and 3).

Total U.S. installed capacity derived from wind, geothermal, solar, and biomass power increased from 15 GW in 2000 to more than 45 GW in 2009.[3] Figure 4 shows the exponential growth in U.S.-installed wind and solar-photovoltaic (PV) capacity indexed to installed capacity. Solar-PV capacity increased 20-fold between 2000 and 2009, while wind capacity increased by a factor of 15.[4] These increases have been driven by technological progress that has improved performance and reduced costs and by strong policy support (detailed below).

[2] National and state resource data and maps are available at *http://www.nrel.gov/gis/mapsearch/*.

[3] Including traditional hydropower, the U.S. installed generation capacity is 120 GW.

[4] Absolute values are: wind capacity of 2,578 megawatts (MW) in 2000 and 35,159 MW in 2009; solar-PV capacity of 85 MW in 2000 and 1,677 MW in 2009.

Concurrent with rapid market growth, private-sector investment has been pouring into renewable industries, increasing from $46 billion in 2004 to more than $150 billion per year globally since 2008 (UNEP, 2010). Investments range from venture capital through corporate and project financing and cover a broad spectrum of technologies, with recent emphasis on solar, bio-resource fuels and products, and wind power. Complementary investments have been made in demand management, batteries, and hybrid and purely electric vehicles.

Overall, the energy landscape of supply and demand is rapidly expanding from heavy reliance on a few relatively concentrated energy resources with significant distribution infrastructure and a homogeneous demand profile (e.g., internal combustion engines for transportation) to more heterogeneous supply resources and use technologies. For example, transportation, which was solely based on petroleum fuels, now includes biofuels and electricity and flex-fuel, hybrid, and purely electric vehicles.

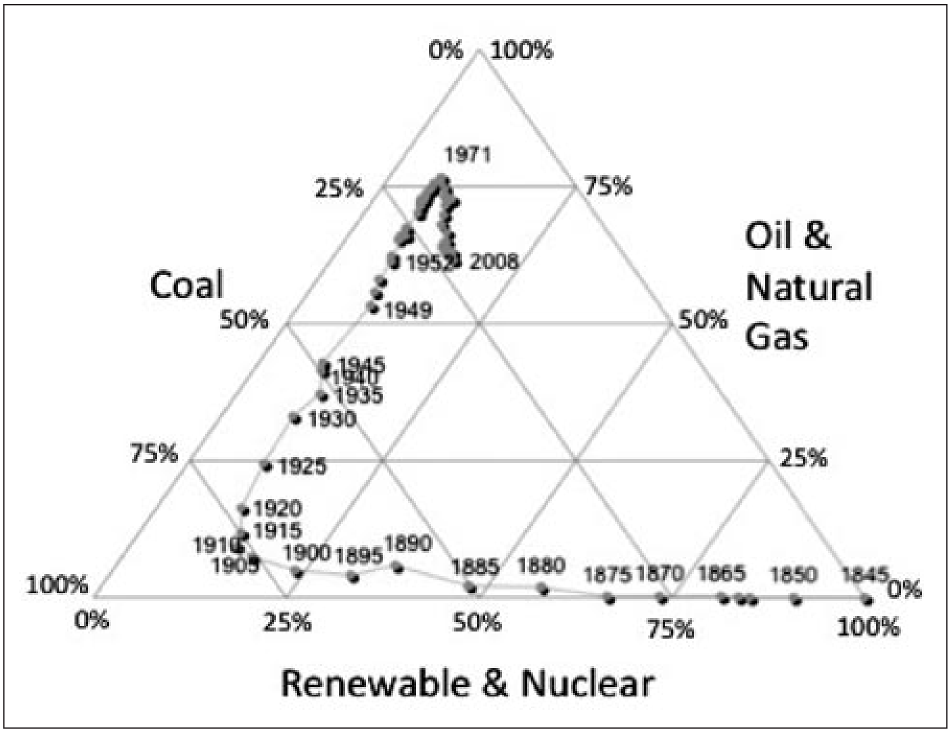


FIGURE 2 Historical U.S. energy supply contributions as a percentage of supply from 1850 to 2008. Source: Energy Information Agency; Annual Energy Outlook 2009; Tables 1.3, 10.1 and E1.

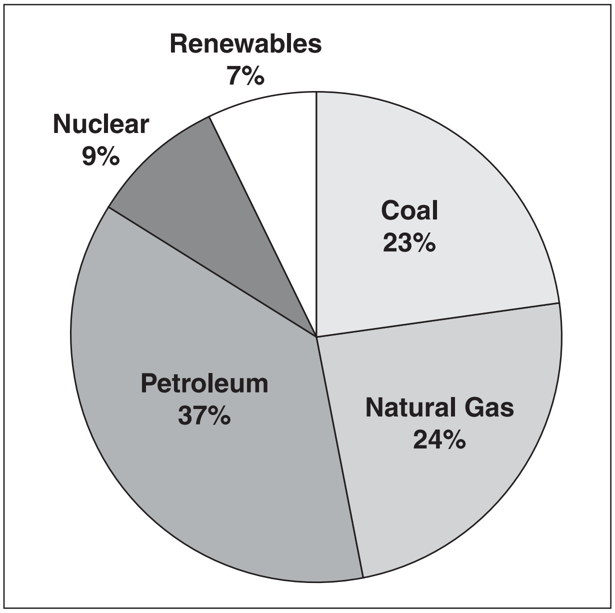


FIGURE 3 Current U.S. energy supply. Renewables include solar, wind, biomass, geothermal, and hydropower. Source: Energy Information Agency; Annual Energy Outlook 2009. Table 10.1.

Technological Advances

The costs of RETs have been reduced significantly in recent decades (Figure 5). Many studies have reported the importance of R&D-induced learning and cost reductions, as well as of market growth (Gillingham et al., 2008; Grübler, 2003; Nemet, 2006).

Cost reductions of 50 to 80 percent have been realized in the past few decades as a result of technological advances. For example, the average size of wind turbines increased from 50 kilowatts (kW) to more than 2 MW per turbine for land-based systems and more than 5 MW per turbine for offshore systems, with weighted average-capacity factors increasing from 22 percent to 34 percent (Wiser and Bolinger, 2009).

Solar-PV conversion efficiencies increased from 10 to 12 percent for single-junction cells and to more than 40 percent for cells with multiple layers that are optimized to collect different wavelengths of light 200 to

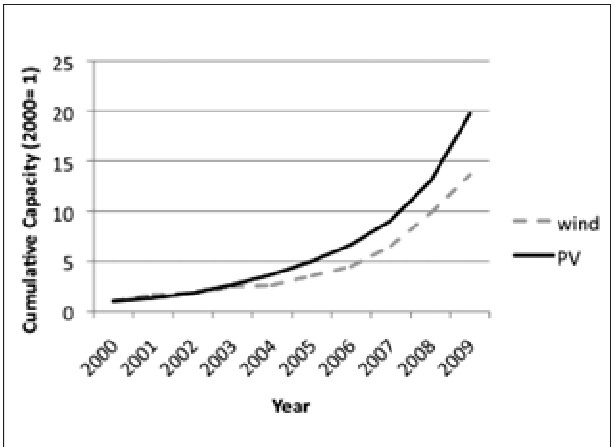


FIGURE 4 Cumulative installed capacity of wind and solar photovoltaic power systems in the U.S. relative to 2000. Sources: U.S. Department of Energy 2008 Renewable Energy Data Book; http://*www1.eere.energy.gov/maps_data/pdfs/eere_databook.pdf*; AWEA's 2009 Year End Market Report, January 2010, *http://www.awea.org/publications/reports/4Q09.pdf*; CSP and PV data taken from SEIA 2009 Solar Industry Year in Review at *http://www.seia.org/2009%20Solar%20Industry%20Year%20in%20Review.pdf*.

400 times as concentrated as normal solar radiation. Worldwide production capacity of solar-PV expanded from 47 MW in 1990 to more than 10,000 MW per year in 2009 (Kazmerski, 2009; SEIA, 2010).

The cost and performance of RETs must, of course, be considered in the context of competing technologies and the policy environment. Nevertheless, continued market expansion and increasing investment in innovation in both the public and private sectors are expected to lead to further cost reductions and technical advancements, which, in turn, will lead to more attractive renewable options, especially as climate-related emissions are priced into more market and investment criteria.

Mitigating Future Climate Change

RETs, with lower GHG emissions relative to other energy resources, have the potential to provide reliable, affordable energy services while simultaneously reducing overall GHG emissions. Derived from domestic resources

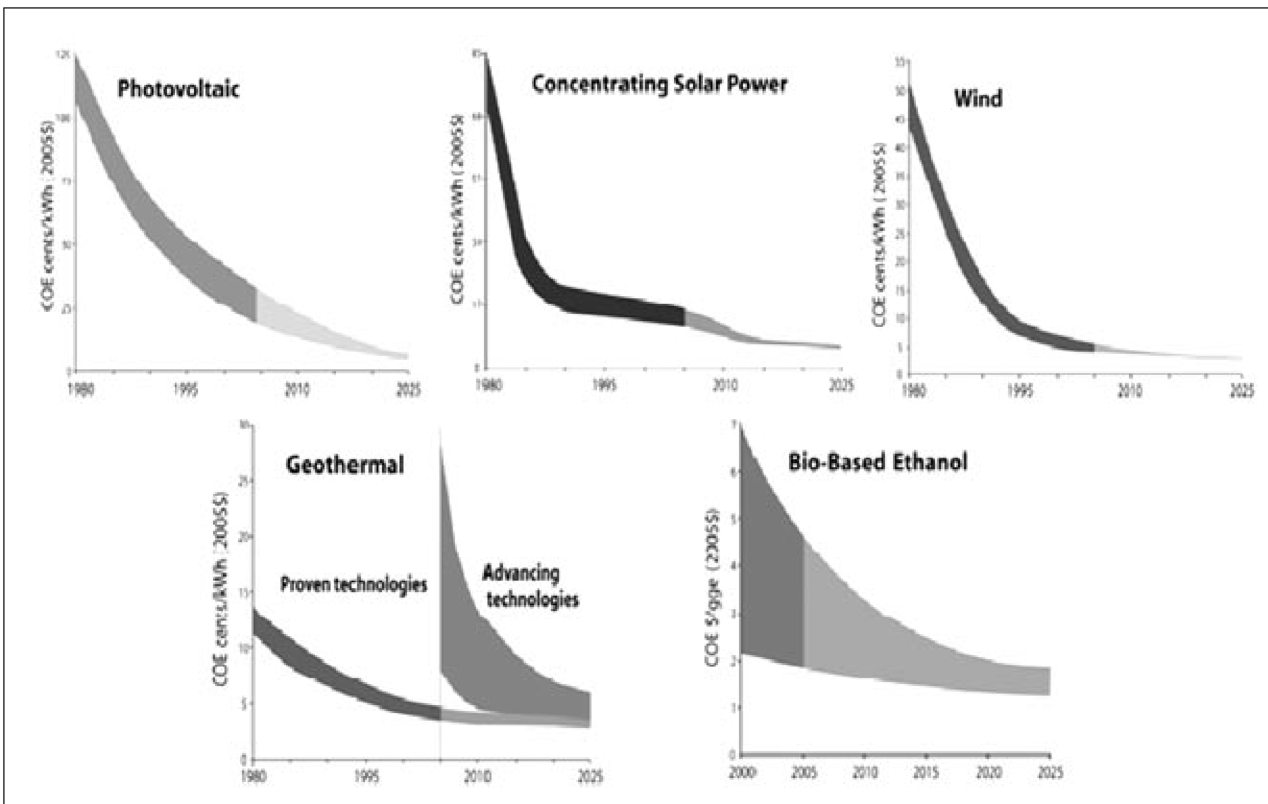


FIGURE 5 Historic and projected levelized cost of energy (in constant 2005 dollars) for major renewable energy technologies. Lower boundary represents costs from high-quality resource areas and range represents breadth of resource and development costs. Note: (1) Projected costs are derived from expected improvements in performance resulting from R&D and other factors. (2) The lower band of the cost curve reflects the availability of high-quality resources (e.g., high-wind areas or sunny areas); the higher band reflects lower quality resources (calm or cloudy areas) at higher costs. (3) Fiscal policies such as tax credits are not included. Source: NREL, 2005.

with no, or lower, variable costs (e.g., compared to volatile oil and natural gas prices), RETs can help mitigate both geopolitical concerns and energy price volatility, as well as providing a basis for continued technology innovation and domestic economic prosperity.

However, we must also take into account unresolved issues related to RETs, such as variability, siting, and visual concerns, and for some issues related to land use (e.g., biofuels), agricultural practices, and the consumption of water and other natural resources. These associated issues have to be appropriately addressed before we can realize the full potential of renewables.

Integrating Renewables into the Current Energy System

Compared to projected power requirements, the resource potential, particularly for solar and wind energy, is enormous. However, remote locations, low energy density, and variability are some of the reasons RETs have not garnered a greater market share thus far.

Numerous studies have been conducted, including major integration studies of the western and eastern grid areas of the United States, in which research teams evaluated the impacts of up to 35 percent renewable power (EnerNex, 2010; IEEE, 2009; Piwko et al., 2010). These studies indicate that renewable energy represents a near-term, leveragable opportunity, provided that the issues of siting, access to transmission, and systems operations can be addressed.

The following conclusion from the recent *Western Wind and Solar Integration Study* (Piwko et al., 2010) reflects, in general, the findings from these studies:

- Renewable energy penetration on the order of 30 to 35 percent (30 percent wind, 5 percent solar) is operationally feasible provided significant changes to current operating practice are made, including:
  - increase in the balancing area to accommodate greater geographic dispersion
  - increase utilization and build new transmission
  - incorporate state-of-the-art wind and solar forecasts in unit commitment and grid operations
  - increase the flexibility of demand and dispatchable generation where appropriate (e.g., reduce minimum generation levels, increase ramp rates, reduce start/stop costs or minimize down time)

In a separate study, *Accommodating High Levels of Variable Generation*, the North American Electric Reliability Corporation evaluated issues associated with the integration of variable resources (NERC, 2009). The key considerations identified in this study for accommodating variable resources are consistent with the results of other studies: (1) diversify supply (e.g., technologies) across a large geographical region to leverage resource diversity, and use advanced control technology to address ramping, supply surplus, and voltage control; (2) ensure access to and the installation of new transmission lines; (3) add flexible resources, such as demand response, plug-in hybrid electric vehicles, and storage capacity (e.g., compressed-air energy storage); (4) improve the measurement and forecasting of variable generation; (5) use more comprehensive system-level planning, from distribution through the bulk power system; and (6) enlarge balancing areas to increase access to larger pools of generation and demand options.

Technical systems-level multi-technology integration is just emerging as a field of inquiry.

Recent and current investigations in the United States and abroad are focusing on systems-level solutions, including the introduction of information technology (IT)-enabled power management, advanced forecasting, adaptive and shiftable loads, and technology advances in energy storage and other areas with the goal of moving toward power systems with a larger share, possibly a majority, of renewable generation (Denholm et al., 2010; DOE, 2010; Krewitt et al., 2009; Sterner, 2009). The combination of mulitiple enabling capabilities is likely to create opportunities for power systems in which renewables will become increasingly important.

Although renewables are clearly a suite of key enabling technologies to address climate change (Clarke et al., 2009; Edenhofer et al., 2010; NRC, 2010), technical systems-level multi-technology integration is just emerging as a field of inquiry. A few studies have considered integration of variable RETs, in combination with other technologies. For example, Krewitt et al. (2007) have investigated the role of RETs in a stabilization scenario, with global primary energy share of about

50 percent by 2050. Østergaard (2008) evaluated the geospatial scale of system boundaries in combination with optimization criteria for scenarios in western Denmark, including heat loads; he concluded that energy savings and reductions in emissions of carbon dioxide must be taken into consideration for wind power generation to be economical.

Lund and Kempton (2008) evaluated integration that included hybrid or electric vehicles with vehicle-to-grid capabilities. In their analysis, the vehicles have a distributed storage and auxiliary services capability, which increases the load-matching abilities of the system with higher penetration of RETs and lower overall GHG emissions. More recently, Denholm et al. (2010) reported on systems-level integration issues associated with wind, solar, storage, and dynamic loads.

These analyses all stress the importance of system-level analysis that accounts for multiple time scales and probability distributions of generation, demand profiles, and a portfolio of enabling technologies with a large share of RET generation. These initial studies conclude that there are no substantial technical barriers to the integration of RETs and that the costs of integration for enough renewables to supply up to 30 percent of energy demand will not exceed $5/MWhr (IEEE, 2009). More insights may also be gained from rigorous technical and economic analyses focused on systems-of-systems solutions.

Most studies have found no substantial technical barriers to the integration of renewables.

The development of the "smart grid" has recently been accelerated with funding from the American Recovery and Reinvestment Act. Intelligent power generation, transmission, distribution, and dynamic demand management will enable a power system that can incorporate larger amounts of variable renewable energy. System-level dynamic control and associated savings in costs and emissions, in combination with innovations in load shifting, energy storage, and real-time information and decision tools, will lead to a rethinking of the nation's energy mix.

Markets, Policy, and Finance

To put U.S. energy policy into a global perspective, as of 2009, at least 85 countries and 35 states and the District of Columbia had renewable-energy promotion policies. More than 50 countries and 10 U.S. states and Canadian provinces have adopted policies that guarantee revenue for renewable power generation (e.g., feed-in policies), and at least 38 states and provinces have enacted renewable portfolio standards (UNEP, 2010). Although national level renewable standards and climate legislation have yet to be passed by both houses of Congress, provisions for manufacturing or production tax credits (PTCs) for RETs have been available at various times.

Targets for biofuels as a share of transport energy have been set in the United States (20 percent by 2022), the European Union (10 percent by 2020), Japan (5 percent by 2030), and several other countries. Tax exemptions for biofuels were enacted in a number of countries in 2005, 2006, and 2007. Policies with feed-in tariffs, national building codes, national tax credits, and capital subsidies to support solar-PV continue to be promulgated.

Policy approaches to RETs, and to energy issues and climate change in general, include market mechanisms to support innovation. Fischer and Newell (2008), Komor and Bazilian (2005), Martinot et al. (2007), and Popp (2010) have reported on approaches that have been used or are being considered to address tactical and strategic requirements, including innovation, knowledge spillovers, performance standards, quotas, and fiscal mechanisms. Key attributes of effective policies include: (1) predictability over a sufficient period of time to reduce investment risks; (2) the creation of a level playing field; and (3) the inclusion of material impacts, such as greenhouse-gas costs and benefits.

In the short to medium term, the impacts of carbon prices under stabilization scenarios are not likely to attract enough investment to expand market penetration of RETs fast enough to have a material impact on climate change, especially if emitters among developing countries do not participate in global efforts (Clarke et al, 2009; Edenhofer et al., 2010). Although a carbon-price framework would provide a strong signal to the investment community, investment decisions for RET projects will continue to be based on risk-adjusted returns. Thus, policy mechanisms that complement a carbon price may be necessary to drive short-term investments in projects and expansions in manufacturing, which depend on fiscal and market policies (as well as local incentives, cost of capital, and profit margins).

Investors in riskier R&D are seeking not only large, growing markets, but also breakthrough technologies that will attract public and private investment. This complex, dynamic innovation-and-investment environment is well suited to the development of a policy portfolio approach that includes a broad range of R&D, as well as renewable fuel standards, renewable portfolio standards, and feed-in tariffs. Complementary measures, such as restructured pricing, guaranteed access to the electricity grid, workforce training, and the development of technical standards, have been implemented in many jurisdictions (e.g., Cory et al., 2009; Darghouth et al., 2010; Doris et al., 2009).

An example of the benefits of predictable policies and fiscal stimulus is the feed-in tariffs in the European Union, which have led to a sevenfold increase in RET electricity generation (compared with the rate of increase elsewhere). Germany's policy of 20-year fixed feed-in tariffs for RET power led to strong, consistent growth and created a wind market with the largest installed capacity in the world, until 2007, even though Germany has significantly less total wind potential than the United States. Spain experienced major growth after passing its RET policy in 1997, which lasted until a recent restructuring of the tariffs. Denmark's wind industry experienced steady growth throughout the 1990s, although the rate has since slowed because of market saturation and land constraints.

The United States has a strong growth curve for wind, driven largely by PTCs and the recent cash-grant option. Since its establishment in 1992, the PTC has been extended a number of times, although it was allowed to lapse in 1999, 2001, and 2003, which led to significant decreases in annual installations in 2000, 2002, and 2004.

With the economic downturn in late 2008 and 2009, few companies had the "appetite" to use the tax credits, and the policy was amended, as part of the American Recovery and Reinvestment Act, to include an option for a tax grant (Bolinger et al., 2009). At the same time, in 2008 Germany and Spain dramatically restructured their feed-in tariffs, effectively lowering the return for potential investors and dramatically curtailing interest in new project development (Campoccia et al., 2009).

To mitigate the public costs of uniform feed-in tariffs and provide transparent, stable policy support, Cory et al. (2009) describe a comprehensive system of feed-in tariff structures for wind energy differentiated by technology, project size, application, and resource intensity. They also evaluate fiscal structures that would reduce the overall differential costs for RETs with enough predictability to attract development and investment. This strategy could be adopted in the United States, as more jurisdictions consider this policy option.

By comparison, the Chinese wind market has increased sharply since 2000, with a 40 percent average annual growth rate from 2000 to 2009. The target for wind power in the recent 10-year plan is for more than 100 GW of wind by 2030, with concomitant investment in manufacturing, installation, and operations.

Feed-in tariffs in the EU have led to a sevenfold increase in generation from renewables.

Conclusions

Increasing interest in renewable technologies in the United States and globally in the past few decades can be attributed to a combination of factors, including the importance of RETS to energy supply, energy security, economic prosperity, and environmental effects, including limiting the impacts of climate change. Technological advancements in RETs have led to dramatic cost reductions and improved the competitiveness of renewables, even in the absence of GHG pricing. Renewable energy markets have grown at double-digit rates to more than $150 billion annually and are in a position to continue growing.

For the United States, with its enormous resource base, advancing technologies, and supportive public policies, renewable energies not only offer a near-term, high-leverage option for mitigating potential climate change and addressing other public policy goals, such as economic prosperity and energy security, but they also provide a long-term technology platform for a sustainable energy economy. The combination of mulitiple enabling capabilities is likely to create opportunities for power systems in which renewables will become increasingly important. However, realizing these benefits will require concerted efforts to adopt and implement coordinated actions on a national scale.

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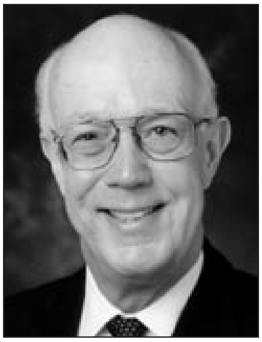
Limiting the rise in global average temperature will require that all nations, including the United States, reduce greenhouse gas emissions to near zero.

The Technological Challenge of Climate Change



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The National Research Council (NRC) report, *Limiting the Magnitude of Future Climate Change* (NRC 2009a), recommends strategies for limiting domestic greenhouse-gas (GHG) emissions to a level consistent with a global effort to hold future temperature increases to acceptable levels. Not surprisingly, technological innovation is a key strategy. Indeed, new technology for the production and use of energy will be essential to limiting future emissions of GHGs. The *Limiting* report suggests that technologies that are in hand today—or nearly so—can go a long way toward meeting a reasonable goal for reducing GHGs from the domestic energy sector by mid-century.

However, simply bringing these known technologies to commercial readiness will not be enough to solve the problem. These technologies must displace an enormous, embedded energy infrastructure, and ultimately, newer and less costly technologies must replace them in turn. In the process, energy consumers will have to learn to live with a transformed energy system.

The Climate Challenge

In 2009, U.S. primary energy consumption was 95.4 quadrillion Btus, 83 percent of which was generated by fossil fuels. Liquid fuels accounted for 45 percent of the fossil fuel supply, and coal and natural gas, in roughly equal measures, accounted for the balance. These proportions have hardly changed in the last 40 years, which is testimony to the difficulty of changing the U.S. energy system. Indeed, the only significant change in the fuel mix in those four decades was the introduction of nuclear power in the 1970s.

Combustion of fossil fuels in the energy system generates about 85 percent of domestic GHG emissions.[1] Forty-one percent of these emissions come from the burning of coal to generate electric power. The transportation sector contributes 33 percent of the total, chiefly from petroleum. Residential and commercial buildings and industry account for the balance.

An important feature of each sector of the energy system is the long lifetimes of most of the assets involved in the production and use of energy. Electric power plants, the building stock, and most industrial facilities have decades of useful life. The transportation stock turns over somewhat faster, but even there the average life span of an automobile is close to 15 years.

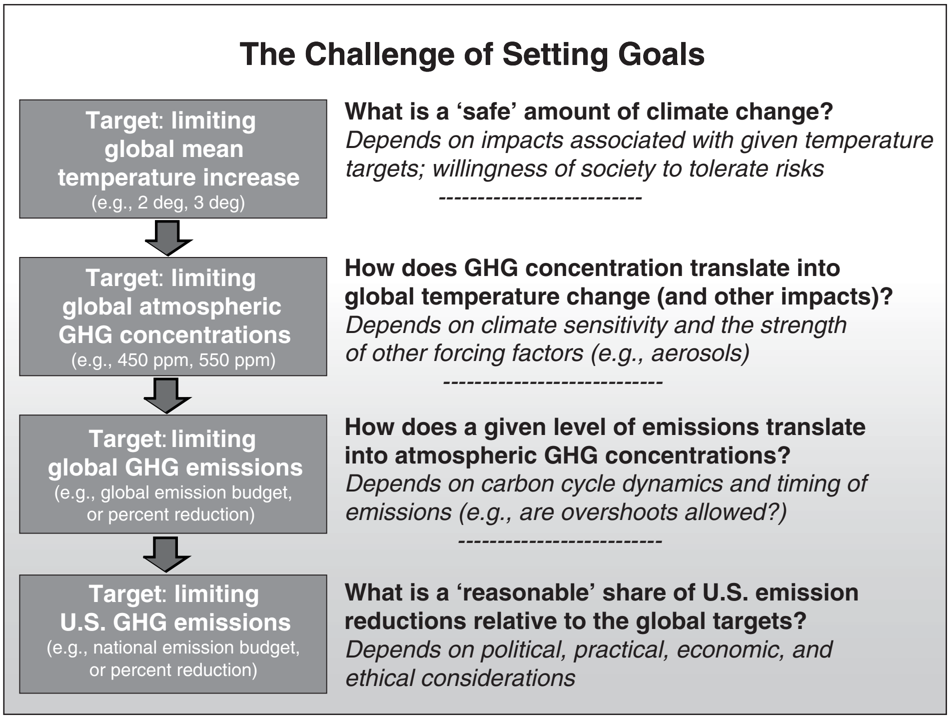

FIGURE 1 Steps in setting a U.S. emissions budget. Based on Box 3.2 in NRC, 2009a. Illustration courtesy of L. Geller.

Limiting the increase in global average temperature from climate change will ultimately require that all nations, including the United States, reduce GHG emissions to near zero. Between now and then, a limited amount of GHGs can be emitted. Thus, the first issue that must be addressed in a U.S. technology strategy is how to set the limit for U.S. domestic GHG emissions. Figure 1 shows conceptually the steps required to establish a U.S. emissions budget.

As a practical matter, setting that limit will be very difficult. At the start, we will need an agreement on the acceptable rise in global average temperature. Then significant scientific challenges will have to be met, notably but not exclusively because the sensitivity of the climate to increases in atmospheric concentrations of GHGs has not been pinned down. In addition, translating a global limit on GHG emissions to a target for the United States will involve important non-scientific judgments about fairness.

The Issue of Fairness

Between 1850 and 2000, the United States was responsible for about 30 percent of global GHG emissions. During that time, all of the developing nations together accounted for about 20 percent of the total. For this reason, some now argue that the United States should do more than developing nations to limit its emissions in the future. Others, acknowledging that meeting the global limit will be an expensive proposition, argue that it should be done in the least expensive way.

The differences between these two positions are profound. The least-cost criterion places a heavier burden on developing countries, where energy systems are typically less efficient than in industrialized countries, and as developing economies grow, opportunities are created to use new technologies. By contrast, the equity requirement—for example, equal per capita emissions integrated over a given period of time—shifts the burden to industrialized countries.[2]

[1] Non-energy sources of GHG account for about 15 percent of the total, but only the energy system is considered here.

[2] It is possible to combine equity and efficiency through the use of offsets, which would allow an industrialized country to pay for an emissions-limiting project in a developing country. However, an offset system would be very difficult to manage.

The NRC *Limiting* report relies on recent modeling by the Energy Modeling Forum (EMF) to suggest that a representative U.S. budget for emissions from the domestic energy system from 2012 to 2050 would be between 170 gigatons (Gt) and 200Gt of carbon-dioxide equivalent (CO_2–e) in GHG emissions. This modeling uses a least-cost criterion for determining the U.S. budget. However, an equity criterion (e.g., equal per capita emissions globally) could mean reducing the U.S. budget by nearly an order of magnitude.

The Technological Response

Setting a domestic emissions budget would provide a yardstick for measuring the challenge we face in transforming the energy system. One clear result of applying the yardstick would be to highlight the need for decisive action in spite of the considerable inertia of the existing system. The United States presently emits about 7Gt CO_2–e annually, so it's easy to see that unless we take action to limit emissions, the proposed budget of 170 to 200Gt CO_2–e would be exhausted long before 2050. A crucial question, therefore, is whether it is possible to meet the budget constraint with available technology.

The models on which the emissions budget is based also produce scenarios of technology deployment in the energy system that would enable us to stay within the budget constraints. Several deployment scenarios were produced based on the different models used in the EMF project. Although none of these scenarios should be regarded as an immutable forecast of a future energy system, taken together they do provide a plausible range of deployment levels for major technologies.

In another large study, America's Energy Future (AEF), the NRC examined the full range of technologies now available, as well as technologies being developed, for the supply and use of energy in the United States. The AEF committee estimated the technical potential of deploying these technologies in 2020 and/or 2035. In the AEF report, "technical potential" was a measure of whether a technology would be technically ready for commercial deployment before 2020 and whether, at that point, it could be deployed at the maximum rate short of a crash program. Thus technical potential was a committee judgment based on a determination of how fast energy technologies have penetrated the market in the past (NRC, 2009b).

In effect, then, the combination of EMF modeling and AEF technical potential creates a picture of the demand for technologies to meet a GHG emission budget and of the ability to deploy these technologies at the required rate. Table 1 illustrates this comparison for the year 2035 for one emissions budget.

TABLE 1

	Requirement	Potential
Energy efficiency (percent reduction from reference case)	5–33	30
Nuclear (Twh/yr)	1,292–2,092	1,453
Coal with CCS (Twh/yr)	233–1,593	1,200/1,800
Renewable electricity (Twh/yr)	453–1,155	1,454
Biomass fuels (cellulosic) mmgal/yr	17,000–33,000	26,000

Source: From Table 3.2 in NRC (2009a). Requirement = the range of possible deployment for each class of technology for a GHG emissions budget of 167Gt CO_2–e. Potential = the technical potential estimated in the AEF report. The potential for coal with carbon capture and sequestration (CCS) is 1,200 Twh/yr for retrofitting or repowering existing plants and 1,800 Twh/yr for new plants. Requirements for an emissions budget of 203Gt CO_2–e are correspondingly lower.

Based on this very rough comparison, the *Limiting* report makes the following observations:

- GHG emissions from electricity production could be nearly eliminated by 2035 with a combination of improved end-use efficiency and the production of energy from renewable sources, nuclear fission, and coal combustion with carbon capture and storage (CCS). A prerequisite would be the demonstrated commercial feasibility of new nuclear power plants and CCS by 2020.
- Improved end-use efficiency could reduce emissions in the transportation sector by about half. However, alternate fuels from coal and biomass would not be able to close the rest of the gap. Other energy options, most likely electric or hydrogen power, would be required.

The good news is that available (or nearly available) technology could potentially move the nation a long way toward satisfying a plausible domestic GHG emissions budget. However, realizing this potential in the real world is another matter. And even if it were realized, it might not be the best answer. In the remainder of this article, I discuss three major reasons for tempering our technological optimism.

Barriers to Deployment

Two key assumptions underlie the AEF estimates of technical potential. First, it is assumed that a technology will be demonstrated to be commercially feasible between today and 2020. This means that the cost and performance characteristics of the technology will be understood well enough to attract private-sector investment.[3] Second, AEF assumes that this technology can be deployed, essentially unimpeded, in the energy system at an accelerated rate. These assumptions are useful for ensuring that the AEF estimates of technical potential are both transparent and comparable for a variety of technologies, but of course neither is a sure thing.

Technological Readiness

First consider technological readiness. Today, only improved energy efficiency and renewable technologies (shown in Table 1) can be considered commercially feasible. Numerous studies have confirmed that a number of efficiency technologies are ready for commercial deployment; a few renewable technologies can also make that claim. One of the AEF series of studies, *Real Prospects for Energy Efficiency in the United States* (NRC, 2010), provides a comprehensive review of energy efficiency.

The main commercially feasible renewable energy resource is wind, and wind technology is widely deployed, albeit with considerable government financial and regulatory support. The AEF estimate of technical potential for renewables is based mainly on the continued deployment of wind technology.

However, CCS and new nuclear technology have not been commercially proven at this point. AEF concludes that their feasibility could be demonstrated by 2020 with an aggressive program to build commercial-scale facilities. However, the challenges for these two technologies are quite different.

The new generation of nuclear technology is on offer today, and plants are being built abroad using this technology. However, the United States has not built a nuclear power plant for more than 30 years. Our challenge is to show that we can do so in a commercially feasible way.

By contrast, CCS has never been demonstrated at scale as a complete system. Although the components of the CCS system appear to be technically feasible, and hopes for the system are justifiably high, CCS has yet to meet the twin challenges of technical and commercial feasibility.

Market Penetration

To reduce GHG emissions substantially, feasible new technologies must rapidly replace the existing infrastructure of the energy system. As noted above, the AEF report assumes that replacement will be essentially frictionless, but of course it won't be. For one thing, the new technologies will have to find their way through the maze of laws, regulations, and public opposition that impedes all new energy projects.

Today, only some energy efficiency measures and a few renewable technologies can be called commercially feasible.

In addition, AEF points out that replacing the present energy infrastructure will also require overcoming other significant industrial and economic challenges:

- Large amounts of private investment capital will have to be mobilized. The U.S. Census Bureau reports that total domestic investment in buildings and equipment in 2007–2008 was around $1.3 trillion, of which utilities and transportation accounted for about $175 billion (U.S. Census Bureau, 2010). A strong economy could probably accommodate accelerated investments in those two sectors, but the additional requirement would be consequential.
- The change will require retiring or retrofitting existing power plants that still have long useful lives. According to estimates by the U.S. Energy Information Administration, in the absence of policy to the contrary, only 0.6 percent of U.S. generating capacity is retired every year, almost all of it fueled by natural gas (EIA, 2010).

[3] Note that commercial feasibility depends on the existence of a market in which private-sector investment is profitable. In the absence of policies to compel action to limit GHG emissions—a price on carbon, for example—markets for CCS and other technologies may not exist.

- We will have to educate and train the industrial and workforce capacity to build new facilities that we have never built before or, in the case of nuclear and coal power plants, have not built for many years.
- We will have to develop and produce key supporting technologies, notably in the electricity supply and distribution system.

Meeting these challenges is possible, and even desirable, but it will clearly be a formidable task.

Current public and private investment in energy research is incommensurate with the need.

New Technology

As was suggested above, technologies that are likely to be available by 2020 could substantially decarbonize the electric power sector, but they would fall short in the transportation sector. Plainly, then, further technological innovation will be necessary to meet GHG emission-reduction targets. The obvious need is for non-fossil fuels in the transportation sector. If AEF is correct in concluding that liquid fuels from biomass have limited technical potential, then the likely candidates at this point would seem to be electricity or hydrogen power.

However, we will need innovation not only in the transportation sector but in other sectors as well. For example, the technologies available by 2020 to decarbonize the electric-power sector are likely to be only a first step toward creating an electric system that not only emits little or no carbon dioxide but also is both reliable and affordable. Many problems will have to be solved:

- The cost of CCS will have to be reduced. Carbon capture, especially as a retrofit on existing power plants, creates large parasitic loads on the power plant, mainly because of the energy required to regenerate the catalyst. Research to reduce this parasitic load would pay off by reducing cost considerably.
- Renewable power will have to be integrated into the system. Because wind and solar power are intermittent energy sources, integrating them into an electric system in which production closely tracks demand will be a significant challenge. However, recent integration studies in the U.S. have reported that 30 to 35 percent of intermittent energy sources can be accommodated with adaptive management practices and improved forecasting, at relatively low cost.[4] Large-scale storage will be helpful at a use-level above 35 percent, but except for compressed-air storage systems, the storage problem has yet to be addressed.
- Electricity transmission and distribution systems will have to be upgraded and expanded. Modern power electronics to manage flows and advanced controls to improve reliability would strengthen the transmission system. We will probably need a larger, more interconnected transmission system to accommodate new generating sources, especially renewable sources. Better communication with customers through smart meters would greatly improve distribution and demand management. If electric vehicles become popular, the distribution system will also have to extend service to the transportation sector.

Support for Research

The developments described above will be necessary to deploy technologies that are already reasonably well along. We will also need support for research to create new technologies with more favorable performance and cost characteristics than those of the technologies already on the drawing boards. Examples of breakthrough technologies might include artificial photosynthesis, more efficient solar cells, and the application of nanotechnology and bioengineering to energy problems. In any case, the climate problem will be with us for many decades, and it's hard to imagine that late 20th century technology will be the best available by the mid-21st century or later.

According to the *Limiting* report, current public and private investment in energy research is incommensurate with the need. Government support for research has remained at a relatively low level (except for stimulus funding) compared to support in other countries and compared to U.S. research expenditures on other national priorities such as health and space. Similarly, private-sector investment in energy research, although

[4] For a discussion of integration studies, see the article by Arent in this issue (p. 31).

difficult to track, appears to be well below the level of investment in other industries that require technological innovation for their survival.

The NRC is notoriously reluctant to suggest specific research budgets in its reports, and it does not do so in the *Limiting* report. However, a group of senior technologically savvy business leaders recently published a report in which they recommended an annual government investment of $16 billion (AEIC, 2010). This contrasts sharply with the current government budget of about $5 billion and would be consistent with the analysis in the *Limiting* report.

Household Decisions

As difficult as it will be to replace the existing energy infrastructure, however, that is only half the battle. Getting people to use new technology will also be a major challenge. A familiar but important example documented in numerous studies is that economically attractive energy-efficiency technology and practices are massively underused; the AEF efficiency report (NRC, 2010) reviews this issue. For reasons that seem to mystify economists, people just do not act rationally.

Household behavior is a crucial, often overlooked, element of the energy system. Dietz et al. (2009) estimate that direct energy use by households accounted for 38 percent of domestic GHG emissions in 2005. In other words, energy-conscious decisions at the household level could determine almost 40 percent of GHG emissions in the United States. These decisions could include improving heating, ventilation, and air conditioning systems (HVAC), adopting more efficient appliances, maintaining existing equipment more regularly, changing temperature settings, and altering behaviors such as driving habits.

In addition, household decisions indirectly influence another 25 percent of domestic GHG emissions through the energy used in the production and distribution of consumer goods. Dietz et al. (2009) studied how to nudge household decisions in the direction of lower energy use that would result in lower GHG production. Being social scientists, they know something about how to do the nudging.

For example, Dietz examines the "plasticity" of household behavior, that is, the degree to which behavior can be changed by reasonably well known techniques without requiring major changes in lifestyle. Behavior plasticity varies substantially depending on the type of change desired. Thus, stimulating action to improve HVAC systems and weatherization is much easier than changing driving habits. The former simply requires investing in more efficient equipment, while the latter affects lifestyle. The study estimates that reasonably well known techniques could encourage household decisions that could reduce emissions by 20 percent over the next 10 years.

The social science focus on household energy decisions is recent but important, and it raises at least two interesting questions. First, what are the most effective ways to influence household decisions about energy use? It seems clear that householders do not respond to purely economic signals, so something more is required. Deitz explains that a combination of tools usually works best. For example, financial incentives alone are not necessarily enough, but when combined with programs that promote customer convenience, provide quality assurance, and employ marketing that advocates the social value of energy efficiency, the results can be impressive. Still, this is a relatively unexplored application of social science techniques to energy and climate issues, and further research and experience could prove valuable.

A second question is whether social science can have a long-term effect on household decisions. Dietz proposes actions focused on household decisions that directly affect energy use to bring emissions down in the relatively short term. In the longer term, however, we may need societal support for deploying low-emission production technologies and demand for consumer products with smaller carbon footprints.

Getting people to use new technology will be a major challenge.

Conclusion

Managing climate change to acceptable levels is a significant challenge, and the *Limiting* report makes the case that meeting that challenge will require prompt, sustained action. Much of the action, of course, involves the development and deployment of new technology. Ideally, we would begin immediately to make better use of available technologies; strive to bring CCS, nuclear, and other technologies to the point of commercial deployment by 2020; and invest heavily in future breakthroughs that would meet the economic and social challenge of climate change at least cost. That is a tall order for scientists and engineers, but the *Limiting* report is essentially optimistic that these communities can deliver.

Overcoming the barriers to putting all of this technology to work will be more difficult. To move as quickly as we must, we will have to make transformational changes in a deeply embedded energy system that has resisted change for decades. Assembling the financial and human resources to support those changes will be challenging. In addition, ordinary householders and consumers will have to change behaviors, which will require bringing social scientists into the energy picture in new and unfamiliar ways. Perhaps the most unexpected result of the *Limiting* report was to expand the scope of the challenge to include these additional considerations.

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NAE News and Notes

NAE Newsmakers

Three NAE members, **Howard J. Bruschi**, retired senior vice president and chief technology officer, Westinghouse Electric Company; **Robert Langer**, David H. Koch Institute Professor, Massachusetts Institute of Technology; and **Charles H. Vest**, president, National Academy of Engineering, and President Emeritus and professor, Mechanical Engineering, Massachusetts Institute of Technology, have been elected **International Fellows of the Royal Academy of Engineering**. Founded in 1976, the Royal Academy of Engineering promotes the engineering and technological welfare of the United Kingdom.

The Association for Computing Machinery (ACM) has awarded the **2010 ACM/IEEE A.R. Newton Award** to **Randal E. Bryant**, dean and University Professor, School of Computer Science, Carnegie Mellon University. Dr. Bryant received the award for his revolutionary use of mathematical techniques to prove that hardware and software designs function as intended.

Federico Capasso, Gordon MacKay Professor of Applied Physics and Vinton Hayes Senior Resident Fellow in Electrical Engineering, Harvard University, has been awarded the **2010 Berthold Leibinger Zukunftspreis** (the future prize), an international award for research on the application or generation of laser light. The €30,000 prize was presented at a ceremony in Ditingen, Germany, on July 9, 2010. The jury cited Dr. Capasso's contributions "to laser technology with [his] research on the quantum cascade laser."

John J. Cassidy, retired engineering manager, Bechtel Corporation, was elected an **Honorary Diplomate-Water Resources Engineer** by the American Academy of Water Resources Engineers (AAWRE). AAWRE is an organization in the Environmental Water Resources Institute (EWRI) of the American Society of Civil Engineers. Honorary diplomate, AAWRE's highest award, is given to a water resources engineer who (1) has attained a position of eminence in the water resources engineering profession; (2) has made a singular, noteworthy achievement or sustained noteworthy contributions to the advancement of the water resources engineering profession; and/or (3) has rendered outstanding service over a sustained period of time to the work of AAWRE. The award was presented at the EWRI Congress in Providence, Rhode Island, on May 17, 2010.

Y. Austin Chang, Wisconsin Distinguished Professor Emeritus of the Department of Materials Science and Engineering, University of Wisconsin, Madison, was elected an **Academician** (member) **of Academia Sinica**, Republic of China. The election took place in July at the 29th Convocation of Academicians in Taipei, Taiwan.

The American Institute for Aeronautics and Astronautics (AIAA) has announced that **Eugene E. Covert**, T. Wilson Professor of Aeronautics, Emeritus, Massachusetts Institute of Technology, has been awarded its highest honor for achievement in aeronautical science and engineering. The **Reed Aeronautics Award** was presented to Dr. Covert for "lifelong contributions to aeronautics teaching; research through advancements in state-of-the-art wind tunnel testing at subsonic, supersonic, and hypersonic speeds; and public service." AIAA also awarded the **2010 Daniel Guggenheim Medal** to **Arthur E. Bryson**, Paul Pigott Professor of Engineering, Emeritus, Department of Aeronautics and Astronautics, Stanford University. Dr. Bryson was honored "for a lifetime of seminal contributions to real systems, creating and applying practical optimal control and estimation techniques to airplanes, rotorcraft, and missiles."

Women in Technology International (WITI) has announced the recipients of the **15th Annual WITI Hall of Fame Awards**. **Ruth A. David**, president and chief executive officer, ANSER (Analytic Services Inc.), will be inducted to the Hall of Fame during an award ceremony on September 13, 2010, at the WITI Summit in San Jose, California. Women chosen for induction have had exceptional careers in their respective fields, have made outstanding contributions to society, and have mentored, inspired, and empowered other women and girls to pursue careers in science and technology.

The Association for Computing Machinery (ACM) and IEEE have honored **William J. Dally**, Willard R. and Inez Kerr Bell Professor of Computer Science, Stanford University, with the **Eckert-Mauchly Award**, which is considered the world's most prestigious prize for computer architecture. Dr. Dally was recognized for his work on the system and network architecture, signaling, routing, and synchronization technology used in most large parallel computers today.

Robert G. Dean, Graduate Research Professor Emeritus, Department of Civil and Coastal Engineering, University of Florida, and **Ahsan Kareem**, Robert M. Moran Professor of Engineering, Department of Civil Engineering and Geological Sciences, University of Notre Dame, were recently named **Distinguished Members of the American Society of Civil Engineers** (ASCE). Of ASCE's 144,000 members worldwide, only 192 are Distinguished Members, ASCE's highest honor. Dr. Dean is being honored for "his eminence in wave theory, beach erosion, and the effects of waves on tidal inlets and coastal structures, as well as for his inventions and his mentorship of coastal engineers." Dr. Kareem is being honored for "his contributions to civil engineering." Both men will be formally inducted at the Celebration of Leaders Luncheon during ASCE's 140th Annual Civil Engineering Conference in Las Vegas in October 2010.

Three NAE members have been elected to the **American Academy of Arts and Sciences** (AAAS). Founded in 1780, AAAS recognizes international achievements in science, the arts, business, and public leadership. The new members are **Evelyn L. Hu**, professor, School of Engineering and Applied Sciences, Harvard University; **Chung K. Law**, Robert H. Goddard Professor of Mechanical and Aerospace Engineering, Princeton University; and **Raymond E. Ozzie**, chief software architect, Microsoft Corporation.

Takeo Kanade, the U.A. and Helen Whitaker University Professor of Computer Science and Robotics, Carnegie Mellon University, has been chosen by the Tateisi Science and Technology Foundation of Japan as the **inaugural recipient of the Tateisi Grand Award and Prize**. Dr. Kanade, director of the Quality of Life Technology Center at Carnegie Mellon, is being honored for his pioneering contributions to digital technologies that have enhanced people's lives. Established by Kazuma Tateisi, the late founder of OMRON Corporation, the Tateisi Foundation supports the development of electronics and information technologies that promote harmony between humans and machines. Dr. Kanade received a medal and a cash prize of $50,000 at an award ceremony on May 18 in Kyoto, Japan.

Robert Liebeck, professor of the practice of aerospace engineering, will receive the **Daniel Guggenheim Medal**, one of the most prestigious awards in aviation. Jointly sponsored by the American Institute for Aeronautics and Astronautics, American Society of Mechanical Engineering, the American Helicopter Society, and the Society of Automotive Engineers, the medal is given to individuals who have made profound contributions to advancing aeronautics. Dr. Liebeck is cited for "distinguished engineering as evidenced by the conception and development of Liebeck airfoils and blended wing body aircraft." He will receive the Guggenheim Medal at a ceremony in Washington, D.C., in May 2011.

Subhash Mahajan, Regents' Professor and Fulton Fellow, Ira A. Fulton School of Engineering, Arizona State University, was elected a **Fellow of the Materials Research Society**, engineers and scientists who have been recognized for "their distinguished research accomplishments and their outstanding contributions to the advancement of materials research worldwide." Dr. Mahajan was honored specifically for "pioneering research on defects in solids, structure-property correlations in semiconductors, magnetic materials, and materials for lightwave communications, and for the successful mentoring of students and faculty members."

The IEEE Microwave Theory and Techniques Society (MTT-S) has presented the **Microwave Career Award** to **Arye Rosen**, Academy Professor of Biomedical and Electrical Engineering, School of Biomedical Engineering, Science and Health Systems, Drexel University. The award was presented "for a career of leadership, meritorious achievement, creativity, and outstanding contributions in the field of microwave theory and techniques."

Jonathan M. Rothberg, chairman and founder, Ion Torrent Systems, has been named the 2010 winner of the **Connecticut Medal of Technology** for the development of innovative genomic technology. The Medal of Technology, the state's highest honor for scientists and engineers, recognizes extraordinary achievements in scientific fields crucial to Connecticut's economic competitiveness and social well-being. Modeled after the National Medal of Technology and Innovation, this award is bestowed by the Board of Governors for Higher Education, with the assistance of the Connecticut Academy of Science and Engineering, in alternate years with the Connecticut Medal of Science. Dr. Rothberg is the sixth recipient of the Medal of Technology.

Stanley I. Sandler, Henry Belin du Pont Chair of Chemical Engineering, University of Delaware, was presented with the **Properties and Phase Equilibrium for Process and Product Design (PPEPPD) Eminence Award** during the International PPEPPD Meeting held in May in Suzhou, China. This was the first such award given in the 37-year history of the meeting. A dinner honoring Dr. Sandler was held the evening of May 17. Xiaohau Lu, chairman of the PPEPPD International Organizing Committee and professor at Nanjing University of Technology, delivered the opening remarks.

Surendra P. Shah, Walter P. Murphy Professor of Civil and Environmental Engineering, Northwestern University, was recently **inducted into the Chinese Academy of Engineering (CAE) as a foreign member**. The induction took place at the 10th CAE General Assembly in Beijing, with Chinese President Hu Jintao in attendance.

Joel S. Spira, chairman and director of research, Lutron Electronics Company Inc., will donate materials related to the company's 50-year history to the Smithsonian National Museum of American History in response to a request for objects and papers that would provide insight into Spira's career as an inventor. The donation includes an early version of the original solid-state Capri dimmer manufactured by Lutron in September 1964. The Lutron materials, along with other artefacts, will be exhibited as part of the Electricity Collection, which includes experimental light bulbs from Thomas Edison, dimming light sockets from the 1910s, theatrical lighting controls from the 1920s, and many types of light switches.

At the IEEE Honors Ceremony in Montreal, Quebec, Canada, on Saturday, June 26, **Richard M. Swanson**, president and CTO, SunPower Corporation, was honored with the **2010 IEEE Jun-ichi Nishizawa Medal,** which is sponsored by the Federation of Electric Power Companies, Japan, and the Semiconductor Research Foundation, Japan. Dr. Swanson was recognized for "the conception and commercialization of high-efficiency point-contact crystalline-silicon solar cell technology."

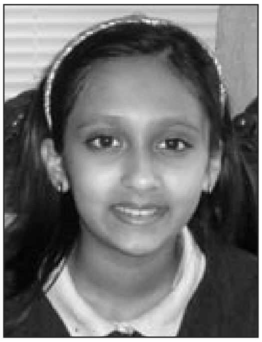
James M. Tien, Distinguished Professor and dean, College of Engineering, University of Miami, is the recipient of the **2010 IEEE Richard M. Emberson Award**. Sponsored by the IEEE Technical Activities Board, the Emberson Award is being given in recognition of Dr. Tien's vision and leadership in advancing IEEE's global visibility and his innovations in technical, publication, and educational services. The award was presented on June 26, 2010, at the IEEE Honors Ceremony in Montreal, Quebec, Canada.

The **2010 Marconi Society Prize** will be awarded to Adobe Systems founders **John E. Warnock**, chairman, Adobe Systems Inc., and **Charles M. Geschke**, chairman of the board, Adobe Systems Inc. Drs. Warnock and Geschke were selected for their research on printing and imaging technology and their development of Adobe® PostScript®, a revolutionary software technology that is now the worldwide printing and imaging standard for print service providers, publishers, corporations, and government agencies. The $100,000 Marconi Prize, considered the highest honor specifically for information and communications science, will be conferred on October 15 at the annual Marconi Awards Dinner in Menlo Park, California.

On April 24, 2010, IEEE honored **Wm. A. Wulf**, President Emeritus, National Academy of Engineering, and University Professor and AT&T Professor of Engineering and Applied Sciences, Department of Computer Science, University of Virginia, with the **IEEE-USA Award for Distinguished Public Service**. The award was presented to Dr. Wulf during the IEEE-USA Annual Meeting in Nashville, Tennessee, for the advancement of engineering professionalism and the promotion of U.S. competitiveness in science and technology.

Winners of the 2010 *EngineerGirl!* Essay Contest Survival Design Challenge

Quin Nardone



Satvika Kumar

Brielle Seaman

EngineerGirl! (*www.engineergirl.org*) recently announced the winners of its 2010 essay contest, "Survival Design Challenge." Students in grades 3 through 12 were asked to describe how they would use the clothing or accessories they were wearing, the contents of their backpacks, and items in the environment to create a shelter, gather food and water, or get the attention of a rescue party if they were lost during a field trip to a national forest.

This year, NAE received more than 800 entries from students all over the country. Prizes were awarded in three categories, grades 3 through 5, 6 through 8, and 9 through 12, ranging from $500 for first place to Certificates of Honorable Mention. The essays were judged on the basis of creativity and originality, design potential and feasibility, and communication. Students were encouraged to make creative use of available materials and to think carefully about how to meet their potential needs.

The first prize in the grades 3 through 5 category was awarded to Quin Nardone, a 3rd-grader being home schooled in Fort Lauderdale, Florida. He created simple but practical tools, such as smoke signals, paper boats, and drums, to attract attention from a rescue party.

In the 6th through 8th grade category, first place was awarded to Satvika Kumar, a 6th grader from Nysmith School for the Gifted in Lorton, Virginia, for her description of efforts to attract a rescue party using signal fires, notes, and a handmade whistle.

In the 9th through 12th grade category, the first-place prize was awarded to Brielle Seaman, a 12th grader from A.C. Mosley High School in Panama City, Florida, for her essay on creating a system to gather, filter, and purify water.

Additional winners included Brittany Ngia, Troy, Michigan; Raga Justin, Texarkana, Texas; Maddy Garretson, El Cerrito, California; Summer Wu, Lake Forest, Illinois; Zachary Neubauer, Wasilla, Alaska; Alexandra Kung, Chappaqua, New York; Emily Pace, Conyers, Georgia; Jahvan Innerarity, Conyers, Georgia; and Kristina Henderson, Louisiana, Missouri. All of the winning essays can be found on the *EngineerGirl!* website.

The 2010 *EngineerGirl!* Contest was made possible by the generous sponsorship of Northrop Grumman Corporation, Ford Motor Company, and Bechtel.

EngineerGirl!, NAE's innovative website for middle school girls, provides information about various fields of engineering and careers, as well as games, books, and other resources. For further information on *EngineerGirl!*, see *www.engineergirl.org* or e-mail *engineergirl@nae.org*. A companion website, *www.EngineerYourLife.org*, is geared for academically prepared high school girls.

Engineering to Improve the Operations of Manufacturing Enterprises NAE Regional Meeting at the University of Michigan

The NAE Regional Meeting and National Symposium, Engineering to Improve the Operations of Manufacturing Enterprises, was held on April 13, 2010, at the University of Michigan (UM) in Ann Arbor. The 162 participants included 27 engineering students and faculty from 23 different universities. Twenty-four NAE members also attended the symposium, which was followed by a meeting chaired by NAE President **Charles Vest**. A dinner for speakers and NAE members was hosted by UM Dean of Engineering David Munson.

Chair of the symposium, NAE member **Don Chaffin**, gave the introductory remarks, in which he stressed that engineers involved in manufacturing must be capable of using a variety of modeling and simulation tools to address the complexities of contemporary manufacturing operations in a global economy. In subsequent presentations, NAE member **Steven Forrest** and UM Dean David Munson emphasized the importance of manufacturing to the Midwest and the need for multidisciplinary and cooperative educational and research programs by industry and academia to ensure that graduating engineers have the skills and tools they need to succeed in this complex environment.

UM Professor Sridhar Kota, who is currently assistant director for advanced manufacturing in the White House Office of Science and Technology Policy, gave the next presentation. He pointed out that, although American academic and national research laboratories are still the major source of conceptual innovative ideas, we often fall short in translating those ideas and research results into the U.S.-based manufacture of products and processes.

NAE President Charles Vest then graphically described the continuing decline in U.S. manufacturing (now about 13 percent of GDP, involving less than 20 percent of workers). When a company exports its manufacturing operations to another country, he said, off-shoring of related technologies and associated engineering leadership often follows. We need to add 17 million new jobs in the next decade, he continued, which will take a new generation of manufacturing technologies and robotics and the establishment of cooperative centers of manufacturing excellence in various regions of the country.

The first technical session, Operations Engineering in Customer-Driven Manufacturing, was organized by NAE member **Stephen Pollock**. The keynote speaker, Larry Burns, former vice president of research and development (R&D) and strategic planning at General Motors, argued that, contrary to popular wisdom, the world is not “flat.” It is, he said, nonlinear and filled with uncertainties, interdependencies, and complexities. For a manufacturing company to survive in this world, it must understand changing customer needs and wants and use analytical models of operations early in the design process when assessing the real value of producing certain types of products. Through careful modeling of available operations data, he said, a firm can steadily improve the quality and sustainability of its products.

A panel of speakers, MIT Professor Stephen Graves, Ulrich Raschke of Siemens Corporation, and Dev Pillai of Intel Corporation, then addressed issues related to educating operations engineers to deal with complex manufacturing systems; how digital models of people are being used to improve the ergonomics, safety, and performance of workers; and how software has become the key to enabling teams of engineers and managers to work together effectively.

The second session, organized by UM Professor Wally Hopp, was entitled Operations Engineering toward Green Manufacturing Systems. Keynote speaker Sharon Nunes, vice president for Big Green Innovations at IBM, argued that we are only about one-tenth of the way toward knowing how to design and operate truly green, sustainable manufacturing systems. Improvement, she said, will be based on systems thinking. Energy usage, carbon production, waste reduction, and greenhouse gas (GHG) emissions can be measured, but effective policies must be informed by the results of statistical and economic modeling. Government regulations and customer demands, she said, will require the development of new models of operations and policies to ensure that manufacturing systems and supply chains are sustainable.

The session then moved to a discussion panel, Joseph Wolfsberger of Eaton Corporation, UM Professor Steven Skerlos, and University of California, Berkeley, Professor

David Dornfeld, on how becoming "green" can add value to a company, improve a company's public image and recruitment, and provide opportunities for new R&D. In the future, they argued, people will demand completely recyclable products produced by highly efficient, precision manufacturing systems that minimize waste. Models of these systems will be necessary to determine how social, economic, and technological factors interact. The panel called for cooperative programs among government, academia, and industry to support the development of green manufacturing operations.

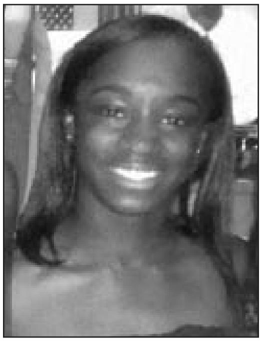
Operations Engineering in Defense Systems Acquisition, Manufacturing, and Maintenance, the third technical session, was organized by NAE member **Seth Bonder**. As keynote speaker, NAE member General **David Maddox**, U.S. Army (ret), observed, the U.S. Department of Defense (DOD), which spends about $200 billion annually on equipment, uses a life-cycle review process that relies heavily on models of proposed systems to demonstrate their operation under a variety of field conditions. Based on a DOD Statement of Needs, potential manufacturers develop proposals using various models to design and verify that a system can meet those needs. Before the final design is approved for production, prototypes must be built and more data gathered and modeled.

NAE member **Peter Cherry**, of SAIC, Mark McNitt, of BAE Systems, and General Benjamin Griffin, U.S. Army (ret), then participated in a speakers' panel on how system modeling and simulation methods can be used to design and produce new equipment, facilitate team decision making, address concerns about software tools that are not highly integrated and are often not available to small vendors in the supply chain, and improve the modeling of maintenance and logistical requirements of military manufacturing and maintenance operations.

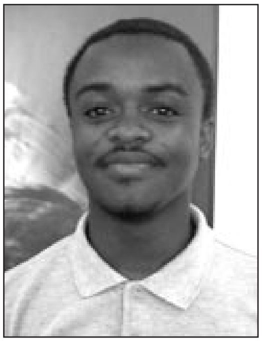
The final session, organized by NAE member **Yoram Koren** and UM Professor Jack Hu, was a presentation of "Innovation and Operations of Manufacturing Systems," a preliminary report of a National Science Foundation (NSF) workshop. A complete report will be posted on the NSF website (*www.nsf.gov*) later this year.

The NAE/UM symposium agenda, information about speakers and panelists, and videos of major presentations are available online at *www.eiome.edu*

Interns Join Program Office



Safoah Agyemang



Charles Ajaegbu

Ori Perl

Safoah Agyemang, a first year Anderson-Commonweal Intern at the National Academies, worked this summer in the NAE Program Office with Catherine Didion on several projects: updating content for the *EngineerGirl!* and *Engineer Your Life* websites; checking and repairing broken links on both sites; gathering information for the NSF-sponsored Minority Males Colloquy run by CASEE; and preparing mailings of the new NAE report, *Gender Differences at Critical Transitions in the Careers of Science, Engineering, and Mathematics Faculty*, to send to civil engineering and electrical engineering departments at research-intensive universities. Although Safoah does not intend to study engineering herself, she hopes to interest elementary school children in engineering and to encourage those who have already expressed an interest in the field to continue on that path.

In her free time, Safoah enjoys listening to and creating music on both the piano and guitar. As a junior at Paint Branch High School, she was a student in the Medical Careers Pathway Program, through which she earned a license as a certified nursing assistant (CNA). As a volunteer and as a CNA intern at Holy Cross Hospital, she helps deliver palliative care to patients. This fall she will be a freshman at Mount Saint Mary's University, where she plans to major in biology and eventually attend medical school. Her ultimate goal is to become an obstetrician and gynecologist.

Charles Ajaegbu, a second year Anderson-Commonweal intern and a pre-med sophomore at the University of Oklahoma, is working on a degree in biomedical engineering. At NAE, he worked with Greg Pearson, Catherine Didion, and Norman Fortenberry on several projects and/reports and collected data for the next Changing the Conversation report.

Ori Perl, summer intern in the NAE Program Office, will be a senior at Montgomery Blair High School in Silver Spring, Maryland, next year. Ori, who has been active in FIRST robotics competitions, is looking forward to pursuing a degree in engineering beginning in the fall of 2011. At NAE, he worked with Randy Atkins and Nathan Kahl on media/public relations projects, such as the WTOP Radio series and the USA Science and Engineering Festival. He also helped with the Changing the Conversation project.

Inaugural USA Science and Engineering Festival

Nationwide activities and planning are under way for the first USA Science and Engineering Festival (*http://www.usasciencefestival.org/*), which will be held October 10–24, 2010. NAE is developing an exciting exhibit for the huge Expo to be held in Washington, D.C., on October 23 and 24.

In collaboration with The Walt Disney Company, NAE will present several of the Grand Challenges for Engineering (*www.engineeringchallenges.org*) in the context of Disney's upcoming major motion picture *TRON: Legacy*. The walk-through experience will combine props and clips from the film with cutting-edge, real-life engineering related to the *TRON* story line.

Just as a laser digitizes characters in *TRON* and transports them into a cyber world, visitors to the exhibit will see how engineers are "Engineering the Tools of Scientific Discovery" with laser scanners that send real objects into a 3-D cyberspace. In another part of the exhibit that touches on several of the NAE Grand Challenges, they will be able to manipulate digital brain scan images as they perform surgery in virtual reality. Finally, with the assistance of Disney's world-renowned Imagineers, participants will have an opportunity to create art with light—a key element in *TRON* and an engineering tool.

In addition to NAE, several other major units of the National Academies will have a presence in the tent. Other exhibits will include: The Bone Detective; Bon Appetit! Better Eating through Chemistry; The Scoop on Crime Scene Investigation: Separating Fact from Fiction; Text, Drive, and Die: Simulate Distracted Driving; and Perception and the Art of Decision Making.

The festival is expected to attract hundreds of thousands of people, and the National Academies will have a prime location in a large tent near the Capitol reflecting pool. Five hundred organizations are expected to have a presence at Expo locations on and around the National Mall.

Calendar of Events

September 23–25	U.S. Frontiers of Engineering Symposium IBM Learning Center, Armonk, New York
September 30	Workshop on Synthetic Biology and Engineering Ethics
October 1–2	NAE Council Meeting
October 2	Peer Committee Meetings Orientation Session for the NAE Class of 2010
October 3–4	NAE Annual Meeting
November 5	Online Ethics Center Advisory Group Meeting
November 9–10	NRC Governing Board Meeting
November 30–December 1	Committee on Implementing Engineering Messages Meeting and Workshop
December 4	2011 NAE Election Committee on Membership Meeting Irvine, California
December 13–16	Frontiers of Engineering Education Symposium Irvine, California

All meetings are held in the National Academies Keck Center in Washington, D.C., unless otherwise noted.

In Memoriam

ARTHUR G. HANSEN, 85, President Emeritus, Purdue University, and retired educational consultant, died July 5, 2010. Dr. Hansen was elected to NAE in 1976 "for pioneering work in flow phenomena in turbomachine blade row and ducts and contributions to engineering education."

EDWIN E. KINTNER, 90, retired executive vice president, GPU Nuclear Corporation, died on June 7, 2010. Mr. Kintner was elected to NAE in 1990 "for significant contributions to the development of nuclear submarine propulsion, nuclear power operation and management of magnetic fusion programs."

DORIS KUHLMANN-WILSDORF, 88, president, Kuhlmann-Wilsdorf Motors, died on March 25, 2010. Dr. Kuhlmann-Wilsdorf was elected to NAE in 1994 "for contributions to dislocation theory and its application to mechanical behavior."

HARVEY F. LUDWIG, 93, consulting environmental engineer, died on April 28, 2010. Dr. Ludwig was elected to NAE in 1969 "for advances in environmental engineering research and development in water and waste-processing methods."

EDWARD A. MASON, 85, retired vice president, research, Amoco Corporation, died on June 23, 2010. Dr. Mason was elected to NAE in 1975 "for contributions to research on fluidized solids, organic-cooled reactors and power system optimization and leadership in complex nuclear projects."

DALTON H. PRITCHARD, 88, retired fellow of the Technical Staff, RCA Corporation, died on April 18, 2010. Mr. Pritchard was elected to NAE in 1983 "for significant contributions to the development of the NTSC color system with subsequent continued improvements and innovations in video technologies."

WILLIAM L. WEARLY, 94, retired chairman and CEO, Ingersoll-Rand Company, died on April 30, 2010. Mr. Wearly was elected to NAE in 1990 "for leadership in the development and manufacture of equipment contributing to safety and productivity in mining and in related industries."

Publications of Interest

The following reports have been published recently by the National Academy of Engineering or the National Research Council. Unless otherwise noted, all publications are for sale (prepaid) from the National Academies Press (NAP), 500 Fifth Street, N.W., Lockbox 285, Washington, DC 20055. For more information or to place an order, contact NAP online at *http://www.nap.edu* or by phone at (888) 624-8373. *(Note: Prices quoted are subject to change without notice. Online orders receive a 20 percent discount. Please add $4.50 for shipping and handling for the first book and $0.95 for each additional book. Add applicable sales tax or GST if you live in CA, DC, FL, MD, MO, TX, or Canada.)*

Memorial Tributes: National Academy of Engineering, Volume 13. The 13th volume in the Memorial Tributes series compiled by the National Academy of Engineering provides personal remembrances of the lives and outstanding achievements of NAE members and foreign associates. These volumes provide an enduring record of the many contributions of engineers and engineering to the benefit of humankind. In most cases, the authors are contemporaries or colleagues who had personal knowledge of the interests and engineering accomplishments of the deceased. Hardcover, $68.00.

Engineering, Social Justice, and Sustainable Community Development: Summary of a Workshop. This is the first in a series of biennial workshops on the theme of engineering ethics and engineering leadership. The workshop addressed conflicting positive goals for engineering projects in impoverished areas and areas in crisis, both in the United States and elsewhere in the world. Besides the explicit goal of economic development or progress, project sponsors and participants often have implicit goals, such as protecting human welfare, ensuring social justice, and striving for environmental sustainability. At the workshop summarized in this volume, participants discussed how to (1) improve research in engineering ethics; (2) improve engineering practice in situations of crisis and conflict; (3) improve engineering education in ethics and social issues; and (4) involve professional societies in these efforts.

NAE members on the study committee were **John F. Ahearne** (chair), Executive Director Emeritus, Sigma Xi, The Scientific Research Society, and **Wm. A. Wulf**, University Professor and AT&T Professor of Engineering and Applied Sciences, University of Virginia, and President Emeritus, National Academy of Engineering. Paper, $21.00.

Preparing Teachers: Building Evidence for Sound Policy. Improving educational outcomes depends on teachers and thus on the abilities of individuals attracted to teaching and the quality of their education and training. Yet teacher preparation is often treated as an afterthought in discussions of improving public education. This report addresses the issue of teacher preparation, specifically for the teaching of reading, mathematics, and science. The authoring committee evaluates the characteristics of the candidates for teacher preparation programs, the kinds of instruction and experiences they receive, and the extent to which required instruction and experiences are consistent with converging scientific evidence of the requisites for good teaching. The committee discusses the need for a data-collection model to provide valid, reliable information about the content knowledge, pedagogical competence, and effectiveness of graduates from various kinds of teacher preparation programs. This information is crucial to federal and state policy makers and the educators of teachers.

NAE member **Ronald M. Latanision**, corporate vice president and director, mechanics and materials, Exponent Inc., was a member of the study committee. Paper, $44.00.

Review of the WATERS Network Science Plan. The availability and quality of water is changing as a result of increasing population, urbanization, land use, and climate change, and shortages are becoming more frequent in many parts of the country. The Water and Environmental Research Systems (WATERS) Network, an initiative being considered by the National Science Foundation, could provide advances in basic science to enable the effective management of water resources. The WATERS Network would be an integrated national network of observatories and experimental facilities to support research,outreach, and education on large-scale, water-related environmental problems. The proposed observatories would provide researchers with access to linked sensing networks, data repositories, and computational tools connected through high-performance computing and telecommunications networks. This report, the final volume in a series about the WATERS project, provides a detailed review of the Science Plan and advice for effective collaboration with other federal agencies.

NAE members on the study committee were **George M. Hornberger** (chair), director, Vanderbilt Institute for Energy and Environment, and Distinguished University Professor, Department of Civil and Environmental Engineering, Vanderbilt University; **Glen T. Daigger**, senior vice president and chief technology officer, CH2M Hill Inc.; **Daniel P. Loucks**, professor, School of Civil and Environmental Engineering, Cornell University; and **Charles R. O'Melia**, Abel Wolman Professor of Environmental Engineering Emeritus, Johns Hopkins University. Paper, $21.00.

Capabilities for the Future: An Assessment of NASA Laboratories for Basic Research. In the past five years, or more, budget reductions have caused a steady, significant decrease in NASA's laboratory capabilities, including equipment, maintenance, and facility upgrades. The effects have strained support for NASA scientists and impaired NASA's ability to make basic scientific and technical contributions crucial to programs of national importance. Not only has the fundamental research community at NASA been severely impacted, but NASA's ability to support its future goals is in serious jeopardy.

NAE members on the study committee were **Joseph B. Reagan** (co-chair), retired vice president and general manager, Lockheed Martin Missiles & Space Company; **William F. Ballhaus Jr.**, retired president and CEO, The Aerospace Corporation; **Peter M. Banks**, Astrolabe Ventures; **Wesley L. Harris**, Charles Stark Draper Professor of Aeronautics and Astronautics and associate provost, Massachusetts Institute of Technology; **Eli Reshotko**, Kent H. Smith Professor Emeritus of Engineering, Case Western Reserve University; and **James M. Tien**, Distinguished Professor and dean, College of Engineering, University of Miami. Paper, $29.75.

Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use. The production, distribution, and use of energy has negative, as well as positive effects, most of which are not reflected in market prices. When markets fail, governments may justifiably intervene in the form of regulation, taxes, fees, tradable permits, or other instruments to bring external or hidden costs into view. In the aggregate, the negative costs of energy include damage from air pollution associated with electricity generation, motor vehicle transportation, and heat generation; climate change; adverse health effects; and risks to national security. The study committee that produced this report concludes that major initiatives will be necessary to reduce emissions, improve energy efficiency, and ultimately change to a cleaner electricity-generating mix. As we move toward that goal, a first step in minimizing the adverse consequences of new energy technologies will be to identify their external effects. This report will be a vital tool for government policy makers, scientists, and economists, especially in the early stages of the research and development of new energy technologies.

NAE member **Elisabeth M. Drake**, retired associate director for new energy technology, Energy Laboratory, Massachusetts Institute of Technology, was a member of the study committee. Paper, $47.00.

Real Prospects for Energy Efficiency in the United States. In the last decade, the prices of oil, natural gas, and coal have increased dramatically, leaving consumers, industries, and service sectors looking for ways to reduce energy use. Increasing energy efficiency will require new technology, informed consumers and producers, and investments in energy-efficient industrial processes, businesses, residences, and transportation. In this report, part of the America's Energy Future Project, the study committee looks into the potential of reducing energy demand by improving efficiency with existing technologies, technologies developed but not yet widely used, and prospective technologies. The committee evaluates technologies based on their estimated times to initial commercial deployment and analyzes costs, barriers, and research needs. This quantitative characterization of technologies is intended to guide policy makers toward planning the future of energy use in America. The report will also be of great interest to industry leaders, investors, environmentalists, and others looking for a practical assessment of the potential benefits of energy efficiency.

NAE members on the study committee were **Maxine L. Savitz** (vice chair), retired general manager, Technology/Partnerships, Honeywell Inc.; **Magnus G. Craford**, chief technology officer, LumiLeds Lighting; **Alexander MacLachlan**, retired senior vice president, research and development, E.I. du Pont de Nemours & Co.; and **William F. Powers**, retired vice president, research, Ford Motor Company. Paper, $49.95.

Testing of Body Armor Materials for Use by the U.S. Army—Phase II: Letter Report. This Phase II report provides detailed assessments of the methodologies used for testing body armor, such as the validity of using the column-drop performance test for assessing the part-to-part consistency of a clay body to the level of precision identified in Army test procedures. More detailed discussions of the issues surrounding the testing of body armor, both present and future, will be presented in the final Phase III report.

NAE members on the study committee were **Morton M. Denn**, Albert Einstein Professor of Science and Engineering, City College of New York, CUNY; **Henry I. Smith**, professor of electrical engineering, Massachusetts Institute of Technology; and **Kenneth L. Walker**, executive vice president, Luna Innovations Incorporated. Free PDF.

Persistent Forecasting of Disruptive Technologies—Report 2. "Disruptive technologies" cause one or more discontinuities in the normal evolutionary life cycle of technology, which may lead to unexpected destabilization of an older technology order and an opportunity for new competitors to displace incumbents. Frequently cited examples of disruptive technologies are digital photography and desktop publishing. The first report in the series reviewed how technology forecasts were made in the past, assessed existing forecasting systems, and identified desirable attributes of a next-generation, persistent, long-term forecasting system for disruptive technologies. This second report sketches out high-level forecasting-system designs and provides further evaluations of the system attributes defined in the first report and of the feasibility of creating a system with those attributes. Taken together, the two reports are intended to help the U.S. Department of Defense and the intelligence community identify and develop a forecasting system that can help detect and track global technology trends, provide long-term forecasts of disruptive technologies, and characterize their potential impact on future U.S. war-fighting and homeland defense capabilities.

NAE members on the study committee were **Ruth A. David**, president and CEO, ANSER (Analytic Services Inc.); **Stephen W. Drew**, Drew Solutions LLC, Summit, New Jersey; and **Jennie S. Hwang**, Board Trustee and Distinguished Adjunct Professor, Case Western Reserve University, and president and CEO, H-Technologies Group Inc. Paper, $21.00.

Realizing the Energy Potential of Methane Hydrate for the United States. Methane hydrate is a potentially enormous and as yet untapped source of methane, the major component of natural gas. The cleanest of all the fossil fuels, natural gas emits 25 to 50 percent less carbon dioxide than either oil or coal for each unit of energy produced. In recent years, natural gas has supplied approximately 20 to 25 percent of all energy consumed in the United States. The U.S. Department of Energy Methane Hydrate Research and Development Program has been tasked since 2000 with implementing and coordinating research on methane hydrate to stimulate the development of knowledge and technology necessary for the safe, environmentally responsible commercial production of methane. This report provides an evaluation of the research projects and management processes since the program was re-authorized by Congress in 2005 and offers recommendations for future research and development initiatives.

NAE member **Sidney J. Green**, research professor, University of Utah, and Schlumberger Senior Advisor, was a member of the study committee. Paper, $42.25.

Steps Toward Large-Scale Data Integration in the Sciences: Summary of a Workshop. This report summarizes a National Research Council workshop held in August 2009 to identify major challenges hindering large-scale data integration in the sciences and some technologies that could address those challenges. To inform participants about the commonalities and differences in the data-integration challenges facing various research communities, the workshop included explorations of a number of areas of scientific research and explanations by experts on the issues and current best practices of each. In addition, experts working on the cutting edge of techniques for handling data integration described the problems they face and their progress toward solving them, thus giving participants insights into the current state of the art. The goals of the workshop were to identify areas in which the emerging needs of research communities are not being addressed and to suggest opportunities for addressing these needs through collaboration with researchers in cutting-edge computer science.

NAE members on the study committee were **Michael R. Stonebraker** (chair), adjunct professor of electrical engineering and computer science, Massachusetts Institute of Technology, and **Josephine Cheng**, IBM Fellow and vice president, IBM Almaden Research Center. Paper, $21.00.

Selling the Nation's Helium Reserve. Helium has long been the subject of public policy deliberation and management, largely because of its many strategic uses and because it is a product derived from natural gas. Thus the helium market has several anomalous characteristics. Shortly after sources of helium were discovered at the beginning of the 20th century, the U.S. government recognized the potential importance of helium and placed its production and availability under strict governmental control. In the 1960s, the strategic value of helium in the cold war was reflected in policies that resulted in the accumulation of a large helium reserve owned by the federal government. The latest manifestation of public policy is expressed in the Helium Privatization Act of 1996, which directs that substantially all of the helium accumulated as a result of earlier policies be sold off by 2015 at prices sufficient to repay the federal government for its outlays associated with the helium program. The present volume assesses whether the interests of the United States have been well served by the 1996 Act and, in particular, whether selling off the helium reserve has had any adverse effects on U.S. scientific, technical, biomedical, or national security users of helium.

NAE members on the study committee were **Robert R. Beebe**, independent consultant, Tucson, Arizona; **W. John Lee**, Peterson Chair and Regents Professor, Harold Vance Department of Petroleum Engineering, Texas A&M University; and **Michael Prats**, president, Michael Prats and Associates Inc. Paper, $34.25.

Defending Planet Earth: Near-Earth Object Surveys and Hazards Mitigation Strategies: Final Report. The United States spends approximately $4 million dollars each year searching for near-Earth objects (NEOs) that may collide with Earth. The majority of the funding supports the operation of several observatories that scan the sky searching for NEOs. However, the majority of NEOs that may present a threat to humanity still go undetected. A significantly smaller amount of funding is allocated to support ways to protect the Earth from a potential collision, so-called "mitigation." In 2005, Congress mandated that NASA be able to detect 90 percent of NEOs with diameters of 140 meters or more by 2020. The authoring committee of this report argues for the detection of objects as small as 30 to 50 meters in diameter, which can be highly destructive. The committee evaluates four main types of mitigation: civil defense; "slow push" or "pull" methods; kinetic impactors; and nuclear explosions. The committee argues that effective response to the hazards posed by NEOs requires national and international cooperation. The report is a useful guide for scientists, astronomers, policy makers, and engineers.

NAE member **David J. Nash**, president, Dave Nash & Associates LLC, was a member of the study's Mitigation Panel. Paper, $36.50.

NOAA's Education Program: Review and Critique. The National Oceanic and Atmospheric Administration (NOAA), the agency responsible for understanding and predicting changes in the Earth's environment and conserving and managing coastal and marine resources to meet the nation's economic, social, and environmental needs, has a broad mandate to coordinate public education on these topics. Since NOAA's creation in 1970, it has supported a variety of education projects covering a range of topics related to the agency's scientific and stewardship mission. NOAA uses formal and informal learning environments to improve the public understanding of science, technology, engineering, and mathematics (STEM) and to advance environmental education, often overlapping or duplicating the work of other federal agencies, institutions of higher education, and private and nonprofit organizations. Coordination among these agencies and organizations has been challenging. However, because of NOAA's limited educational resources and the inherently global nature of its mission, strategic partnerships are critical for the agency to accomplish its goals. This report provides a summary of the context for NOAA's twofold role in education: (1) to advance the environmental literacy of the nation, and (2) to promote a diverse workforce in ocean, coastal, Great Lakes, atmospheric, and climate sciences. The committee describes the strengths and weaknesses of NOAA's strategic plan and recommends improvements to the agency's education evaluation process.

NAE member **James M. Coleman**, Boyd Professor, Coastal Studies Institute, Louisiana State University and Agricultural and Mechanical College, was a member of the study committee. Paper, $44.25.

Waste Forms Technology and Performance: Interim Report. This interim report includes a review of the requirements for waste-form technology and performance in the context of the disposal system in which the waste will be placed. The U.S. Department of Energy (DOE) Office of Environmental Management (EM) requested this report to obtain timely information for planning its technology development for fiscal year 2011. The authoring committee focuses on three tasks:

- state-of-the-art tests and models of waste forms for predicting their performance for time periods appropriate to their disposal systems
- potential modifications of waste-form production methods that may lead to more efficient production of waste forms that meet performance requirements
- potential new waste forms that may improve performance or lead to more efficient production

The committee judges that the opportunities identified in this report are sufficiently mature to justify consideration by DOE-EM in its plans for technology development for fiscal year 2011.

NAE members on the study committee were **Milton Levenson** (chair), consultant and retired vice president, Bechtel International, and **David W. Johnson Jr.**, editor, *Journal of the American Ceramic Society*. Free PDF.

Nuclear Forensics: A Capability at Risk (Abbreviated Version). Nuclear forensics, the "interrogation" of discovered or seized nuclear materials and devices and the analysis of post-explosion or post-radiological-dispersal debris and detonation signals, is important to national security. Nuclear forensic evidence supports the efforts of law enforcement and intelligence agencies to prevent, mitigate, and attribute nuclear or radiological incidents. The United States has demonstrated the value of its nuclear forensics capability in real-world incidents of interdicted materials and in post-nuclear detonation exercises. The study committee for this report, which was requested by the U.S. Department of Homeland Security, the National Nuclear Security Administration, and the U.S. Department of Defense, recommends measures for sustaining and improving U.S. nuclear forensics capabilities and expresses its concerns about the program, which is in need of strong leadership, careful planning, and additional funds.

NAE member **Milton Levenson**, consultant and retired vice president, Bechtel International, was a member of the study committee. Free PDF.

Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles. This report evaluates technologies and methods of improving the fuel economy of medium- and heavy-duty vehicles, which consume more than 25 percent of the transportation fuel used in the United States. These vehicles include tractor-trailers, transit buses, and work trucks. The study committee recommends how federal agencies charged with regulating the fuel consumption of these vehicles should proceed. Currently, there are no fuel-consumption standards for them, and the miles-per-gallon measure used to regulate the fuel economy of passenger cars is not appropriate for medium- and heavy-duty vehicles, which are designed above all to carry loads efficiently. The committee recommends that a metric for regulating their fuel economy reflect the efficiency with which a vehicle moves goods or passengers, such as gallons per ton-mile (the amount of fuel a vehicle uses to carry a ton of goods one mile). The committee estimates that technological advances could greatly reduce fuel consumption. For example, advanced diesel engines in tractor-trailers could reduce fuel consumption by as much as 20 percent by 2020, and improved aerodynamics could yield an 11 percent reduction. Hybrid power trains could reduce consumption in vehicles that stop frequently, such as garbage trucks and transit buses, by as much 35 percent.

NAE members on the study committee were **Andrew Brown Jr**. (chair), executive director and chief technologist, Innovation and Technology Office, Delphi Corporation; and **Dennis N. Assanis**, Jon R. and Beverly S. Holt Professor of Engineering, University of Michigan. Paper, $61.50.

The National Academies Keck Futures Initiative: Complex Systems: Task Group Summaries. The National Academies Keck Futures Initiative was launched in 2003 to stimulate scientific inquiry and break down conceptual and institutional barriers to interdisciplinary research.

At the 2009 annual conference, which focused on complex systems, participants were divided into 12 interdisciplinary working groups and asked to explore specific challenges at the interface of science, engineering, and medicine. Over a period of two days (about nine hours of discussion), each group, made up of researchers in science, engineering, and medicine, as well as representatives of private and public funding agencies, universities, businesses, journals, and science media, faced a primary challenge of communicating among themselves and overcoming differences in their perspectives and areas of expertise. The summaries in this volume describe the problems presented to each group; the approach taken, including research to understand the relevant fundamental science; the plan proposed for engineering the application; the reasoning behind decisions; and descriptions of the benefits to society.

NAE members on the steering committee were **James B. Bassingthwaighte**, professor of bioengineering and radiology, University of Washington, and **M. Elisabeth Pate-Cornell**, Burt and Deedee McMurtry Professor and chair, Management Science and Engineering, Stanford University. Paper, $31.25.

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