term carbon reduction and capture international market share arising from the 50-year service life of power plants. The low-carbon fuels pathway faces moderate risks both technologically and commercially, although ATSs for stand-alone systems are probably low risk. The energyplex pathway faces low to moderate technical risk related to the challenges for system integration, and moderate to high risk related to the breakthroughs in capture, including those related to novel combustion configurations. The health and ecological risks are considered low to moderate.

Supporting science and crosscutting technologies needed to achieve these pathways include combustion; materials for high-temperature and corrosion-resistant performance; industrial ecology; hydrogen separation or production, transportation, and storage; improved processes for low-cost separation of oxygen; advances in fuel cells; and identification of alternative working fluids and determination of their thermodynamic properties.

Collateral Benefits

These pathways not only will reduce GHG emissions but also will provide a clean, secure energy future and help the nation respond to its international commitments. An accelerated RD&D program will enable the United States to capture a larger share of the $1.4 trillion export market for coal technologies between now and 2010 and help the U.S. economy grow by creating an energy technology export business. An accelerated R&D program would also allow U.S. industry to take advantage of the domestic markets for ATSs and fuel cells, which are estimated to be worth tens of billions of dollars between now and 2010.

Strategy and Recommendations

For the high-efficiency coal-based pathway, about $70 million per year is currently being spent on DOE programs. For the low-carbon fuel pathway (fuel cells and advanced turbines), about $90 million per year is currently being spent on DOE programs. As part of this initiative, accelerating and completing the development of these technologies is recommended. For the energyplexes pathway, relevant technical ideas (such as fuel cells and coal liquefaction) are currently being funded at various levels. Pursuing the grand challenges envisioned both for this pathway and for additional options is recommended for the next two decades.

In summary, the technology pathways described provide a range of options for using coal, natural gas, and other solid fuels—such as biomass, synthesis gas, and hydrogen—to generate power at competitive power costs, to reduce emissions of criteria pollutants and CO_2 to the atmosphere, and to develop strong positions in crucial technologies important to economic growth in the next century. Not all of these will necessarily enjoy widespread commercialization; however, they represent a family of options that spread technology risks, address fuel flexibility, and hedge against upsets in fuel prices. They include both improvements on familiar technologies, which should pose reduced commercialization risks, and bold new concepts that may pose as yet unrecognized commercialization risks.

2.4.3 Nuclear Energy

Nuclear power is deployed worldwide to produce 20% of world electrical generating capacity (in some countries, as much as 80%). Electricity generation using nuclear power results in very small emissions of GHGs, so nuclear power is an important tool in reducing global CO_2. In the period when France converted 70% of its electricity generation to nuclear, all related emissions were reduced dramatically. CO_2 was reduced by 80%, SO_2 by 90%, NO_x by 60%, and particulates by 97% (Fig. 2.9). Today, in the United States, 109 nuclear power plants generate nearly 22% of U.S. electrical capacity (100 GWe). This nuclear generating capacity avoids the emission of about 140 MtC/year compared with generating this electrical capacity by burning fossil fuels.

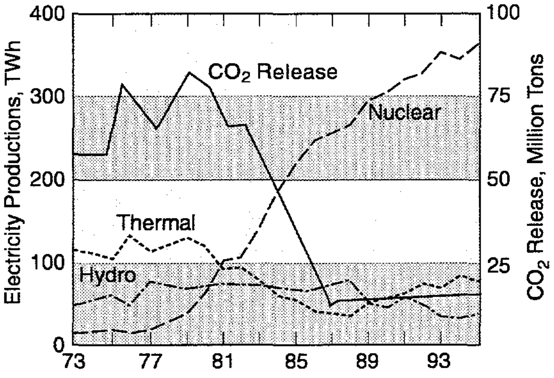

Fig. 2.9. Relationship between CO_2 release and electricity production in France, 1973–1996.

The Potential for Reduced Emissions

In the near term, the development and use of technologies for lifetime extension and for generation optimization (LEGO) of existing nuclear power plants could reduce carbon emissions by increasing nuclear electricity contributions from existing plants over the next several decades. A modest carbon reduction is also assumed for new nuclear plants in 2020 and 2030. Total potential reductions are shown in the following table.

Estimated carbon emissions reductions (MtC/year)

	2010	2020	2030
Total nuclear	0–15	30–70	70–150

Assumes successful technology development and subsequent marketplace adoption without significant policy changes.

If the current 100 GWe of nuclear electrical generating capacity were eventually replaced by next-generation nuclear plants, the United States would continue to avoid emissions of more than 100 MtC/year. If, in addition, electrical demand in the United States continued to grow at 1.5% per year and the installed nuclear generating capacity grew along with it to maintain its current share of the U.S. market (22%), then this new nuclear capacity could result in the avoidance of about 160 MtC/year by 2030. If the market for nuclear generated electricity expanded to 30%, then the result would be an avoidance of about 250 MtC/year by 2030 (see Fig. 2.10).

In the long term, by 2030, the development and use of evolutionary and advanced fission reactors are projected to reduce carbon emissions by about an additional 100 MtC/year. In the longer term, the second half of

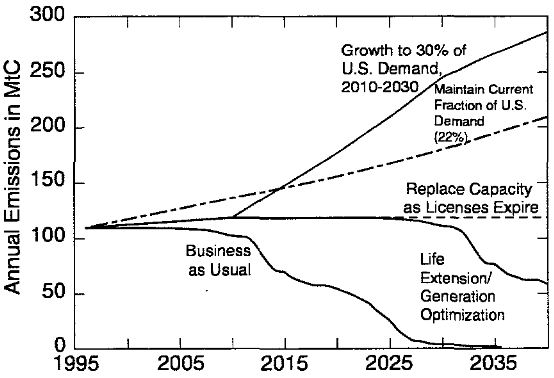

Fig. 2.10. Carbon emissions avoided under various scenarios of nuclear electricity generation.

the twenty-first century, fusion energy systems may become a significant economic power generation source, free of GHG emissions. The actual amount of nuclear-generated electricity will depend on the future financial viability of the nuclear option.

Technology Pathways and Opportunities

Lifetime Extension and Generation Optimization. The near-term approach to the use of nuclear energy should be to provide technologies to increase electricity generation and extend lifetimes of the existing set of 108 nuclear power plants. The initial 40-year license period for these reactors will expire roughly from 2005 to 2030. If the United States is faced with replacing this capacity with fossil-fueled generating plants, CO_2 emissions will ***increase*** more than 100 MtC/year. Both the renewal of plant licenses and increases in plant capacity factors can be enabled by new nuclear and nonnuclear technologies. With targeted R&D investments in monitoring, diagnostic, and materials technologies, these nuclear plant lifetimes could be extended for an additional 20 years, and the efficiency and output of the plants could be incrementally increased, thus avoiding the GHG emissions that would result from replacing this nuclear capacity with other power generation systems.

Examples of generation optimization technologies include advanced technologies for on-line monitoring of cables and conventional equipment (pumps, valves, etc.) to minimize losses of production because of unplanned outages. In addition, improved materials measurement and diagnostic technologies could reduce scheduled downtime for diagnostics and repairs. Plants could be operated at higher net power output to the grid by using sensors and controls that more accurately measure operational parameters, thereby reducing in-plant power demands, improving the thermal-to-electric conversion efficiency, and increasing the core power.

Nuclear power plant life extension hinges on the resolution of issues related to the aging of key components, including reactor pressure vessel embrittlement, stress corrosion cracking of reactor internals, degradation of instrumentation and power cables, and steam generator tube cracking. The effort to resolve these issues could also benefit from improved instrumentation and materials characterization technologies. In addition, R&D on in situ component annealing and on materials cladding processes could provide effective and economical repair technologies. Specific examples of approaches that offer the promise of resolving these issues include gas-fired thermal annealing, water chemistry control to avoid stress corrosion cracking, and various approaches to the deposition of lining materials.

Next-Generation Fission Reactors. The mid-term approach to the use of nuclear energy is to develop and install next-generation fission reactors. Even if LEGO technologies were fully utilized, a major increase in carbon emissions could only be avoided through new nuclear capacity after 2015, which would replace existing reactors that reach the end of their lives.

Evolutionary designs for next-generation fission reactors have received Nuclear Regulatory Commission licensing certification and are available for construction today without significant research;

several have been built in Japan. These designs are simple and rugged, and they incorporate passive safety features intended to provide safer, more trouble-free operation over 60-year design lifetimes. Advanced fission reactors, which use fuel cycles that are proliferation resistant, are also designed for higher efficiencies coupled with improved safety compared with currently operating plants.

The long-term (beyond 2030) approach to the use of nuclear energy would likely use nuclear reactor concepts, such as the liquid-metal cooled fast-spectrum reactor, that extract far more of the energy available in the uranium fuel than the 1% currently used and that produce less waste per GWe, thus extending the resource. In addition, efforts are under way to develop accelerator-driven systems using high-energy protons to produce nuclear energy from subcritical targets.

Finally, one can conceive of a new set of technologies that could be implemented in the next century. The concept of a hybrid nuclear-hydrogen cycle in which nuclear heat is used for production of hydrogen, with subsequent use of hydrogen as an energy source, has considerable potential. R&D on fission heat-to-hydrogen conversion technologies and on hydrogen distribution technologies has the longer-term potential to produce fundamental changes in the world's energy supply approach and make it consistent with our ecological goals.

Fusion Power. Fusion power, when developed and deployed, would be a carbon-free energy source. The U.S. domestic fusion energy sciences program is concentrating on science and innovation supporting the development of attractive fusion systems based on toroidal magnetic configurations. It also supports a small R&D effort on driver systems for inertial fusion energy. Most of the research effort for the inertial approach to fusion energy is supported for its defense applications. The development of technologies required for fusion, and the pursuit of ignited or burning plasmas, are being pursued through international collaboration.

Collateral Benefits

One collateral benefit of the continued pursuit of nuclear power would be the economic benefit of serving as a domestic and international supplier for this major electric power technology. The increased use of nuclear energy is foreseen around the developing world, especially in the Pacific Rim countries. As of today, the United States has invested $200 billion in nuclear power plants and has 400,000 nuclear-related jobs. In addition, a benefit of pursuing LEGO technologies would be enhanced safety and reduced worker radiation dose at existing plants.

Furthermore, if the United States did not pursue research into next-generation reactors, there would be several negative impacts. The first would be the loss of the technical infrastructure to support the nuclear enterprise, which also supports nuclear medicine, isotope production, and neutron science. This loss could also lead to increasing safety concerns for existing reactors. The second would be the decreased ability to design and construct fission, and eventually fusion, plants to export or to replace the existing ones in the United States at the end of their lives. Finally, with the loss of U.S. infrastructure, the ability to influence the nuclear policy of other countries would disappear.

Technical Risks and Other Issues

Nuclear power faces environmental risks and issues, including the disposal of nuclear wastes. But most of all, the risk is economic. Nuclear power shares the same economic attributes of many renewable technologies—a high fixed cost and a low variable cost—that make market penetration difficult today in the United States. Technology R&D along the technology pathways outlined here could have a major impact on alleviating all of these risks.

Strategy and Recommendations

Nuclear technology is currently offsetting approximately 140 MtC emissions per year. Pursuit of technologies for both LEGO and next-generation nuclear power would allow this offset to continue, as well as provide additional GHG emission reductions in the future. Successful development and use of improved nuclear power technologies could also have a major impact on global GHG emissions.

This study recommends pursuit of nuclear energy R&D to provide the United States and the world with an improved nuclear technology option to help address the very challenging climate change issue. Continued support of a broad base of concepts in fusion R&D is required, and, as these concepts mature, investment will be necessary and appropriate.

2.4.4 Renewable Energy

The Potential for Reduced Emissions

Renewable energy pathways—using energy from sunlight, wind, rivers and oceans, the hot interior of the earth (geothermal energy), and biomass (agricultural and industrial wastes, municipal solid waste, energy crops) to produce electricity, fuels, and heat—hold significant potential for reducing GHG emissions in the next century by displacing fossil-fuel-generated electricity or petroleum transportation fuels. This potential is shown in the table below and is compared with the business-as-usual carbon projections in Fig. 2.11.

Estimated carbon emissions reductions (MtC/year)

	2010	2020	2030
Total renewable energy	30–60	75–130	135–260

Assumes successful technology development and subsequent marketplace adoption without significant policy changes.

All regions of the United States have renewable resources of one type or another. Renewable resources currently account for about 8 to 10% of the energy consumed in the United States; most of this is from hydropower and traditional biomass sources. Solar, wind, and geothermal technologies are cost-effective today in small and niche markets, which are important steps to full commercialization.

- In the electricity sector, renewable power avoids emission of about

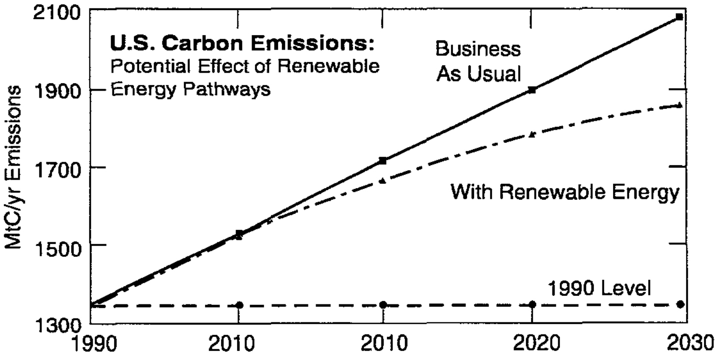

Fig. 2.11. Renewables have the potential for significant reductions of U.S. carbon emissions.

70 MtC per year at the present emissions rate of 0.17 MtC/TWh for electricity.

- Renewable energy technologies are well along a path of decreasing cost (Fig. 2.12), making their expanded commercialization prospects very realistic for early in the next century.
- A level of 20% use in 2025 and 50% use in 2050 is foreseen for the world in a number of projected energy scenarios from, for example, Shell Petroleum Limited (1996), the World Energy Council, and the International Panel on Climate Change (1995). A group of U.S. environmental organizations has also projected the future uses of renewables in the United States in a just-released report, *Energy Innovations* (1997).

Each of the renewable energy technologies is in a different stage of research, development, and commercialization; and all have differences in current and future expected costs, current industrial base, resource availability, and potential impact on GHG emissions. Appendix B describes each of these aspects of the various technologies.

While today's renewables are usually more expensive than the conventional competition on a first-cost basis, they are cost-effective in certain niche markets, especially on a life-cycle-cost basis. Several technologies produce electricity from renewable sources; those nearing commercialization face common problems such as difficulty in obtaining capital, uncertainties related to future electric utility restructuring, and current competition from natural gas. Those technologies further from commercialization need more emphasis on R&D, from fundamental research to resolution of process scale-up issues.

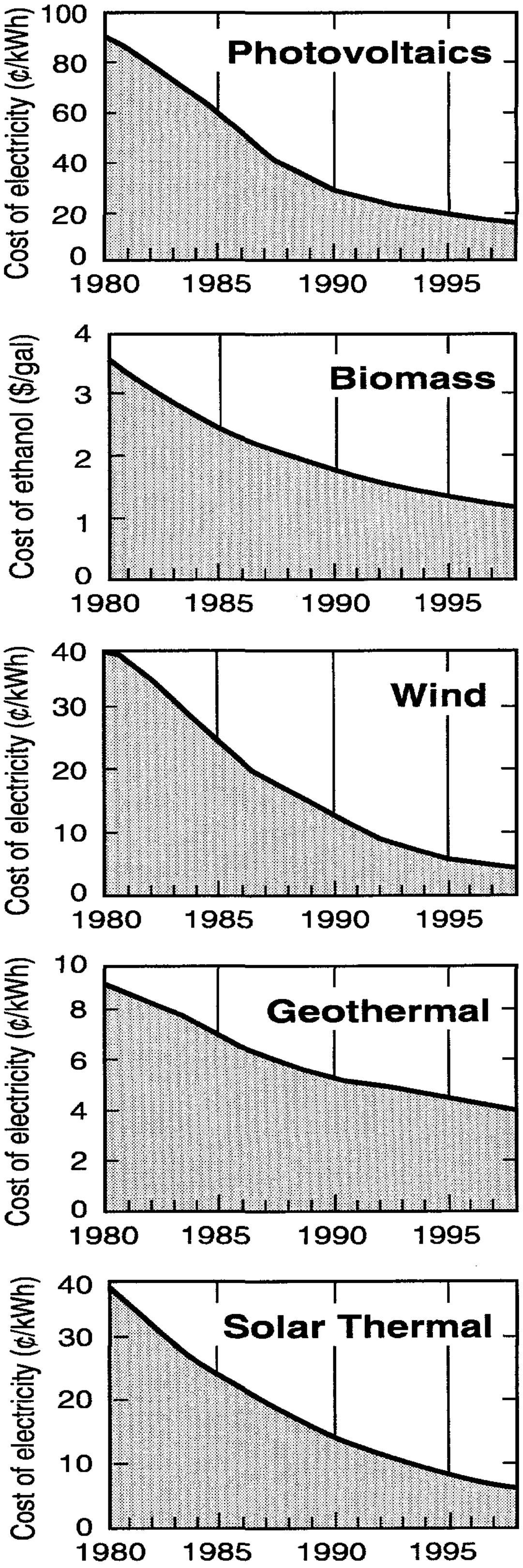

Fig. 2.12. Renewable energy technologies are well along a path of decreasing costs.

Technology Pathways and Opportunities

Biomass Electric refers to technologies that generate electric power from such biomass resources as cofiring biomass with coal, using biomass as the sole fuel in new power plants, or gasifying biomass to replace natural gas. From now through 2010, new biomass electric technologies (including landfill gas) are likely to be commercialized and should have a strong impact on CO_2 emissions. Biomass cofired with coal could also replace a significant portion of coal in electricity production in the near term. Biomass gasification could have a major impact in the forest products industry during the next 10 to 15 years, when many existing boilers will be replaced. RD&D challenges include resolving issues around ash chemistry and NO_x reduction, demonstrating long-term operation of gas turbines on synthesis gas, improving materials, developing sufficient energy crops for feedstocks, and demonstrating advanced technologies.

Wind Energy systems today are very close to being cost-competitive, on a levelized cost basis, with projects at $0.04 to $0.07 per kWh; nearly 1800 MW are installed in the United States, and another 6000 MW in other nations. High-quality wind resources are available in 34 of the 50 states and could provide major carbon offsets before 2010. Technology challenges to achieve lower cost and increased reliability include further advances in the understanding of wind flow, aerodynamics, structural dynamics, advanced power conversion devices, and development of durable and lightweight structural components. In the near term, up to 10 to 20% of a region's electrical capacity could be from wind power without any adverse operating or economic effects. Larger market penetrations in the mid to long term would require addressing the impact of the variation of wind through modification of systems operation, hybrids with other technologies, energy storage, transmission and infrastructure, and improved wind forecasting.

Studies on the effects of avian–wind turbine interactions have shown that when wind turbines are properly sited in areas of low avian usage (away from high resident local populations and migratory flyways), then bird fatalities are negligible.

Hydropower currently generates 10% of the nation's electricity, but generation is declining. Current technology often has adverse effects on fish and downstream water quality and quantity; the goal is to generate electricity without these adverse effects. R&D challenges include quantifying the biological response of fish affected by hydropower projects, modeling the forces inside turbines to predict stress levels on fish, and demonstrating the cost-effectiveness of retrofits.

Solar Photovoltaic (PV) technology uses semiconductor-based cells and modules to directly convert the energy of sunlight to electricity. PV can be used to produce electricity on almost any scale, depending only on how many PV modules are connected together. About 100 MW of PV modules were sold in 1997; annual growth has been 15 to 20%. Hundreds of U.S. applications are currently cost-effective for off-grid electric power needs, such as powering remote telecommunications installations and utility sectionalizing switches. International interest is also very high. PV costs are currently too high for bulk power generation, but costs are decreasing rapidly. Goals are to compete for peak power shaving by 2010, then daytime utility electricity by 2020. RD&D challenges including improving the fundamental understanding of materials and processes to provide a technology base for advanced PV options, optimizing cell and module materials and design, scaling up cells to product size, validating performance in outdoor and accelerated conditions, and improving manufacturing processes.

Geothermal Energy technologies use energy from within the earth to produce electricity or provide heat for industrial processes. Geothermal heat pumps use the thermal mass of the earth as a heat sink for air-conditioning and heating. Hydrothermal reservoirs produce about 2100 MWe in the United States and about 6000 MWe worldwide. In the United States, direct-use applications produce about 400 MWt; heat pumps produce 4000 MWt and are increasing by 25% per year. Only a small fraction of the huge geothermal resource can be used economically today. With research and policy support, electricity production could be doubled, and thermal production (including heat pumps) could be tripled or more. Geothermal RD&D challenges include improved methods for predicting reservoir performance and lifetime, innovative low-cost drilling technologies, new concepts to expand the use of the resource, improved energy conversion through thermal and fluids science and modeling, and lowering costs through thermal science and process chemistry.

Solar Thermal Electric and Buildings includes technologies that concentrate the heat of the sun to generate electricity or use the heat directly. Solar thermal electric technologies have been successfully demonstrated in nine commercial plants (354 MW) operating in California. Using existing, relatively conventional technology, including unique cost-effective storage, hundreds of additional megawatts of peaking power could be on-line by 2005; and evolutionary R&D improvements will allow bulk power market penetration by 2020. Solar hot water systems are commercially available, and ventilation preheat systems using unglazed transpired collectors have made significant progress in commercial/industrial markets. RD&D challenges include improving performance and lifetime and reducing manufacturing costs with improved designs and manufacturing technologies, and addressing commercialization challenges similar to those facing wind energy.

Biomass Transportation Fuels include methanol, ethanol, and hydrogen, which can displace petroleum in internal combustion engines. Biomass sources, including agricultural and other wastes, energy crops, and microalgae, are converted to fuels through biotechnology methods (using microbes) or through thermochemical processes. R&D goals are to demonstrate a biomass waste-to-fuels process with an industrial partner by 2000 and larger-scale production and conversion technologies by 2005. By 2010, energy crops should begin to be available, allowing biofuels to compete with petroleum for direct fuel replacement. R&D challenges include low-cost production of enzymes, development of microorganisms for consolidated processes, improved performance of thermochemical processing, and advances in energy crop productivity, cultivation, and harvesting. Biomass transportation fuels are also discussed in Transportation Sect. 2.3.3.

Solar Advanced Photoconversion technologies use the energy of sunlight to directly produce fuels, materials, chemicals, and electricity from renewable sources such as water, CO_2, and nitrogen. Most of these technologies—involving photobiological, photochemical, and photoelectrochemical approaches—are in the fundamental research stage where technical feasibility must be demonstrated. Examples of these natural and artificial photosynthesis processes include producing hydrogen from water or biomass and producing biodiesel, methane, and methanol from water, waste, and CO_2.

Collateral Benefits

A significant increase in the use of renewable energy pathways would provide benefits beyond reducing GHGs, such as lessening the reliance on foreign oil (especially biomass for transportation fuels), contributing little to waste storage or safety problems, and reducing pollutants. Renewable resources are widespread around the world, are highly attractive to developing countries, and represent a huge potential market for U.S. companies.

Technical Risks and Other Issues

The technical risks vary among the pathways, but there are clear R&D paths to address these risks. Overall, ecological and human health risks are low. Commercial, regulatory, and economic risks are generally moderate to high. In many cases, first costs are higher than for conventional energy choices, while the benefits of renewables do not currently motivate and reward private investment. Mechanisms are required that acknowledge the public value of renewables and help to attract private capital to develop these technologies. Small renewable energy companies in the United States face very strong international competition. Finally, decisions made under utility restructuring will have a major impact on market penetration for renewable electricity technologies.

Supporting R&D is needing in a variety of basic science and crosscutting areas, such as photosensitive materials, innovative semiconductors, corrosion-resistant and higher-temperature materials, biotechnology, catalysts and separations systems, sustainable agriculture, sensors and controls, electrical components, and computational modeling. A wide range of energy storage and transmission systems—along with the production of hydrogen as transportation fuel—would broaden the opportunities for the deployment of intermittent renewable energies, such as wind, solar photovoltaic, and solar thermal electric.

Strategy and Recommendations

Eventually, the private sector is likely to complete the development and commercialization of renewable energy technologies. But well-considered and sustained government investments, both in the underlying R&D and in actions that will remove deployment barriers, are critical. This is the most important step in realizing the full potential that renewable energy pathways can contribute to reducing carbon emissions early in the next century.

Significant investment would be required from both the private and the public sectors. Currently, the annual federal investment is about $250 million for these pathways. Increased federal investments to reduce carbon emissions would also return additional environmental benefits and the opportunity for U.S. companies involved in the area to be key players in the $1 trillion global energy market and the $400 billion market for environmental technologies.

2.5 CARBON SEQUESTRATION AND MANAGEMENT

This section discusses the reduction of net carbon emissions by capturing and sequestering CO_2 after combustion, decarbonizing fuel before combustion, or increasing the absorption of CO_2 from the atmosphere. These approaches are required for the continued use of fossil fuels as energy sources with reduced impacts on concentrations of atmospheric CO_2. For both approaches, there are a number of technological options, ranging from storage of CO_2 in the ocean or in geologic formations to chemical or biological stimulation of the absorption of CO_2 from the atmosphere.

The eventual path to stabilization of atmospheric CO_2 concentrations would require portfolios of GHG reduction technologies, portfolios that would vary from nation to nation and require systems-level analysis. Risks associated with any one pathway suggest that developing an effective approach to large-scale carbon sequestration would require evaluation of a number of alternatives as described in this report. These ideas and technologies should have a sound basis in science, both for understanding each technology and for evaluating the effectiveness of the technologies in actually ameliorating the atmospheric carbon loading. Thus it is imperative that we have a science-based model of the carbon cycle (atmospheric, oceanic, and terrestrial ecosystems) and that we verify the actual effectiveness of our model through measurements. One set of essential elements are models of each part of the carbon cycle, anchored with georeferenced measurements and verified by checking performance predictions against data gathered using remote sensing technologies on local, regional, and global scales. The resulting science-based program would permit us to direct our investments with greater confidence and with improved cost-effectiveness.

The Potential for Reduced Emissions

The developmental status of the carbon sequestration technologies discussed in this report varies widely. For example, the injection of CO_2 into oil wells or coal seams to enhance oil or methane production is a commercial practice today, whereas the understanding of soil biochemistry is not yet adequate to identify the most promising means for increasing soil uptake of atmospheric CO_2. Therefore, estimating the potential impacts of these carbon sequestration technologies on net carbon emissions is difficult. It is generally believed that net carbon emission reduction from carbon sequestration could be very high in the time frame of the late 2030s and beyond. In the nearer term, carbon sequestration potentials are uncertain, but they may range from low to medium. All of these estimates should be considered possible targets and should only be considered within an order of magnitude indication of what might be likely to result from R&D on these technologies.

Technology Pathways and Opportunities

CO_2 and Carbon Storage Technologies. Promising concepts for reducing CO_2 emissions are the storage of CO_2 in the ocean or in geologic formations. The technical feasibility of both of these storage concepts has been established, and it is believed that the CO_2 escape rates in both cases could be low enough to consider the carbon as permanently sequestered. However, the ecological impacts of various specific approaches—which are likely to depend on the location and type of storage media—are not known, nor are the economics of different oceanic or terrestrial CO_2 injection technologies.

For ocean storage, the most critical R&D questions include the stability of CO_2 clathrates and hydrates at various temperatures and ocean depths, as well as the diffusivity of CO_2 in the ocean, again as a function of temperature, depth, and concentration. In addition, the biological impacts of oceanic injection need to be studied.

Terrestrial storage of CO_2 in depleted oil or gas wells, coal seams, or underground aquifers deserves analysis. For the injection of CO_2 into oil or gas wells or coal seams, which has enhanced oil and gas production (as well as, perhaps, mine safety), to be commercially motivated, the critical research questions center on understanding the total potential storage capacity and the economics of different specific candidate sites. Answers to these questions will depend on proximity to CO_2 sources, as well as on the size and other characteristics of the site.

For storage in underground aquifers, the critical research questions include fluid, thermal, geological, and chemical properties of aquifers and the implications of that environment for injected CO_2. For example, would the formation of complex carbonates result from CO_2 injection, and at what rate? The economics of such CO_2 storage also needs to be analyzed.

A third approach to reducing net emissions through storage is the terrestrial storage of elemental carbon. This concept basically entails removing some or all of the carbon from a fossil fuel and then storing the carbon as a solid. For this approach, the challenge is primarily economic, because the carbon component of the starting fossil resource represents a major part of the energy value of that resource. Not using the carbon fraction in effect increases the energy cost of the remaining hydrogen-rich energy fraction. The advantage of this approach is that it should be less expensive to store carbon than to store CO_2. It may also be possible to market the carbon as a materials commodity to offset the increased energy cost. If carbon is placed in retrievable storage, the carbon energy may be used at a later date under less severe CO_2 emission control conditions.

Currently, storage is believed to be relatively less expensive than capture technologies, but neither is being employed on a large scale. This, however, will change with time as combustion processes are reengineered to facilitate capture. As the cost of capture comes down, storage becomes a greater part of the cost equation. Managing this cost suggests that storage near the point of combustion is advantageous because it reduces the transportation cost of the waste carbon.

Which of the storage pathways is best matched to any single combustion or conversion location will vary, so parallel development is required. As discussion of the individual technology pathways highlights, it is important to emphasize that very clear technological and environmental risks are associated with these technologies. The R&D agenda must therefore be very aggressive if cost-effective technologies are to be in place in time.

Advanced Chemical and Biological Sequestration. There are also several advanced chemical and biological concepts for CO_2 sequestration, including

- chemical sequestration as a mineral carbonate
- direct solar conversion of CO_2 to methanol or other benign products
- reducing the carbon/hydrogen ratio of fossil fuels and capturing the excess carbon
- microalgae sequestration

Advanced chemical and biological sequestration is aimed at permanent stable sequestration and at recycle of carbon to new fuels and chemical feedstocks. Reduction of emissions is accomplished through converting CO_2 into an environmentally benign product, reducing atmospheric CO_2 while generating liquid fuels, generating hydrogen as a fuel from coal without CO_2 emissions, and converting CO_2 into organic compounds. The major advantage of these technologies is that they eliminate the hazards to humans and to the environment that are intrinsic in the disposal of gaseous CO_2. Carbonate disposal accomplishes this by forming environmentally benign and thermodynamically stable waste forms; the other approaches instead generate viable products. All of these are at a research stage, with conceptual engineering design currently being completed. A better understanding of the basic processes is needed before practical achievable technology performance or cost levels can be estimated. However, because of the inherent attractiveness of these sustainable solutions, further work is merited.

Technologies for Removing CO_2 from the Atmosphere. The annual exchange of CO_2 between the atmosphere and the combination of the ocean and terrestrial biosphere is very large (IPCC 1995):

- gross annual atmosphere–ocean exchange—approximately 92 GtC
- gross annual atmosphere–terrestrial exchange—approximately 63 GtC (IPCC 1995)
- oceans currently hold 44,000 GtC

By comparison, the total annual anthropogenic emissions of CO_2 are only around 7 GtC. This suggests that small increases in the absorption of CO_2 as a manipulation of the global carbon cycle could have a very significant effect on net GHG emissions.

Dissolved CO_2 in the oceans is removed by the growth of phytoplankton. When carbon is thus removed, it is ultimately replaced by CO_2 drawn from the atmosphere. Two concepts have been proposed for enhancing oceanic uptake of atmospheric CO_2. These are iron enrichment or nitrogen enrichment, both targeted at stimulating the growth of phytoplankton. The general understanding of these approaches is in its infancy. While some experiments on iron fertilization have been conducted, no such studies of nitrogen fertilization exist. Key questions include what rates of CO_2 uptake can be achieved, what the biological impacts are, and to what extent the gains would be offset by carbon or methane emissions resulting from increasing harvests or decay of higher levels of the food chain. The economics of these approaches, which depend directly on the costs and efficacy of different fertilization approaches and rates, also need to be studied. An important risk factor is that of anoxia, or oxygen depletion, which needs to be understood as a function of site characteristics and fertilization rates.

An important component of terrestrial uptake of CO_2 is plant growth, which is treated in the Agriculture and Forestry technology pathway. However, carbon sequestration in soils is also a key of the carbon cycle. The fundamental concept here is the level of "soil organic matter" (SOM). Many agricultural practices, such as breaking of grasslands for crop farming or draining of wetlands, tend to decrease SOM. Technologies that can increase SOM include minimum tillage agriculture, increased return of crop residues to the soil, use of irrigation and fertilizers at levels that maximize crop and root biomass, and return of lands to forests or perennial plants. The most critical R&D needs include research on soil productivity (including the interactions of fertilization levels), tillage practices, water management practices, different plant species, regional soil biochemistry and climate, and the implications of these for affecting SOM. A better understanding of these factors and their interactions can then enable the analysis of the economics of specific technological approaches to increasing SOM.

Collateral Benefits

The most important benefit of successes with these carbon sequestration technologies would be that they could help to enable the continued extensive use of fossil fuels without harm to the climate. Thus they could indirectly have a major impact on global economics, given that economic growth is highly dependent on energy use, about 75% of which is derived from fossil fuels.

Technical Risks and Other Issues

The most important risks for these carbon sequestration technologies are environmental and economic. Each has the potential for environmental damage, and developing means to prevent that is a primary research need in each case. The economics for all of these technologies should be analyzed to determine their actual carbon sequestration potential and their associated costs.

The risks that are difficult to quantify today, however, are those associated with scaling up limited but promising field experiments to full-scale practice. The global infrastructure requirements for realizing large net carbon sequestration rates from carbon sequestration technologies would require a system of technologies that match or exceed the infrastructure requirements of the fossil fuel combustion enterprise of the next century. It will only be through an aggressive R&D program that we can develop a fundamental understanding of these risks.

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3. BASIC AND APPLIED RESEARCH AND CROSSCUTTING TECHNOLOGIES

Scientific research and the technological advances associated with it have been the basis for a multitude of new technologies that have appeared in the last 20 years. Many of the most successful and globally competitive industries in the United States (e.g., semiconductors, pharmaceuticals, aeronautics, biotechnologies) have strong ties to the products of U.S. R&D. The future security of our energy resources, the quality of our lives and health, and the competitiveness of our industries increasingly depend on further scientific and technological advances (*R&D Magazine* 1997). To create the innovative technologies required for energy systems with reduced carbon emissions requires (1) a broad interdisciplinary and visionary research program that develops the scientific understanding of the problem and (2) a strong industrial base.

Are there critical paths forward that require technological advances? If so, what types of research will enable those advances? At a workshop on R&D integration, Dr. Mary Good, until recently an undersecretary for technology for the U.S. Department of Commerce, concluded that basic research is the major factor that will determine the long-term outcomes of the technologies used to control carbon emissions. But reducing the levels of carbon emissions in the United States will require a commitment to both basic and application-driven research. In addition, disparate technologies for emissions control often will require work in the same critical basic research areas. Advances in both crosscutting basic research and enabling technologies are required to provide technological options like those outlined in Chap. 2 to reduce GHG emissions (Table 3.1).

This chapter addresses basic research needs and identifies a set of enabling technologies that will support the development of a wide range of technology pathways. Basic research needs and crosscutting technology developments are aggregated in the following list.

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Table 3.1. Most pressing research and enabling technology needs identified for each of the technology pathways presented in Chapter 2. Shaded boxes indicate a strong need for specific basic science or enabling technologies to advance a specific technology pathway. White boxes indicate that work in that basic research or technology area could be useful to develop a technology pathway

	Energy efficiency				Clean energy				CS
	Bld	Ind	Trn	A&F	FRD	FPG	Nuc	Ren	
Modeling and measurements	▨	▨	▨	▨	▨	▨	▨	▨	▨
Materials	▨	▨	▨		▨	▨	▨	▨	▨
Chemical sciences	▨	▨	▨	▨	▨	▨	▨	▨	▨
Biotechnology		▨		▨				▨	▨
Geosciences				▨	▨				▨
Environmental and ecological sciences		▨		▨	▨		▨	▨	▨
Nuclear sciences							▨		
Computational sciences	▨	▨	▨	▨	▨	▨	▨	▨	▨
Hydrogen and fuel cells	▨	▨	▨			▨	▨		
Electrical transmission distribution, and components	▨	▨	▨	▨	▨	▨	▨	▨	
Sensors and controls	▨	▨	▨	▨	▨	▨	▨		
Energy storage and retrieval	▨	▨	▨			▨	▨	▨	▨

Bld = buildings, Ind = industry, Trn = transportation, A&F = agricultural and forestry, FRD = fossil resource development, FPG = fossil power generation, Ren = renewables, CS = carbon sequestration.

- basic research to understand the global carbon cycle (i.e., computational modeling and measurements to understand the ocean–atmosphere–terrestrial–biosphere interactions)
- basic research supporting GHG reduction technologies (i.e., materials, chemical sciences, biotechnology, geosciences, environmental and ecological sciences, nuclear sciences, and computational sciences)
- enabling technologies supporting GHG reduction technologies (i.e., hydrogen and fuel cells; electrical transmission, distribution and components; sensors and controls; and energy storage)

The sections of this chapter of the report draw heavily upon the draft white paper, *Carbon Management: Fundamental Research Needs Assessment* (August 6, DOE-OER) and the report of the Secretary of Energy Advisory Board (SEAB 1995).

3.1 RESEARCH TO ADVANCE UNDERSTANDING OF THE GLOBAL CARBON CYCLE

CO_2 emissions from fossil fuels are divided among the atmosphere, ocean, and terrestrial biosphere. Measurements indicate that the atmosphere is storing carbon at a rate roughly equivalent to 60% of the emissions being produced by fossil-fuel consumption. Additional quantities of the excess carbon emissions are being stored in the ocean, where they do not affect the earth's radiation balance. Carbon storage changes in the terrestrial biosphere are difficult to measure and/or model; but there is reason to suspect that, while some areas are losing their ability to store carbon as a result of land-use changes, carbon storage is increasing in other areas. Therefore, a satisfactory balance of the contemporary global carbon budget has not yet been reached. In order to plan, assess, and verify the performance of CO_2 sequestration strategies, the fate of emitted CO_2 must be understood and quantified on a global scale. Verification of the fate of anthropogenic CO_2 via direct measurement programs is now technically feasible in both the atmosphere and the oceans. It is becoming possible to infer changes in terrestrial carbon storage using tracer methodologies, remote sensing, and modeling.

In general, CO_2 sequestration strategies and scenarios must be based on the assumption that the natural carbon cycle will function largely as it has over the past several thousand years. However, in the context of elevated CO_2 levels and perhaps of altered climates in the future, this assumption is not necessarily valid. Basic research is therefore required to identify and evaluate possible feedback on future atmospheric levels of CO_2. This feedback could arise from either direct effects (e.g., CO_2 fertilization of terrestrial plant growth, ocean ecosystem changes due to CO_2-related pH changes) or indirect effects (e.g., climate-related changes in deep-ocean circulation that might alter the sequestration of fossil-fuel CO_2).

3.1.1 Global Carbon Cycle Modeling and Measurement

Coupled atmospheric, terrestrial, and oceanic models are required for basic understanding of the integrated response of the global environmental system and for predicting changes in the global carbon cycle (see Fig. 1.1). This level of complex systems modeling demands high-performance computing (e.g., Accelerated Strategic Computing

Initiative) and fundamental research in the earth and ecological sciences. High-performance computing is critical to increase spatial and temporal resolution, to implement coupling between subsystems, and include important processes in the global systems model needed to assess carbon mitigation strategies. Research is necessary to quantify feedback among the terrestrial, atmospheric, and oceanic subsystems—including the implications of global changes for local and regional environments and economies and, conversely, local and regional inputs to the global systems. These models can be used to evaluate the effectiveness of carbon mitigation technologies and, through integrated assessments, to determine the cost-effectiveness and ecological impacts of carbon mitigation strategies.

In conjunction with the modeling activities, observations of the global environment are critical to document changes in the carbon cycle and to provide the basis for how and why changes are occurring. The strategy for systematic monitoring of CO_2 storage is now based on direct measurements of changes in atmospheric CO_2, oceanic storage of CO_2, and the inferred terrestrial carbon storage. The atmospheric and oceanic measurements should be continued, and measurement systems that directly estimate terrestrial storage must be developed. These measurements must then be used to verify the predictions and to suggest continuous improvement of the models.

The U.S. Global Change Research Program (USGCRP) is implementing a global observing and monitoring system for certain key physical measurements. This should be augmented with global and regional measurements that are especially pertinent to the global carbon cycle. These efforts should be coordinated and should take advantage of all available technologies and measurement systems in addition to those of the USGCRP.

3.2 BASIC RESEARCH RELATED TO GREENHOUSE GAS EMISSIONS

Scientific discovery is difficult to mandate or even predict. It can, however, be stimulated by the nature of basic R&D. The returns on investments in basic research have been immense. Who could have anticipated the profound impacts on society of the revolutionary technologies enabled through the development of, for example, antibiotics, gene therapy, transistors, structural polymers, nuclear fission, and superconductivity. Areas of visionary research that could be profitably explored to reduce GHG emissions might include developing a hydrogen-based economy, producing electric power from nuclear energy without any radioactive by-products, developing global electrical transmission using high-temperature superconductors, and significantly increasing photosynthesis processes via genetic engineering.

Scientific understanding from basic research efforts will provide the United States with a sound basis to advance technological options. Creating a strong science base makes it likely that the United States will be capable of developing a portfolio of technological options to meet GHG reduction targets. Discoveries resulting from basic research will almost certainly provide the United States with technologies that today might seem highly uncertain and unrealistic but that tomorrow might be essential problem-solving tools. Our long history of scientific progress has shown that basic scientific research alters the technological options available for responding to threats to our environment, security, and quality of life.

The following examples of progress in the areas of materials science, chemical sciences, biotechnology, environmental and ecological sciences, geosciences, nuclear sciences, and computational sciences could offer vastly improved or completely new technologies for reducing GHG emissions. We have already seen the pull of technology in Chap. 2; here is the push of basic science and its promise for the future.

3.2.1 Materials Science

Improvements in materials can significantly impact the production of GHGs and wastes. Materials found in systems that produce energy (e.g., combustors and turbines), store energy (e.g., batteries and fuel cells), and use energy (e.g., vehicles and industrial/chemical processing) can improve system efficiencies, extend component lifetimes, and increase performance or capacity (Fig. 3.1). Furthermore, the production and processing of materials consumes the largest fraction of the energy used by U.S. industry. Reducing the energy required to supply materials is essential to reducing GHG production.

Basic research into materials synthesis and processing is needed to provide new ways to produce the materials currently used and enable the creation of new materials for energy systems. Areas in which breakthroughs are needed include nonequilibrium thermodynamics, microstructure-properties characterization, interface science, optical and electronic property optimization, and computational modeling of materials processes. Examples of potential near-term improvements include high-temperature-tolerant materials that allow improvements in the efficiency of combustion processes, heterogeneous catalysts that increase yields and selectivity, high-temperature superconductors to reduce energy losses in electrical systems, lightweight materials to decrease vehicle weight, improved magnets for sensors and motors, improved coatings and surface treatments to reduce wear and surface degradation, improved insulation to reduce heat loss, and miniaturization of equipment to improve efficiency and reduce cost.

Interdisciplinary theoretical and experimental research in condensed

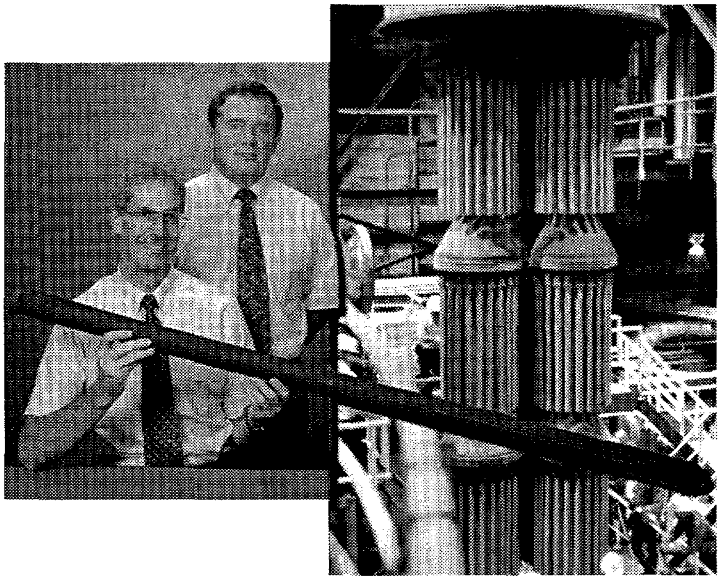

Fig. 3.1. Ceramic composite hot gas candle filters can be used to remove particulates from gas streams in combined cycle fossil and biomass power facilities. The filter is made up of an oxide fiber structure into which silicon carbide is deposited by a chemical vapor infiltration process.

matter physics, metallurgy, bioscience, and materials chemistry are key components of a long-term research strategy. For example, cross-disciplinary efforts are needed to develop bio-inorganic composite materials systems or "smart" materials that are self-constructing or self-adapting. Interdisciplinary biological and materials research is needed to create biomimetic materials—materials patterned after nature. The development of materials engineered at the nano-scale requires the merger of materials science and condensed matter physics; the result will be opto-electronic, organic-electronic, thin film, and semiconductor materials for use in energy generation and distribution (e.g., solar cells, sensors in power plants, and power grid control circuits) and in energy-efficiency applications (e.g., engine sensors and processors, solid-state lighting and displays, advanced windows).

3.2.2 Chemical Sciences

Chemistry is central to the design and synthesis of a wide range of useful materials, as well as to the conversion of energy into heat, work, and light. Advances in the chemical sciences in key areas of separations, catalysis, and combustion are necessary for significant GHG reductions.

Separation processes are used to purify raw materials, separate by-products, and remove contaminants. The membrane materials market alone is currently $1 billion. Improved separation techniques using membranes, novel separating agents, or hybrid processes could make many industrial processes more efficient while enhancing productivity and reducing environmental impacts. For example, distillation, which consumes more than 40% of the energy used in chemicals and petroleum manufacturing, seldom exceeds a thermodynamic efficiency of 10%. It would benefit greatly from improved separations technology. Other industries, such as microelectronics, require new standards in separation performance to improve the purity of the components and materials used. Adsorption and ion exchange processes are attractive for removing and recovering materials from dilute systems. Pharmaceuticals, biotechnology, food processing, and pulp and paper processing use separation technologies for product preparation or waste recovery and reuse. Waste treatment and recovery constitute another potentially large market for membrane and adsorption or ion exchange systems.

Catalysts and catalytic processes account for nearly 20% of the U.S. gross domestic product and nearly 20% of consumer products. Improved catalysts could increase efficiency to shrink energy requirements, while increasing product selectivity and thereby decreasing wastes and emissions. New catalytic processes could also reduce GHG emissions in alternative fuel resources, electricity production, transportation, and carbon sequestration. Several studies (e.g., the Council on Chemical Research's Vision 2020 document) have cited critical areas for innovation in catalysis including

- the development of theoretical and experimental tools to improve understanding of catalytic processes at the molecular level, and to enhance predictive capabilities and the ability to design catalysts and develop industrial catalytic processes to increase yield, selectivity, and reliability
- methods to improve the speed of catalyst discovery

- novel reactors and reaction engineering including reactive separation concepts
- low-temperature selective oxidation of fuel-value feedstocks to high-value chemicals
- conversion of gases (e.g., methane) to liquid fuels and chemical feedstocks
- novel methods for producing recyclable polymers and other materials with specific designed properties
- new catalyst systems for achieving high regio- and/or stereo-selectivity, including supported catalysts
- biomimetic synthesis of chemicals and materials,
- fuel cells for cogeneration of chemicals and energy
- new, more economical abatement technologies
- on-line monitoring and in situ catalyst characterization technologies

Combustion is employed in the conversion of 90% of primary energy to end uses in the United States. It powers practically all electric power and provides most heating and process heating (either directly or indirectly, by electricity). Key R&D needs include improved basic understanding and advanced analysis of combustion processes; nonintrusive (e.g., laser and microwave) diagnostics to improve understanding of the chemical, heat transfer, and fluid mechanics relationships that characterize combustion processes; understanding of processes that control flame shape and stability under different conditions; and flame chemistry to control emissions.

3.2.3 Biotechnology

Biotechnology as a crosscutting technology affects four of the nine major technology impact areas shown in Table 3.1: industry, agriculture/forestry, renewables, and carbon sequestration. However, under the broad realm of biotechnology as it applies to reducing carbon emissions, the status of research and technology-development efforts varies greatly.

The range of technological areas where biotechnology could have an impact on GHG/global carbon cycle issues is broad and includes crop improvement (including energy crops), alternative fuels other than biomass (noncellulosic), carbon cycle manipulation/sequestration, bioprocessing for fuels and chemicals, and biological/biochemical hydrogen production. Energy crop production and efficiencies in the agriculture and forest products sectors will result from advances in genetics and cropping systems. In addition to biomass energy crops, biotechnological approaches offer promise for production of other alternative fuels, including oils/lipids from algae and certain higher plants, and hydrogen from photosynthesis or enzymatic conversion of cellulosic biomass. The recent discovery of a one-photon photosynthesis system and protein engineering of the carboxylase/decarboxylase pathway offers the promise of increases in the efficiencies of carbon fixation by plants.

Fundamental studies of global carbon cycles and the importance of the biosphere as a major sink could lead to major breakthroughs in deploying biological phenomena in strategies to sequester CO_2. Bioprocessing of cellulosic biomass into alternative fuels is necessary in order to realize the full value of biomass-based energy. In addition, cells and enzymes are capable of synthesizing many organic chemicals of industrial interest. Because of mild reaction conditions, unique specificity, and selectivity, biocatalytic conversions are now being considered for many industrial uses. Organic-phase bioprocessing, a particularly promising application, employs microorganisms and enzymes in nonaqueous media such as organic liquids, gases, or supercritical fluids. This technique could provide alternatives for processing fossil fuels, synthesizing organic chemicals, and converting alternative feedstocks to fuels and chemicals.

3.2.4 Geosciences

The geosciences play a central role in understanding and mitigating the impacts of carbon emissions. A better understanding of the terrestrial, atmospheric, and ocean carbon cycles—and the interactions among them—will lead to new ideas for managing excess carbon and provide the foundation for comparing alternative technologies that could contribute to carbon emissions reductions. Moreover, evaluating the feasibility of most of the mitigation technologies under consideration today will require new knowledge in such disciplines as geophysics, flow and transport, geomechanics and geochemistry. For example, the geosciences are critical for developing or enhancing technologies to inject CO_2 into oil reservoirs, aquifers, and the deep oceans; increasing production of clean fuels such as natural gas; tapping into the huge natural gas supplies found in methane hydrates; and enhancing the natural carbon cycle to capture and sequester more carbon. In addition, closing the nuclear fuel cycle through geologic disposal of nuclear waste is critical to the widespread future use of nuclear power generation.

A fundamental research program in the geosciences would include studies of transport phenomena and the movement of fluids, the kinetics of geochemical systems, and the modeling of complex interactive systems.

3.2.5 Environmental and Ecological Sciences

Ecological and environmental sciences provide the fundamental knowledge of the structure and function of ecosystems (carbon and nutrient cycling) and, therefore, understanding of the responses of ecosystems to the effects of increased GHG emissions. Ecological science is fundamental to quantify the role of the world's ecosystems as net carbon sources or sinks, and to predict ecosystem response to future climate change events and/or carbon mitigation strategies.

Key research goals in ecological and environmental science include

- quantifying current carbon sequestration potential in both managed and unmanaged ecosystems, including soils
- understanding the response of ecosystems to increased atmospheric concentrations of CO_2
- understanding how future changes in climate variables will affect ecosystems and their role in carbon cycling
- developing carbon cycle models to predict future carbon sequestration
- understanding how land use changes and land management options affect carbon storage and exchange
- developing biological productivity potentials to offset fossil fuel usage with biomass energy

3.2.6 Nuclear Sciences

From the birth of nuclear power to the present, the United States has been the technological and policy leader. U.S. technology has been exported and adapted for use throughout the world. U.S. nuclear plant technology is among the safest and most reliable of nuclear technologies available worldwide.

Nuclear science and engineering is a discipline that is rapidly disappearing in the United States. If the United States is to maintain nuclear fission as an option for its future energy generation and is committed to avoiding additional carbon emissions, then a vital nuclear science basic research program is essential. It is likely that nuclear power will continue to be developed globally, with or without U.S. technology.

Research on nucleonics, new fission reactor concepts, proliferation-resistant technologies, fusion and fission-fusion hybrids, hybrid accelerator-driven subcritical systems, advanced fuel cycle technologies, advanced component design, waste transmutation (both accelerator and reactor based) and fast neutron burning, and systems safety are all vital to a successful industry in the future and to U.S. viability in this important area. In addition, research reactors form a vital component in this system and in our national research and educational infrastructure. They are essential and critical to many national priorities in addition to reducing carbon emissions, such as health care, environmental science and education, and technology transfer. Perhaps the most important goal of nuclear science is to improve the acceptance—by the public and by industry—of nuclear energy as a safe, reliable, and cost-effective resource for a sustainable future.

3.2.7 Computational Sciences

Advanced energy technologies with low carbon emissions can benefit greatly from modern simulation technology, particularly in the areas of combustion modeling, airborne particulates, and global carbon cycle modeling. High-fidelity simulations of manufacturing and power generation operations and the distribution of gases resulting from internal combustion engines (Fig. 3.2) can be used to predict the behavior of pollutants in the atmosphere at scales ranging from a few rooms in a building all the way to global simulation of the buildup of GHGs. Process design and optimization using simulations including social and economic components can result in improved processes and reduced environmental impact, without the expense of trial-and-error experimental designs. These tools can aid development of advanced energy technologies by allowing advanced modeling and visualization

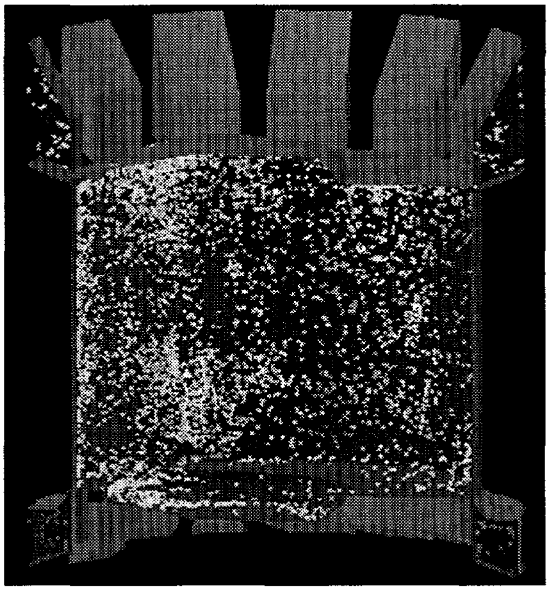

Fig. 3.2. This KIVA prototype 3-D simulation of an advanced diesel engine includes the regions where gas exchange and combustion occur. The simulation includes the flow of gases, heat transfer, combustion, and creation of pollutants.

where direct experimentation or prototyping is very expensive, inaccessible, or otherwise unfeasible.

Predictive modeling and simulation involves the use of the most advanced parallel computers—in speed, memory capacity, and I/O capability. By the year 2000, U.S. vendor systems will be capable of 10 thousand billion floating point operations per second. Advanced visualization and analysis techniques, including virtual reality, will be necessary for scientists and decision makers to understand the huge amounts of data generated by these simulations and to compare these simulations with observational and experimental data. Advanced network communications will allow the establishment of national and international collaborations, as well as enabling the remote operation of unique experimental facilities.

Effective use of this immense capability will require development of new mathematical models of relevant physical, biological, social, and economic processes; stable programming paradigms that support—over a decade or more—changing hardware capabilities; algorithms and computational techniques that can efficiently make use of parallel, distributed computing resources; software frameworks that allow rapid prototyping of new capabilities; and, perhaps most important, a verification and validation methodology that provides both qualitative and quantitative assurance of what can and cannot be predicted.

3.3 CROSSCUTTING TECHNOLOGIES SUPPORTING GREENHOUSE GAS REDUCTIONS

In addition to the broad portfolio of technological opportunities for reducing GHG emissions presented in Chap. 2, a number of technologies crosscut a wide range of applications, including those which impact U.S. carbon emissions. Advancing these enabling technologies integrates the pull of technology with the push of basic science.

This subsection presents four crosscutting technology areas: hydrogen and fuel cells; electrical transmission, distribution, and components; sensors and controls; and energy storage.

3.3.1 Hydrogen and Fuel Cells

Hydrogen is a carbon-free energy carrier that can be used to fuel every aspect of society. For example, it can fuel transportation vehicles (air and ground), provide process heat for industrial processes, supply domestic heating needs through cogeneration or

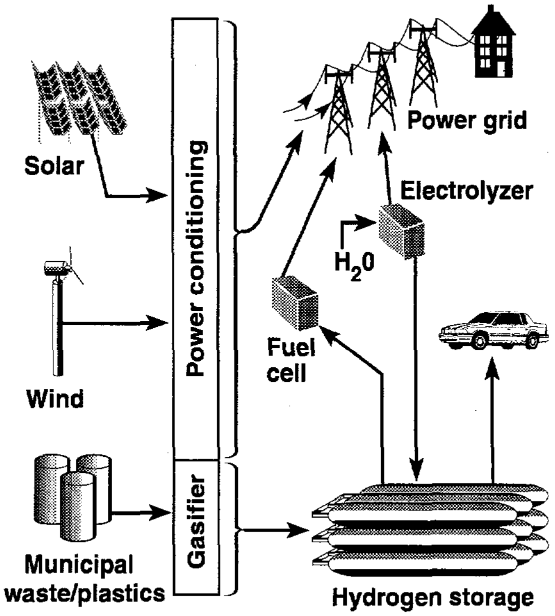

Fig. 3.3. Integrating utilities with the hydrogen transportation fuel system would enable greater penetration of renewables into the marketplace at a faster rate.

heat recovery systems, and fuel power plants for centralized or distributed electrical generation (Fig. 3.3). Hydrogen is an energy carrier that must be produced efficiently from a primary energy source. Depending on the source, its production may or may not involve CO_2 emissions. Hydrogen also burns cleanly and efficiently, an advantage that lowers the operating cost. Expanded production-related R&D is needed on biological, thermochemical, and electrochemical processes. Goals of the RD&D for production include a 10 ton/day process demonstration using municipal solid waste by 2000 and the development of advanced steam electrolysis, photobiological, and photoelectrochemical processes by 2010.

Hydrogen can be used in modified conventional combustion energy conversion devices (e.g., engines) to ease the transition to a completely new energy infrastructure where hydrogen will be used in fuel cells for energy conversion. Fuel cells promise potentially higher system efficiency and solid-state operation with water as the only effluent.

Lack of suitable hydrogen storage technologies is the greatest obstacle to its use as a transportation fuel. For 2000, the RD&D goals are to develop an automotive on-board hydrogen storage system capable of a 300 to 400 mile range and to demonstrate a fuel cell or hydrogen-powered internal combustion engine hybrid vehicle fleet with associated infrastructure. For 2010, the goals are to develop (1) advanced solid-state storage systems based upon such innovative materials as carbon fibers and structures and metal hydrides and (2) a conversion system for waste and biomass capable of producing hydrogen at a cost of $10/GJ (lower heat value of hydrogen).

Fuel cells convert chemical energy directly into electrical energy; no combustion is involved. They are significantly more efficient than other power-generation technologies or internal combustion engines operating on conventional fuels. Individual cells produce less than 1 V and are stacked in electrical series to produce higher voltages for utility, industrial, transportation, and residential use. Fuel cells span all important energy use sectors. Molten carbonate and phosphoric acid fuel cells target power generation, both large-scale and distributed power production. Solid-oxide fuel cells, which in stacks have recently reached the 100-kW size, are mostly considered for stationary application. Proton exchange membrane fuel cells target transportation as well as distributed power applications.

Key targets for R&D are materials and fabrication issues concerning the catalyst/electrode/membrane designs, as well as the cell stacking design. Future improvements in manufacturability will strive to reduce the currently high cost of fuel-cell fabrication to levels competitive with combustion devices.

3.3.2 Electrical Transmission, Distribution, and Components

Many proposed GHG reduction technologies involve alternative ways of producing electricity. In most cases, the U.S. electric transmission and distribution system is the means by which these alternative approaches will be made available to energy users. Almost 40% of the capital investment currently required to produce and deliver electricity goes to construct transmission and distribution facilities, and the availability of reasonably priced transmission capacity will be crucial in determining the commercial success of alternative generation strategies. This is particularly a concern for large-scale development of such remote resources as renewable generation, which could require significant investments in new transmission capacity because of the distances between the best resource areas and load centers. At the same time, public opposition to the construction of conventional transmission lines for environmental reasons has focused attention on opportunities for increasing the capacity of existing corridors, as well as on development of transmission technologies that are compatible with public concerns and therefore present a minimum of permitting risk. In addition, the importance of other collateral benefits of these technologies cannot be overlooked, especially their contribution to improving power quality.

R&D is needed on automated system control technologies that better use the capacity of existing systems, as well as advanced composite-reinforced high-strength overhead line conductors to increase the capacity of individual lines. Developments in power electronics—including wide-bandgap semiconductors for high-power switching devices and advanced converter designs—are needed to improve power management on existing systems and to enable high-voltage DC transmission for long-distance power transfers. Improvements in superconducting materials and associated refrigeration technologies will lead to development of superconducting cables and power transformers that offer half the energy losses and many times the capacity of conventional devices while taking up less space and reducing environmental impact.

While electrical transmission and distribution system improvements are essential to enable deployment of alternative electrical generating strategies, power system component development also offers significant opportunities to reduce GHG production. Energy losses in U.S. transmission and distribution systems were 7.2% in 1995, accounting for 2.5 quads of primary energy and 36.5 MtC of carbon emissions. Roughly 70% of these losses are due to the resistance of the conductors used on transmission and distribution lines, while 20% are in the distribution transformers used by utilities and commercial building owners to provide the last step of voltage reduction for customer equipment. In addition, the bulk of U.S. electricity production goes to drive motors—most commonly the ubiquitous polyphase induction motor, whose limited speed control reduces associated process efficiency by as much as 30%.

Research needed to improve the efficiency of power system components includes the development of superconducting generators, motors, and transmission cables, as well as low-cost methods for manufacturing amorphous metal materials for high-efficiency distribution transformers. R&D on advanced power electronic converters and controls for variable-speed motor drives, integrated with high-efficiency motors, could substantially improve industrial process efficiency and product quality.

3.3.3 Sensors and Controls

Sensors and controls will play a significant role in any technological advances for reducing CO_2 emissions and in CO_2 sequestration processes. Each primary area of clean energy production, energy efficiency, and carbon-cycle/carbon sequestration, will require sensors and controls technology for ensuring maximum efficiency at minimal cost.

R&D is needed to develop sensors that can improve the efficiency of primary energy production. For example, chemical sensors capable of operation in boreholes can improve fossil fuel recovery. Both refining processes and fossil fuel reforming for CO_2 sequestration require substantial chemical processing that can be enhanced through real-time process sensors and controls. Sensors and controls that more accurately measure operational parameters can be used to increase the output of nuclear power plants.

In the area of energy efficiency, transportation remains a major factor in energy consumption. Novel sensors are needed to enable the use of more efficient engine technologies. Almost all industrial processes depend on sensors and controls to ensure the quality of goods produced, and advanced sensors can help to reduce wasted energy and thus CO_2 emissions. In carbon cycle/carbon sequestration, innovative sensors for analyzing photochemical processes and carbon fixation are needed. They may also be required for efficient biomass energy production.

Often a single fundamental sensor technology will meet the needs of different applications, so sensors are a true crosscutting technology. The best example is the solid-state oxygen sensor developed for the space program in the 1960s. This sensor is now universally used in gasoline engine control and is common in industrial combustion control, touching virtually every major energy-consuming industry.

A large variety of novel sensor technologies that are robust, sensitive, cost-effective, and capable of supporting real-time control will be required in a successful climate change technology development program, as will commensurate methods of data analysis and fusion for control. Across the industrial arena, sensors are needed that can be used in harsh environments and that will measure such on-line process parameters as viscosity, moisture, chemical composition, density, flow, temperature, and pressure. Research is also needed in the development of multi-analyte sensors and in the integration of sensors and microtechnologies, such as microflow devices. Further RD&D is necessary in the development of "smart controllers" that couple a multitude of sensors and/or sensor arrays to sophisticated data analysis systems that can provide real-time on-line process control and improve process efficiencies.

3.3.4 Energy Storage

Stationary energy storage is now primarily in the form of bulk storage of fossil fuels (piles of coal, oil in tanks, gas in pipelines) and water in reservoirs. Reversible energy storage technologies in use today include pumped hydropower, compressed air, and chemical batteries for small uninterruptible power. Advanced storage technologies under active development include processes that are mechanical (flywheels, pneumatic), electrochemical (advanced batteries, reversible fuel cells, hydrogen), and purely electrical (ultracapacitors, superconducting magnetic storage). The major hurdle for all storage technologies is cost reduction.

In transportation, hybrid powertrains that use batteries, flywheels, or ultracapacitors in conjunction with engines allow the reduction of engine size. A hybrid powertrain can increase overall efficiency by up to 100% without a loss in vehicle performance (acceleration, range, and passenger capacity). When combined with other vehicle improvements, such as weight reductions, aerodynamic improvements, and rolling friction, this efficiency increase results in up to three times the equivalent mileage of current direct-drive automobiles, which is the current goal of the PNGV.

Key R&D needs for energy storage include developing

- new electrocatalysts, electrode materials, and structural materials for electrochemical systems
- higher specific-energy composite rotors, magnetic bearings, fail-safe designs, and lightweight containment for flywheels
- better corrosion-resistant materials for higher power-density batteries
- commercial high-temperature superconductors (operating at liquid nitrogen temperatures) for superconducting magnetic energy systems
- higher energy-density ultracapacitors for light-duty vehicles
- improved power conditioning systems.

The greatest value of advanced energy storage for electric utilities is that it can enable better use of intermittent renewable energy sources, such as solar PVs and wind, that produce no direct CO_2.

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4. TECHNOLOGY INNOVATION APPROACHES

4.1 INTRODUCTION

Previous chapters of this report identified a set of technology pathways that we believe offer the United States affordable options to reduce GHG emissions to sustainable levels. We have emphasized that R&D, both fundamental and applied, needs to be continued and/or initiated to advance the technologies identified within the pathways, thereby moving them closer to the goal of deployment in the marketplace. This section discusses three technology innovation approaches and presents several factors for consideration in deciding which approach to use to develop a particular technology. While each of the approaches provides a viable option, we believe that in most cases public–private strategic alliances are the best approach for developing and deploying these technologies.

4.2 APPROACHES

In this section, we evaluate the pros and cons of three approaches for advancing the RD&D of GHG reduction technologies. These approaches can be characterized as

- government led and financed
- industry led and financed
- public–private strategic alliances

Although we recommend public–private strategic alliances as the best approach for developing and deploying most of the technologies discussed in the technology pathways section, in some cases one of the other approaches may be more appropriate.

When selecting an approach to pursue the RD&D of a technology, we recommend the following factors be considered:

- national strategic value of the technology
- target market of the technology
- return on private-sector investment

A technology has *strategic value to the nation* when it provides a significant benefit to national security, economic well-being, environmental quality, and/or public health. National defense is the casebook example of high strategic value to the nation. Historically, the strategic value criterion has also been a justification for government support of technologies in the areas of space, health, energy, and agriculture.

The *target market* factor refers to the expected end-user or consumer of the technology. In some cases, a technology is developed for a specific target market or end-user (e.g., the federal government), and the technology has little application beyond that market. For example, technologies to process uranium have had little application beyond the nuclear industry. In other cases, a technology, such as the transistor, has applications in multiple markets and industries. Technologies that are applicable to a variety of markets and industry are sometimes referred to as "generic technologies" (Bloch 1991).

The third criterion refers to whether the private sector believes it can attain a large enough *return on its RD&D investment* within a reasonable time frame and at acceptable levels of risk to warrant supporting the innovation process. The complexity and the length of time needed to develop and deploy a technology are key variables considered by private industry when it is deciding whether to invest in a technology, because both factors can increase the risk of not receiving the expected return on investment. Of the three factors presented, expected return on investment is the key factor companies consider when deciding whether to invest in the development of a technology. Although this factor is of primary importance to the private sector, it is not necessarily mutually exclusive from the national strategic value criterion. In many cases, companies have led and financed the development of technologies that have underpinned the formation of industries with a high strategic value to the nation (e.g., computer software, drug, and automobile industries).

The following sections discuss the characteristics and relationship among the three approaches to technology innovation in an effort to provide selection criteria for determining the optimum approach to achieving the RD&D goals for individual technologies (Table 4.1).

4.2.1 Government Led and Financed Approach

The government typically leads and finances projects throughout the RD&D process when a technological innovation has a high strategic value to the nation, the public sector is the intended end-user of the technology, and the expected return on investment is too low to warrant the private sector's bearing the RD&D costs (Table 4.1). Examples of projects led and financed primarily by the federal government include the Manhattan Project, which

Table 4.1. Approaches to technological innovation

	National strategic value	Target market	Return on private sector investment
Government led and financed	High	Public sector	Low
Industry led and financed	Low-medium	Specific market	High
Public–private alliance	Medium-high	Multiple markets	Low-medium

developed the atomic bomb in World War II, and the Apollo Project, which put a man on the moon in 1969. Government led and financed projects have been very successful in meeting their goals when the conditions warrant government leadership and it has been able to focus the best resources of the nation on solving a problem with clearly defined technological goals and large public benefits and support.

The government led and financed approach could be applied to reducing GHGs, but it contains some inherent barriers to full effectiveness. In contrast to the examples given earlier, the government is not the primary target market for GHG reduction technologies, and there is no single technological solution to stabilizing atmospheric concentrations of CO_2. Therefore, significant GHG reductions will be achieved only if a number of technologies penetrate a broad spectrum of commercial target markets. In addition, some of the GHG technologies will have economic benefits in reduced fuel use, higher productivity, and reduced waste generation. Therefore, we expect the private-sector return on investment in the innovation process to be at a sufficiently high level for some of the technologies to warrant private-sector RD&D cost sharing.

4.2.2 Industry Led and Financed Approach

The private sector typically leads and finances projects throughout the RD&D process when a technological innovation has a high potential return on investment from specific commercial markets, regardless of its national strategic value. Historically, technological innovation leading to products for the commercial market has been primarily the responsibility of the private sector. Numerous examples exist of technology innovation led and financed primarily by industry, including plastics, pharmaceuticals, scientific instrumentation, information systems, and robotics. These technologies were driven by the demands of consumers in target markets, not by the federal government. Market-driven technology development is critical to continued economic growth because it enables companies, through the deployment of technological innovations, to profit by meeting the demands of consumers.

The strong relationship between technological development and quality of life in America in the twentieth century is a testament to the value of the industry led and financed approach to innovation. However, for this to be the primary approach for developing and deploying GHG reduction technologies, carbon mitigation would have to be highly valued in the marketplace to enable private companies to profit from their RD&D investments. Some technologies that result in GHG reduction may attract sufficient private-sector investment because they offer additional benefits that consumers are willing to pay for to amortize the RD&D costs and to provide adequate profits. However, short of policies that create a large economic incentive for reducing carbon emissions, industry is not likely to lead and finance RD&D on a broad spectrum of GHG reduction technologies.

4.2.3 Public–Private Strategic Alliances

Public–private alliances are typically established to share the costs of RD&D and deployment of technologies that have a strategic value to the nation and have value for multiple markets and industries, but do not promise sufficient return on investment to motivate the private sector to bear all the RD&D costs. Many of the technology pathways for reducing GHGs have these characteristics, making public–private strategic alliances the optimum approach for promoting their development and deployment.

The Clinton administration has been a strong advocate of forming partnerships to advance science and technology in America and has "forg[ed] a closer working partnership among industry, federal and state governments, workers and universities" (Clinton and Gore 1993, p.1). During the past decade, the process by which federally funded technology makes its way to the private sector for commercial use has improved substantially. In addition, the federal government is now working hand-in-hand with industry, combining resources to achieve common technology objectives (OSTP 1997).

Numerous examples of public–private alliances exist, such as SEMATECH, PNGV, IOF, the International Energy Agency Greenhouse Gas R&D Programme, the Clean Coal Technology program, the Advanced Light Water Reactor program, and PVMaT. In the case of PNGV, technologies to increase the fuel efficiency of automobiles have a *high strategic value to the nation* because they reduce our consumption of oil, thereby increasing our economic and national security, and mitigate GHG emissions, thereby reducing global warming and improving the quality of the air we breathe. In addition to being deployed in the automobile industry, many of the technologies being developed by the PNGV consortia are likely to be deployed in *multiple markets*. For example, one of the goals of PNGV is to increase fuel economy threefold. In order to meet this goal the vehicle weight must be reduced 40%; therefore, a significant portion of the steel and cast iron components in these vehicles must be replaced with aluminum and polymer composites. These new lightweight, high-strength materials will be deployed in other transportation markets (e.g., aircraft and rail), as well as multiple segments of our infrastructure (e.g., bridges, buildings, energy). Finally, although the technologies being developed by PNGV have a high strategic value, the *market return* on fuel efficiency investments is currently very small because the cost of gasoline in the United States has been decreasing at an average annual percentage rate of 1.8% (in constant dollars) since 1978.

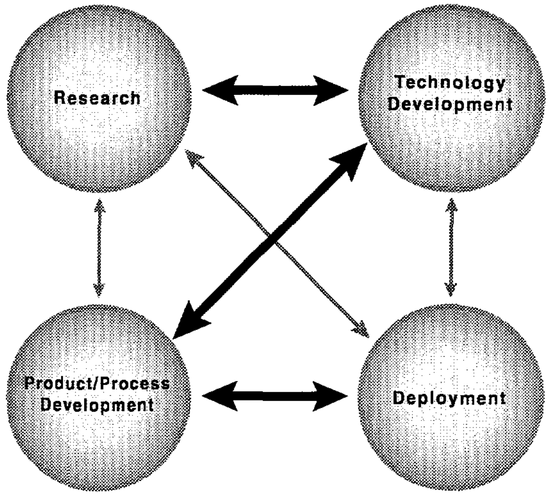
The combination of high strategic value, multiple target markets, and expected low return on investment makes public–private strategic alliances the optimal approach for developing and deploying GHG reduction technologies. This approach will allow sharing of costs and pooling of resources, thereby motivating private companies to invest in the technology even though the return on investment is likely to be low in the short term, and encouraging government agencies to support the RD&D process even though the public sector may not be the targeted end-user of the technology.

The interactive nature of the innovation process is another reason to use public–private alliances to develop and deploy GHG reduction technologies. It is now widely recognized (Kline 1991; OTA 1995; Branscomb et al. 1997; *R&D Magazine* 1997) that most complex technological innovations advance through a nonlinear, interactive innovation process (Fig. 4.1), in which there is synergy between scientific research, technology development, and deployment activities. The interactive process is a more effective model for developing and deploying technology than the linear model that depicts the innovation process as starting with basic scientific research and then advancing sequentially through the technology development and deployment phases (Fig. 4.2). This linear approach can take longer and can result in potential innovations being delayed or never making it to the marketplace. The interactive process has several advantages in that it provides the following:

- a continuous feedback loop for development and use of new scientific capabilities and facilities that can expedite the innovation cycle
- effective dialog between the research and user communities on innovation needs
- an effective basis for focusing research in the highest priority areas and evaluating progress along the technology pathways

4.3 STRATEGIC ALLIANCE ROLES

One of the major benefits of strategic alliances is that they help maximize the efficiency of the innovation process by bringing together an interdisciplinary team of scientists, engineers, and analysts (e.g., market, social, and financial) from industry, government laboratories, universities, and nongovernment organizations who can ensure that the scientific, technical, and commercial challenges that arise throughout the innovation process are successfully resolved. We recognize that there will be many stakeholders in a climate change technology strategy and that over the course of time, some of the technology pathways will dramatically restructure the nation's energy, buildings, industrial, and transportation sectors. International customers and suppliers will be concerned about their costs and their markets. The financial community, insurance industry, and standards organizations all have a stake in the process; the list is long. Their input will be important for formulating effective public–private alliances, monitoring progress toward GHG reductions, and sustaining interest in the climate change technology strategy over the decades that will be required to implement it.



The thicker lines indicate high degrees of interaction.

Fig. 4.1. Interactive model of innovation.

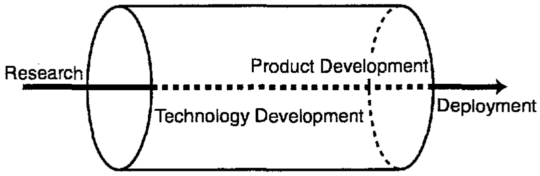


Fig. 4.2. Linear model of innovation.

In many respects, the whole is greater than the sum of its parts in strategic alliances, for while private companies, universities, federal laboratories, government organizations, and nongovernment organizations each have unique capabilities, a synergy results when their resources are applied strategically toward a common goal, such as developing technologies to reduce GHG emissions. For example,

- Private companies and industrial consortia, such as the Electric Power

Research Institute and the Gas Research Institute, play a key role in the innovation process by identifying requirements for technologies that help ensure their commercial viability, by performing R&D in collaboration with federal laboratories and universities, and eventually by demonstrating and deploying the technologies.
- Government laboratories and nongovernment research organizations provide scientific staff who have conducted and managed research for more than 50 years. These laboratories have conducted much of the research that provides the scientific underpinning for many technological breakthroughs. This scientific resource can provide new approaches to reducing emissions in the future. The national laboratories also provide unique facilities for use by researchers from industry and academia, as well as by their own researchers, in the development of these technologies.
- Universities provide a wealth of scientific talent to undertake the scientific research required to understand the role of GHGs in global climate change and to understand the basic mechanisms of biological and chemical processes that might be used to reduce GHG emissions. The linking of science and technology in the interactive process of innovation makes the scientific resources of universities and laboratories critical throughout the innovation process. In addition to providing scientific resources, universities are the training ground for future scientists and engineers needed for a sustained national effort to minimize the effect of GHGs on climate change.

Along with private companies, federal laboratories, and universities, it is important that government agencies, international organizations, and other nongovernmental organizations that are stakeholders in global climate change have a role in strategic alliances.

- Government agencies at the federal, state, and local levels contribute financial resources that are critical for advances in scientific research and basic technologies, as well as legislative mechanisms that can play an important role in removing barriers to the deployment of climate change technologies. In addition, government institutions can help educate the American public about climate change and can provide a forum for stakeholders to express their views on this subject.
- Climate change is a global issue, and international collaborative RD&D efforts will be needed. Japan has recently announced a national program to support international R&D on technologies to mitigate global climate change and pollution. Other efforts involving the U.S. federal government and U.S. companies are under way (e.g., the International Energy Agency Greenhouse Gas R&D Programme).
- Nongovernment organizations, including end-users, environmental organizations, financial institutions, and other interest groups, possess expertise that can be valuable to scientists, engineers, and market analysts as they work to better understand climate change and market issues.

4.4 CONCLUSION

Three specific approaches for implementing RD&D and deployment activities on GHG technologies are considered: (1) government led and financed, (2) industry led and financed, and (3) public–private strategic alliances. In selecting an implementation approach, we encourage the consideration of three factors: strategic value to the nation, target market, and expected return on private-sector investment. A systematic assessment of the relationship between the technology being developed and the three implementation approaches will allow selection of the optimum approach.

For most of the GHG emission reduction technologies discussed in this report, we believe that the public–private strategic alliance approach is the best choice. Although many of these technologies will be able to compete cost-effectively in the marketplace in the future, industry may not be willing to lead and finance the innovation process for many of these technologies because of the high risk associated with developing technologies that will not be deployed for decades and because the market currently does not place a high value on carbon mitigation. Additional factors favoring public–private strategic alliances include the *interactive nature* of the innovation process and the need to develop and deploy a variety of technologies in a number of target markets to reduce GHG emissions significantly. A public–private alliance will enhance the efficiency of the innovation process by bringing together stakeholders who can meet the scientific, technical, and commercial challenges involved in developing and deploying the required technologies. In this context, institutional efforts, such as collaborative RD&D enterprises, that help bring together industries, government laboratories, universities, government agencies, and nongovernment organizations to focus on common technological issues will be of great value in fostering the development of public–private alliances.

While public–private strategic alliances are only one part of the nation's climate change technology strategy, we feel they are a vital element if we hope to efficiently and effectively develop and deploy the GHG reduction technologies discussed in this report.

4.5 REFERENCES

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5. SYNTHESIS AND MOVING FORWARD

5.1 SYNTHESIS

In this report to Secretary of Energy Peña, the directors of 11 DOE national laboratories conclude that

1. Advances in science and technology are necessary to reduce GHG emissions from the United States while sustaining economic growth and providing collateral benefits to the nation.
2. Success will require the pursuit of multiple technology pathways, providing choices and flexibility for reducing GHG emissions.

One cost-effective strategy for reducing long-term GHG emissions while continuing economic growth is to develop and deploy a portfolio of new and improved technologies (as described in Chapter 2). Successful development of these technologies would require advances in many fields of basic science (as described in Chapter 3) along with strong public–private strategic alliances (as described in Chapter 4). Rapid and widespread deployment may also require the development and implementation of supportive programs and policies. The features of such programs and policies are not specified in this report.

5.1.1 The RD&D Path to Carbon Stabilization

Chapter 2 described the broad menu of technology pathways that could significantly reduce U.S. carbon emissions over the next three decades. If a vigorous, accelerated RD&D program were pursued, these pathways would enable the transformation of our nation's energy system. Given the breadth of technology options, this transformation could take place in an orderly fashion. Industry and consumers would be able to recover their investments in the nation's current energy infrastructure, while new energy and carbon sequestration technologies were gradually absorbed, as they became profitable, through the normal process of capital stock turnover.

By offering a technology-based, evolutionary—not revolutionary—path to a sustainable energy future, this report outlines the possibility of a transition that could be profitable to a wide array of potential constituents.

Over a 30-year planning horizon, implementing a climate change technology strategy could quickly expand the portfolio of options available for reducing U.S. GHG emissions. The three decades of this planning horizon appear to be distinct in terms of the dominant climate change technology opportunities.

- In the first decade, significant advances in energy efficiency technologies would reduce carbon emissions substantially by reducing the energy intensity (E/GDP) of the U.S. economy. Based on the five-laboratory study, the increased use of these technologies could offer energy-savings benefits that exceed their implementation costs (Interlaboratory Working Group 1997). Clean energy technologies would continue to gain market share, and carbon sequestration technologies could begin to emerge.
- Along with continued improvements in energy efficiency, research-based advances in clean energy technologies would begin to reduce the carbon intensity (C/E) of the U.S. energy economy significantly during the second decade. A wide range of renewable, fossil, and nuclear technologies could be introduced and widely deployed in this period. These clean energy options could begin to overshadow the impact of increased end-use efficiencies by the year 2030.
- Complementing ongoing advances in clean energy and efficiency technologies well into the third decade, carbon sequestration technologies would add a third important dimension to the package of solutions. We assume that these would not be widely available until the 2020 to 2030 time frame; however, successful introduction earlier could result in significantly greater reductions in carbon emissions. Success in this technology area could enable the nation to continue its extensive use of fossil fuels without changing the climate.

This technological progression can be seen in Table 5.1, which summarizes the carbon reduction estimates of each of the nine technology areas described in Chapter 2. Estimates of carbon-saving potential are difficult because of the many factors that can affect the performance and market penetration of a new technology. Consistent with these uncertainties, the values shown in Table 5.1 are provided in five ranges from low to high.

These estimates of carbon reduction potential were made relative to the *Annual Energy Outlook 1998* reference (business-as-usual) case (EIA 1997). They assume an accelerated federal RD&D program and a continuation of current federal programs and policies. The estimates do not presume the creation of any new incentives. The carbon reduction estimates were made individually for each technology area; competition between technologies and other effects of one technology on the success of another were not fully considered.

Because of the uncertainties associated with the carbon impacts of each pathway and the complexities associated with aggregation across pathways, our estimate of the combined potential effects of all of the pathways has a wide range. In total, it is estimated that an accelerated RD&D effort could provide advanced technologies with the potential to reduce U.S. carbon emissions by 400

Table 5.1. Potential reduction of U.S. carbon dioxide emissions from nine technology areas
(in MtC)*

	2010	2020	2030
Energy efficiency			
Buildings	L/M	M/H	H
Industry	L/M	M/H	H
Transportation	M	H	H
Agriculture and forestry	L	L	L/M
Clean energy			
Fossil resource development	L	M/H	H
Fossil power generation	L	M	H
Nuclear energy[a]	L	M	H
Renewables	L/M	H	H
Carbon sequestration	NA	NA	NA

*Assumes successful technology development and subsequent marketplace adoption without significant policy changes. Greater impacts could be expected with the addition of vigorous new policies and deployment programs, particularly in early years when the market penetration of existing and near-term technologies could be accelerated.

L = 0–25 MtC, L/M = 25–50 MtC, M = 50–75 MtC, M/H = 75–100 MtC, and H = 100+ MtC. Shaded areas show significant additions to the technology routes to reducing greenhouse gases. NA = Not applicable because the carbon reductions require policy changes.

[a] The 2020 and 2030 estimates for nuclear energy (M and H, respectively) are relative to an adjusted reference case forecast, which takes into account the large capacity of nuclear power scheduled for retirement after 2010. By extending the operation of one-third to one-half of these plants, significant carbon emissions can be avoided.

to 800 MtC/year in the year 2030. This represents a significant portion of the carbon emission reductions that may be targeted by the United States for 2030.

Table 5.1 and the discussions of each pathway in Chapter 2 also indicate that no single area or pathway can deliver sufficient GHG emission reductions; success will require pursuit of multiple technology pathways. The lower range of the estimated impact (400 MtC per year) could result from major technological advances and market success in several of the pathways. Achieving the upper range (800 MtC per year) would require technological breakthroughs and market success in a wider spectrum of pathways. This higher, more optimistic range is viewed as unlikely without also strengthening the policies and deployment programs that exist today. We did not attempt to quantify the potential reductions from a combination of accelerated RD&D and more vigorous deployment programs, policies, and financial incentives. However, it is believed that such a combination could drive U.S. carbon emissions down much further than the 400 to 800 MtC range described in this report.

This report's estimates of carbon reduction potential are quite modest compared with the estimates produced by many other studies. The smaller overall impacts estimated by this report are due primarily to our focus on the potential of accelerated RD&D within the context of today's policies and programs. Additional reductions would result from the implementation of new policies and deployment programs, particularly in early years when the market penetration of existing and near-term technologies could be accelerated.

The 1991 report by the Office of Technology Assessment titled *Changing by Degrees* (OTA 1991) analyzed the potential for energy efficiency to reduce carbon emissions by the year 2015, starting with the base year of 1987. Its "moderate" scenario results in a 15% rise in carbon emissions, from 1300 MtC/year of carbon in 1987 to 1500 MtC/year of carbon in 2015 (compared with a business-as-usual forecast of 1900 MtC/year). Its "tough" scenario results in a 20% to 35% reduction in emissions relative to 1987 levels, or emissions levels of 850 to 1000 MtC/year of carbon in 2015.

Scenarios of U.S. Carbon Reductions by the Interlaboratory Working Group (1997) modeled three scenarios of carbon emissions in the year 2010 based on an array of assumptions about increased RD&D efforts, supporting policies, and deployment programs (see Chapter 1 for further details). The results were carbon reduction estimates of 120, 230, and 390 MtC in the year 2010. The most aggressive scenario reduces carbon emissions in 2010 to their levels in 1990 and reduces energy consumption in 2010 to 1997 levels.

Energy Innovations (1997) provides a third point of comparison. It estimates the levels of carbon emissions that are possible in 2010 and 2030 as the result of vigorous RD&D, deployment, and policies. It estimates that by 2010, carbon emissions could drop to a level that is 10% below emissions in 1990. By 2030, it suggests, carbon emissions could possibly be reduced to 728 MtC per year, which is almost half of the 1990 benchmark and well below the estimates provided in this report.

A fourth study by the National Academy of Sciences (NAS), *Policy Implications of Greenhouse Warming* (1992), identified a set of energy conservation technologies that would have either a positive economic return or a cost of less than $2.50 per tonne of carbon. Altogether, NAS concluded that these technologies offer the potential to reduce carbon emissions by 463 million tonnes, with more than half of the reductions arising from cost-effective investments in building energy efficiency. The NAS study characterized the current technological potential available at the time; thus it did not take into account stock turnover rates and other factors that prevent the instantaneous, full market penetration of technologies. Nor did it describe the role of RD&D in expanding future technology opportunities.

5.1.2 Factors Influencing GHG Reduction Potential

Many factors influence the ability of technology development efforts to reduce future U.S. GHG emissions. These include the magnitude of available R&D resources, technological risk, market size, stock turnover rates, and public acceptance issues. While this study has not attempted to analyze the effects of all of these various factors, it has compiled a considerable amount of information on them in its review of nearly 50 technology pathways. That information can be found in Appendix B, which includes a two-page description of each pathway that explains many of the factors.

Table 5.2 summarizes some of this information for technology areas grouped as energy efficiency, transportation fuels, electricity, and carbon sequestration. The table expands on the information in Table 5.1 in two ways. First, it includes information for those specific sectors and technologies that at this time appear to represent the largest potential carbon emission reductions over the 30-year planning period. For example, in the transportation sector, light-duty vehicles represent 58% of the CO_2 emissions in the transportation sector. Therefore, one entry in Table 5.2 summarizes information for the two technology pathways that address light-duty vehicles: (1) advanced conventional technologies for light-duty vehicles and (2) hybrid, battery-electric, and fuel cell vehicles.

Second, Table 5.2 provides information on several of the key factors that will influence future carbon emission reductions. This includes a column listing some of the significant issues or opportunities that will impede or enable the realization of potential carbon reductions. These issues and opportunities are selected from a more comprehensive accounting in Appendix B.

Altogether, Table 5.2 provides the reader with an indication of the most important results of this study in the form of the sectors and technologies that can play the largest role, as well as the factors and considerations that will determine their future contributions to GHG emission reductions.

The key factors that are used in Table 5.2 are defined as follows:

- Total market size: current total market in terms of carbon emissions (MtC/year) that is relevant to the technology
- Turnover rate: rate of retirement of the current stock of energy equipment or systems displaceable by this technology, with

  "Fast" corresponding to less than 10 years average lifetime
  "Moderate" corresponding to 11 to 20 years average lifetime
  "Slow" corresponding to greater than 20 years average lifetime

- Estimates of carbon emissions reductions: best estimate of the carbon emissions reductions (in MtC/year) that are likely to be achieved given this accelerated RD&D effort and continuing government deployment programs and policies. The estimates are based on the overall market size, the stock turnover rate, some consideration of the expected competitive position of the technology, and so on. For energy efficiency and clean energy technologies, the estimates assume no new fiscal incentives such as a carbon charge. See Sect. 2.1.2 for a more complete description of the study's assumptions. The entries are defined as follows:

  "High" corresponding to >100 MtC/year
  "Medium" corresponding to 50 to 100 MtC/year
  "Low" corresponding to 0 to 50 MtC/year

- Technological risk: subjective estimate of the risk that the technology will not be developed to the point that it can compete in its market as expected with

  "High" reflecting research that is still at the basic sciences level or involves complex systems integration
  "Moderate" reflecting research that is currently at both the basic research and technology prototype level
  "Low" reflecting development activities for technologies at the prototype or more advanced stage

- Significant issues or opportunities: illustrative major factors particularly noteworthy for this technology

Table 5.2. Potential reduction of U.S. carbon dioxide emissions from selected sectors and technology pathways*

Sector/area[a]	Technologies	Market size (MtC in 1995)[b]	Turnover rate	Estimated carbon emission reductions[c]			Technical risk	Significant issues and opportunities
				2010	2020	2030		
Efficiency—Buildings (1)		489	Mod	L/M	M/H	H	Lo	• minimal private sector R&D
	Building Equipment and Appliances (1.1)	489	Mod to Fast	L/M	L/M	L/M	Lo	• slow adoption of innovations • CFC ban accelerates chiller turnover
Efficiency—Industry (2)		463	Mod	L/M	M/H	H	Med	• short payback periods required
	Industrial Energy Conversion (2.1)	463	Mod	L	L/M	L/M	Med	• pollution prevention often saves energy
Efficiency—Transportation (3)		457	Mod	M	H	H	Med	• cost of lightweight materials
	Light-Duty Vehicles (includes trucks through class 6) (3.1 and 3.3)	265	Mod	L/M	M/H	H	Med to High	• consumer preference for power and size over high mpg
Transportation fuels (5.2 and 8.7)		457	Fast	L	L/M	L/M	Med	• distribution infrastructure barriers
	Biomass Fuels (8.7)	457	Fast	L	L/M	L/M	Med	• limited stocks at competitive prices
Electricity—Fossil (6)		494	Slow	L	M	H	Med	• large domestic coal resources
	Accelerated Development of High-Efficiency Power Generation (6.1)	494	Mod	L	L/M	M/H	Lo	
Electricity—Nuclear[d] (7)		494	Slow	L	M	H	Med	• public acceptance • nuclear waste storage
	Lifetime Extension and Generation Optimization (7.1)	113	Mod	L	L/M	M/H	Lo	• competition with natural gas

Table 5.2. (continued)

Sector/area[a]	Technologies	Market size (MtC in 1995)[b]	Turnover rate	Estimated carbon emission reductions[c]			Technical risk	Significant issues and opportunities
				2010	2020	2030		
Electricity—Renewables (8)		494	Slow	L/M	H	H	Med	• competition with natural gas • large domestic resources
	Biomass Electric (8.1)	494	Mod	L	L	L/M	Lo	• biomass resource limitations at competitive prices
	Wind and Photovoltaics (8.2, 8.4)	247	Slow	L	L/M	M	Med	• price penalty for intermittent power
Carbon Sequestration (9)		>6200	NA	NA	NA	NA	High	• small potential impact without regulations, incentives, or growth in markets for CO_2 • extends fossil fuel use
	Enhanced Carbon Cycle (4.3, 9.1, 9.4)	>6200	NA	NA	NA	NA	High	• ecological risk
	Capture and Sequestration (9.2, 9.3, 9.4, 9.5, 9.6)	1400	NA	NA	NA	NA	High	• stability of clathrates and and hydrates • diffusivity of CO_2 in the ocean • permanency

NA=not applicable because the carbon reductions require policy changes. The carbon sequestration pathways could enable the nation to continue its extensive use of fossil fuels without changing the climate.

*Assumes successful technology development and subsequent marketplace adoption without significant policy changes. Greater impacts could be expected with the addition of vigorous new policies and deployment programs, particularly in early years when the market penetration of existing and near-term technologies could be accelerated.

[a] Technology pathways identified in ( ) are cross-referenced to Table 2.1

[b] The technologies and sectors shown in this table overlap in terms of the carbon reductions they can deliver. For instance, decarbonization of the electricity sector through the introduction of clean energy technologies will reduce the potential carbon reductions from end-use sector efficiency technologies. As a result, it is not valid to simply add either the market size or the carbon reduction estimates.

[c] L=0–25 MtC, L/M=25–50 MtC, M=50–75 MtC, M/H=75–100, and H=100+ MtC. These estimates assume an enhanced federal RD&D program aimed at developing GHG reduction technologies. They do not presume the creation of any new financial incentives for reducing carbon emissions. The technologies covered in this table could deliver even greater GHG reductions if incentives, such as a carbon emissions trading program, or more vigorous deployment programs and policies, were implemented.

[d] Estimated carbon emission reductions are relative to the reference case in the *Annual Energy Outlook 1997* (EIA 1996), extended to 2020 and 2030 by *extrapolating current carbon emission growth rates. The exceptions are the 2020 and 2030 estimates for nuclear energy* (M and H, respectively). These are relative to an adjusted reference case forecast, which takes into account the large capacity of nuclear power scheduled for retirement after 2010.

The estimates of potential GHG reductions shown in Table 5.2 are consistent with the conclusions that were offered in conjunction with Table 5.1; that is, substantial reductions are available by 2030, and many technology areas can be contributing to these savings at that point.

Table 5.2 also shows that technology areas face different challenges, opportunities, and issues. Many of the technology issues can be addressed by the technology RD&D outlined in this report.

Technical risks are low to moderate in each of the energy efficiency areas and especially in the buildings sector. Counterbalancing this advantage in terms of delivering carbon impacts is the low level of private-sector R&D, the slow pace of adoption of innovations by builders, and the moderate rate of stock turnover in the buildings sector. The transportation and industrial sectors face generally moderate levels of technical risk. In transportation, economic risk is increased by consumer preferences for power and size over efficiency; and in industry, economic risk results from high discount rates that impede investments in efficient equipment.

Many of the clean energy options for generating electricity are threatened by the uncertainty of utility industry restructuring and competition with inexpensive natural gas combined-cycle technology. Nuclear power also has the additional institutional risks of a long-term waste repository solution and concerns over proliferation.

Carbon sequestration technologies face high technical risks because of the exploratory stage of their development. In addition, environmental and economic issues need to be resolved. However, these technologies hold the potential to extend the continued use of fossil fuel.

In most cases, risk can be reduced by technology and basic research programs that include analysis of economic and social consequences. Modeling tools and analyses are needed to complement the technology RD&D process to assess the potential acceptance of developmental technologies, identify likely concerns, and develop mechanisms to address those concerns. Such efforts to understand the social and economic risks are critical.

5.1.3 The Time-Line of Technology Products

Consistent with the notion of an orderly technology evolution, the products of a vigorous RD&D program to develop GHG reduction technologies could be adopted and implemented in time frames that mirror the typical pace of capital stock turnover. As a result, improvements in energy efficiency, clean energy, or carbon sequestration technologies would typically be available long before their impact on carbon emissions could be discerned. Thus, it is useful to forecast when different incremental improvements and breakthrough technologies will be available as cost-effective alternatives, recognizing that many years will typically be required before they are mature technologies.

Figures 5.1 and 5.2 present time lines of selected technology products. They illustrate the steady stream of important accomplishments that the vigorous RD&D program could produce. (Many more technology products are identified in Appendix B.) The technology products shown in these figures are consistent with the trend in carbon savings from energy efficiency gains in the first decade, to significant contributions by a variety of clean energy technologies in the second decade, followed by the emergence of carbon sequestration technologies in the third decade.

A second trend illustrated in these figures is the transition from the development of individual components to the emergence of novel, integrated systems. Over the next two decades, many components will be designed and engineered that can be woven into existing technology and capital infrastructures to improve their performance while reducing carbon emissions. Ultimately, these components will overhaul many of the systems that exist today. Such orderly sequencing of component development, with the ultimate goal of creating entirely new systems, can minimize the costs of capital displacement and economic disequilibrium. Two examples are provided below.

- The gasoline/electric hybrid vehicle (envisioned for development before 2005) is a precursor to the hydrogen fuel cell vehicle, which could be available by 2015. Following breakthroughs in hydrogen production, such as the manufacture of hydrogen from the solar conversion of water (perhaps by 2020), we envision a transformed transportation system by 2025 with a mature hydrogen supply infrastructure fueling multiple modes of transportation
- By 2010, we envision that biofuels could be cost-competitive with transportation fuels and that they could be distributed by the existing infrastructure of filling stations (worth hundreds of billions of dollars) with only modest modifications. By 2015, RD&D could enable the widespread production of chemicals from biomass feedstocks. Ultimately, 2030 could see a broad-based biomass industry with new crops, feedstocks, and distribution systems producing food, transportation fuels, chemicals, materials, and electricity, and possibly an entirely new distribution system at the wholesale and retail levels

The two examples illustrate the need for pursuing multiple technology pathways in critical areas (e.g., for alternative transportation fuels), because the success of any single pathway cannot be guaranteed. In addition, no single pathway appears able to deliver the amount of GHG reductions that may be needed.

Figures 5.1 and 5.2 portray a possible time line for the commercial introduction of new technology. The technologies themselves will endure much longer than the 30-year horizon indicates. They will become the legacy of the technology strategy that eventually is followed. With many of these technologies is an infrastructure and a whole economic system. Just as the introduction of the mass-produced Model-T Ford and the interstate highway system transformed transportation, these technologies will have comparable enduring effects.

Of course, RD&D programs by their very nature cannot guarantee that anticipated outcomes will result. Many technical and market risks prevent laudable efforts from producing successful technologies. However, there will also be important technological successes not foreseen at this time. If we invest in a portfolio of RD&D activities, historic data indicate that the winners will more than compensate for the cost of the failures (Brown 1997).

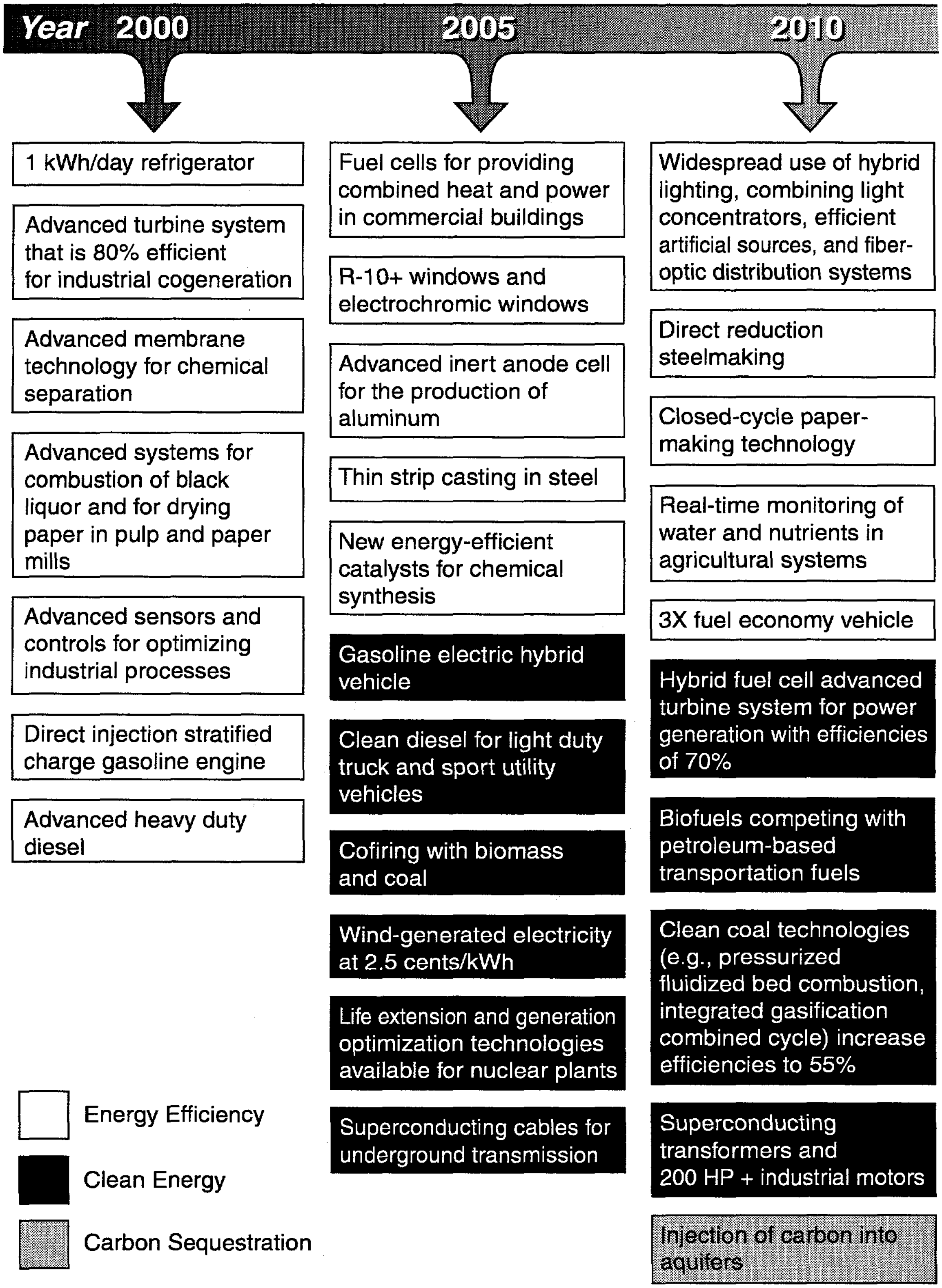

Fig. 5.1. Illustrative time-line of anticipated technology products: 2000–2010.

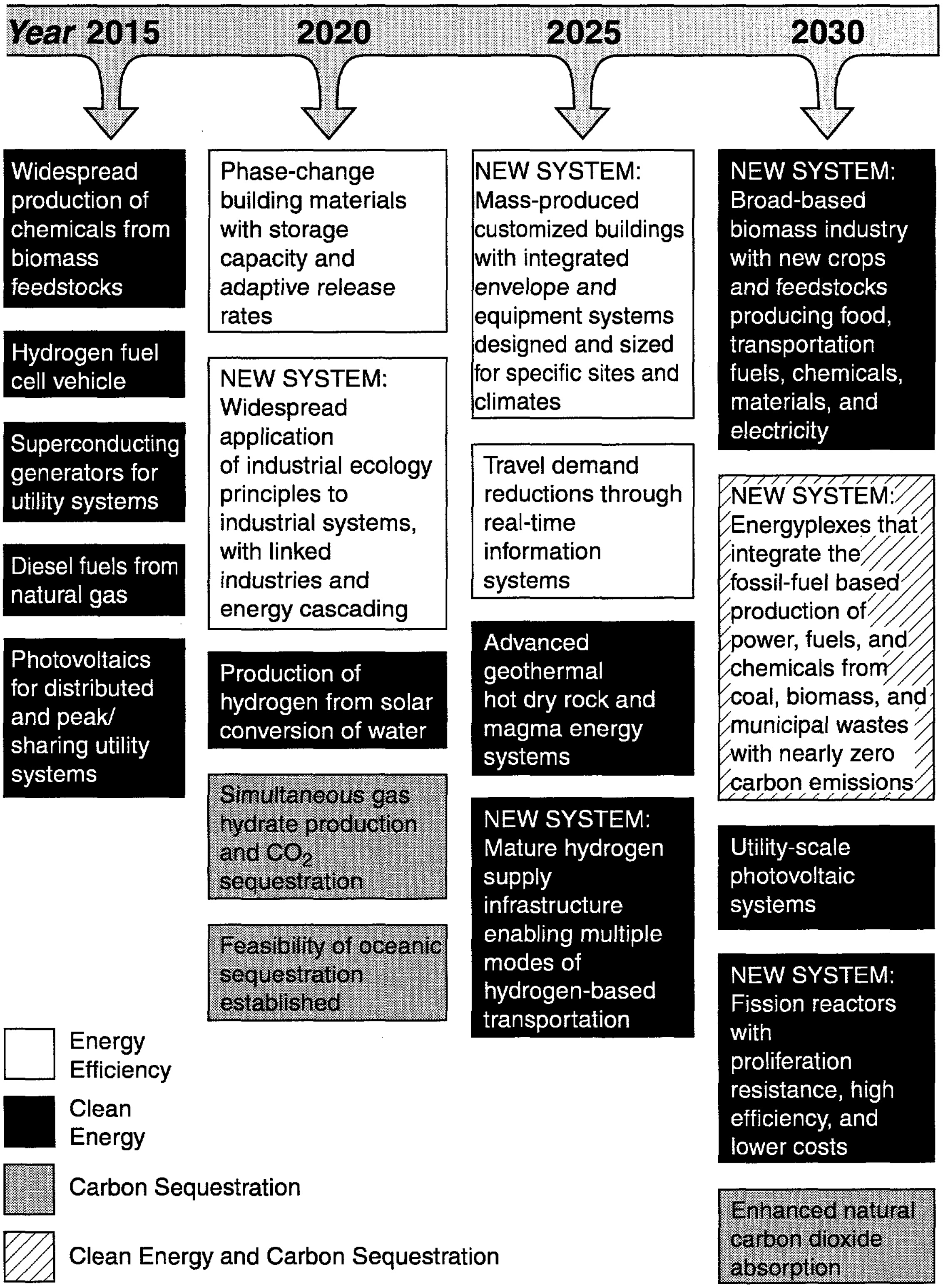

Fig. 5.2. Illustrative time-line of anticipated technology products: 2015–2030.

5.1.4 Performance Goals

Another way of viewing the products of the proposed technology pathways is by specifying performance goals they could achieve. These goals do not rely on particular technology developments; rather, they specify performance criteria that could be met by many alternative technologies. Recommended goals are presented, along with some of the technologies that could contribute to meeting them.

Energy Efficiency

- Use electricity more efficiently through the deployment of advanced technologies (e.g., intelligent building control systems, cost-effective refrigerators that use half as much electricity as today's models, and fuel cells for heat and power in commercial buildings).
- Reduce the use of gas and oil for space and water heating through building efficiency measures (e.g., super insulation, gas-fired heat pumps that provide highly efficient space heating and cooling, and building envelopes that capture and store solar energy for later use).
- Improve industrial resource recovery and use (e.g., develop an IGCC power technology, which can convert coal, biomass, and municipal wastes into power and products) and industrial processes to save energy (e.g., advanced catalysis and separations technologies).
- Increase transportation efficiency through new technologies (e.g., a hybrid electric vehicle that is three times more fuel efficient than today's standard model).

Clean Energy

- Change the energy mix to increase the use of sources with higher generating efficiencies and lower emissions—natural gas, safer and more efficient nuclear power plants, renewable energy (e.g., solar and wind power; electricity and fuels from agricultural biomass), and hydrogen (to produce electricity through fuel cells).
- Develop "energyplexes" that would use carbon efficiently without emitting GHGs for the integrated production of power, heat, fuels, and chemicals from coal, biomass, or municipal wastes.
- Distribute electricity more efficiently to reduce emissions (e.g., distributed generation using superconducting transformers, cables, and wires).
- Switch transportation to energy sources with lower emissions (e.g., trucks that run on biodiesel fuel; ethanol from cellulosic feedstocks).
- Remove carbon from fuels before combustion.

Carbon Sequestration

- Sequester CO_2 in large-capacity geological formations in deep oceans.
- Efficiently remove CO_2 from combustion emissions before they reach the atmosphere.
- Increase the rate at which oceans, forests, and soils naturally absorb atmospheric CO_2.
- Develop carbon storage technologies sufficient for geologic times.

5.1.5 Basic and Applied Research Are Needed

Meeting the goals described above also depends upon incremental improvements and breakthroughs in the basic sciences. These basic research needs include

- basic research to understand the global carbon cycle (i.e., computational modeling and

measurements to understand the ocean–atmosphere–terrestrial biosphere interactions) and judge the benefits and risks of sequestration options
- basic research supporting GHG reduction technologies (i.e., materials, chemical sciences, biotechnology, environmental and ecological sciences, geosciences, nuclear sciences, and computational sciences)

To support multiple technology pathways, enabling technologies also must be improved, especially those that enhance the utilization of energy carriers and systems. Relevant enabling technologies include

- hydrogen production/storage/distribution
- fuel cells
- electrical transmission, distribution, and components
- sensors and controls
- energy storage systems

5.1.6 Collateral Benefits and Costs

In addition to the benefits of GHG avoidance, the technology pathways described in this report could have significant secondary effects, as such pathways have in the past. For example, in the buildings area, there is a remarkable record of success in federally supported RD&D leading to products in the marketplace that have generated energy savings far exceeding their costs of development. In addition to reducing energy costs, the pathways would lead to improved environmental quality and public health, reduced U.S. dependence on imported oil, and increased exports of U.S. technologies to help other nations reduce GHG emissions, all of which will sustain economic growth.

The environmental and public health benefits of new and improved GHG reduction technologies could be very large. Clean energy options for generating electricity offer the prospect of significantly reducing air pollution. The development of efficient low-carbon transportation fuels would reduce pollutant emissions and abate ground-level ozone. Pollution prevention and waste minimization are important hallmarks of improved industrial process efficiencies. These collateral benefits would lead directly to major improvements in public health (Romm and Ervin 1996).

These environmental and public health benefits would not be limited to the United States. Better technology options would help to control the GHG emissions of other countries for many decades to come. They could also position the United States as the provider of choice for these new energy and environmental systems, with major economic growth consequences. The global energy market is estimated at $1 trillion, and the market for environmental technologies is estimated to be $400 billion. Renewable resources are widespread around the world, are highly attractive to developing countries, and represent a huge potential market for U.S. companies. An important collateral benefit of continued pursuit of nuclear power is the economic benefit of serving as an international supplier. The increased use of nuclear energy is foreseen around the developing world, especially in the Pacific Rim countries. The international market for ATSs and fuel cells is also likely to grow rapidly. Thus, implementation of a technology strategy would help to grow the U.S. economy by creating an energy technology export business.

The reductions in petroleum use that would result from the technology pathways would cut U.S. oil import dependence and could lower oil prices to consumers (Interlaboratory Working Group 1997, p. 5.47). It is estimated that efficiency improvements and alternative fuels in the transportation sector could result in reductions of one billion barrels per year by 2010.

Some of the pathways might also spawn significant collateral costs. For instance, increased nuclear waste might result in negative environmental repercussions, large-scale biomass production might cause soil and water contamination, and ocean fertilization might precipitate ecosystem damage. Regions that flourish in today's energy economy might be negatively impacted by shifts in the resource and labor requirements of new energy systems. The workplace requirements associated with advanced energy technologies might strain the nation's capacity to train and educate its labor force. History has shown that such challenges often can be managed. Further, if multiple pathways are pursued, those judged unacceptable can be set aside in favor of those that are preferred.

5.1.7 Research, Development, and Demonstration Resources

This report describes the carbon emission reductions that could result from an accelerated RD&D program. It does not consider collateral benefits from initiating complementary deployment programs or policies aimed at stimulating markets for GHG reduction technologies. It is believed that an integrated approach (i.e., science and technology in combination with deployment programs and supporting policies) is the most cost-effective one.

To achieve the annual emission reductions of 400 to 800 MtC by 2030 described in this report, absent any additional deployment or policy thrusts, federal RD&D budget increments would be necessary in three areas:

- The annual federal RD&D budget for the development of advanced energy technologies would need to grow to produce a sufficient number of the technological solutions.
- Additional resources are needed to initiate research into carbon sequestration technologies, which would also require supporting research on carbon cycle modeling, monitoring, and ecosystems.
- Supplemental RD&D support is needed to strengthen the basic research areas that are the wellspring of future technological breakthroughs.

The projects listed in Appendix B represent a catalog of promising technologies without prioritization. We believe that effective progress toward greenhouse gas emission reductions can be made with an additional RD&D investment of approximately $1B/year once priorities are established. Any budget decisions should be based on more detailed planning and analysis than was possible during development of this report. Initiation of that analysis and planning, which is a primary recommendation for moving forward, is discussed further in Sect. 5.2.

Actual budgets should be ramped up over several years in a way consistent with sound program development. Also, resource requirements for the outyears obviously would be affected by developments between now and then. Finally, it is anticipated that additional private-sector research effort would be leveraged by this federal increment.

5.2 MOVING FORWARD

This report identifies in general terms a set of future technologies that appear to hold great promise for reducing U.S. GHG emissions. By summarizing the status and potential of a broad range of technologies relevant to reducing GHG emissions, this report provides one key element, namely, the "technology basis," for developing a climate change technology strategy. However, full definition of such a strategy requires several additional steps, including

- an assessment of alternative programs and policies to promote deployment
- analysis of the costs and benefits of alternative technology and policy options to develop priorities
- development of technology goals and performance metrics for measuring progress
- identification of key players for pursuing these promising technology pathways
- estimation of budget requirements and appropriate allocation for each technology pathway
- mechanisms for ensuring strong ties between technology development activities and supporting basic sciences
- delineation of public- and private-sector responsibilities
- linkages to related ongoing activities in the United States and abroad
- a plan for managing the technology RD&D programs to be pursued over the years and decades ahead

The strong recommendation of this report is that the United States should develop and pursue a detailed and comprehensive climate change technology strategy.

Further, the planning process should begin immediately, and implementation of the strategy should occur quickly.

As the federal agency with the most involvement in the full range of technologies described in this report, the U.S. DOE should initiate and lead the planning required for implementation of this strategy. However, that planning effort must include significant participation from industry and business, the university community, Congress, and other federal agencies, as well as DOE and the national laboratories. Indeed, this planning should be a collaborative effort, just as is recommended for implementation of the technology RD&D programs.

While not all of the details of this planning and strategy implementation can be defined here, two clear needs should be explicitly addressed. The first is establishing a collaborative national planning effort to provide leadership and guidance to meet the RD&D challenges of a climate change technology strategy. The second is initiating an analysis activity to provide the information necessary for making sound decisions on the issues indicated. Both of these steps should be taken immediately.

Several other issues deserve immediate attention. One of these is the connection between developing promising technology pathways and designing policies to promote their deployment. There are many tradeoffs among how fast one pushes development, how much emphasis is placed on deployment of technologies that are ready to contribute to reduced emissions, and the timetable for achieving different reduced emission levels.

Another issue requiring study is the relationship between the implementation of promising technology pathways and the phenomenon of climate change, as well as the need for a better understanding of the phenomenon itself. This report strongly endorses the need to continue to improve our understanding of GHG emission levels, atmospheric concentrations of GHGs, climate change, and their impacts on our biosphere. A science-based understanding of the carbon cycle is essential as a framework for guiding our technology investments and ensuring their cost-effectiveness.

A third issue is consideration of the organizational structure of the technology RD&D programs. The recommendation to use strategic alliances recognizes the need to move away from the technology partnerships of the past. While there is no single organizational structure for creating strategic alliances, the traditional roles of users, industry, federal agencies, universities, states, national laboratories, and not-for-profit organizations may require redefinition as strategic alliances are formed to develop and deploy climate change technologies. Flexibility and adaptability in the structure of these partnerships is critical to the most effective pursuit of technology development programs to reduce GHG emissions.

A fourth issue is that of relating and coupling this domestic technology strategy with related international GHG emission reduction efforts. International collaboration can provide important domestic savings and global benefits.

Finally, it is important to understand the consequences of not developing and pursuing a technology strategy. Perhaps one of the greatest risks is underestimating the magnitude of the impact we are attempting to achieve. Energy is central to development and modern civilization. We are talking about transforming a national and global infrastructure that currently includes all of the things that support combustion as a means of energy generation. This is not a trivial matter. The generation of CO_2 is embedded deeply in the social infrastructure of this nation and is being embedded in the developing world right now.

The availability of advanced technologies on a timely basis to address future GHG emission reduction commitments requires initiation of the RD&D now and a commitment to following through on all the pathways that continue to show promise. Technologies not pursued are likely to result in lost opportunities to apply them to mitigating climate change, as well as a loss of their collateral benefits.

5.3 CONCLUSION

This report concludes that a national investment in a technology RD&D program over the next three decades would provide a portfolio of technologies that could significantly reduce GHG emissions well into the twenty-second century. Many technology opportunities exist that could accomplish this goal without harming the nation's economy. A strategic plan that includes deployment policies to complement technology R&D will be necessary for success. Hence, development of a climate change technology strategy is the recommended next step. Based on the conclusions of this report, the strategy should specify an approach that pursues multiple technology pathways, that emphasizes public–private strategic alliances, and that is designed in close coordination with supportive government policies and deployment programs.

By delivering a portfolio of highly promising technologies, a climate change technology strategy could produce savings and revenues that far exceed the cost of an accelerated research program. The bottom line: with the help of technology and appropriate government programs and policies, we can slow GHG emissions and grow the economy. DOE's national laboratories stand ready to champion this enterprise.

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Appendix A
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