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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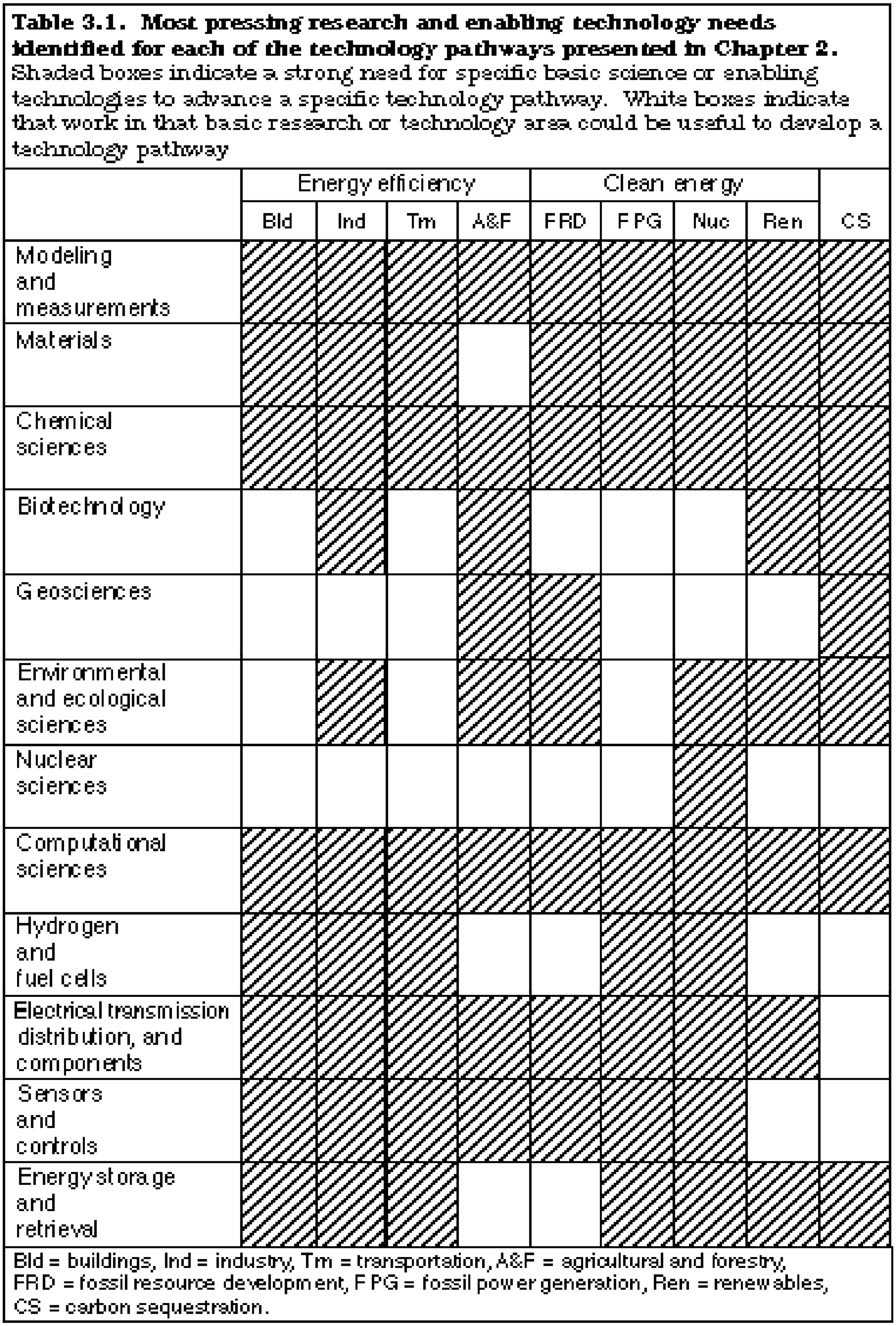

Table 3.1. Most pressing research and enabling technology needs identified for each of the technology pathways presented in Chapter 2. Shaded boxes indicate a strong need for specific basic science or enabling technologies to advance a specific technology pathway. White boxes indicate that work in that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

	Energy efficiency				Clean energy				
	Bld	Ind	Trn	A&F	FRD	FPG	Nuc	Ren	CS
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

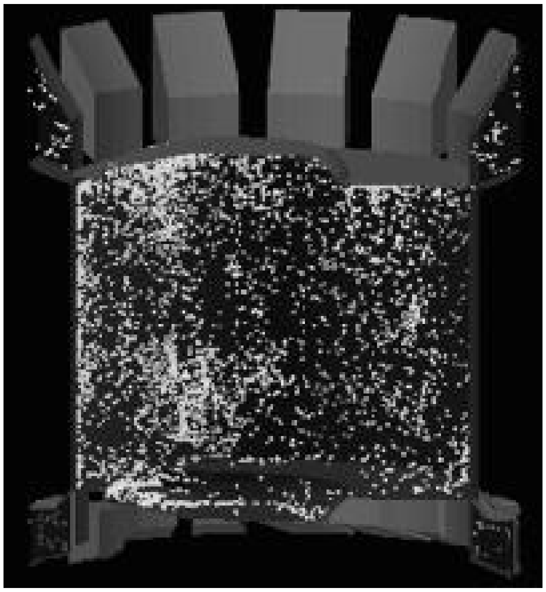

Fig. 3.2. This KIVA prototype 3-D simulation of an advanced diesel engine includes the regions where gas exchange and combustion occur. The simulation includes the flow of gases, heat transfer, combustion, and creation of pollutants.

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

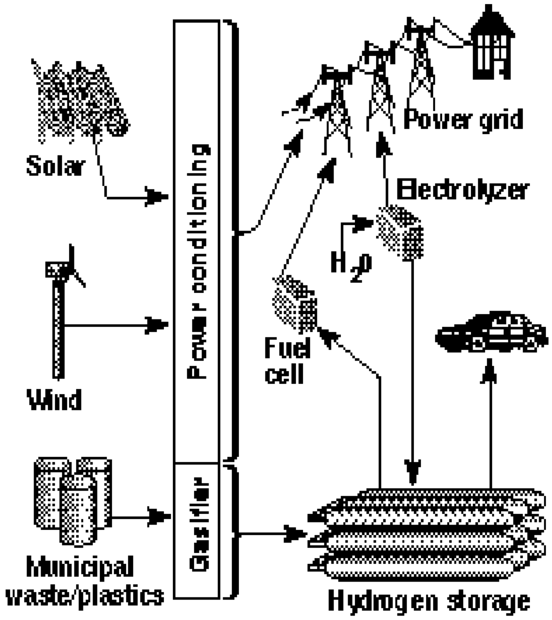

Fig. 3.3. Integrating utilities with the hydrogen transportation fuel system would enable greater penetration of renewables into the marketplace at a faster rate.

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.

3.4 REFERENCES

Carbon Management: Fundamental Research Needs Assessment 1997. (Draft), DOE-Office of Energy Research, August 6.

R&D Magazine 1997. ”Basic Research White Paper: Defining Our Path to the Future,” *R&D Magazine*, A. Cahners Publication, Des Plaines, Ill.

SEAB (Secretary of Energy Advisory Board) (D. Yergin, Chairman) 1995. *Energy R&D: Shaping Our Nation’s Future in a Competitive World* , U.S. Department of Energy, Washington, D.C.