

ASSESSMENT OF BASIC RESEARCH NEEDS FOR GREENHOUSE GAS CONTROL TECHNOLOGIES

S. M. Benson¹, W. Chandler², J. Edmonds², J. Houghton³, M. Levine¹,

L. Bates², H. Chum⁴, J. Dooley², D. Grether¹, J. Logan², G. Wiltsee⁶ and L. Wright⁵

¹Ernest Orlando Lawrence Berkeley National Laboratory, CA, ²Pacific Northwest National Laboratory, WA,

³Department of Energy, Office of Biological and Environmental Research, MD, ⁴National Renewable Energy Laboratory, CO, ⁵Oak Ridge National Laboratory, TN, and ⁶Apple Consultants, Inc., CA

ABSTRACT: This paper is an outgrowth of an effort undertaken by the Department of Energy's Office of Energy Research to assess the fundamental research needs to support a national program in carbon management (Benson et al, 1998). Five topics were identified as areas where carbon management strategies and technologies might be developed: (1) capture of carbon dioxide, decarbonization strategies, and carbon dioxide disposal and utilization; (2) hydrogen development and fuel cells; (3) enhancement of the natural carbon cycle; (4) biomass production and utilization; and (5) improvement of the efficiency of energy production, conversion, and utilization. Within each of these general areas, experts came together to identify targets of opportunity for fundamental research likely to lead to the development of mid- to long-term solutions for stabilizing or decreasing carbon dioxide and other greenhouse gases in the atmosphere. Basic research to support the options outlined above are far reaching—from understanding natural global processes such as the ocean and terrestrial carbon cycles to development of new materials and concepts for chemical separation. Examples of fundamental research needs are described in this paper.

KEY WORDS: Carbon capture and sequestration, natural carbon cycle, energy efficiency, biomass, hydrogen.

INTRODUCTION

This paper is an outgrowth of an effort undertaken by the Department of Energy's Office of Energy Research to assess the fundamental research needs to support a national program in carbon management (Benson et al, 1998). Carbon management, for the purpose of this assessment, includes:

- Decarbonization strategies, and carbon dioxide capture, transport, sequestration, and use
- Development of hydrogen and fuel cell technologies
- Enhancement of the natural carbon cycle to capture and sequester carbon
- Biomass production and utilization
- Improved efficiency of energy conversion and utilization

Fundamental research is needed to develop the scientific foundations for improving existing technologies and developing a new generation of technologies to moderate the atmospheric concentration of greenhouse gases. Research will also help increase understanding of the long-term impacts of intensive deployment of these technologies. Experts were brought together to identify targets of opportunity for research likely to lead to the development of mid- to long-term solutions for stabilizing or decreasing carbon dioxide and other greenhouse gases in the atmosphere.

DECARBONIZING FUELS

The goal of decarbonizing a carbonaceous feedstock is to convert the feedstock into two products before combustion—a mostly pure stream of CO₂ or C to be sequestered, and a low-carbon, hydrogen-rich fuel. There are two principal methods for decarbonizing feedstocks: (1) gasification by partial oxidation or indirect heating of the carbonaceous feedstock followed by a water-gas shift and separation of the CO₂ and H₂ streams; and (2) thermal decomposition of the carbonaceous fuel (most likely methane) to produce elemental carbon and H₂. The thermal decomposition process would eliminate the need to sequester CO₂ since the “waste product” from this process is elemental carbon—not gaseous CO₂. These and other decarbonization processes look promising, but many basic science questions remain:

- Can we achieve a major breakthrough in the cost and efficiency of gas separation technologies needed for a wide variety of carbonaceous fuel decarbonization processes?
- How can we develop a wide range of catalysts, including highly selective enzymatic catalysts and catalysts that are optimized for very short residence times, high throughput, and continuous processes? How can we build partial enzymes and lay them on an engineered substrate?
- Can we attain atomic-level understanding and predictive capabilities for designing materials for the high-temperature environments needed for carbonaceous fuels' thermal decomposition reactors?
- What are biological processes for decarbonizing carbonaceous feedstocks? Can methane-consuming bacteria (methanotrophs) and recently discovered “extremophile” organisms be engineered to ingest a feedstock like CH₄, sequester the CO₂, and give off H₂?

CAPTURE FROM FLUE GASES

The extraction of CO₂ from flue gases is technically feasible with existing technology, but its application increases the cost of busbar electricity by as much as 50 percent or more above current levels because large amounts of capital and energy are needed for the CO₂ removal systems. Therefore, a major research priority is to examine different system configurations that would jointly optimize power generation and CO₂ recovery. The basic science issues for CO₂ capture from flue gases are very similar to those listed in the decarbonization section above. However, for capture from flue gases, the concentrations of CO₂ would be significantly lower, and therefore some of the scientific challenges could be more daunting. Fundamental questions include:

- Can purpose-built chemical solvents be developed to react less (or not at all) with SO_x, NO_x and other impurities? Can solvent losses be reduced or methods developed to remove SO_x, NO_x and other impurities upstream?
- Can purpose-built selective membranes remove CO₂ from flue gases? Membranes are used commercially, for example in hydrogen separation, but can they be developed to be used on a significant scale for the capture of CO₂?
- Can we gain a better atomic and molecular-level understanding of and predictive capability for designing purpose-built catalysts? Can we apply this knowledge to the removal of CO₂ from flue gases?
- Are there inherently fewer energy intensive processes for fixing CO₂? How can the energy intensity of producing O₂ be reduced for use in oxygen-blown (as opposed to air-blown) gasification/combustion processes? Are there research opportunities to create highly efficient processes for the cryogenic distillation of oxygen, or for creating highly efficient ionic membranes for separating O₂ from air, or are there other processes for economically producing large quantities of O₂? Can cryogenic distillation of CO₂ for flue gas streams that have very high CO₂ concentrations become more efficient and less energy intensive?
- Can developments in corrosion science (surface physics and chemistry of oxide layers) result in better corrosion-resistant materials for high concentration solvent environments to extract CO₂ from flue gases?

CO₂ UTILIZATION

A high-purity stream of CO₂ from decarbonizing fossil fuels might have economic value as a raw material for new products and processes or as a replacement for existing feedstocks. Opportunities to utilize CO₂ have been identified in four major areas: (1) for enhanced oil, gas, and coalbed methane recovery; (2) to accelerate the growth of crops for food and for biofuels in hothouses; (3) as a feedstock for chemical products; and (4) as a building block for cleaner transportation fuels. By nearly all accounts, the amount of CO₂ that could be utilized is a small fraction of the world's annual emissions of freely vented CO₂. Therefore, absent a radical breakthrough, CO₂ utilization will play a valuable but limited role in overall efforts to manage CO₂ on a global scale. Fundamental research questions include:

- What catalysts can be used for the production of synthetic middle distillates from CO₂? In particular, can metal oxides be used to reduce CO₂? What catalysts can be used for the carboxylation of CO₂ to produce organic chemicals that will eventually replace the use of phosgene in reactions for producing organic chemicals with CO₂?
- How can catalysts for "artificial photosynthesis" be improved? Can we build molecular photonic devices that can mimic biological photosynthetic phenomena for the fixation and utilization of power-plant-derived CO₂, e.g., photocatalytic reduction of carbon dioxide with water to produce methane?
- How can binding and agglomerating be accomplished for the fine particulates of carbon black that would be produced as a byproduct of the thermal decomposition process? Would there be uses for this fine particulate carbon, such as in structural building materials?
- What biological processes and engineered microbes could fix power-plant-derived CO₂ and directly produce a useful byproduct (e.g., recent Japanese reports of an engineered blue-green algae that can fix CO₂ from air and produce a biodegradable plastic)?

FUEL CELL AND HYDROGEN TECHNOLOGIES

Fundamental research needs for the development of fuel cell and hydrogen technologies stem from the physical problems in both the utilization of hydrogen fuel in cells and from problems associated with the production and storage of hydrogen. Not surprisingly, the solutions to these problems are thought to depend on the development of advanced catalysts and membranes, which facilitate the reaction and separation of chemicals. Research questions include:

- Can better catalysts be found for proton exchange membrane (PEM) electrode interfaces to enable charge transfer from hydrogen at low temperatures (below 90°C)? How can we better understand the molecular structures and processes for the formation of fluorocarbon compounds used as the electrolyte in low-temperature PEM fuel cells? Can we use this understanding to reduce costs of production?
- How can a stable catalyst be developed to facilitate conversion of hydrocarbons to hydrogen using the water shift reaction of methane at lower temperatures and to higher percentages of H₂?

- Can we develop a high-temperature catalyst for the electrolysis of water to hydrogen and oxygen using direct electric current in order to lower temperatures of the reaction and to increase the rates of electrolysis?
- What inorganic, high-temperature catalysts can be found (other than platinum and palladium) that are stable in severe sulfur and oxidizing environments and lower in cost?
- What enzymes act as catalysts in biological systems to promote reactions forming hydrogen?
- How can high-temperature membranes for separating low-concentration H₂ be developed?
- Can an electrolyzer—an electrochemical electrode/electrolyte/electrode membrane sandwich or liquid cell—electrochemically form H₂ and O₂ from water or impure fluids?
- Can a complex metal oxide transport protons at high temperatures?
- Can we develop a fiber composite membrane for separating hydrogen and purifying gases that contain H₂?
- Is it possible to improve development of low-cost proton electrolytes—materials that conduct electrical current by protons or equivalent ions?
- Can high temperature solid oxide electrolytes be developed to operate at temperatures of 1000°C?
- Can mixed ionic-electronic membranes—conductors of electrical current simultaneously by both ions and electrons—be developed?
- Can membranes composed all or in part of materials that are catalysts promote simultaneously the reactions, the separation of the products from the reaction area, and/or the production reactants for the reactions to promote reactions to completion?
- For hydrogen storage, can metal hydrides be developed for absorption of hydrogen on metals at elevated temperature and pressure, and gas-on-solid absorption, including nanotube structures, fullerenes, and other highly porous materials?

CO₂ SEQUESTRATION IN GEOLOGIC FORMATIONS

Sequestration of CO₂ in geologic formations is one option for mitigating CO₂ emissions. Formations under consideration include oil and gas fields, unmineable coal seams, deep saline groundwater systems and clathrates. While current technology is satisfactory for small-scale CO₂ sequestration, implementation on a scale needed to impact atmospheric CO₂ concentrations requires a more fundamental understanding of the subsurface fate and transport processes of CO₂ over decades to millennia. In addition, new methods for monitoring subsurface CO₂ concentrations, phase behavior, and reaction products will be needed to ensure the effectiveness and safety of geologic sequestration. Priority scientific questions include:

- Can we substantially improve the modeling techniques and criteria used to determine the ability of abandoned oil and gas fields to sequester CO₂ for long periods? What can models reveal about pore-scale and injection-well-scale flow, transport, and reaction? At the micro scale, what are the relevant issues in multiphase fluid movement, phase transition, density and viscosity effects, and geochemical reactions? At the injection-well scale, what are the effects of hydraulic issues such as lateral and vertical migration, well integrity, caprock integrity, permeability, pressure buildup, sweep efficiency, density and viscosity effects, and storage capacity?
- How are complex carbonates formed in deep saline formations? How does CO₂ injected into deep saline formations react with minerals found there? Are complex carbonates produced and, if so, does the process occur at geologic time scales or are these reactions much more rapid in the presence of concentrated CO₂ (e.g., a stream of liquid CO₂)? How do these reaction products alter the hydraulic properties of the formation?
- How can we monitor the fate and transport of CO₂ in the subsurface? How can reaction products be identified?
- What, if any, additional chemicals or microbiota need to be injected to ensure safe and effective sequestration?

CO₂ SEQUESTRATION IN OCEANS

Ocean sequestration is currently under investigation as one option for disposal of concentrated streams of CO₂. The current state of knowledge about the fate and transport of CO₂ at various depths in the ocean is very primitive. More experiments and improved models are needed in this area. Priority scientific questions include:

- Can better modeling increase our understanding of deep-sea currents and their impact on proposed CO₂ sequestration methods? How can ocean global circulation models be adapted so that they can start to model the long-term fate of CO₂ injected into the ocean? What are the best sites, the overall effectiveness, and far-field environmental impacts of CO₂ injection? What can tracer studies reveal about environment effects?
- How can we improve understanding of the equilibrium mechanics of carbonates, particularly in the area of ocean chemistry of carbonates and the buffering ability of the ocean?
- What is the ultimate fate of CO₂ hydrates in the oceans?
- What are the near- and far-field biological impacts of CO₂ sequestration in oceans?

ENHANCING THE NATURAL CARBON CYCLE

The natural carbon cycle is nearly balanced, with net annual exchanges into and out of the atmosphere being small compared to the gross annual exchange rates. The gross annual exchange between the atmosphere and the oceans

(approximately 90 GT) and between the terrestrial biosphere and the atmosphere (c. 60 GT) are large compared to the annual atmospheric increase (c. 3.5 GT) and fossil fuels emissions (c. 6 GT). The large relative magnitude of these annual exchanges suggests that modification of the natural carbon cycle presents a significant opportunity for stabilizing or decreasing atmospheric CO₂ concentrations. Fundamental research needs to support development of methods to enhance the natural carbon cycle are described below.

Fundamental Understanding of Carbon Cycling in Soils: The cycling of carbon in soils involves the complex interaction among living and dead biomass, microorganisms, water, solutes, and mineral constituents of a soil. Turnover times for the various forms of carbon (the time required to convert organic carbon to inorganic forms such as CO₂) vary from less than a year for microbial biomass to thousands of years for some of the humic and fulvic acids found in soils. While the studies of soil productivity and associated topics are century-old research endeavors, we still have only a rudimentary understanding of the biogeochemical processes that control turnover times. Key fundamental research questions that could provide this knowledge are given below.

- What are the forms of dissolved organic carbon and nitrogen in terrestrial systems? What are their molecular structures? How are they formed? How are they transported in soil systems? How stable are they? What environmental factors influence their stability? What are the degradation mechanisms? How are they associated with soil minerals? What are the influences of mineral associations on degradation rates?
- What are the physical, chemical, and biological processes involved in conversion of plant material to carbon-containing compounds that are chemically and physically inert?
- How do the interactions among the carbon, nitrogen, sulfur, phosphorus, and water cycles affect carbon storage?

Understanding Mechanisms to Enhance Carbon Storage in Soils: Developing methods for incorporating and storing more carbon in agricultural soils will require mechanistic understanding of the influence of soil cultivation and conservation practices on the carbon cycle. Methods for monitoring and verifying increases in soil carbon storage will also be needed. Below are some of the key questions that must be addressed:

- What are the mechanisms by which agricultural practices such as tillage, fertilization, pesticide and herbicide application, crop rotation, irrigation fallowing, and erosion control influence carbon storage?
- How will soil quality and crop productivity be influenced by carbon capture and storage technologies?
- Which of these practices or combinations of practices will lead to enhanced carbon storage without unduly interfering with agricultural productivity or causing ecological harm?
- How can soil carbon storage be monitored and verified, particularly the creation of long-lived forms of carbon in soils?

Understanding How Climate Change and Anthropogenic Emissions Affect the Natural Carbon Cycle: The natural carbon cycle in the terrestrial biosphere is also influenced by anthropogenic emissions. Data indicate both positive and negative feedback to carbon capture and sequestration caused by increased concentrations of atmospheric carbon dioxide, nitrogen, ozone, and sulfur compounds. Moreover, climate changes created by anthropogenic emissions of greenhouse gases will lead to regional shifts in temperature and precipitation. These shifts will influence carbon capture and storage in the terrestrial biosphere. Understanding this feedback will be important for developing a comprehensive strategy for carbon management. Ecosystem-scale research underpinned by mechanistic studies of key processes is needed to understand anthropogenic influences on the natural carbon cycle.

Fundamental Understanding of the Carbon Cycle in the Ocean: The exchange of carbon between the atmosphere and oceans depends on the gradient in the CO₂ partial pressure as well as the rate of gas exchange across the air/sea interface. The CO₂ partial pressure in surface waters is controlled by three primary mechanisms, which are often referred to as the solubility pump, the biological pump, and the carbonate pump. The complex interplay of these processes with ocean circulation can create either a sink or a source of CO₂, or both, depending on the season. Understanding these processes and how they vary on a daily, intra- and inter-annual time scale is essential before it will be possible to formulate any management strategy for capturing and sequestering more carbon in the oceans. Integrated field, laboratory, and modeling studies are needed to answer some of the key questions listed below:

- What are the forms of dissolved and particulate organic carbon in the ocean? What are their molecular structures? How are they formed? How are they transported? How stable are they? What environmental factors influence their stability? What are the degradation mechanisms?
- How variable are the components of the ocean carbon cycle on daily, inter-annual, and event-driven time scales?
- What is the community structure of the marine organisms that drive the biological and carbonate pumps? What is the relationship between the community structure and carbon export?
- How would shutdown of thermohaline circulation as a result of climate change influence carbon storage in the ocean?

Fundamental Understanding of Mechanisms for Enhancing Carbon Capture and Sequestration: Increasing ocean productivity could lead to enhanced carbon capture and sequestration by some or all of the following mechanisms: (1) increasing air-sea transfer of CO₂, (2) enlarging the oceanic food web, (3) increasing organic carbon sedimentation rates, (4) increasing the efficiency of particulate carbon export from surface waters, and (5) decreasing remineralization efficiency. Exploratory experiments have already been performed to stimulate ocean productivity by iron fertilization, but many more laboratory, field, and modeling studies are needed to explore this and other strategies for enhancing ocean productivity and determining the effectiveness of enhanced biological productivity on carbon capture and sequestration. Below are some of the key questions that need to be addressed:

- What are the optimal mechanisms for enhancing ocean productivity? What kinds of nutrients could be added to the oceans to enhance productivity? How could these nutrients be delivered where and when they are needed? What will be the food-web response to nutrient additions? Where could nutrients be added to achieve the desired effect?
- Could biomass be cultivated in the oceans and harvested for food or fuel? How could it be captured without adverse ecological consequences?
- What are the ecological consequences of enhancing ocean productivity? What will be the effect of enhanced carbon storage in the oceans on marine life?
- What would be the climate feedback caused by enhancing ocean productivity?

BIOMASS PRODUCTION AND UTILIZATION

Biomass could be a major renewable energy source in the twenty-first century; it already supplies about 3 percent of U.S. and 15 percent of world energy for human use. Biomass can be converted to electricity, liquid fuels, gases, chemicals and materials, and used directly for heat. Crops grown for food, feed, fiber, chemicals, and materials, and crops grown specifically for energy can supply renewable resources for energy production and provide biomass that can offset the use of fossil fuels. Technologies based on direct combustion are under development and are expected to be able to achieve conversion efficiencies above 40 percent. More advanced technologies, based for example on combining gasifiers with fuel cell/microturbine combined cycles, could achieve efficiencies approaching 57 percent. Transportation fuels from biomass, including ethanol, ethers, and hydrogen; and chemicals and materials from biomass can replace products now made from oil and gas. Fundamental knowledge in the following areas will increase opportunities for use of biomass.

Basic Plant and Growth Processes: To ensure the yields necessary for biomass production to be competitive with other energy production, we need to select desirable plant species and variations, engineer genetically the changes that will improve conversion efficiency and plant growth and survival, and manage the growth process for maximum yield. Some of the important research questions include:

- What are the physiological and genetic controls or limitations of photosynthetic pathways? What are physiological and genetic controls or limitations of the efficiency of sunlight capture and conversion to biomass? What processes are involved in saturating light intensity, turnover of electron transport apparatus, carbon partitioning, and photorespiration?
- What are the underlying genetic bases and physiological processes contributing to the differences in the ability to grow on low nitrogen and to recycle nitrogen? How can the use of nitrogen and other nutrients be optimized?
- How do cell wall macromolecules (e.g., cellulose, lignin, hemicelluloses in woody materials) assemble into different tissues and organelles? How are cell walls formed? How can we evaluate the effects of genetic engineering on both conversion efficiency and plant growth and survival? How do plants and algae regulate biosynthesis of lipids and starch and store these desirable fuel and food precursors?
- How can we routinely accomplish stable gene insertion into host genomes? How can we ensure reliable expression of these genes over time and in diverse environments?

Biomass Disassembly and Conversion: Studying natural processes that break down and recycle plant material can help us maintain inherent plant energy content while extracting intermediate products or building blocks for producing biofuels or materials with very low net carbon emissions. Basic research will enable us to maximize these options and enhance natural plant disassembly processes. After selective disassembly of plants into components, further conversion reactions become more efficient. Biomass provides many chemical building blocks: monomers, oligomers, and polymers. We need separation and pretreatment technology that retrieves these components from biomass cleanly and reproducibly. Because biomass has high hydrogen and oxygen contents, coupled with low fractions of pollutant precursors, it can be used to produce alcohols and other oxygenates. More knowledge is needed in the following areas.

Biological, chemical, and thermochemical disassembly. Natural enzymes degrade some biomass components with a very high degree of specificity and offer approaches that may prove promising if they can be accelerated. Furthermore, understanding the kinetic and thermodynamic pathways that control plant disassembly reactions will allow for an increase in their rates and selectivity. Thermochemical processes can rapidly disassemble solid plant materials. These processes involve multiple and competing reaction pathways, and lead to a wide variety of

secondary reactions. Multiple and competing pathways lead to poor yields of any single product and thus require additional complex separation technologies. Frequently the secondary products condense into tars and chars that are difficult to process further.

Feedstock characterization and improvements for process use. The steps involved in preparing biomass-derived materials and feeding them to conversion processes are crucial and the major sources of operational problems, energy use, and cost. We need to answer questions such as—What are the microscopic, physical, chemical, and biological characteristics of biomass-derived feed components? What are the mechanics and fluid dynamics of fibrous and particulate materials? What are the physical and chemical separations of inorganics and cell wall constituents? What are the inorganic-biopolymer molecular interactions?

Biological, chemical, and thermochemical conversion. Current bioconversion technology is limited by microbial pH tolerance, product inhibition, stress, and other factors. Can we solve the problems of negative effects on microbes, for example, by removal of inhibitors or immobilization? How can we control or manipulate the intrinsic “microbial ecology” to allow proper operation under nonsterile conditions typical of large-scale bioprocessing? Can we establish new pathways to more efficient energy forms or new carbon-containing products such as hydrogen, hydrocarbons, and oils? How can microbial function in the reactor and in the end-use environment be optimized? What are effective processes for simultaneous conversion and separation? Similarly challenging questions remain for chemical and thermochemical conversion processes.

IMPROVED EFFICIENCY OF ENERGY PRODUCTION, CONVERSION, AND UTILIZATION

The previous sections focused on new technologies that are currently not part, or only relatively minor parts, of our current energy production, conversion, and utilization technologies. These new technologies hold promise of an energy future with very low or perhaps zero net carbon dioxide emissions; however, the transition to such technologies will be a lengthy one. In the interim, there are many opportunities to reduce carbon dioxide emissions from what they otherwise would have been through increased efficiency of fossil fuel power plants and energy end uses. Within the above context, key areas for basic research include:

Catalysts: Catalysts are used extensively in many industrial sectors, particularly in petroleum refining, chemical production, and production of the basic chemical building blocks for a wide range of materials. Catalysts function by interacting directly with the molecules in the chemical reaction. For this reason the design of the optimal catalyst for a particular reaction depends on a detailed knowledge of the structure of the catalyst and the chemistry of its participation in the reaction. The structure of many catalysts is not well known, nor is the mechanism of their catalytic activity. Further, our ability to design a catalyst of a particular structure and/or for a particular reaction is extremely limited.

Combustion: Virtually all energy-related carbon dioxide emissions are from the combustion process. Improving the efficiency and reducing emissions (e.g., NO_x and particulates) from the combustion process is an important part of a carbon management program.

Structural Materials: Improved structural materials could significantly reduce energy consumption. Vehicles made of lighter materials would reduce transportation energy consumption. Manufacturing structural materials is in itself energy intensive, leading to opportunities for energy use reduction through increased manufacturing efficiency, increased materials lifetime (decreased corrosion, metal fatigue and cracking), and increased use of recycled feedstocks. Even small improvements in the soft magnetic materials used in power transformers throughout the power generation infrastructure could dramatically reduce energy use by reducing heat losses in these devices. “Smart” materials that can adjust to their environment by changing their properties in a controlled way have the potential to reduce energy consumption in buildings, for example by changing the insulation value of a wall or the albedo of a roof.

High Temperature Materials: Heat engines become more efficient as the temperature of combustion is increased, all else being equal. Therefore, the development of materials that can withstand increasingly high temperatures is integral to the improvement of the efficiency of combustion processes.

Electrochemical Processes: Rechargeable batteries, fuel cells, and capacitors hold great promise for more efficient energy conversion and storage devices. Significant advances have been made to improve these electrochemical systems during recent years; however, important technical challenges remain to be met before advanced rechargeable batteries, fuel cells, and capacitors find widespread use in the transportation, building, and industrial sectors.

Optical, Thin Film, and Semiconductor Materials: Optoelectronic, thin film, and semiconductor materials are used extensively in energy generation, distribution, and use. Improvements in light-emitting diodes and lasers that function in the visible region of the spectrum will reduce energy consumption through increased efficiency. Application of solid-state devices on the large scale in signs, displays, and lighting would directly reduce energy consumption because these devices are highly efficient. New flat panel displays based on concepts such as field emission and electroluminescence will be more energy efficient than CRTs. Electrochromic and other advanced coatings can permit active control of the optical and thermal properties of the windows in a building or vehicle. Fundamental research will lead to new concepts for more efficient optical, thin film, and semiconductor materials.

Sensors and Controls: The energy production and utilization sectors both involve complex industrial processes. These industrial processes need to be controlled and optimized to produce or utilize energy effectively. Improved sensors, controls, and information systems can help to optimize these processes and consequently increase efficiency.

Computation, Visualization, and Communications: Advanced simulation, visualization, and communication will enable process improvements and operational enhancement of buildings, transportation systems, and industrial processes.

ACKNOWLEDGMENTS

The authors acknowledge the contributions of their many colleagues who participated in the workshops. This project was supported by the Department of Energy, Office of Energy Research, under Contract No. DE-AC03-76SF00098.

REFERENCES

Benson, S. M., Chandler, W., Edmonds, J., Levine, M., Bates, L., Chum, H., Dooley, J., Grether, D., Houghton, J., Logan, J., Wiltsee, G., and Wright, L., 1997. Carbon Management: Assessment of Fundamental Research Needs. Office of Energy Research, Department of Energy, DOE/ER-0724.