Bolster Basic Science Contributions to Technology Development

The challenge of encouraging and sustaining economic growth, while simultaneously reducing greenhouse gas (GHG) emissions, calls for the development of an array of new and advanced technologies. Such an undertaking depends on scientific knowledge gained from basic research. Fundamental discoveries can reveal new properties and phenomena that can give rise to improved understanding of technical barriers and illuminate pathways toward innovative solutions. Fundamental discoveries can include breakthroughs in understanding biological functions, properties and phenomena of nano-materials and structures, improved computing architectures, applications and methods, progress in plasma and environmental sciences, and many more breakthrough developments now unfolding on the frontiers of active scientific and technical disciplines.

One of CCTP's core approaches (Approach #2) focuses on strengthening basic research in Federal laboratories, universities, and other research organizations. Basic research will give rise to knowledge and technical insights necessary to enable technical progress throughout CCTP's portfolio of applied research and development, explore novel approaches to new challenges, and bolster the underlying knowledge base for new discoveries (Figure 9-1).

In considering the roles for basic research and related organizational planning in advancing climate change technology development, CCTP characterizes opportunities for contributions as follows:

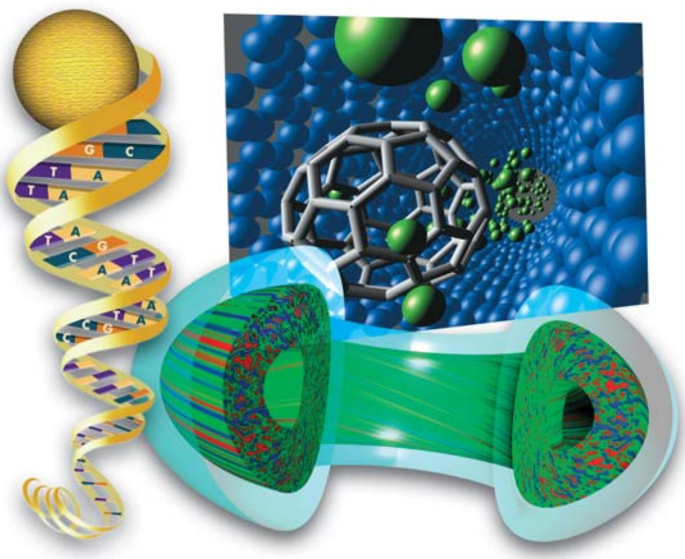


Figure 9-1. Fundamental science is critically important in the creation of new knowledge and improved understanding of technological innovation.

Courtesy: DOE, Office of Science

- **Fundamental Science:** Fundamental science is basic research that provides the underlying foundation of scientific knowledge that can lead to fundamental new discoveries. It is the systematic study of system properties and natural behavior that can lead to greater knowledge and understanding of the fundamental aspects of phenomena, processes, and observable facts, but without prior specification toward applications to design or develop specific processes or products. It includes scientific study and experimentation in the physical, biological, and environmental sciences and many interdisciplinary areas, such as computational sciences. Although not directly related to CCTP, it is a source of underlying knowledge that will enable future progress in CCTP.
- **Strategic Research:** Strategic research is basic research that is inspired by technical challenges in the applied research and development programs. It is research that may lead to fundamental discoveries (e.g., new properties, phenomena, or materials) or scientific understanding, but is primarily aimed at providing better understanding of underlying phenomena that are believed to be relevant to specific problems, challenges, or

technical barriers impeding progress in technology development. For CCTP, strategic research are basic research endeavors relevant to R&D on energy supply; end-use; CO_2 capture, storage and sequestration; mitigation of emissions of non-CO_2 GHGs; and means for enhancing measurement and monitoring (M&M) of GHGs. This "strategic" research builds on knowledge gained from fundamental science and extends it to the technical challenges associated with technology R&D.

- **Exploratory Research:** Exploratory research is basic research, or early and exploratory study of application-inspired concepts, undertaken in the pursuit of high-risk, novel, emergent, integrative or enabling approaches, not elsewhere covered. Many such concepts may be pursued within existing applied research and development programs, but often truly novel concepts do not fit well within the established constructs of existing mission-directed or discipline-oriented programs. In addition, some early experimental research may be too risky or multi-disciplinary for a particular research program to justify or support unilaterally. Therefore, not all of the research on innovative concepts for climate-related technology is, or should be expected to be, aligned directly with an existing Federal R&D mission-related program. This *Plan* calls for exploratory research that could lead to new breakthroughs in technology development and thereby dramatically change the way energy is produced, transformed, and used in the global economy. Exploratory research of innovative and novel concepts, not elsewhere covered, is one way to uncover such "breakthrough technology," stimulate innovation across the research community, and enrich the overall R&D portfolio.

- **Integrated Planning:** Effective integration of fundamental science, strategic research, exploratory research, and applied technology research and development presents challenges to and opportunities for both the basic research and applied research communities. These challenges and opportunities can be effectively addressed through innovative, integrative planning processes, augmented by analysis and decision-support tools. These processes emphasize communication, cooperation and collaboration among the many associated communities. CCTP encourages and expects to build on the successful models and best practices in this area and plans to improve its analyses and tools.

This chapter discusses the potential research contributions to climate-related technology development of each of the above categories. Section 9.1, "Strategic Research," describes the basic, problem-inspired science underway, planned or under consideration that explores key technical challenges associated with CCTP's five strategic goals, as discussed in Chapters 4 through 8. Section 9.2, "Fundamental Science," describes the basic research that provides the underlying scientific foundation of knowledge needed to enable breakthrough technology. Section 9.3, "Exploratory Research," addresses research of high-risk, novel, emergent, integrative or enabling concepts, and others, important to climate change technology development, but not elsewhere covered. Finally, acknowledging that clarifying and communicating research needs of the applied technology research and development programs can help inform and guide basic research plans and programs, Section 9.4, "Toward Enhanced Integration in R&D Planning Processes," describes a generalized approach to integrate better basic research with the applied research and development programs related to climate change technology development.

9.1 Strategic Research

Scientific research enables both current and new generations of technologies that are needed to address the problem of GHG emissions. The outcomes expected from scientific research are time-variant:

- In the near term, a significant role of research is to overcome bottlenecks and barriers that presently limit or constrain the development and application of technologies that are progressing toward commercial status. Some of the barriers include a lack of suitable materials, advanced processing and manufacturing, the need for information on key processes, and the need for new instrumentation and methods (Figure 9-2). Research will contribute to studying the feasibility of new technologies, solving key materials and process issues, developing new instrumentation and methods, and reducing costs. For example, science-based analyses will help to assess the viability of carbon storage and sequestration over the next decade; to better understand the interactions between engineered systems and natural systems (e.g., in systems involving biotechnology); and to solve materials and chemistry problems in advanced energy systems, such as hydrogen production and fuel cells. The development of novel space-based monitoring systems could enhance GHG M&M strategies.

- In the mid-term, science will take nascent ideas and develop them to the point they can enter the technology cycle. For example, innovations achieved through the support of science programs may result in new nanomaterials and devices for energy transformation, the ability to capture bioenzymes in biomimetic membranes for various energy applications, advances in plasma science for the development of fusion energy, and identification of new materials and efficient processes for hydrogen production, storage, and conversion.
- In the long-term, the current wave of research "at the frontier" may open up entirely new fields involving genomics and the molecular basis of life, computational simulations, advanced analytical and synthetic technologies, and novel applications of nanoscience and nanotechnology. It is hard to predict discoveries that will open entirely new ways of producing and using energy or dramatically alter industrial processes. However, the history of science and technology contains many examples of such transformations.

Much of the research needed to address the challenges of climate change technology development requires cross-cutting strategic research approaches. These are discussed in the sections that follow, organized by the five CCTP strategic goals (Chapters 4 through 8):

- Reduce Emissions from Energy End-Use and Infrastructure
- Reduce Emissions from Energy Supply
- Capture and Sequester Carbon Dioxide
- Reduce Emissions of Non-CO_2 GHGs
- Enhance Capabilities to Measure and Monitor GHGs.

The section concludes with a description of cross-cutting strategic research areas that underpin the sixth CCTP goal: to strengthen the basic research foundations that enable climate technology advances.

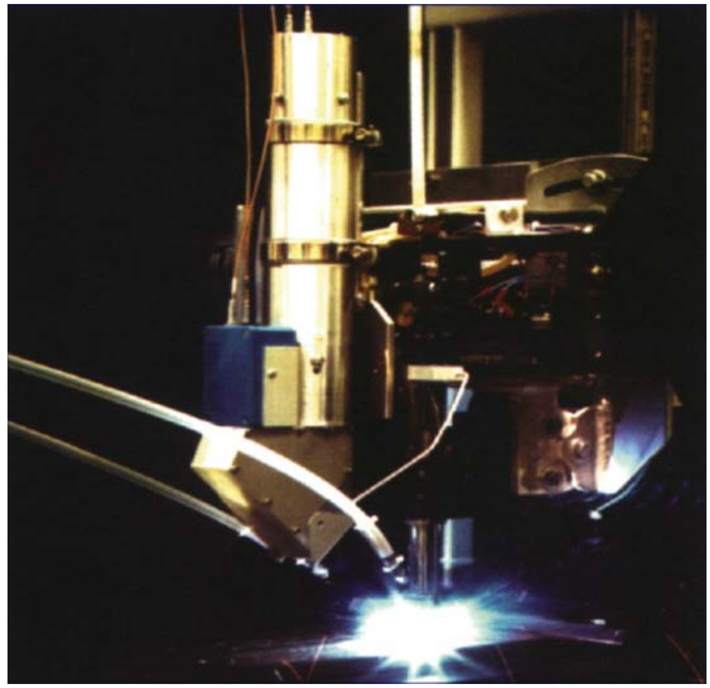


Figure 9-2. Scientific research can help in overcoming barriers to the development of advanced process technology, such as the laser-assisted welding imaging system shown above.

Courtesy: DOE Office of Science

Research Supporting Emissions Reductions from Energy End-Use and Infrastructure

A broad array of research underpins emissions reductions from energy end-use and infrastructure, spanning the areas of transportation, buildings, industry, the electric grid, and infrastructure. The promising basic research directions for each of these areas are discussed below, with illustrative examples.

Transportation

Strategic research is needed to address major sources of CO_2 emissions from vehicles and other key transport modes. Research on reducing vehicle weight while maintaining strength and safety includes **materials science** that improves efficiency, economy, performance, environmental acceptability, and safety in transportation. Foci are ceramics and other durable high-temperature, wear-resistant materials and coatings; and strong and lightweight alloys, polymers, and composite materials for structural components. **Joining, welding, and corrosion sciences** will enable the application of new polymer composites and bimetallic alloys, which also require the development of low-energy techniques for materials processing.

The **nanosciences** can potentially contribute to many aspects of energy efficient vehicles, engines, and engine processes. Research can build on basic research in materials, chemistry, and computation to develop fundamentally new types of **materials with specific, tailored properties**, including innovative applications such as highly conductive nanofluids for lubrication and cooling.

Materials and membrane research for fuel cell stacks and advanced fuel cell concepts for vehicles will improve the efficiency of fuel cells along with their performance, durability, and cost. **Nanostructured catalysts** will reduce the need for noble metals and can be operated at lower temperatures while producing fewer side products.

Electrochemistry, materials, and catalyst research, including research at the nanoscale, may lead to innovations in onboard energy storage for electric hybrid and hydrogen-powered vehicles. For conventional and novel sources of power in mobile applications, energy conversion cycles can be made more efficient and **thermoelectric materials** can enable more beneficial use of waste heat.

Research in **thermo- and electro-chemistry and materials** for advanced sensors that are robust and inexpensive could improve vehicle fuel economy by predicting system failure and optimizing system parameters.

For both combustion and other transportation energy sources, research on the **energetics of chemical reactions** and the interactions of **chemistry at interfaces** may significantly improve or transform the efficiency of energy-producing reactions. The design and development of efficient, clean-burning designs can be accomplished more quickly and with a higher probability of success if combustion models are improved.

Research on intelligent transportation systems needs to include **complex systems science** for sustainable transportation as well as computational science and **improved mathematical algorithms and models** for improved traffic handling/management and for design and performance simulation.

Genomics, biochemistry, and other biological sciences will lead to more productive biomass feedstocks and more efficient conversion to biofuels. This strategic research is described in more detail in the following section on "Renewable Energy and Fuels."

Buildings

Three aspects of buildings that could significantly reduce CO_2 emissions would benefit from strategic research: the building envelope, building equipment, and integrated building design.

In improving energy efficiency in the building envelope, **materials science** will have a broad range of impacts, from a next generation of smart building insulation with phase change materials to transparent films for energy-efficient adaptive windows to new classes of lightweight structural materials. **Robotics,** along with the **joining and welding sciences,** will support the fabrication and construction of high-efficiency envelopes.

Building equipment will become more energy efficient through research in **plasma science** for arc lighting and **semiconductor alloys** for solid-state lighting, as well as light-emitting polymers. More efficient heating and cooling systems will be possible because of **combustion, materials, heat transfer, and engineering research**, and fundamentally new approaches to heating and cooling will result from research into **thermoacoustics and thermoelectrics**. Breakthroughs in **magnetism** will enable more efficient motors.

Research in whole-building integration will draw on the basic science research in **condensed matter physics** that enables improvements in smart transistors for energy-saving sensors and electronic devices to optimize space conditioning, new and improved self-powered smart windows through research in **constricted-plasma source thin film applications**, **electrochromics and dye-sensitized solar cells**, as well as **multilayer thin film materials and deposition processes** to control the interior environment, and smart filters for water systems based on **tailored pore sizes** and **pore chemistry**.

Industry

Strategic research is needed to address current and anticipated sources of emissions of CO_2 and other GHGs from energy conversions and process inefficiencies. Strategic research is also needed to facilitate improvements in energy efficiency and resource utilization.

Research on **advanced materials** with attributes such as the ability to operate in varied hostile environments, such as high temperatures and pressures and corrosive environments, can enable improved process efficiencies.

Advances in high-temperature **materials research** (Figure 9-3) will lead to increased energy efficiency in industrial processes; for instance, increased temperature will improve the efficiency of industrial boilers (super-critical steam cycles) and Integrated Gas Combined Cycle (IGCC) systems for recycle of byproduct streams in the paper and pulp industry. Other areas of materials science include ion implantation, thin films, carbon-based nanomaterials, ceramics, alloys, composites, and quasicrystals; welding, processing, and joining; and foundations for nanomechanics and nano-to-micro assembly.

Solid-state physics and related sciences will support advanced, energy-efficient computer chip concepts and manufacturing.

Because of the very wide diversity of industrial applications, environments, processes, and products, **strategic research in nearly all basic research disciplines** is needed for new and advanced industrial sensors. For example, superconducting quantum interference devices (SQUIDS) that can measure extremely weak signals via tiny variations in a magnetic field will provide feedback to systems and reduce energy use as situations change.

Research on **advanced separations, chemistry, and higher-selective catalysts** can increase resource recovery and utilization of industrial byproduct or waste material. **Advanced membranes and adsorption processes** can lead to improved industrial process efficiencies and costs.

Research into the **magneto-caloric effect** will lead to new, energy-efficient forms of industrial refrigeration.

Advances in **electronics research**, tailored to power electronics applications, will enable more efficient motor and drive systems with improved ability to vary motor speed to enable higher efficiencies in loads such as fans, pumps, and compressors.

Research on key **biotechnology platforms** and designs for biorefineries will enable chemical products to be derived from biomass rather than fossil fuels as described in the section below on "Renewable Energy and Fuels."

Electric Grid and Infrastructure

A balanced portfolio of strategic research addressing conductor technology, systems and controls, energy storage, and power electronics is needed to meet the need for secure and reliable power leading to reduced CO_2 emissions from electric generation.

Materials that improve the transmission and storage of electricity will achieve highly improved energy efficiency. **Solid-state physics and materials science** will enable high-performance semiconductors and high-temperature superconductors for efficient, high-capacity transmission of electric power. **Superconductivity research** will also make possible innovative storage devices and efficient motors. The, 2006 workshop report, *Basic Research Needs for Superconductivity*, examined the prospects for superconducting grid technology and its potential for significantly increasing grid capacity, reliability, and efficiency to meet the growing demand for electricity over the next century (DOE-BES 2006).

High-Temperature Materials Research

Figure 9-3. Advances in high-temperature materials research, facilitated by the use of synchrotron radiation, can make significant contributions towards improving the energy efficiencies of industrial equipment and electricity generation.

Courtesy: DOE, Office of Science

Other **tailored materials research** can lead to highly conductive high-strength nanowires; superlattices; high-strength, lightweight composites and corrosion-resistant materials; nanostructured materials for semiconductors; and metallic glasses for vastly improved transformers and sensor implementation.

Basic Research Needs for Superconductivity (DOE-BES 2006)

Silicon carbides and thin-film diamond switching devices will improve performance and energy efficiency of power electronics and controls. **Sensors and adaptive controls** will enable optimization of the grid; development of responsive loads for peak shaving; and accommodation of distributed solar and wind supply on the grid.

Electrochemistry research, including electrolytes, electrode materials, thin films, and interfaces, will improve commercial batteries and other electric storage devices so important to integrating intermittent renewable resources into electric grid operations and for load leveling and optimized grid operations.

Computational science and computer/network science will improve real-time control of the utility transmission infrastructure and, thus, its energy efficiency.

Research Supporting Emissions Reductions from Energy Supply

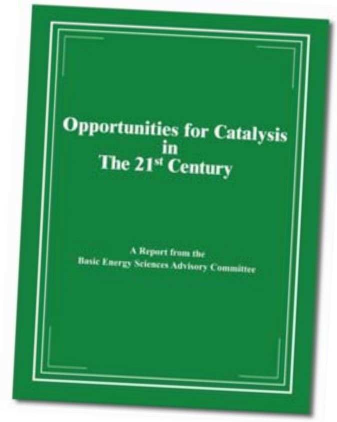
Strategic research underpinning emissions reductions from energy supply targets low-emissions fossil-based power, hydrogen, renewable energy and fuels, nuclear fission, and fusion. Research in these areas includes the following:

Low-Emissions Fossil-Based Power

Strategic research is needed to achieve the principal fossil energy objective of a zero-emission, coal-based electricity generation plant that has the ability to co-produce low-cost hydrogen.

Since high temperatures result in lower GHG emissions, **combustion, materials research, and condensed matter physics (crystalline structure)** can contribute improved and new materials for high temperature, pressure, and corrosive environments. The result will be more efficient gasification processes for advanced coal plants and higher temperature turbine blades and heat exchangers to allow more efficient conversion of natural gas into electricity.

Research in **thermo- and electro-chemistry and materials** for advanced sensors will lead to improved monitoring and control of processes in fossil fuel combustion. Separation sciences will enable improved gas phase separations in coal liquefaction and reduced energy requirements for oxygen separations in oxycombustion options.



Opportunities for Catalysis in the 21st Century (BESAC 2002)

Computational sciences will advance simulation and design, especially for improved models and codes for fluid dynamics, turbulence, and heat transfer modeling.

Catalysis research employing **nanostructured materials** will find efficient pathways for the selective and efficient conversion of fossil fuels, including a catalyst for petroleum refining and chemical manufacturing and catalysis of carbon-hydrogen bonds. The *2002 Opportunities for Catalysis in the 21st Century* workshop report describes research directions for better understanding of how to design catalyst structures to control catalytic activity and selectivity (BESAC 2002).

Geosciences research for higher recovery rates of fossil fuels with lower societal impact will be needed to provide feedstocks for higher efficiency, new low-emission power plants.

Hydrogen

The development of energy-efficient and economically competitive technologies for H_2 delivery, storage, and production will require a broad portfolio of strategic research.

Research will focus on understanding the atomic and molecular processes that occur at the interface of hydrogen with materials in order to develop new materials suitable for use in a hydrogen economy. New research is needed for **tailored materials, membranes, and catalysts**, leading to fuel cell assemblies that perform at much higher levels, at much lower cost, and with much longer lifetimes.

In the hydrogen production area, a key focus is on **catalysts** and better understanding mechanisms for hydrogen production. **Biological enzyme catalysis**, **nanoassemblies** and bio-inspired materials and processes are areas of basic research related to hydrogen production from biomass. **Photoelectrochemisty and photocatalysis** research may lead to breakthroughs in solar production of hydrogen. Also, **thermodynamic modeling, novel materials research and membranes, and catalyst research** may support nuclear hydrogen production.

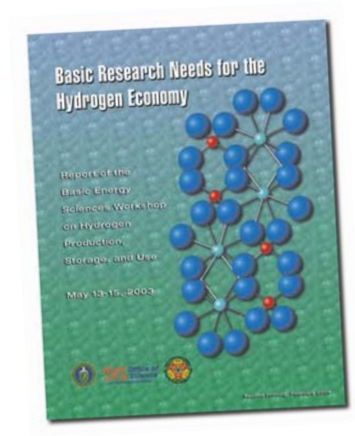
Hydrogen storage is a major challenge. Basic science research related to storage includes the study of **hydrogen storage-hydrides** and **tailored nanostructures** and the development of high-density reversible membranes. For instance, research on complex metal and chemical hydrides may support on-board recharging of fuel cell vehicles.

In the fuel cells area, **electrochemical energy conversion mechanisms** and materials research are important. In addition, there are identified needs for higher temperature **membranes and tailored nanostructures** that basic science research could support. The *2004 Basic Research Needs for the Hydrogen Economy* workshop report identifies fundamental research needs and opportunities in hydrogen production, storage, and use, with a focus on new, emerging, and scientifically challenging areas that have the potential to deliver significant impacts (BESAC 2004). An NSF (2004a) workshop on *Future Directions for Hydrogen Energy Research & Education* emphasized the promise that nanotechnology offers for hydrogen and fuel cell development, and the importance of developing a more interdisciplinary approach to future hydrogen research and development.

Renewable Energy and Fuels

Strategic research is needed to enable a transition from current reliance on fossil fuels to a portfolio that includes significant renewable energy sources, with a shift in infrastructure to allow for a more diverse mix of technologies.

Biochemistry, bioenergetics, genomics, and **biomimetics research** will lead to new forms of biofuels and capabilities for microbial conversion of feedstocks to fuels. This includes research on strategies for cellulose treatment, sugar transport, metabolism, regulation, and microbial systems designed to optimize the use of microbes that are known to break down different types of complex biomass to sugars and ferment those sugars to ethanol or other fuels. The 2006 workshop report, *Breaking the Biological Barriers to Cellulosic Ethanol: A Joint Research Agenda*, outlines a detailed research plan for developing new technologies to transform cellulosic ethanol—a renewable, cleaner-burning, and carbon-

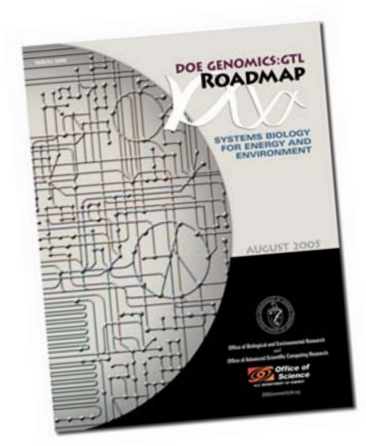


Basic Research Needs for the Hydrogen Economy (BESAC 2004)

neutral alternative to gasoline—into an economically viable transportation fuel (DOE-BER-EERE 2006). The research may lead to scientific breakthroughs in the design of a single microbe for making ethanol from cellulose. **Nanoscale hybrid assemblies** will enable the photo-induced generation of fuels and chemicals. **Plant genomic research** and gene function studies will make possible increased crop yields, disease resistance, drought resistance, improved nutrient-use efficiency, tissue chemistry that enhances biofuel production and carbon sequestration. The NSF workshop report on *Catalysis for Biorenewables Conversion* (2004) identifies the need for a reinvigoration and redirection of U.S. catalysis research for the purpose of developing fuels and chemicals production from biorenewables.

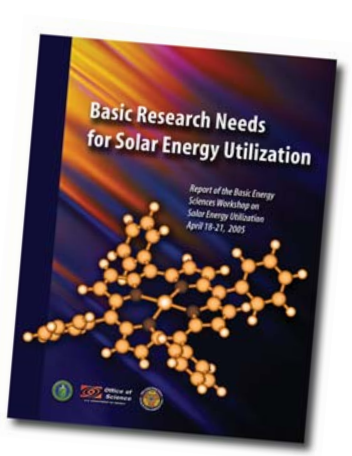
Plant biology, metabolism, and enzymatic properties research will support the development of improved biomass fuel feedstocks and will enable the

Breaking the Biological Barriers to Cellulosic Ethanol: A Joint Research Agenda (DOE-BER-EERE 2006)



Genomics: GTL Roadmap (DOE-SC 2005a)

design of crops for bioconversion. For example, expression of thermostable cellulases directly in plant cell walls could facilitate enzymatic hydrolysis of cellulose. Research on key **biotechnology** platforms includes designs for biorefineries to produce biofuels, biopower, and commercial chemical products derived from biomass rather than fossil fuels. The *Roadmap for Biomass Technologies in the United States* prepared by the Biomass Research and Development Technical Advisory Committee (2002) itemizes a broad supporting R&D agenda that spans feedstock production, processing and conversion, and product uses and distribution. Complementing this agenda, the 2005 *Genomics: GTL Roadmap* (DOE-SC 2005a) describes an aggressive systems microbiology plan to accelerate the scientific discovery needed to support such developments.



Basic Research Needs for Solar Energy Utilization (DOE-SC 2005b)

Basic research in **photochemistry** and **photocatalysis** will provide foundations for future, alternative processes for light-energy conversion, thin-film, and nanosciences research for photovoltaics. Bio-inspired systems offer the promise of engineered systems that mimic photosynthesis at higher efficiencies and rates. The 2005 *Basic Research Needs for Solar Energy Utilization* (DOE-SC 2005b) workshop report examines the challenges and opportunities for the development of solar energy as a competitive energy source and to identify the technical barriers to large-scale implementation of solar energy and the basic research directions showing promise to overcome them.

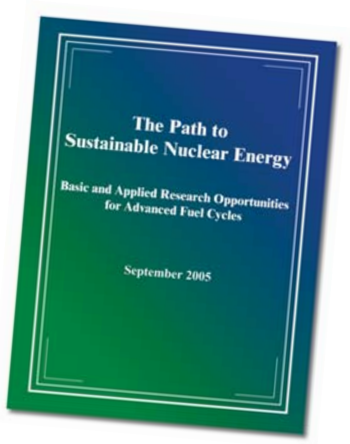
Geosciences and **hydrology** research will support a broad range of siting issues related to hydro and geothermal power sources as well as assessing the availability of low-grade geothermal energy. Needed research includes mapping and monitoring geothermal reservoirs, predicting heat flows and reservoir dynamics, mapping the natural distribution of porosity and permeability in deep geologic media, and developing new methods to enhance or reduce permeability.

Research in **materials** and **composites** will lead to improved wind energy systems by enabling larger blades on wind turbine systems leading to lower unit costs for wind power and the economic use of wind turbines with low-speed wind resources. Research in **electro-chemistry, superconductivity, and solid-state physics** can aid advances in electric storage to help deal with the problem of intermittency that currently makes it difficult to integrate wind (and solar) energy into large-scale power dispatch systems. Research in **materials chemistry, electro-chemistry and solid-state physics** can lead to advances in development of power electronics, which will lead to power systems that can integrate with multi-level photovoltaics and inverters for solar and wind power systems and can convert DC power into 60-hz AC power.

Nuclear Fission Energy

Through strategic research addressing issues of safety, sustainability, cost-effectiveness, and proliferation resistance, advanced nuclear fission-reactor systems can play a vital role in diversifying the Nation's energy supply and reducing GHG emissions.

Heavy element chemistry, advanced **actinide and fission product separations** and extraction, and fuels research will support better process controls in nuclear fission cycles. The 2005 Workshop report on



The Path to Sustainable Nuclear Energy (DOE-BES-NP 2005)

The Path to Sustainable Nuclear Energy identifies new basic science that will be the foundation for advances in nuclear fuel-cycle technology in the near term, and for changing the nature of fuel cycles and of the nuclear energy industry in the long term (DOE-BES-NP 2005).

Fundamental research in **heat transfer** and **fluid flow** will lead to improved efficiency and containment.

Basic research will meet the **materials sciences** challenges of Gen IV reactor environments, with emphasis on the search for radiation-tolerant, ultra-strong alloy and composite materials. Increased temperatures enabled by high-temperature materials allow higher thermal-to-electricity conversion efficiencies. **Materials processing, welding, and joining** sciences will also play a critical role in reducing failure rates and ensuring system integrity, and research into **basic defect physics in materials**, equilibrium and radiation-modified **thermodynamics of alloys and ceramics** will improve reactor design. **Deformation and fracture studies** and analyses of **helium and hydrogen effects on materials** will contribute to safety and reliability of advanced nuclear energy systems, as will atomistic and 3D **dislocation dynamics studies**.

Geophysical research and **geological permeability engineering** will support nuclear siting and waste disposal in geologic repositories, potentially employing remote sensing technologies similar to the approaches used in siting renewable energy facilities.

Chemistry and **corrosion research** will improve design, operation, and predictability for performance.

Fusion Energy

Strategic research on magnetic confinement approaches, **materials science, plasma physics, and**

Computational Sciences

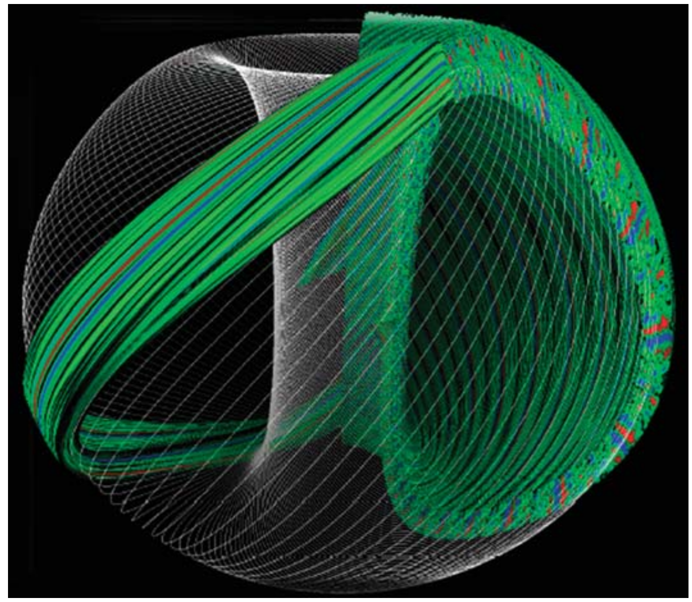


Figure 9-4. Computational sciences applied toward fusion energy research will aid in testing agreement between theory and experiment, and simulate experiments that cannot be conducted in the laboratory.

Courtesy: DOE, Office of Science

high energy density physics is needed to define and develop the most promising fusion concept.

Research in **burning plasmas** will validate the scientific and technological feasibility of fusion energy. Moreover, research aimed at a fundamental understanding of **plasma behavior** will provide a reliable predictive capability for fusion systems. Studies will identify the most promising approaches and configurations for confining hot plasmas for practical fusion energy systems.

Research in **materials tailored** for a fusion energy environment leading to components and technologies that will be necessary to make fusion energy a reality.

A broad underpinning of **computational sciences** (Figure 9-4) will advance fusion research, including computational modeling to test the agreement between theory and experiment, and simulating experiments that cannot readily be investigated in the laboratory.

Research Supporting CO_2 Capture and Sequestration

Research supporting carbon capture and sequestration underpins the development of technologies and strategies for CO_2 capture and sequestration that are described in Chapter 6.

Carbon Capture and Storage in Geologic Repositories

Realizing the possibilities for point source CO_2 capture requires a research portfolio covering numerous technology areas, including post-combustion capture, oxy-fuel combustion, and pre-combustion decarbonization to reduce costs and energy penalties. Carbon storage in geologic repositories will require comprehensive understanding of the economic, health, safety, and environmental implications of long-term, large-scale geologic storage.

Membranes and **chemistry** research will enable separating CO_2 in post-combustion stack gases, capturing it, and if needed, transforming it to another form of carbon that may be more useful, or more safely or permanently stored.

Geophysics, geochemistry, hydrology, and geological permeability engineering research of CO_2 repositories in geological formations will increase understanding of how CO_2 injected into such formations interacts with minerals and what the long-term fate of CO_2 would be after injection. This research will probe the factors that determine the residence time of carbon sequestered in soils, and ways in which the quantity and residence time of carbon sequestered in soils can be increased. Such research provides the scientific foundation for credible calculation of sequestration by terrestrial ecosystems.

Modeling, simulation, and assessment of geological repositories research are necessary to identify sites that have been or could be selected for use in storing CO_2 removed from industrial flue gases. Such research will help meet the need for a more definitive understanding of geologic storage potential.

Research is also needed on **microbial processes** that act to metabolize CO_2 in geologic structures.

Terrestrial and Ocean Sequestration

Realizing the potential to sequester carbon in terrestrial systems requires research on equipment, processes, management systems, and techniques that can enhance carbon stocks in soils, biomass, and wood products, while reducing CO_2 concentrations in the atmosphere.

Basic **biological** and **environmental research** on terrestrial carbon sequestration could enhance the natural carbon cycle—plants that store even more CO_2. For example, this could involve development of technologies for enhancing the ability of trees to sequester carbon by modifying their root systems. Another possibility is genomic research on black cottonwood to characterize key biochemical functions related to photosynthesis, tree growth, and carbon storage. **Environmental science** research can analyze how efforts to increase terrestrial carbon sequestration might influence other environmental processes, such as nutrient cycling, the emissions of other GHGs, and albedo effects on climate at all scales.

Genomic research will identify traits that would enable plant species to grow and persist in environments that are of marginal quality and, hence, may not be useful for purposes other than capturing carbon in plant biomass. Genomic research on microalgae and photosynthetic bacteria may identify traits that enable the organisms to efficiently capture and fix CO_2 separated from other industrial flue gases before it is released into the atmosphere. Research related to **modifying plants** and **soil micro-organisms** can provide the basis for capturing and retaining nitrogen and other essential plant nutrients and engineering the pathways for lipid synthesis to trap a larger fraction of photosynthate directly in hydrocarbon precursors.

Soil science research on the formation and transformation of soil organic matter will enable efficient application of technologies to enhance soil carbon sequestration, increase plant productivity, and reduce non-CO_2 GHGs (e.g., nitrous oxide [N_2O]) from soil.

Materials research may enhance carbon sequestration by substituting carbon-based products for steel, cement, and other commodities. Examples include carbon fiber from black liquor used in the manufacture of carbon composite lightweight materials and wood composites used in place of steel beams.

Research will explore ways of injecting CO_2 into the deep ocean, how long the injected CO_2 would remain isolated from the atmosphere, and what the potential **ecological** and **chemical** effects might be of injecting relatively pure streams of CO_2 into the deep ocean. Research on methods of enhancing the abiotic uptake of CO_2 by the ocean, and/or storing carbon in the ocean in forms other than acid-producing, easily degassible CO_2 will also be considered.

A roadmap of various technology development approaches to carbon sequestration is described in *Carbon Sequestration Research and Development* (DOE-SC-FE 1999).

Research Supporting Emissions Reductions of Non-CO_2 GHGs

Basic and applied research is also supported by Federal agencies to develop ways of reducing emissions of non-CO_2 GHGs. This includes research in the **physical sciences, biological, and environmental sciences, and in computational sciences**.

Work on **materials** and **chemistry** will lead to replacements for high global warming potential non-CO_2 GHGs, such as sulfur hexafluoride (SF_6) and perfluorocarbons that are used in industrial processes. For example, research in materials chemistry, electro-chemistry, and solid-state physics can lead to advances in development of power electronics needed to minimize SF_6 emissions from transformers by leak reduction, replacement of SF_6 with other dielectric material, and development of new power transmission equipment that does not require SF_6 insulation.

Research on **thin films and membranes** will isolate non-CO_2 GHGs in industrial flue gases and other waste streams; **combustion research** will reduce emissions of N_2O, ozone precursors, and soot; and **catalysis research** will reduce emissions of non-CO_2 GHGs.

Basic research in the **biological and environmental sciences**, including microbial processes in the rumen of farm animals, animal metabolism, and animal grazing will enable reductions in methane emissions by livestock. **Biological research** will increase understanding of soil microbes to reduce methane emissions from livestock feedlots.

Basic **biogeochemistry** coupled with **microbial ecology and soil science research** may enable reductions in N_2O emissions from soils.

Basic Research Supporting Enhanced Capabilities to Measure and Monitor GHGs

There is a continuing need to enhance capabilities to measure and monitor GHG emissions and concentrations across a range of scales and applications so that carbon management strategies can be designed and implemented consistent with economic and environmental goals. Basic research in this area includes the following:

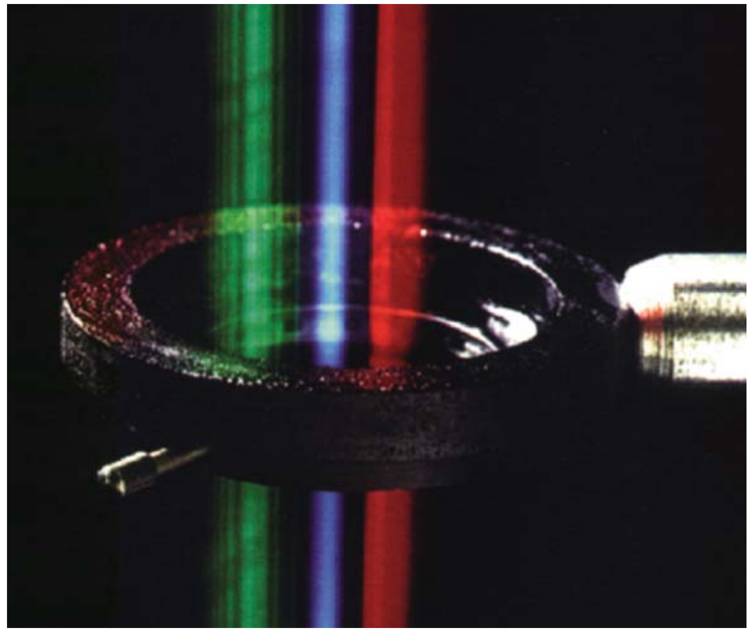


Figure 9-5. Advances in material chemistry can support the development of technologies that reduce GHG emissions. Shown here, laser-based surface analysis using resonant ionization of sputtered atoms identifies and accurately measures trace impurities in solid materials.

Courtesy: DOE, Office of Science

Various kinds of measurement for GHGs in the atmosphere are necessary. Observed vertical profiles of GHG concentrations are a result of surface emissions and atmospheric physical and chemical processes. Remote sensing methods will determine spatially resolved vertical GHG profiles rather than column-averaged profiles. Combined airborne and surface-based scanning techniques for remote sensing will yield 3D, real-time mapping of atmospheric GHG concentrations. Specific technologies for airborne remote sensing will measure methane surface emissions at a 10-km spatial resolution. Technologies for the long-term monitoring of global black carbon (BC) sources and transports, along with other aerosols, will enable solutions tailored to emission sources and their regional impacts.

Research in **materials chemistry, electro-chemistry and solid-state physics** can lead to advances in development of high-fidelity sensors needed for making precise and accurate measurements of GHGs in remote and hostile environments (Figure 9-5). Innovative technologies for non-invasive measurement of soil carbon will provide rapid methods for monitoring the effectiveness of carbon management approaches applied to terrestrial ecosystems and agricultural practices. **Microbial**

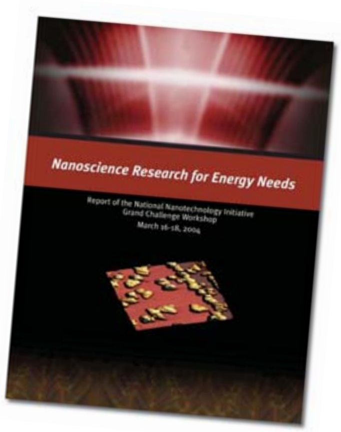
genomics research will seek to identify or develop eco-genomic sensors and sentinel organisms and communities for use in monitoring the effects of sequestering CO_2 in terrestrial soils and in the ocean.

Models will simulate and predict GHG emissions based on dynamic combinations of human activity patterns, energy technologies and energy demand, and industrial activities. **Environmental science and computational science** can develop models that can simulate and predict carbon flows resulting from, for example, specific carbon management policy actions that provide a consistent picture of the effectiveness of efforts to reduce GHG emissions.

Cross-cutting Strategic Research Areas

As the five previous sections illustrate, dissimilar technologies often require similar scientific advances to succeed. For example, degradation-resistant materials that perform well under high temperature conditions are essential to improving the energy efficiency of industrial processes; they are also needed to advance to a next generation of fossil and nuclear power plants, and are essential to realizing fusion energy. Similarly, plant and microbial genomics are central to advancing biofuels and biobased chemicals, improving terrestrial sequestration of carbon dioxide, and reducing methane emissions from landfills and livestock. Table 9-1 describes twenty cross-cutting strategic research areas and identifies the climate change technology goals that depend on their success.

This broad agenda of strategic research is inspired by the technical challenges of specific climate change technologies. If adequately funded, research will successfully convert many of today's emerging technologies into cost-competitive and attractive products and practices. However, to address the century-scale problem of climate change, scientific breakthroughs will be needed to broaden the range of today's options. The next section (9.2) describes the role of fundamental research, which enriches the underlying foundation of scientific knowledge necessary for problem-solving. Attention then turns to the novel approaches, advanced, integrative, and enabling concepts that fall under the category of "exploratory research" (Section 9.3).



Nanoscience Research for Energy Needs (DOE-BES-NSET 2005)

9.2 Fundamental Science

At the outset of the 21st century, science is in the midst of an information revolution that is bringing on the rapid development of many new and promising discoveries across a variety of fields. In addition, the rapidly developing global infrastructure for computing, communications, and information is expected to accelerate scientific processes through computational modeling and simulation and to reduce the time and cost of bringing new discoveries to the marketplace. These potential discoveries and infrastructure developments portend a rapid advancing of capabilities to further the development of CCTP technologies. Fundamental research is needed in the following areas, which are representative of the opportunities afforded and serve as a reminder of the importance of sustained leadership and continued support of the pursuit of fundamental scientific knowledge.

Physical Sciences

Many of the advances in lowering energy intensity stem from developments in the materials and chemical sciences, such as new magnetic materials; high strength, lightweight alloys and composites; novel electronic materials; and new catalysts, with a host of energy technology applications. Two remarkable explorations—observing and manipulating matter at the molecular scale, and understanding the behavior of large assemblies of interacting components—may accelerate the development of more efficient, affordable, and cleaner energy technologies. Nanoscale science research—the study of matter at the atomic scale—will enable structures, composed of just a few atoms and molecules, to be engineered into useful devices for desired characteristics such as super-lightweight and ultra-strong materials. The 2004 *National Nanotechnology Initiative Workshop* report describes many of these opportunities (DOE-BES-NSET 2005).

Cross-Cutting Strategic Research Areas

Goal 6: Basic Rearch		Goal 1: Energy End Use				Goal 2: Energy Supply					Goal 3: Capture & Sequestration			Goal 4	Goal 5
Fundamental Research Area	**Strategic Research Area**	Transportation	Buildings	Industry	Grid	Fossil	Hydrogen	Renewable	Nuclear	Fusion	Capture	Geo-Storage	Terrestrial Sequestration	Non-CO_2 Gases	Measurement and Monitoring
Physical Sciences	Materials: High Temperature	Potential	Potential	Central	Not expected	Central	Expected	Expected	Central	Central	Potential	Potential	Not expected	Potential	Expected
	Materials: Tailored Mechanical Chemical Properties	Central	Central	Central	Central	Central	Central	Central	Central	Expected	Expected	Potential	Not expected	Expected	Central
	Materials: Tailored Electrical Magnetic Properties	Expected	Central	Central	Central	Expected	Expected	Expected	Potential	Central	Potential	Not expected	Not expected	Expected	Central
	Heat Transfer & Fluid Dynamics	Potential	Expected	Expected	Potential	Central	Expected	Expected	Central	Central	Expected	Expected	Not expected	Potential	Potential
	Combustion	Expected	Potential	Expected	Not expected	Central	Expected	Expected	Not expected	Not expected	Not expected	Not expected	Not expected	Expected	Not expected
	Chemistry (Electro, Thermo)	Central	Expected	Expected	Central	Central	Central	Central	Expected	Expected	Potential	Not expected	Potential	Expected	Expected
	Chemistry (Photo, Radiation)	Potential	Expected	Expected	Potential	Potential	Central	Central	Central	Central	Not expected	Potential	Potential	Expected	Expected
	Membranes & Separations	Expected	Potential	Central	Not expected	Central	Central	Potential	Expected	Not expected	Central	Potential	Not expected	Central	Not expected
	Condensed Matter Physics	Potential	Expected	Expected	Central	Expected	Expected	Expected	Potential	Central	Not expected	Not expected	Not expected	Potential	Expected
	Nanosciences	Expected	Expected	Potential	Expected	Expected	Central	Expected	Potential	Potential	Potential	Potential	Not expected	Potential	Potential
	Geosciences & Hydrology	Not expected	Not expected	Not expected	Not expected	Expected	Not expected	Central	Expected	Not expected	Potential	Central	Expected	Not expected	Potential
	Chemical Catalysis	Central	Not expected	Central	Not expected	Expected	Central	Expected	Potential	Not expected	Expected	Potential	Expected	Expected	Potential
Biological Sciences	Bio-Catalysis	Central	Not expected	Central	Not expected	Potential	Central	Central	Not expected	Not expected	Potential	Potential	Central	Expected	Not expected
	Plant and Microbial Genomics (Biotechnology)	Central	Not expected	Central	Not expected	Not expected	Expected	Central	Not expected	Not expected	Not expected	Not expected	Central	Expected	Expected
	Bio-Based & Bio Inspired Processing	Expected	Not expected	Expected	Not expected	Not expected	Expected	Central	Not expected	Not expected	Not expected	Not expected	Central	Central	Expected
Environmental Sciences	Environmental Science	Potential	Expected	Expected	Potential	Expected	Expected	Expected	Potential	Not expected	Expected	Expected	Central	Central	Expected
	Atmospheric Science	Not expected	Not expected	Potential	Not expected	Not expected	Not expected	Potential	Not expected	Not expected	Expected	Potential	Expected	Expected	Central
Advanced Scientific Computing	Computational Sciences (Models & Simulations)	Central	Expected	Expected	Central	Expected	Expected	Central	Central	Central	Central	Central	Central	Expected	Central
Fusion Sciences	Plasma Sciences	Not expected	Potential	Expected	Potential	Not expected	Not expected	Not expected	Not expected	Central	Not expected	Not expected	Not expected	Expected	Not expected
Enabling Research	Strategic Research for Sensors & Instrumentation	Expected	Central	Central	Central	Central	Expected	Expected	Central	Expected	Central	Central	Expected	Central	Central

Central: A strategic research area that is **central to advancing** the technology approach.

Expected: A strategic research area that is **expected to contribute significantly** to the technology approach.

Potential: A strategic research area that has the **potential to contribute significantly** to the technology approach.

Not expected: A strategic research area that is **not expected to contribute** significantly to the technology approach.

Table 9-1. Cross-Cutting Strategic Research Areas

Underpinning these basic research explorations are the powerful tools of science, including a suite of specialized nanoscience centers and the current generation synchrotron x-ray and neutron scattering sources, terascale computers, higher resolution electron microscopes, and other atomic probes. Fundamental research in the physical sciences includes research in material sciences, chemical sciences, and geosciences, all of which are described in more detail below.

- **Materials sciences** research helps in the development of energy generation, conversion, transmission, and use. Research currently being conducted by the U.S. Department of Energy (DOE) and relevant to climate-related technology involves fundamental research for the development of advanced materials for use in fuel cells, exploration of corrosion and high-temperature effects on materials with potential cross-cutting impacts in both energy generation and energy use technologies, investigations of

Nanoscale Materials Science

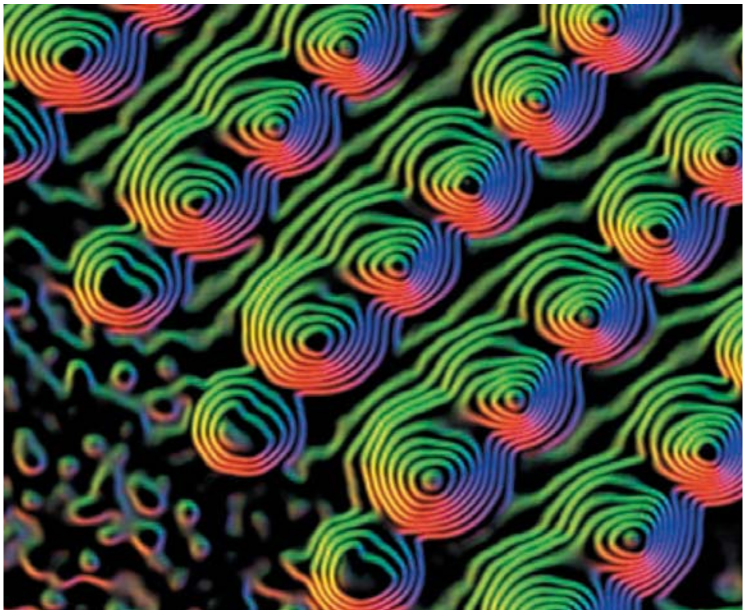


Figure 9-6. Nanoscale materials science contributes to the design of materials and devices at the atomic and molecular level to achieve entirely new functionality.

Courtesy: DOE, Office of Science

radiation-induced effects relevant to nuclear fission and fusion technologies, fundamental research in condensed matter physics and ceramics that might lead to high-temperature superconductors and solid-state materials, chemical and metal hydrides research related to hydrogen storage, and nanoscale materials science (Figure 9-6) and technology that offer the promise of designing materials and devices at the atomic and molecular level to achieve entirely new functionality.

- **Chemical sciences** research provides the fundamental understanding of the interactions of atoms, molecules, and ions with photons and electrons; the making and breaking of chemical bonds in gas phase, in solutions, at interfaces, and on surfaces; and the energy transfer processes within and between molecules. The fundamental understanding resulting from this research—an understanding of the chemistries associated with combustion, catalysis, photochemical energy conversion, electrical energy storage, electrochemical interfaces, and molecular specific separation from complex mixtures—could result in reductions in carbon dioxide emissions. Advances in chemical sciences will enable the development of hydrogen as an energy carrier; new alternative fuels; low-cost, highly-active, durable cathodes for low-temperature fuel cells; separations and capture of CO_2; catalysts for new industrial and energy processes; and better energy storage devices. Being at the interface of materials and biology, chemical sciences will also be key to bio-inspired materials and processes.

- **Geosciences** research supports mineral-fluid interactions; rock, fluid, and fracture physical properties; and new methods and techniques for geosciences imaging from the atomic scale to the kilometer scale. The activity contributes to the solution of problems in multiple Federal agency mission areas, including development of the scientific basis for evaluating methods for sequestration of CO_2 in subsurface regions; for the discovery of new fossil resources, such as oil and gas, and methane hydrates; and for techniques to locate geothermal resources, to map and model geothermal reservoirs, and to predict heat flows and reservoir dynamics. The nanoscience capabilities of geochemistry are answering fundamental questions involving the electric double layer, which occurs at the interface of electrolytes.

Biological Sciences

The revolution in genomics research has the potential to provide entirely new ways of producing forms of energy, sequestering carbon, and generating materials that require less energy to produce. It includes research to investigate the underlying biological processes of plants and microorganisms, potentially leading to new processes and products for energy applications, thereby enabling the harnessing of natural processes for GHG mitigation. Research includes:

- **Genomic research on microbes** focusing on their ability to generate, harvest, store, and manipulate energy-supplying compounds in almost any form to carry out life's functions. Current genomic research is focused on sequencing microbes that either aid in carbon sequestration or produce fuels, particularly ethanol or hydrogen.

- **Genomic research on plants**—for example, on the genome of Poplar, a common tree species—is identifying genes that determine key biochemical functions which could improve the ability of these trees to sequester carbon in their root systems or produce biofuels more efficiently. Selecting, propagating, and modifying crops specifically for soil carbon sequestration (i.e., below-ground storage) would accelerate carbon fixation while minimizing terrestrial impacts because harvesting would not be necessary. Other crops could be modified to produce more lipids and other useful products. Fast-growing crops could be modified to improve bioconversion.

- Research on **biological catalytic reactions** aims to improve the understanding of reactions in photoconversion processes and advanced techniques for screening and discovering new catalysts and biomemitic approaches to materials synthesis. This research could provide insights into biochemical regulatory interventions that could improve the rate or efficiency of these processes.
- Research related to modified **plants and soil micro-organisms** can provide a basis for using and renewing marginal lands for bio-based energy feedstocks, incorporating stress-resistant plants and microbes, and developing advanced bioengineering approaches to capturing and retaining nitrogen and other essential plant nutrients. Sustainability could be ensured by engineering traits such as increased below-ground storage of photosynthate.
- **Biotechnology** has the potential to provide the basis for direct conversion of sunlight into hydrogen, lipids, sugars, and other fuel precursors. Work in this field can accelerate an understanding of fundamental aspects of microbial and plant production systems, including thermophilic, algal, and fermentative approaches.
- New **bio-based industrial processes** can be developed, involving combining biological functionality with nano-engineered structures to achieve new functionalities and phenomena. Incorporating biological molecular machines (such as elements of photosynthetic chromophores) into nanostructures has the potential to achieve the selectivity and efficacy of biological processes with the high intensity and throughput of engineered processes.
- **Advanced structural biocomposites research** could help replace high-energy-intensity material such as concrete and steel with renewable carbon-based natural products.
- Research on key **biotechnology platforms** includes designs for biorefineries to produce biofuels, biopower, and commercial chemical products derived from biomass rather than fossil fuels; fuel cells powered by bio-based fuels or bio-generated hydrogen; engineered systems to support processes such as direct photo-conversion utilizing bio-based processes of water, CO_2, and nitrogen to produce useful fuels; and small modular biopower systems for incorporation of biological processes.

Environmental Sciences

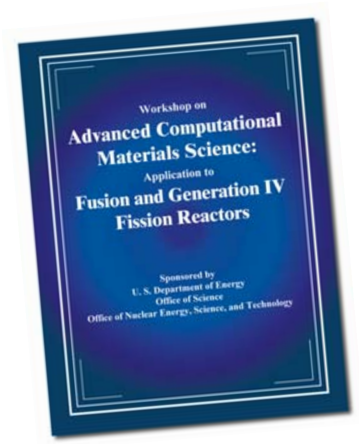
Research in the environmental sciences is rapidly evolving with the development and application of new tools for measuring and monitoring environmental processes both *in situ* and remotely at scales never before possible. These new tools will provide data on the functioning of ecological systems, including the provision of goods and services such as sequestering carbon and how they are affected by environmental factors. Genomics research is and will continue to contribute to the advances in environmental sciences by providing understanding of the fundamental processes, structures, and mechanisms of complex living systems, including ecological systems. Examples of such fundamental research include the following:

- **Carbon sequestration research** could identify how efforts to increase terrestrial carbon sequestration might influence other environmental processes, such as nutrient cycling, the emissions of other GHGs, and local, regional, and global climate through impacts on heat balances and albedo (Figure 9-7);
- In **biological and ecological systems** there is a need to understand, quantify, predict, and manage biological and ecological processes affecting carbon allocation, storage, and capacity in terrestrial systems;

Free-Air CO_2 Enrichment Facility

Figure 9-7. Carbon sequestration research, such as that being conducted at the Free-Air CO_2 Enrichment Facility, can help to identify how efforts to increase terrestrial sequestration might influence other environmental processes.

Courtesy of DOE, Office of Science



Advanced Computerized Materials Science (DOE-SC-NEST 2004)

- Research can be focused on the development of sensors that allow **measuring and monitoring** of environmental carbon flows. Computational models can be developed that can simulate and predict carbon flows resulting from, for example, specific carbon management policy actions and that provide a consistent picture of the effectiveness of efforts to reduce anthropogenic emissions; and
- Research can be conducted on **indoor air quality** and its inter-relationship with other buildings-related environmental factors, so as to understand the possible ramifications of increasing the energy efficiency of buildings.

Advanced Scientific Computation

Computational science is increasingly central to progress at the frontiers of almost every scientific discipline. The science of the future demands advances beyond the current computational capabilities. Accordingly, new advanced models, tools, and computing platforms are necessary to dramatically increase the effective computational capability available for scientific discovery in such areas as fusion, nanoscience, climate and environmental science, biology, and complex systems. With advances in computation, its role will become even more central to a broad range of future discoveries and subsequent innovations in climate change technologies. Examples of areas in which exploratory modeling and simulation research are being employed to assist in the development of advanced energy systems include the following:

- Modeling and simulation of advanced fusion energy systems to support ITER and the National Ignition Facility (NIF).
- Modeling of combustion for advanced diesel engines and other combustion systems; modeling of heat transfer in thermoelectric power systems.
- Modeling and simulation of nanoscale systems, including thin-film polymer-based photovoltaics. The computational effort required to simulate nanoscale systems far exceeds any computational efforts in materials and molecular science to date.
- Improved models of the aerodynamics of wind turbines and other fluid dynamics processes.
- 3D computational fluid dynamics modeling for next-generation nuclear reactors. This should include coupling of neutronics physics to heat transfer and fluid dynamics, as well as 3D models for critical heat flux or dry-out prediction. Significant validation will be required for such powerful models to be used in a regulatory environment.
- Further development of tools to model gasification accurately and reliably. This should include multiphase model development to improve computational efficiency for the unsteady flows found in gasification combustion systems. Ash, slagging, and fouling are some of the most important technical challenges facing gasification systems, and the relevant computational fluid dynamics models need to be developed and validated to better understand these chemical processes.
- Integrated assessment models of global climate change.

The 2004 *Advanced Computational Materials Science Workshop* report describes how an increased effort in modeling and simulation could help bridge the gap between the data that is needed to support the implementation of advanced nuclear technologies and the data that can be obtained in available experimental facilities (DOE-SC-NEST 2004).

Fusion Sciences

The majority of fusion energy sciences research is aligned, generally, with the goal of providing the knowledge base for environmentally and economically attractive energy sources (summarized in Section 9.1.2); the remainder of the basic research is fundamental in nature. This research includes general plasma sciences, the study of ionized gases as the underpinning scientific discipline for fusion research, through university-based experimental research, theory, plasma astrophysics, and plasma processing and other applications. See also Section 5.5.

9.3 Exploratory Research

Typically, applied R&D programs, as described in Chapters 4 through 8, focus on well-defined research projects and deployment activities designed to achieve results-oriented, specific metrics and meet deadlines. As described in Section 9.1, strategic research has a long-term, basic research focus, yet it is still oriented toward and inspired by the need to understand and contribute to solving problems associated with currently supported technology development thrusts. To meet the challenges associated with the CCTP goals, there is another need, that is, to augment existing applied R&D and strategic research programs with exploratory research. Such research would pursue novel, advanced or emergent, enabling and integrative concepts that do not fit well within the defined parameters of existing programs, and are not elsewhere covered.

Exploratory research would not duplicate, but complement, and potentially enrich, the existing R&D portfolio of climate-change-related strategic research and applied technology R&D. If the explored concepts proved meritorious, it would be expected that they would then become better positioned to be considered favorably in future plans among the existing Federal R&D programs, or form the basis for new R&D programs. This approach would stimulate innovative, novel, or cross-cutting technical approaches, not predisposed to one technology or another, and ensure that a full measure of the most promising technology options was explored.

CCTP plans to review agency experiences with exploratory research programs, including those of the Defense Advanced Research Projects Agency, and encourage the pursuit of exploratory approaches, as appropriate, within the Federal climate change technology portfolio. An exploratory research program would be expected to support research to explore novel "out-of-the-box" transformational technologies. Projects would be selected through widely advertised competitive solicitations. Awards would be made through merit-based grants, cooperative agreements, and contracts with both public and private entities, including businesses, Federal research and development centers, and institutes of higher education. Multi-agency coordination might be required for integrative ideas that span technical disciplines and economic sectors. Exploratory research conducted under such a program could add to scientific and engineering knowledge and contribute to U.S. technological leadership, while addressing long-term challenges in global warming.

Some important generic areas for exploratory research include novel, advanced, integrative, and enabling concepts, as elaborated upon below. Exploratory research also includes the development of decision-support tools to assess and better understand the role, impacts, and potential limits of technology in meeting CCTP goals.

Novel Concepts

Novel concepts, by definition, are "atypical" ideas. They often do not have funding support within the boundaries of traditional research and development organizations or other means to demonstrate their potential applications and value. They may build on scientific disciplines outside the usual disciplines in that field or attempt to apply previously unexplored methods, and may offer approaches that compete with the more traditional approaches already being pursued. These novel approaches may lead to better ways to reduce GHG emissions, reduce GHG concentrations, or otherwise address the effects of climate change.

Novel concepts might include, for example, innovative ways to produce or convert energy (e.g., high-altitude wind kites, direct energy conversion, immiscible liquid/liquid heat exchangers). Novel concepts might be used to mitigate the effects of global warming in the stratosphere (e.g., geo-engineered solar insulation) or sequester carbon (e.g., enhancement of the natural carbon cycle, or microbial fixation of carbon in geologic formations). Another approach might be to combine the biosciences with fields such as nanotechnology, chemistry, computers, medicine, and others (e.g., Bio-X) to create novel solutions for technology challenges. This could lead to innovative concepts such as the use of "enzyme machines" or even new materials (e.g., bio-nano hybrids) that could replace traditional technology altogether (Figure 9-8). Spaceborne measurements of the Earth system from the Lagrange points or other non-traditional orbits are another novel concept that could advance our understanding of regional and global GHG distributions.

Advanced Concepts

Advanced concepts are high-risk, long-term ideas that are often too risky or unconventional for applied R&D programs to support, but are also often too purposeful or applied for basic research programs to support. These ideas draw upon conventional scientific disciplines and concepts but seek to take them beyond the realm of current capabilities. Over the long-term, the pursuit of advanced concepts in such fields as solar energy, biotechnology, ocean and tidal energy, and other fields could lead to dramatic changes in the way we produce and use energy.

For example, advanced concepts are emerging in the field of biotechnology and could be applied to the production of bioenergy as well as methods for sequestering carbon. Plant metabolic engineering could be used to improve the properties of plants for conversion to bioenergy, or to increase the storage of photosynthates as hydrocarbons that could be extracted as energy. Advances in plant genomics could be utilized to develop new crop species that maximize soil carbon storage in marginal lands, or to convert annual crops to perennial crops to facilitate carbon sequestration and provide more viable feedstocks for bioenergy. Further, the natural chemical reactivity of CO_2 could be exploited to remove CO_2 from the air or from waste streams, while forming stable, storable carbon compounds or useful products.

Advances in other areas might include solar fuels derived from carbon dioxide via artificial photosynthetic systems. Alternatively, solar-powered photo-catalyzed systems could be developed to produce liquid transportation fuels from hydrogen and carbon dioxide. Energy could potentially be derived from wave and tidal power conversion systems using slow wave motion, or from tidal dams producing energy based on ebb tides.

Integrative Concepts

Integrative concepts cut across traditional R&D program boundaries and combine systems, technologies, disciplines, and in some cases, sectors of the economy. For example, a net-zero GHG emission building could integrate energy for heating, cooling, and lighting with on-site power production for an electric vehicle. Developing such integrative concepts is an interdisciplinary, complex undertaking and would involve coordination across multiple agencies or across existing R&D program or mission areas. A more concerted effort might be needed to explore these concepts and manage multi-mission R&D. The combing of multiple concepts into integrated, more efficiently functioning systems could, however, have potentially large implications for climate change and should be encouraged.

Integrative concepts might include, for example, the combination of coal power and aquifer sequestration, or biochemical and thermochemical conversion of biomass. Also, an integrated process that converts biomass wastes into hydrogen fuel and a char-based fertilizer (sequestering carbon), while scrubbing CO_2 and other flue gases, may have potential. Another example is engineered urban design, where land use is designed to reduce vehicle-mile requirements and allow co-location of activities with common needs for conserving energy, water, and other resources. The integration of transport, electricity, residential and commercial buildings, and industrial complexes within communities is a potential way to optimize the use of energy and reduce GHGs through co-location of energy sources and sinks. A related concept is the integration of plug-in hybrid electric vehicles with wind, solar, zero-energy buildings, and utility peak-saving, which could dramatically reduce GHGs from vehicles and optimize use of intermittent energy sources such as solar and wind.

Energy used to support the water infrastructure is another area where integration of systems could be beneficial. Technologies to minimize energy requirements for water use could include, for example, buildings designed to reduce use and conveyance of water; gray-water re-use; and integration of water storage and treatment with intermittent renewable energy supplies.

Enabling Concepts

Enabling technologies contribute indirectly to the reduction of GHG emissions by facilitating the development, deployment, and use of other important technologies that reduce GHG emissions. Enabling technologies often represent the scientific and engineering breakthroughs needed to move next-generation concepts forward along the development cycle. In addition, enabling technologies often cut across multiple disciplines and can lead to the diffusion of new concepts in multiple areas.

Enabling technologies may span or be applicable to many aspects of energy end-use, supply, and GHG mitigation and sequestration, from power generation to instrumentation to separations, new materials, and storage. For example, enabling technology is needed to support a next-generation electricity grid and supply a potential nationwide fleet of hybrid electric vehicles. Such research might encompass the development of electrochemical, kinetic, thermal, or electromagnetic storage systems. Enabling technology (e.g., electron transmission via nanotubes) is also needed to make low-resistance power transmission possible without the use of cryogenics. Similarly, wireless transmission of electrical energy—or power beaming—would enable large solar-based energy conversion systems to be located far distances from population centers, such as in the Earth's deserts, in low-Earth orbit, outer space, or even on the moon, and still supply large quantities of energy to where it would be needed on Earth. Two technologies that might be pursued under this category of exploratory research suitable for power beaming involve microwave or laser energy.

Research to develop breakthrough processing technology will be needed to take advantage of emerging fields with great promise, such as nanotechnology. Exploratory research might include the integration of nanotechnology with engineering and other disciplines, joining technologies for new nanomaterials, and advanced processing technologies for nanomaterials and nano-bioengineering systems. Advances in these areas could enable the greater use of nanomaterials in applications that could lead to reduction and/or mitigation of GHG emissions.

Integrated Planning and Decision-Support Tools

Decision-support tools include analytical, assessment, software, modeling, or other quantitative methods for better understanding and assessing the role of technology in long-term approaches to achieving stabilization of GHG concentrations in the atmosphere. While individual R&D programs sponsor the development of such tools, the tools developed are applicable mainly within each program's respective areas of responsibility or technologies. Broader analytical tools can provide intelligence for integrated planning and making research decisions that span disciplines, industries, and agencies.

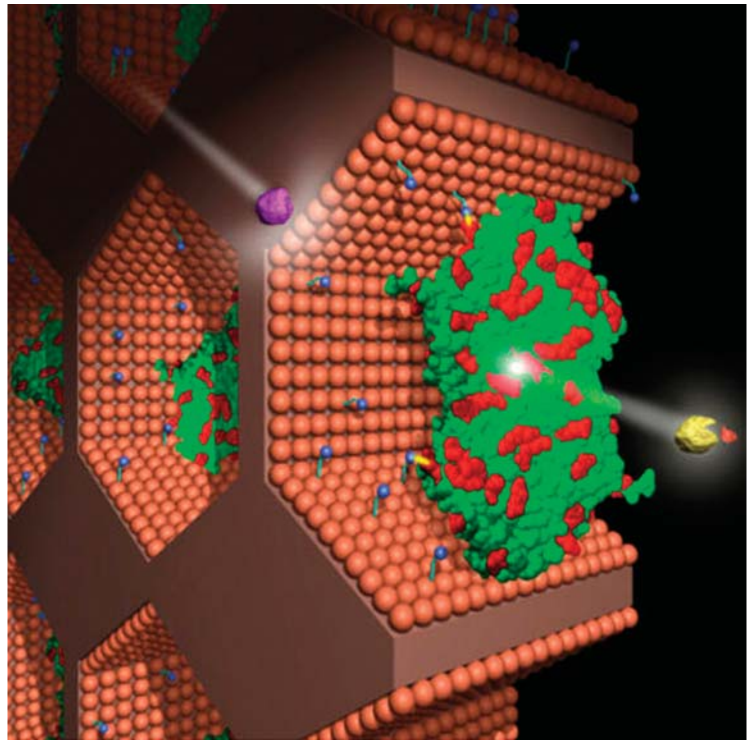


Figure 9-8. Nanoscale research to develop breakthrough processing technology can lead to greater use of nanomaterials in advanced technologies that reduce or mitigate GHG emissions. One such example is shown above, where stable enzymes are embedded in a biomimetic nanomenbrane.

Credit: DOE/PNNL

An important evaluation tool is the analysis of the net environmental benefits of various climate change technologies (i.e., bringing science to the decision process). Understanding the response of the environment and long-term impacts can influence how the research portfolio will be structured to achieve the maximum benefits. Lifecycle analysis is another important assessment tool. Guidelines and standards are needed to develop lifecycle analysis that examines carbon flux, land use, energy use, economics and other factors related to the adoption of technologies that could potentially impact climate change. Along with lifecycle analysis, ecosystem models are needed to integrate improved genetics and metabolic processes for land use, CO_2 fixation, and soil processes.

An integrated system architecture approach for GHG M&M across varying spatial and temporal scales would provide a framework for assessing and implementing GHG reduction strategies.

9.4 Toward Enhanced Integration in R&D Planning Processes

Effective integration of fundamental science, strategic research, exploratory research, and applied technology research and development presents challenges and opportunities for any mission-oriented research campaign. These challenges and opportunities can be addressed by CCTP through enhanced and integrative R&D planning processes that emphasize communication, cooperation, and collaboration among the affected scientific and technical research communities. Appropriate means for regularly assessing the success of basic research in supporting the technology development programs also need to be established, including criteria, to ensure that basic research is a productive, indeed, enabling component of the larger CCTP R&D portfolio.[1]

Technology development programs are often hindered by incomplete knowledge and lack of innovative solutions to technical bottlenecks. Information can be shared and potential pathways to solutions can be suggested by bringing together multidisciplinary research expertise and applied technology developers. Increased discussion among research personnel from various complementary fields and face-to-face exploration of ideas is a good way to foster innovative ideas and create synergies. The traditional structure of research, operating mainly within the narrower confines of specific disciplinary groups, will not be sufficient.

A model integrated planning process would include the following:

- Systematic exploration of various technology program issues, challenges and impediments to progress.
- Mechanisms to communicate technology program needs to the basic research community.
- Exploration of a wide range of potential research avenues to address the identified issues, challenges and impediments; this can effectively be accomplished through an R&D or technology roadmapping activity.
- Design of strategic research program areas to pursue the most promising avenues, including clear articulation of research goals.
- Solicitations of research proposals to address the identified areas.
- Funding of specific meritorious research projects, selected by a peer review process.

The first few steps in the model process described above could be accomplished using workshops and other multi-party planning mechanisms. Technical workshops can bring together the applied and basic research communities and focus on research strategies and barriers impeding development in a particular technology area. The resulting report can form the basis for a framework of high priority research needs, a solicitation for proposals, and awards.

For instance, in recognition of the growing challenges in the area of energy and related environmental concerns, the Department of Energy's Office of Basic Energy Sciences (DOE-BES) initiated a series of workshops in 2002 focusing on identification of the underlying basic research needs related to energy technologies. The first of these workshops, held in October 2002, undertook a broad assessment of basic research needs for energy technologies to ensure a reliable, economical, and environmentally sound energy supply for the future (BESAC 2003). More than 100 people from academia, industry, the national laboratories, and Federal agencies participated in this workshop.

More than a dozen such workshops have been held since 2002. Many apply directly to goals and

Basic Research Needs fto Assure a Secure Energy Future (BESAC 2003)

[1] Criteria for "success" in basic research are well established, as are the multiple modes for evaluating related programs and projects. Such evaluations occur continuously in both pre-award and post-award settings.

technical challenges of CCTP. A number of these are cited throughout this chapter. More are scheduled for the near future, including basic research needs for superconductivity (2006); solid-state lighting (2006); advanced nuclear energy systems (2006); and energy storage (2007).

CCTP seeks to encourage continued and broadened application, across all agencies, of best practices in integrated research planning. In its periodic reviews of the adequacy of the CCTP R&D portfolio, CCTP identified a number of topical areas for consideration, in addition to those already planned, for future basic research needs assessments in support of CCTP technology development. These areas include: architecture and control systems for the electric grid; thermoelectrics by application (e.g., refrigeration, power generation); "bio-x", combining nanosciences and genomics; plant genetic engineering; measuring and monitoring of climate change mitigation, with an international focus; sensors, controls, and communication technologies; batteries–power & energy (basic chemistry); heat transfer–material insulation, cryogenics, thermal conducting coolants; power electronics–conversion; and ocean sequestration of carbon dioxide.

Based on the experiences of past and successful workshops held by the Office of Science, Basic Energy Sciences, and Biological and Environmental Research, the following principles are identified to help guide future planning:

- **Make Merit-Based Decisions:** All decisions should be based on merit and need. Once this principle is compromised, the process degenerates quickly.
- **Share Ownership:** Long-term commitment and ownership by those in positions of authority and responsibility is a must for success.
- **Understand and Formalize Relationships:** Roles, responsibilities, rules of integration, allocation of resources, and terms of dissolution should be formalized at the start.
- **Measure Performance:** At the start, participants must agree on goals, objectives, operational elements, and methodology for measuring progress, outputs, and outcomes. (Avoid collaboration for collaboration's sake and integration for integration's sake.)
- **Ensure Commitment and Stability:** Team members must commit to work seamlessly, with the goal of a stable operation for the time necessary to achieve results.
- **Provide Flexibility:** Within general guidelines, flexibility ensures accountability and fosters innovation and experimentation. The process must allow for unanticipated results and empower people to act on their own.
- **Have a Customer Focus:** A clear understanding of who the customer is, what the customer wants, and the customer's complete involvement in all phases of the activity is critical to success.

Achieving the CCTP vision will likely require discoveries and innovations well beyond what today's science and technology can offer. Better integration of basic scientific research with applied technology development may be key to achievement of CCTP's other goals related to energy efficiency, energy supply, carbon capture and sequestration, M&M, and reducing emissions of non-CO_2 gases. Basic science research is likely to provide the underlying knowledge foundation on which new technologies are built.

The CCTP framework aims to strengthen the basic research enterprise so that it will be better prepared to find solutions and create new opportunities. The CCTP approach includes strengthening basic research in national laboratories, academia, and other research organizations by focusing efforts on key areas needed to develop insights or breakthroughs relevant to climate-related technology R&D. Importantly, in the process, these basic research activities will enable training and developing of the next-generation of scientists who will be needed in the future to provide continuity of such research to find solutions and create new opportunities.

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