9 Bolster Basic Science Contributions to Technology Development

The challenge of encouraging and sustaining economic growth, while simultaneously reducing GHG emissions, calls for the development of an array of new and advanced technologies. Such an undertaking depends on and can be assisted significantly by new scientific knowledge arising from basic research. Chapters 4 though 8 of this *Plan* present a number of technology research and development (R&D) activities believed to be important to technological progress and attainment of Climate Change Technology Program (CCTP) strategic goals. Each technology area appearing in these chapters is associated with a technology strategy for development, replete with highlighted activities, links to ongoing R&D programs, and the identification of promising areas for future research.

All of these technology development activities could potentially benefit from basic research in underlying scientific and technical disciplines. Fundamental discoveries can reveal new properties and phenomena that can be applied to development of new energy technologies and other important systems. These can include, but are not limited to, breakthroughs in understanding of biological functions, properties and phenomena of nano-materials and structures, computing architectures and methods, plasma sciences, environmental sciences, and many more that are currently on the horizon.

Of CCTP's seven core approaches to be followed in pursuit of its six strategic goals, one of the most important for advancing R&D is to strengthen basic research in Federal research facilities and in universities. A strong and creative basic research program can nurture this strengthening. It can also give rise to knowledge and technical insights necessary to enable technical progress throughout CCTP's portfolio of applied R&D, explore novel approaches to new challenges, and bolster the underlying knowledge base for new discoveries.

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

- **Fundamental Research**: Fundamental research is basic research that provides the underlying foundation of scientific knowledge and understanding necessary for carrying out more applied activities of research and problem solving. It is the systematic study of properties and natural behavior that can lead to greater knowledge and understanding of the fundamental aspects of phenomena, properties, 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 the source of much 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 R&D programs. This is research that could lead to fundamental discoveries (e.g., new properties, phenomena, or materials) or scientific understanding that could be applied to solving specific problems or technical barriers impeding progress in technology development in energy supply and end-use, carbon capture, storage and sequestration, non-CO_2 GHGs, and monitoring and measurement. This "strategic" research applies knowledge gained from more fundamental science research to the more practical problems associated with technology R&D.

- **Exploratory Research**: Exploratory research is basic research undertaken in the pursuit of novel or emergent concepts, not elsewhere covered, that are often too risky or multi-disciplinary for a particular R&D program to support. Many such novel approaches are pursued within existing R&D programs, but sometimes new concepts do not fit neatly within the constructs of the existing mission-specific programs. Therefore, not all of the research on innovative concepts for climate-related technology is, or should be, aligned directly with an existing Federal R&D mission-related program. This *Plan* calls for new breakthroughs in technology development that could 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", strengthen the community, and broaden the R&D portfolio.

- **Integrated Planning**: Effective integration of fundamental research, strategic research, exploratory research and applied technology 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 and integrative planning processes that place emphasis on communication, cooperation and collaboration among the many associated communities. CCTP strongly encourages and plans to build on the successful models and best practices in this area.

This chapter discusses the potential research contributions to climate-related technology development of each of the above categories. Section 9.1, *Fundamental Research*, describes the basic science that provides the underlying scientific knowledge needed to underpin other research. Section 9.2, *Strategic Research in Support of Technology R&D Programs*, describes the basic science underway or planned that explores the key technical challenges associated with the five strategic goals discussed in Chapters 4 through 8. Section 9.3, *Exploratory Research on Innovative Concepts and Enabling Technologies*, addresses the basic research of novel concepts and others areas that are important to the climate change technology development agenda, but not elsewhere covered. Finally, CCTP recognizes that clarifying and communicating research needs of the applied technology R&D programs will help the basic science programs plan and focus future efforts in key areas of need. Therefore, Section 9.4, *Toward Enhanced Integration in R&D Planning Processes*, describes an approach to better integrating basic research with the applied programs related to climate change technology.

9.1 Fundamental Research

At the outset of the 21st century, science appears to be on the threshold 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 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 in the following areas is representative of the opportunities afforded and serves as a reminder of the importance of sustained leadership and continued support of the pursuit of fundamental scientific knowledge.

9.1.1 Physical Sciences

Many of the advances in lowering energy intensity have come 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. 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 crosscutting impacts in both energy generation and energy use technologies, investigations of 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, electro-chemistry research leading to better energy storage devices, chemical and metal hydrides research related to hydrogen storage, and nanoscale materials science (see Figure 9-1) and technology that offer the promise of designing materials and devices at the atomic and molecular level.

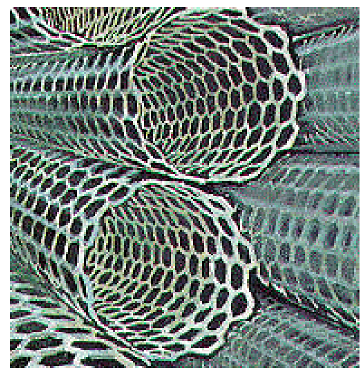

Figure 9-1. Carbon Nanostructure

- *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; and catalysts for new industrial and energy 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 DOE 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.

9.1.2 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 harvest, store, and manipulate energy 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.

- *Genomic research on plants*—for example, on the genome of Poplar, a common tree species—is characterizing key biochemical functions that could improve the ability of these trees to sequester carbon or produce biofuels.

- Research on *biological catalytic reactions* aims to improve the understanding of reactions in photoconversion processes and advanced techniques for screening and discovering new catalysts.

- Research related to *engineered plants and soil microorganisms* can provide a basis for use and renewal of 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.

- *Biotechnology* has the potential to provide the basis for direct conversion of sunlight into hydrogen. Work in this field can accelerate an understanding of fundamental aspects of microbial 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.

- Research on key *biotechnology platforms* includes designs for bio-refineries to produce bio-fuels, bio-power, 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 bio-power systems for incorporation of biological processes.

9.1.3 Environmental Sciences

Research in the environmental sciences is undergoing a revolution 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:

Figure 9-2. Free-Air CO_2 Enrichment (FACE) Facility

- *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 9.2).

- In *biological and ecological processes* there is a need to understand, quantify, predict, and manage biological and ecological processes affecting carbon allocation, storage, and capacity in terrestrial systems.

- Understanding the *ocean biological pump* is important for identifying the biogeochemical mechanisms of conversion and transport of carbon between the atmosphere and surface waters, and between the surface waters and the deep ocean, as well as to identify key processes for carbon cycling in marine sediments and how those processes are coupled to the water column.

- 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.

- Research can be conducted on *indoor air quality* and its interrelationship with other buildings-related environmental factors, so as to understand the possible ramifications of increasing the energy efficiency of buildings.

9.1.4 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 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 are necessary. 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 (the computational effort required to simulate nanoscale systems far exceeds any computational efforts in materials and molecular science to date)
- Improved models of photovoltaics and other materials
- Improved models of the aerodynamics of wind turbines and other fluid dynamics processes
- Computer-assisted simulations of proposed advanced components and energy systems
- Predictive modeling of physical systems.

9.1.5 Fusion Energy Sciences

The majority of fusion energy sciences research is aligned, generally, with the goal of providing the knowledge base for an environmentally and economically attractive energy source (summarized in Section 9.2.2); 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.

9.2 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, the need for information on key processes, and the need for new instrumentation and methods. 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.
- 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 making, transforming, and using energy, or dramatically alter industrial processes.

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

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

9.2.1 Research Supporting Emissions Reductions from Energy End-Use and Infrastructure

There is a broad array of research that underpins emissions reductions from energy end-use and infrastructure, spanning the areas of transportation, buildings, industry, and electric grid and infrastructure. These areas of research include, but are not limited to, the following:

Transportation

Research on reducing vehicle weight while maintaining strength and safety includes *materials science* that improves efficiency, economy, environmental acceptability, and safety in transportation. Foci are ceramics and other durable high-temperature, wear-resistant materials and coatings, strong and lightweight alloys, polymers, and composite materials for structural components. *Joining and welding science* will enable the application of advanced materials.

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 desired properties, including innovative applications such as highly conductive nanofluids for lubrication and cooling.

Advanced fuel cell concepts and materials, including *membrane research* and *fuel cell stack materials* will improved the efficiency of fuel cells along with their performance, durability, and cost.

Electrochemistry research may lead to innovations in onboard energy storage.

For conventional and novel sources of power in mobile applications, *thermoelectric materials* and *energy conversion* cycles can be developed and made more efficient.

Research on intelligent transportation systems can include *complex systems science* for sustainable transportation; and *computational science* and *improved mathematical algorithms and models* for improved traffic handling/management and for science, design, and performance simulation.

For both combustion and other transportation energy sources, research on the *energetics of chemical reactions* and the interactions of *fluid dynamics and chemistry* 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.

Buildings

In improving energy efficiency in the building envelope, *corrosion science* can contribute to more durable materials and coatings for external applications. The *joining and welding sciences* will support fabrication and construction of energy-efficient envelopes. *Materials science* will have a broad range of impacts, from building insulation to transparent films for energy-efficient windows to new classes of lightweight structural materials.

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, 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 include the science behind *smart transistors* for energy-saving sensors and electronic devices, 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

A broad range of *materials research* (Figure 9-3) will lead to increased energy efficiency in industrial processes; areas of study include ion implantation, thin films, fullerenes, ceramics, alloys, composites, quasicrystals, welding and joining; foundations for nanomechanics and nano-to-micro assembly.

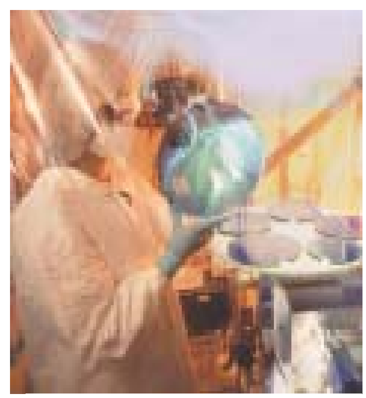

Figure 9-3. Use of Synchrotron Radiation for Materials Research

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

Exotic sensors and controls and *superconducting quantum interference devices (SQUIDS)* will provide feedback to systems and reduce energy use as situations change.

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

Electric Grid and Infrastructure

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. Other materials include *highly conductive high-strength nanowires; superlattices*; high-strength, lightweight *composites* and *corrosion-resistant materials; metallic glasses* for vastly improved transformers. *Silicon carbides* and *thin-film diamond switching* **devices** will improve performance and energy efficiency of power electronics and controls.

Electrochemistry research, including electrolytes, electrode materials, thin films, electrolytes, and interfaces, will improve commercial batteries.

Superconductivity research will make possible innovative storage devices.

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

9.2.2 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 nuclear fusion. Research in these areas includes the following:

Low-Emissions Fossil-Based Power

Since high temperatures result in lower-emissions combustion, *materials research* can contribute improved and new materials for high temperature, pressure, and corrosive environments.

Research in *sensors* and sensor materials will lead to improved monitoring and control of processes in fossil fuel combustion.

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

Catalysis research will find efficient pathways for use of fossil fuels, including a catalyst for petroleum refining and chemical manufacturing and catalysis of carbon-hydrogen bonds

Hydrogen

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 materials are needed for membranes, catalysts, and 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. In addition, biological enzyme catalysis, nanoassemblies and bio-inspired materials and processes are areas of basic research related to hydrogen production from biomass. Solar photelectochemisty and photocatalysis research may lead to breakthroughs in solar production of hydrogen, And, thermodynamic modeling, novel materials research and membranes and caalyst 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, nanofibers, and nanotubes.* For instance, research on complex metal hydrides 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 temperatuve memranes and tailored nnanostructures that basic science research could support.

Renewable Energy and Fuels

Biochemistry, *bioenergetics*, *genomics*, and *biomimetics* 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 design to develop microbes that can break down different types of complex biomass to sugars and ferment those sugars to ethanol or other fuels in a single microbe rather than the current two-step approach that uses enzyme cocktails for sugar production and yeast for fermentation. The research may lead to scientific breakthroughs in the design of a single microbe for making ethanol from cellulose. Similarly, basic research in *photochemistry* and *photocatalysis* will provide foundations for future, alternative processes for light-energy conversion, thin-film, and nanosciences research for photovoltaics, biofuels, and capabilities for microbial conversion. *Nanoscale hybrid assemblies* will enable the photo-induced generation of fuels and chemicals. *Plant genomic research* and function studies will make possible increased crop yields and disease resistance.

Geophysics and *hydrology* research will support a broad range of siting issues as well as hydro and geothermal power sources, e.g., mapping and monitoring geothermal reservoirs, and predicting heat flows and reservoir dynamics.

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

Research in *materials* and *composites* will lead to improved wind energy.

Research on key *biotechnology* platforms includes designs for biorefineries to produce biofuels, biopower, and commercial chemical products derived from biomass rather than fossil fuels.

Nuclear Fission Energy

Heavy element chemistry, advanced *actinide and fission product separations* and extraction, and *fuels research* will support better process controls in nuclear fission.

Fundamental research in *heat transfer* and *fluid flow* will lead to improve 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. Also 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 three-dimensional *dislocation dynamics studies*, and *welding and joining science* to reduce failure rates and improve verification/certification practices.

Geophysical research will support nuclear siting.

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

Fusion Energy

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, components, and technologies will be necessary to make fusion energy a reality.

A broad underpinning of *computational sciences* (Figure 9-4) will advance fusion research.

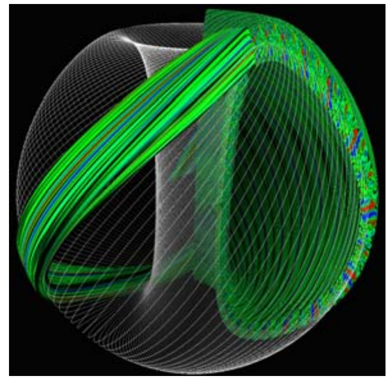

Figure 9-4. Magnetic Fusion Energy Simulation

9.2.3 Research Supporting Capture and Sequestration of Carbon Dioxide

Research on carbon capture and sequestration underpins the development of technologies and strategies for CO_2 capture and sequestration that are described in Chapter 6. Research areas include the following:

Carbon Capture and Storage in Geologic Repositories

Materials and *chemistry* research will enable separating CO_2 in stack gases, capturing it, and if needed, transforming it to another form of carbon that may be more useful.

Geophysics, *geochemistry*, and *hydrology* 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. Environmental science research can identify 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.

Modeling, *simulation*, and *assessment of geological repositories* are necessary to identify sites that have been or could be selected for use in sequestering CO_2 removed from industrial flue gases.

Basic *biological research* could lead to the development of technologies for enhancing the ability of trees to sequester carbon. For example, research on the genome sequence of black cottonwood, an important member of the widespread and important tree genus *Populus*, or poplar, is characterizing key biochemical functions.

Genomic research will develop 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 will develop 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.

Carbon Sequestration

Basic *biological research* could lead to the development of technologies for enhancing the biological capture of CO_2 directly from the atmosphere, including genomic research on algae and higher plants, such as *Populus*, with the objective of selecting or modifying strains to impart traits that result in, for example, increased rates of storage in relatively recalcitrant forms.

Research will discover the potential ancillary benefits and unintended consequences, and will provide the scientific foundation for quantifying and enhancing carbon sequestration in terrestrial ecosystems (in plant biomass and in soils).

Basic research on *ocean carbon sequestration* will aim to better understand the ocean biological pump and how it might be modified to enhance carbon sequestration in the ocean.

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 related to *engineered plants and soil microorganisms* can provide a basis for use and renewal of 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.

9.2.4 Research Supporting Emissions Reductions of Non-CO_2 Greenhouse Gases

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*, the *biological and environmental sciences*, and in *computational sciences*.

Work on *materials* and *chemistry* will lead to replacements for industrial processes that use non-CO_2 GHGs that have a high global warming potential.

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 nitrous oxide, 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.

9.2.5 Basic Research Supporting Enhanced Capabilities to Measure and Monitor Greenhouse Gases

There is a continuing need to develop more robust and sensitive sensors and monitoring systems to measure GHG emissions and concentrations and to understand the fate of GHGs released into the environment so that measurement and monitoring systems can be appropriately designed and sited to measure their fate. Such sensors need to be developed for making precise and accurate measurements in remote and/or hostile environments. Basic research in this area includes the following:

Various kinds of measurement for GHGs in the atmosphere are necessary. *Atmospheric physical and chemical processes* will lead to the observed vertical profiles of GHG concentrations due to surface emissions, while *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 three-dimensional, real-time mapping of atmospheric GHG concentrations. Specific technologies for *airborne remote sensing* will measure methane surface emissions at a 10-km spatial resolution.

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 and that provide a consistent picture of the effectiveness of efforts to reduce GHG emissions.

9.3 Exploratory Research

Typically, the applied R&D programs, as described in Chapters 4 through 8, focus on completing well-defined research projects to meet deadlines and achieve results-oriented, specific metrics. As described in Section 9.2, strategic research has a long-term, basic research focus, yet is still oriented toward and inspired by understanding and contributing to solving problems associated with currently-supported technology development thrusts. To meet the challenges associated with the CCTP goals, there is a need to augment existing applied R&D and strategic research programs with exploratory research aimed at pursuing novel concepts, not elsewhere covered, for meeting CCTP goals. Some important generic areas for exploratory research may include, but would not be limited to:

- *Novel concepts*. Novel concepts, by definition, are “atypical” ideas and do not have funding support within the boundaries of traditional R&D organizations. They may build on scientific disciplines outside the usual disciplines in that field or attempt to apply previously-unexplored methods, and they may offer approaches that compete with the more traditional approaches already being pursued.

Yet, such concepts may lead to better ways to reduce GHG emissions, reduce GHG concentrations, or otherwise address the effects of climate change.

- *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 too purposeful or applied for basic research programs to support. For example, advanced concepts may be emerging in the field of biotechnology. While development of biofuels (e.g., ethanol) could be considered an accepted applied technology R&D area, advanced biotechnology concepts might include attempts to unlock the potential of the biological processes of plants and microorganisms through a combination of genomics, chemistry, biotechnology and bioengineering.

- *Integrative concepts*. Integrative concepts cut across R&D program lines and attempt to combine technologies and/or disciplines. An example might be a scheme that combines sequestration of carbon in soils with the development of a novel form of bio-energy. Integrative concepts might be difficult to coordinate across agencies or across traditional R&D program or mission areas; hence more concerted effort might be required to explore such concepts and manage research in these multi-mission areas.

- *Enabling concepts*. Enabling technologies contribute indirectly to the reduction of GHG emissions by enabling the development, deployment, and use of other important technologies that reduce GHG emissions.

- *CCTP decision-support tools*. Such 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 thus developed are applicable mainly within their respective areas of responsibility or technologies.

Exploratory research on such areas, if not elsewhere covered among the existing Federal R&D programs, 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 exploratory research revealed promising concepts, CCTP would then recommend such concepts for future support within the existing Federal R&D program areas. CCTP plans to explore agency experiences with such exploratory research programs, including those of the Defense Advanced Research Projects Agency, and encourage the pursuit of novel approaches, as appropriate, within the Federal climate change technology portfolio.

9.4 Toward Enhanced Integration in R&D Planning Processes

Effective integration of fundamental science, strategic research, exploratory research and applied technology R&D presents challenges and opportunities for any mission-oriented research campaign. These challenges and opportunities can be addressed by CCTP through enhanced integrative R&D planning processes that place emphasis on communication, cooperation and collaboration among the affected scientific and technical research communities.

Technology development programs are often hindered by incomplete knowledge and lack of innovative solutions to technical stumbling blocks. Information can be shared and potential pathways to solutions can be suggested by bringing together multi-disciplinary 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:

- 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
- 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. 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 (BES) initiated a new series of workshops in 2002 focusing on identification of the underlying basic research needs related to energy technologies. The first of these workshops, 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. More than 100 people from academia, industry, the national laboratories, and Federal agencies attended this workshop. A subsequent meeting in January 2003 focused on specific discussions of energy biosciences (BESAC 2003). Subsequent Office of Science activities have included a workshop on hydrogen production, storage, and use (BESAC, 2004, ANL 2004); catalysis (BESAC, 2002); solar energy utilization (DOE-SC 2005); and the roadmapping of various technology development processes, such as carbon sequestration (SC/FE 1999). CCTP will seek to encourage broader application, across all agencies, of the best practice in integrated research planning.

Based on the experiences of three workshops held by the Office of Science, Basic Energy Sciences, the following principles were 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, measurement and monitoring, 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 Federal research facilities and academia by focusing efforts on key areas needed to develop insights or breakthroughs relevant to climate-related technology R&D. Another important component of basic research is training and developing 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.

9.5 References

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