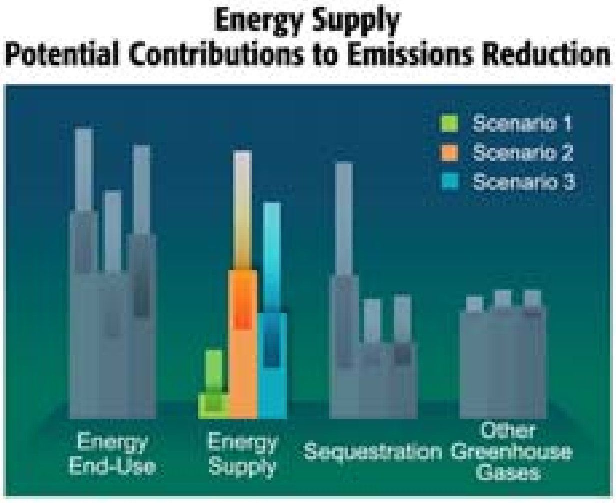
5 Reducing Emissions from Energy Supply

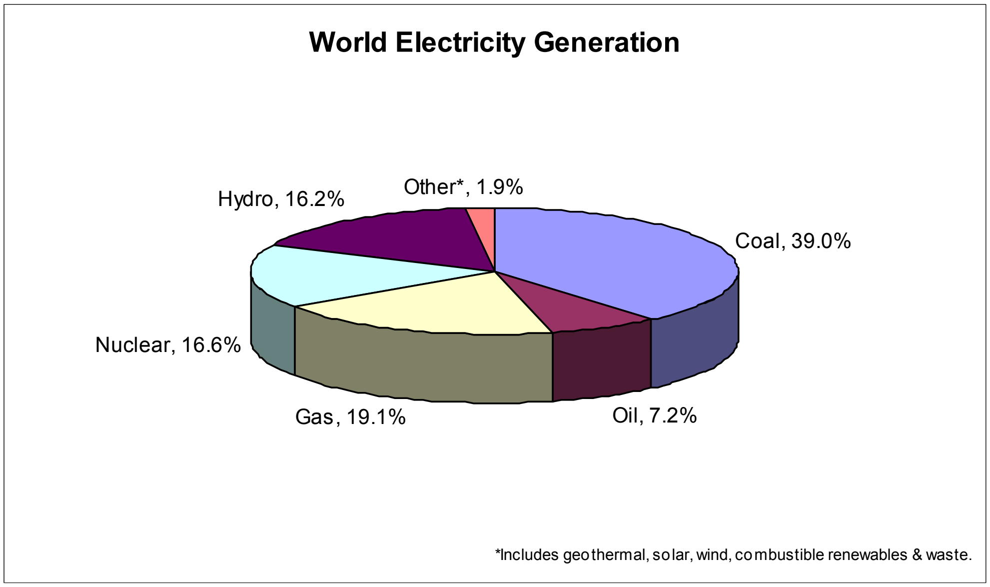
As discussed in Chapters 3 and 4, global energy demand is projected to grow significantly by the year 2100. Some projections show energy demand over the century growing by a factor of 6 or more (from about 400 exajoules [EJ] in 2000 to 2800 EJ in 2100), and mid-range scenarios project an increase of about a factor of 3 or more from today's level, even under scenarios in which energy efficiency is assumed to improve steadily over time. Of this growth, global demand for *electricity* is projected to increase faster than direct use of *fuels* in end-use applications.

Today, a range of technologies using fossil fuels, nuclear power, hydroelectric power, and a relatively small (but fast-growing) amount of renewable energy, supplies the world's electricity demand. Most of global transportation demand is met with petroleum products (see Figures 5-1 and 5-2).



Potential contributions of Energy Supply to cumulative GHG emissions reductions to 2100, across a range of uncertainties, for three advanced technology scenarios. See Chapter 3 for details.

The development of advanced technologies that can significantly reduce emissions of carbon dioxide (CO_2) from energy supply is a central component of the overall climate change technology strategy. Many opportunities exist for pursuing technological options for energy supply that are characterized by low or near-net-zero emissions and whose development can be facilitated by a coordinated Federal R&D investment plan.



*Includes geothermal, solar, wind, combustible renewables & waste.

Figure 5-1. World Electricity Generation
(Source: IEA 2004)

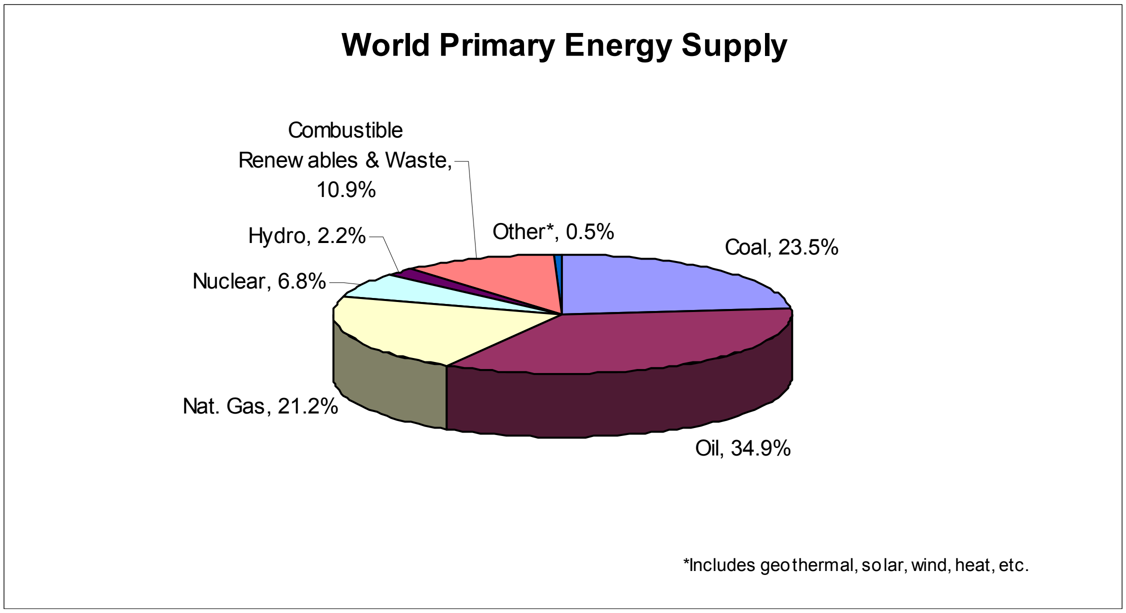


Figure 5-2. World Primary Energy Supply
(Source: IEA 2004)

Some advanced energy supply technologies build on the existing energy infrastructure, which is currently dominated by coal and other fossil fuels. One set of technologies that would allow continued use of coal and other fossil fuels—even under scenarios calling for substantial CO_2 emission limitations—is contained in an advanced coal-based production facility. It is based on coal gasification and production of syngas, which can generate electricity, hydrogen, and other valued fuels and chemicals and would be combined with CO_2 capture and storage and have very low emissions of other pollutants. Some of the emissions-reduction scenarios examined (see Chapter 3) project that if CO_2 capture and storage and improvements in fossil energy conversion efficiencies are achieved, fossil-based energy could continue to supply a large percentage of total energy and electricity in the future (e.g., up to 70 percent of global electricity demand in some scenarios), even under a high carbon constraint. In addition to this mid- to long-term opportunity, lowering CO_2 emissions from fossil fuel combustion in the near term can be achieved by increasing the energy efficiency of combustion technology and by increasing the use of combined heat and power.

Advances in low- and zero-emission technologies have also been identified in a number of scenario analyses as important for reducing GHG emissions. These technologies include advanced forms of: renewable energy, such as wind, photovoltaics, solar thermal applications, and others; biologically based open and closed energy cycles, such as enhanced systems for biomass combustion, biomass conversion to biofuels and other forms of bioenergy; refuse-derived fuels and energy; and various types of nuclear energy, including technologies that employ spent fuel recycling. Variations of these advanced technologies can also be deployed in the production of hydrogen, which may play a big role in reducing emissions from the transportation sector, as well as potentially being used to supply fuel cells for electricity production. Several studies showed that biomass, nuclear, and renewable (solar and wind) energy, combined, would contribute approximately 30 percent of the total reduction in GHG emissions from a "reference case"[1] (see Chapter 3).

Novel energy supply technologies, including breakthrough designs in fusion energy that reduce its cost and increase its rate of deployment; advanced fuel cycles based on combinations of nanotechnology and new forms of bio-assisted energy production, using bioengineered molecules for more efficient photo-synthesis; and hydrogen production or photon-water splitting, may also make important contributions toward reduced GHG emissions. Other possibilities include advanced technologies for capturing solar energy in Earth orbit, on the moon, or in the vast desert areas of Earth—enabled, in part, by new energy carriers and/or low-resistance power transmission over long distances. In one scenario (see Chapter 3), these novel forms of energy were projected to lower cumulative CO_2 emissions by more than 100 GtC over the course of 100-year period, under a very high emission-constraint scenario.

Because outcomes of various ongoing and planned technology development efforts are not known, a prudent path for science and technology policies in the face of uncertainty is to maintain a diverse R&D portfolio. The current Federal portfolio supports R&D activities important to all three of the general technology areas discussed above. The analysis of the advanced technology scenarios suggests that, through successful development and implementation of these technologies, stabilization trajectories could be met across a wide range of hypothesized concentration levels—and the goal could be accomplished both sooner and at significant cost savings, compared to the case without such dramatic technological advances.

This chapter explores energy supply technologies. For each technology area, the chapter examines the potential role for advanced technology; outlines a technology-development strategy for realizing that potential; highlights the current research portfolio, replete with selected technical goals and milestones; and invites public input on considerations for future research directions. The chapter is organized around the following five energy supply technology areas:

- Low-Emission, Fossil-Based Fuels and Power
- Hydrogen as an Energy Carrier
- Renewable Energy and Fuels
- Nuclear Fission
- Fusion Energy

In each of these technology sections, there is a sub-section describing the current portfolio, where the technology descriptions include an internet link to the updated version of the CCTP report, *Technology Options for the Near and Long Term* (DOE/PI-0002) (CCTP 2003). The updated report is available at http://www.climatetechnology.gov/library/2005/tech-options/index.htm

5.1 Low-Emission, Fossil-Based Fuels and Power

Today, fossil fuels are an integral part of the U.S. and global energy mix. Because of its abundance and current relative low cost, coal now accounts for more than half of the electricity generated in the United States, and it is projected to continue to supply one-half of U.S. electricity demands through the year 2025 (EIA 2005). EIA also projects that natural gas will continue to be the "bridge" energy resource, as it offers significant efficiency improvements (and emissions reductions) in both central and distributed electricity generation and combined heat and power (CHP) applications.

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[1] In Chapter 3, the 30 percent value is associated with a hypothesized high emissions constraint.

5.1.1 Potential Role of Technology

Because coal is America's most plentiful and readily available energy resource, the U.S. Department of Energy (DOE) has directed a portion of its research and development (R&D) resources toward finding ways to use coal in a more efficient, cost-effective, and environmentally benign manner, ultimately leading to near-zero atmospheric emissions. Even small improvements in efficiency of the installed base of coal-fueled power stations can result in a significant lowering of carbon emissions. For example, increasing the efficiency of all coal-fired electric-generation capacity in the United States by 1 percentage point would avoid the emission of 14 million tons of carbon per year.[2] That reduction is equivalent to replacing 170 million incandescent light bulbs with fluorescent lights or weatherizing 140 million homes. New U.S. government-industry collaborative efforts are expected to continue to find ways to improve the ability to decrease emissions from coal power generation at lower costs. The objective for future power plant designs is to both increase efficiency and reduce environmental impacts. The focus is on designs that are compatible with carbon sequestration technology, including the development of coal-based, near-zero atmospheric emission power plants.

5.1.2 Technology Strategy

The current U.S fossil research portfolio is a fully integrated program with mid- and long-term market-entry offerings. The principal objective is a zero-emission, coal-based electricity generation plant that has the ability to coproduce low-cost hydrogen. In the midterm, that goal is expected to be accomplished through the FutureGen project. This $1 billion venture, cost-shared with industry, will combine electricity and hydrogen production from a single facility with the elimination of virtually all emissions of air pollutants, including sulfur dioxide, nitrogen oxides, mercury, and particulates—as well as almost complete elimination of atmospheric CO_2 emissions, through a combination of efficiency improvements and carbon capture and storage (called "sequestration" in Figure 5-3). This prototype power plant will

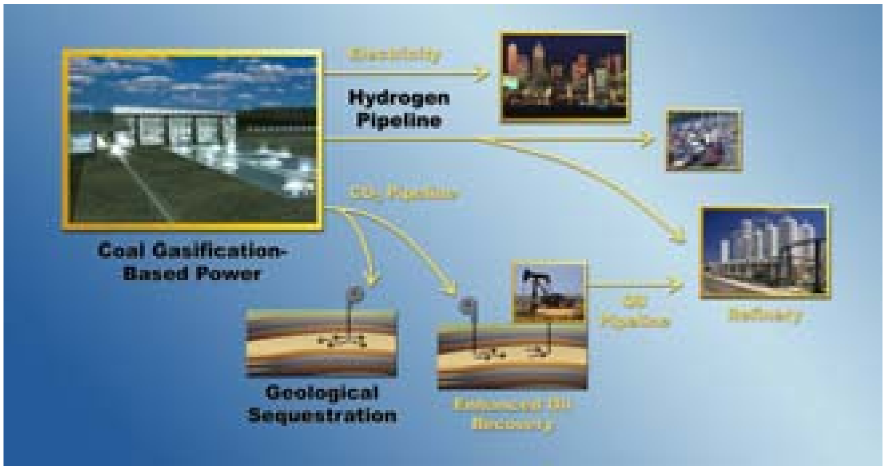

Figure 5-3. Coal-Based Energy Complex
(*Source:* DOE 2004)

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[2] Avoided carbon emissions were calculated based on current coal consumption and power plant efficiencies from the Energy Information Administration's *Annual Energy Outlook 2002*. Using the published efficiencies, 0.574 quads of energy were saved with a 1 percent improved efficiency, which would result in 14.8 MMT of carbon avoided.

serve to demonstrate the most advanced technologies, such as hydrogen fuel cells. See http://www.fossil.energy.gov/programs/powersystems/futuregen/futuregen_report_march_04.pdf.

5.1.3 Current Portfolio

The low-emissions, fossil-based power system portfolio has three focus areas:

- **Advanced Power Systems**: Advanced coal-fired, power-generation technologies can achieve significant reduction in CO_2 emissions, while providing a reliable, efficient supply of electricity.

  Significant reductions in atmospheric CO_2 emissions have been demonstrated via efficiency improvements and co-firing of coal with biomass. While current average power plant efficiencies are about 33 percent, increasing efficiencies to 45-50 percent in the midterm, and ultimately to 60 percent (with the integration of fuel cell technology), will nearly halve emissions of CO_2 per unit of electricity. Development and deployment of CO_2 capture and storage technology could reduce atmospheric carbon emissions to near-zero levels. Recent R&D activities have focused on integrated gasification, combined-cycle (IGCC) plants. Two U.S. IGCC demonstration plants are in operation.

  The research program goal in the Advanced Power Systems area is to increase efficiency of new systems to levels ranging from 48-52 percent by 2010, and to more than 60 percent by 2020, while also achieving an overall electricity production cost that is between 75 percent and 90 percent of current pulverized-coal-based power generation. Additionally, emissions of criteria pollutants are targeted to be much less than one-tenth of current new source performance standards. See Section 2.1.2 (CCTP 2005):
  http://www.climatetechnology.gov/library/2005/tech-options/tor2005-212.pdf

- **Distributed Generation/Fuel Cells**: The fuel cell (FC) program is focused on reducing the cost of fuel cell technology by an order of magnitude.

  In the near- and midterm, fuel cell cost reductions could enable the widespread deployment of natural-gas-fueled distributed generation in gas-only, combined heat and power, and fuel cell applications. In the midterm to long-term, this technology, along with others being developed as part of the Distributed Generation effort, will also support coal-based FutureGen/central-station applications. The goal is to develop a modular power system with lower cost and significantly lower carbon dioxide emissions than current plants. Examples of current R&D projects in this area include (1) low-cost fuel cell systems development, (2) high-temperature fuel cell scale-up and aggregation for fuel cell turbine (FCT) hybrid application, and (3) hybrid systems and component demonstration.

  Research program goals in the natural gas fuel cell and hybrid power systems include demonstrating a gas aggregated FC module larger than 250 kW that can run on coal syngas, while also reducing the costs of the Solid-State Energy Conversion Alliance fuel cell power system to $400/kW by 2010. Additionally, by 2012-2015, the program aims to (1) demonstrate a megawatt-class hybrid system at FutureGen with an overall system efficiency of 50 percent on coal syngas, (2) demonstrate integrated fuel cell and turbine systems achieving efficiencies of 55 percent on coal; and (3) integrate optimized turbine systems into zero-emission power plants. See Section 2.1.3 (CCTP 2005):
  http://www.climatetechnology.gov/library/2005/tech-options/tor2005-213.pdf

- **Coproduction/Hydrogen**: This research area focuses on developing technology to coproduce electricity and hydrogen from coal and, perhaps, using coal and biomass blends, resulting in very large reductions in CO_2 emissions when compared to present technologies. This technology will use synthesis gas generated from coal gasification to produce hydrogen.

  Zero-Emission Power and H_2 coproduction research goals target a 10-year demonstration project (FutureGen) to create the world's first coal-based, zero-emissions electricity and hydrogen power plant. The near-term goals of the program are to (1) design, by 2010, a near-term coproduction plant, configured at a size of 275-MW, which would be suitable for commercial deployment; (2) demonstrate pilot-scale reactors using ceramic membranes for oxygen separation and hydrogen recovery; and (3) demonstrate a $400/kW solid-oxide fuel cell. A longer-term goal, by 2020, is to design a long-term coproduction plant at a scale of 275-MW or larger. See Section 2.1.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-211.pdf

  Carbon emissions from fossil fuel-based power systems can be reduced in the near term principally by improving process efficiency and, in the longer term, via more advanced system components, such as high-efficiency fuel cells. In both the near and long terms, incorporating CO_2 capture into the systems' processes, accompanied by long-term CO_2 storage, will be required to achieve low or near-zero atmospheric emissions from these energy sources. Current research activities focus on (1) ion transport oxygen separation membranes, (2) hydrogen separation membranes, and (3) early-entrance coproduction plant designs. These activities are discussed in more detail in Chapter 6.

5.1.4 Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio. These include:

- Enhancing the hydrogen production technology effort;
- Adding advanced hybrid gasification/combustion, which offers an alternative path to achieve many of the program goals;
- Broadening advanced research in materials development, which offers potential benefits in system efficiency, durability, and performance.

The public is invited to comment on the current CCTP portfolio, including future research directions, and identify potential gaps or significant opportunities. No assurance can be provided that any suggested concept would meet the criteria for investment. However, CCTP can be assisted by such comments in its desire to consider a full array of promising technology options.

5.2 Hydrogen

As discussed above, in a long-term future characterized by low or near-net-zero emissions of GHGs, global energy primary supply can continue its reliance on fossil fuels, provided there are suitable means for capturing and storing the resulting emissions of CO_2. Alternatively, the world could increase reliance on low-carbon and nonfossil energy sources. These approaches share a need for carbonless energy carriers, such as electricity or some alternative, to store and deliver energy on demand to end users. Electricity is increasingly the carbonless energy carrier of choice for stationary energy consumers, but hydrogen could prove to be an attractive carrier for the transportation sector (e.g., highway vehicles and aircraft), as well as stationary applications. If successful, hydrogen could enable reductions in petroleum use and potentially eliminate concomitant air pollutants and CO_2 emissions on a global scale.

Today, hydrogen is used in various chemical processes and is made largely from natural gas, producing CO_2 emissions. However, hydrogen can be produced in a variety of ways that do not emit CO_2, including renewable energy-based electrolysis; various biological and chemical processes; water shift reactions with coal and natural gas, accompanied by CO_2 capture and storage; thermal and electrolytic processes using nuclear energy; and direct photoconversion. Hydrogen can be stored as a pressurized gas or cryogenic liquid, or absorbed within metal hydride powders or physically absorbed onto carbon-based nanostructures. If progress can be made on a number of technical fronts—and costs of producing hydrogen can be reduced—hydrogen could play a valuable, enabling, and synergistic role in heat and power generation, transportation, and energy end use.

5.2.1 Potential Role of Technology

As a major constituent of the world's water, biomass, and fossil hydrocarbons, the element hydrogen (H_2) is ubiquitous. It accounts for 30 percent of the fuel-energy in petroleum, and more than 50 percent of the fuel-energy in natural gas. A fundamental distinction between H_2 and fossil fuels, however, is that the production of H_2, whether from water, methane or other hydrocarbons, is a net-energy consumer. This makes H_2 not an energy source, per se, but a carrier of energy, similar to electricity.

Like electricity, the life-cycle GHG emissions associated with H_2 use would vary depending on the method to produce, store, and distribute it. H_2 can be generated at various scales, including central plants, fuel stations, businesses, homes, and perhaps onboard vehicles. In principle, the diversity of scales, methods, and sources of production make H_2 a highly versatile energy carrier, capable of transforming transportation (and potentially other energy services) by enabling compatibility with many primary energy sources. This versatility opens up possibilities for long-term dynamic optimization of CO_2 emissions, technology development lead times, economics, and other factors. In a future "hydrogen economy," H_2 may ultimately serve as a means of linking energy sources to energy uses in ways that are more flexible, secure, reliable, and responsive to consumer demands than today, while also integrating the transportation and electricity markets.

While its simple molecular structure makes H_2 an efficient synthetic fuel to produce, use, and/or convert to electricity, the storage and delivery of hydrogen are more challenging than for most fuels. Consequently, most H_2 today is produced at or near its point of use, consuming other fuels (e.g., natural gas) that are easier to handle and distribute.

Large H_2 demands at petroleum refineries or ammonia (NH_3) synthesis plants can justify investment in dedicated H_2 pipelines, but smaller or variable demands for H_2 are usually met more economically by truck transport of compressed gaseous H_2 or cryogenic and liquefied hydrogen (LH_2) produced by steam methane reforming. These methods have evolved over decades of industrial experience, with H_2 as a niche chemical commodity, produced in amounts (8 billion kg H_2/yr) equivalent to about 1 percent

(~1 EJ/yr) of current primary energy use in the United States. For H_2 use to scale up from its current position to a global carbonless energy carrier (alongside electricity), new energetically and economically efficient technical approaches would be required for H_2 delivery, storage, and production.

Hydrogen production can be a value-added complement to other advanced climate change technologies, such as those aimed at the use of fossil fuels or biomass with CO_2 capture and storage. As such, hydrogen may be a key and enabling component for full deployment of carbonless electricity technologies (advanced fission, fusion, and/or intermittent renewables).

In the near term, initial deployment of H_2 fleet vehicles and distributed power systems may provide early adoption opportunities and demonstrate the capabilities of the existing H_2 delivery and on-site production infrastructure. This will also contribute in other ways, such as improving urban air quality and strengthening electricity supply reliability. This phase of H_2 use may also serve as a commercial proving ground for advanced distributed H_2 production and conversion technologies using existing storage technology, both stationary and vehicular.

In the midterm, light-duty vehicles likely will be the first large mass market (10-15 EJ/yr in the United States) for hydrogen. Fuel cells may be particularly attractive in automobiles, given their efficiency versus load characteristics and typical driving patterns. Hydrogen production for this application could occur either in large centralized plants or using distributed production technologies on a more localized level.

In the long term, production technologies must be able to produce H_2 at a price competitive with gasoline for bulk commercial fuel use in automobiles, freight trucks, aircraft, rail, and ships. This would likely require efficient production means and large quantities of reasonable-cost energy supplies, perhaps from coal with CO_2 sequestration, advanced nuclear power (high-efficiency electrolysis and thermochemical decomposition of water), fusion energy, renewables (wind-powered electrolysis, direct conversion of water via sunlight, and high-temperature conversion of water using concentrated solar power), or a variety of methods using biomass. Other important factors in the long term include the cost of H_2 hydrogen storage and transportation. Finally, advances in basic science associated with direct water-splitting and solid-state H_2 storage could possibly permit even lower-cost H_2 production; and safer storage, delivery, and utilization in the context of low or near-net-zero emission futures for transportation and electricity generation.

5.2.2 Technology Strategy

Introducing H_2 into the mix of competitive fuel options and building the foundation for a global hydrogen economy will require a balanced technical approach that not only envisions a plausible commercialization path, but also respects a triad of long-run uncertainties on a global scale: (1) the scale, composition, and energy intensity of future worldwide transportation demand, and potential substitutes; (2) the viability and endurance of CO_2 sequestration; and (3) the long-term economics of carbonless energy sources. The influences of these factors shape the urgency, relative importance, economic status, and ideal end state of a future H_2 infrastructure.

The International Partnership for the Hydrogen Economy (IPHE) was formed in November 2003 among 15 countries (Australia, India, Brazil, Italy, Canada, Japan, China, Republic of Korea, Norway, France, Russia, Germany, United Kingdom, United States, and Iceland) and the European Commission. The

IPHE provides a mechanism to organize, evaluate, and coordinate multinational research, development, and deployment programs that advance the transition to a global hydrogen economy. The Partnership leverages limited resources, brings together the world's best intellectual skills and talents, and develops interoperable technology standards.

The IPHE has reviewed actions being pursued jointly by participating countries and is identifying additional actions to advance research, development, and deployment of hydrogen production, storage, transport, and distribution technologies; fuel cell technologies; common codes and standards for hydrogen fuel utilization; and coordination of international efforts to develop a global hydrogen economy. More about the IPHE is available at http://www.iphe.net.

The Department of Energy's Hydrogen Fuel Cells and Infrastructure Technologies Program plans to research, develop, and demonstrate the critical technologies (and implement codes and standards for safe use) needed for H_2 light-duty vehicles (see Figure 5-4). The program operates in cooperation with automakers and related parties experienced in refueling infrastructure to develop technology necessary to enable a commercialization decision by 2015 (DOE 2005). Current research program goals call for validation by 2015 of technology for:

- H_2 storage systems enabling minimum 300-mile vehicle range while meeting identified packaging, cost, and performance requirements.

- H_2 production to safely and efficiently deliver H_2 to consumers at prices competitive with gasoline and without adverse environmental impacts.

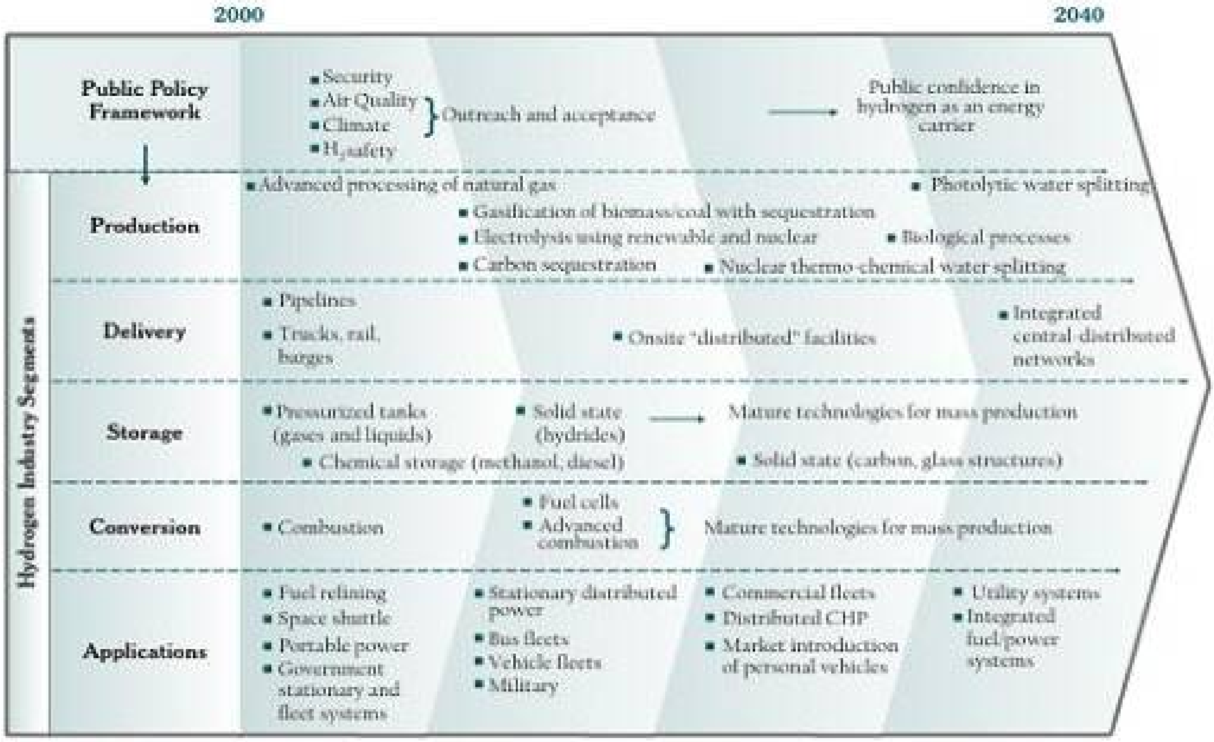


Figure 5-4. Possible Hydrogen Pathways
(*Source:* DOE 2004*)*

- Fuel cells to enable engine costs of less than \$50/kW (in high volume production) while meeting performance and durability requirements.

DOE requested a study by the National Research Council (NRC) and the National Academy of Engineering (NAE) to assess the current state of technology for hydrogen production and use, and to review and provide feedback on the DOE RD&D hydrogen program, including recommendations for priorities and strategies to develop a hydrogen economy. The resulting report (NRC/NAE 2004) addressed implications for national goals, R&D priorities, and criteria for transition to a hydrogen economy. It provided recommendations in the areas of systems analysis, fuel cell vehicle technology, infrastructure, transition, safety, CO_2-free hydrogen, carbon capture and storage, and DOE’s hydrogen RD&D program. In addition to research being conducted within DOE’s Hydrogen, Fuel Cells and Infrastructure Program, the NRC report also addressed DOE’s programs for hydrogen production from nuclear and fossil energy sources.

5.2.3 Current Portfolio

Within the constraints of available resources, the current Federal hydrogen technology research portfolio balances the emphasis on near-term technologies that will enable a commercialization decision for H_2 automobiles by 2015, with the longer-term ultimate development of a mature hydrogen economy founded on advanced H_2 production, storage, and delivery technologies. Elements of the portfolio include

- **Hydrogen Production From Nuclear Fission and Fusion**. High-efficiency, high-temperature fission power plants are projected to produce H_2 economically without CO_2. Hydrogen would be produced by cyclic thermochemical decomposition of water or high-efficiency electrolysis of high-temperature steam.

  Hydrogen production from nuclear power RDD&D goals target high-temperature, high-efficiency fission and, when available, fusion power plants to produce electricity to generate hydrogen from water economically and without generation of CO_2. Major research areas include support for the development of high-temperature materials, separation membranes, advanced heat exchangers, and supporting systems relating to hydrogen production using the sulfur-iodine (S-I) thermochemical cycle and high-temperature electrolysis. Alternative processes having significantly more technical risk (because less is known about them) continue to be evaluated because their expected lower temperature requirements and, in some cases, reduced complexity could render them more economical in the longer term. The RDD&D program goal is to reduce thermochemical facility costs by two-thirds by 2030 and high-temperature electrolysis facility costs by 85 percent in the same time frame. Another goal is a decrease in operating costs by three-fourths in 2030 for both technologies, while thermal efficiency would increase from levels as low as 30 to 40 percent to more than 50 percent by 2030. See Section 2.2.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-221.pdf

- **Hydrogen Production and Distribution Using Electricity and Fossil/Alternative Energy**. Research and development of small-scale steam reformers, alternative reactor technologies, and hydrogen membrane/separation technologies are aimed at improving the economics of hydrogen production from fossil fuels. Demonstration of on-site electrolysis integrated with renewable electricity and laboratory-scale direct water-splitting by photoelectrochemical and photobiological methods are planned.

Near-term research program goals in this area include, by 2006, (1) completion of research of small-scale steam methane reformers with a projected cost of $3.00/kg hydrogen at the pump; (2) development of alternative reactors, including auto-thermal reactors; and (3) evaluation of whether renewable energy—when integrated with hydrogen production by water electrolysis—can achieve 64 percent net energy efficiency at a projected cost of $5.50/kg, delivered at 5,000 psi. Midterm goals call for demonstrating, by 2010, at the pilot-plant scale, (1) membrane separation and reactive membrane separation technology for hydrogen production from coal, and (2) distributed hydrogen production from natural gas with a projected cost of $2.50/kg hydrogen at the pump. Longer-term goals call for demonstrating, by 2015, at laboratory-bench scale, (1) a photo-electrochemical water-splitting system and (2) a biological system for water-splitting (or other substrates) that shows potential to achieve long-term costs that are competitive with conventional fuels—and reduce the cost of hydrogen distribution to $1/kg. See Section 2.2.3 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-223.pdf

- **Hydrogen Storage.** Four methods of high-density, energy-efficient storage of hydrogen are being researched: (1) composite pressure vessels, which will contain the hydrogen as a compressed gas or cryogenic vapor, (2) physical absorption on high-surface-area lightweight carbon structures, (3) reversible metal hydrides, and (4) chemical hydrides. Improving hydrogen compression and/or liquefaction equipment—as well as evaluating the compatibility of the existing natural gas pipeline infrastructure for hydrogen distribution—are also planned.

  The research program goals of hydrogen storage are to, by 2010, develop and verify hydrogen storage systems with 6 weight-percent, 1,500 watt-hrs/liter energy density, and at a cost of $4/kWh of stored energy; and, by 2015, develop associated technologies and verify hydrogen storage systems with 9 weight-percent, 2,700 watt-hrs/liter energy density, and at a cost of $2/kWh of stored energy. See Section 2.2.4 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-224.pdf

- **Hydrogen Use**. DOE aims to demonstrate high-efficiency, solid-oxide fuel cell/turbine hybrid-electric generation systems operating on coal with carbon capture and storage, and to develop efficient and durable polymer electrolyte membrane (PEM) fuel cells appropriate for automotive and stationary applications.

  The research program goals in this area are: (1) by 2010, develop a 60 percent peak-efficient, durable, PEM fuel cell power system for transportation at a cost of $45/kW; and a distributed generation (50-250 kW) PEM fuel cell system operating on natural gas or propane that achieves 40 percent electrical efficiency and 40,000 hours durability at $400-750/kW; and, (2) by 2015, reduce the cost of PEM fuel cell power systems to $30/kW for transportation systems. See Section 2.2.5 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-225.pdf

- **Hydrogen Systems Technology Validation**. A systems approach is needed to demonstrate integrated hydrogen production, delivery, and storage, as well as refueling of hydrogen vehicles and use in stationary fuel cells. This could involve providing hydrogen in gaseous and liquid form.

  The overall goal in this area is to validate, by 2015, integrated hydrogen and fuel cell technologies for transportation, infrastructure, and electric generation in a systems context under real-world operating conditions. Specific goals include: (1) by 2005, demonstrate that an energy station (coproduction of hydrogen as fuel for a stationary fuel cell and for a fuel-cell vehicle) can produce electricity for 8 cents/kWh and $3.60/gallon gasoline equivalent; (2) by 2008, demonstrate stationary fuel cells with a durability of 20,000 hours and 32 percent efficiency; (3) by 2009, demonstrate vehicles with greater than 250-mile range and 2,000-hour fuel cell durability; and (4) by 2009, demonstrate hydrogen production at $3/gallon gasoline equivalent. By 2015, the research program aims to provide critical statistical data that demonstrate that fuel cell vehicles can meet targets of 5,000-hour fuel cell durability, storage systems can efficiently meet 300+ mile range requirements, and H_2 fuel can cost less than $2.50/gallon gasoline equivalent. The technology-validation effort also provides information in support of technical codes and standards development of infrastructure safety procedures. See Section 2.2.2 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-222.pdf

- **Hydrogen Infrastructure Safety**. The approach to safely expand the hydrogen infrastructure is expected to build on current delivery approaches. DOE is working with the U.S. Department of Transportation (DOT) to test and refine existing hydrogen technologies in compliance with Federal Standards while developing new technologies that can improve hydrogen distribution, as well as reduce or eliminate leaks or other risks.

  Hydrogen infrastructure safety goals are to work within the Federal government and with industry to develop, test, and approve new hydrogen storage and monitoring technologies; and conduct a thorough and comprehensive transportation and storage hydrogen infrastructure assessment. This research would address capacity, safety, security, reliability, operations, and environmental compliance, evaluating scenarios for near-term and long-term development and implementation of hydrogen infrastructure including a risk analysis for each technology and application. Additionally, researchers would investigate future systems that offer improved safety, security, reliability, and functionality vs. the current transportation and storage systems. See Section 2.2.6 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-226.pdf

5.2.4 Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio. These include:

- **Commercial Transportation Modes**. If efficient hydrogen-fueled or hybrid-electric vehicles begin to dominate the light-duty passenger vehicle market (beyond 2025), commercial transportation modes (freight trucks, aircraft, marine, and rail) may become the dominant sources of transportation-related CO_2 emissions later in the 21st century. Therefore, the future CCTP portfolio should aim at reducing the cost of hydrogen production *and* liquefaction of H_2 for these modes and explore the infrastructure implications of H_2 production and/or liquefaction on-site at airports, harbors, rail yards, etc. In the case of hydrogen aircraft, the average length of future flights – and whether significant demand for supersonic passenger aircraft that would use hydrogen develops over the 21st century – will be important in determining the relative fuel economy advantages of hydrogen over conventional jet fuel. Research and development programs that support scenarios that include a worldwide shift toward hydrogen aircraft and substitutes for shorter trips (high speed rail) could be considered.

- **Integration of Electricity and H_2 Transportation Sectors.** Eventual full deployment for optimal use of solar, wind, biomass, and nuclear electricity may require significant H_2 storage or increased flexibility in electricity demand. Electrolytic coproduction of H_2 for transportation fuel would provide such a demand profile. This important possibility needs to be examined to determine the economic and technical parameters for electricity demand, generation, and storage; and for hydrogen production, storage and use to achieve a synergistic effect between H_2 vehicles and carbonless electricity generation.

- **Develop Fundamental Understanding of the Physical Limits to Efficiency of the Hydrogen Economy**. Finally, the fundamental electrochemistry and material science of electrolyzers, fuel cells, and reversible devices needs to be fully explored. For example, the theoretical limits on electrolyte conductivity bound the power density and efficiency of both fuel cells and electrolyzers. Advancing the knowledge of these limits should allow efficiency gains in the conversion of electricity to hydrogen (and reconversion to electricity) to approach theoretical limits before hydrogen technology is deployed on a global scale.

The public is invited to comment on the current CCTP portfolio, including future research directions, and identify potential gaps or significant opportunities. No assurance can be provided that any suggested concept would meet the criteria for investment. However, CCTP can be assisted by such comments in its desire to consider a full array of promising technology options.

5.3 Renewable Energy and Fuels

Renewable sources of energy include the energy of the sun, the kinetic energy of wind, the thermal energy inside the Earth itself, the kinetic energy of flowing water, and the chemical energy of biomass. These sources of energy, available in one or more forms across the globe, are converted and/or delivered to end users as electricity, direct heat, fuels, hydrogen, and useful chemicals and materials. Box 5-1 lists the 11 renewable energy technologies discussed in *Technology Options for the Near and Long Term.* In the United States in 2003, of the 71.42 quads of net energy supply and disposition (98.22 quads total energy consumption), renewable resources contributed 5.89 quads (8 percent of supply, or 6 percent of the total). Of the renewable energy, 2.78 quads came from hydropower, 2.72 quads from burning biomass (wood and waste), 0.28 quads from geothermal energy, and 0.12 quads from solar and wind energy combined. An additional 0.24 quads of ethanol were produced from corn for transportation (EIA 2005).

The suite of renewable energy technologies is in various states of market readiness. For example, hydropower is well established, but improvements in the technology could increase its efficiency and widen its applicability. Geothermal technologies are established in some areas and applications, but significant improvements are needed to tap broader resources. The installation of wind energy has been rapidly and steadily expanding during the past several years. In the past decade, the global wind energy capacity has increased tenfold—from 3.5 GW in 1994 to almost 50 GW by the end of 2004. Technology improvements will continue to lower the cost of wind energy onshore and will enable access to the immense wind resources in shallow and deep waters of U.S. coastal areas and the Great Lakes near large energy markets. The next generations of solar—with improved performance and lower cost—are in various stages of concept identification, laboratory research, engineering development, and process scale-up. Also, the development of integrated and advanced systems involving solar photovoltaics, concentrating solar power, and solar buildings are still in quite early stages.

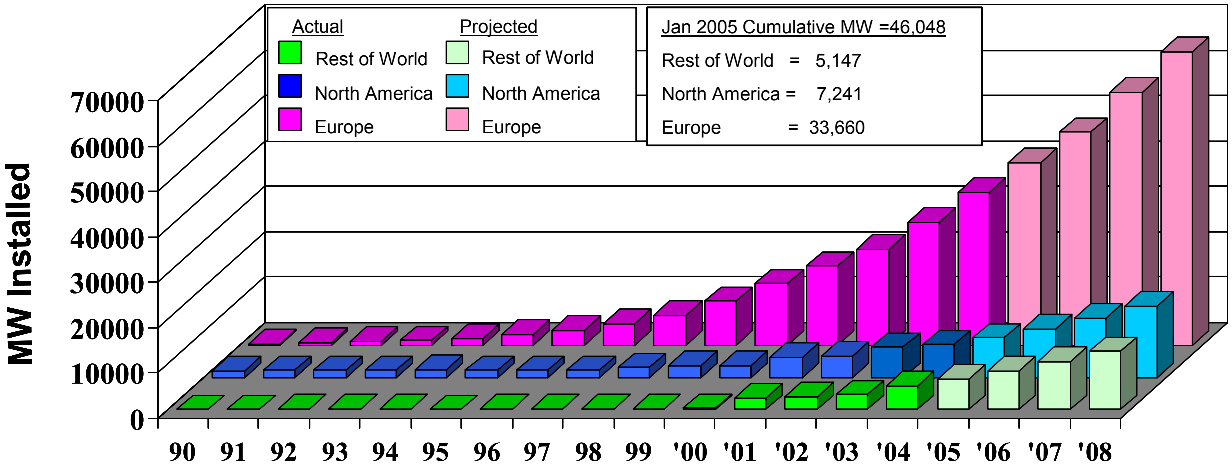
Biochemical and thermochemical conversion technologies also range broadly in their stages of development, from some that need only to be proved at an industrial scale, to others that need more research, to others in early stages of scientific exploration. In the general category of photo-conversion, most technical ideas are at the earliest stages of concept development, theoretical modeling, and laboratory experiment.

The energy-production potential and siting of the various types of renewable energy facilities is dependent on availability of the applicable natural resources. Figures 5-5 through 5-9 show availability of key U.S. renewable resources as estimated by the National Renewable Energy Laboratory (NREL) at the Renewable Resource Data Center (see http://rredc.nrel.gov/).

Box 5-1

Renewable Energy and Fuels Technologies

- Wind Energy
- Solar Photovoltaic Power
- Solar Buildings
- Concentrating Solar Power
- Biochemical Conversion of Biomass
- Thermochemical Conversion of Biomass
- Biomass Residues
- Energy Crops
- Photoconversion
- Advanced Hydropower
- Geothermal Energy



Sources: BTM Consult Aps, March 2003
Windpower Monthly, January 2005
*NREL Estimate for 2005

Figure 5-5. Global Wind Capacity Growth

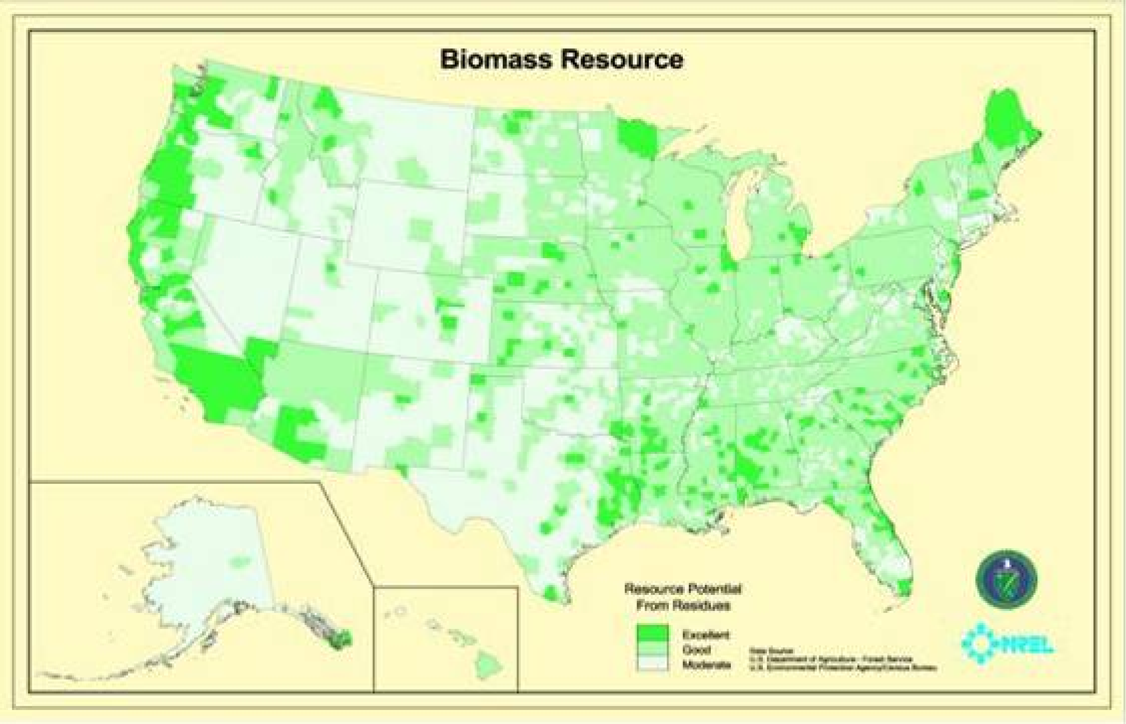


Figure 5-6. U.S. Biomass Resources
(*Source:* DOE Office of Energy Efficiency and Renewable Energy)

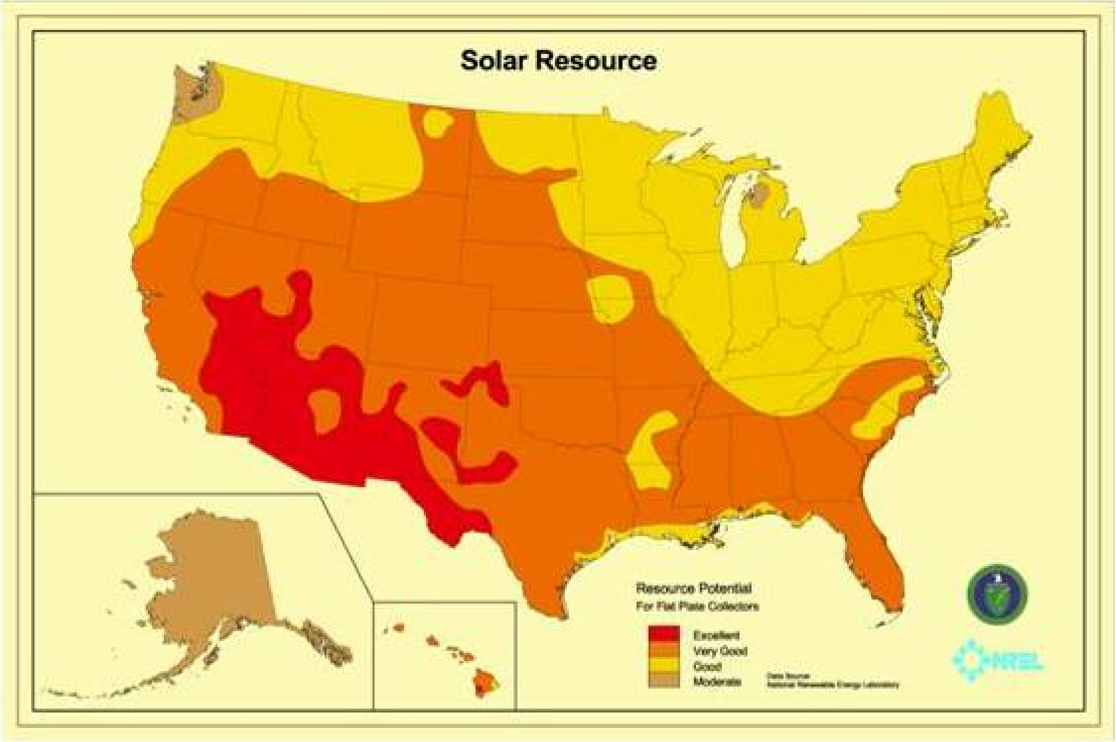


Figure 5-7. U.S. Solar Resources
(*Source:* DOE Office of Energy Efficiency and Renewable Energy)

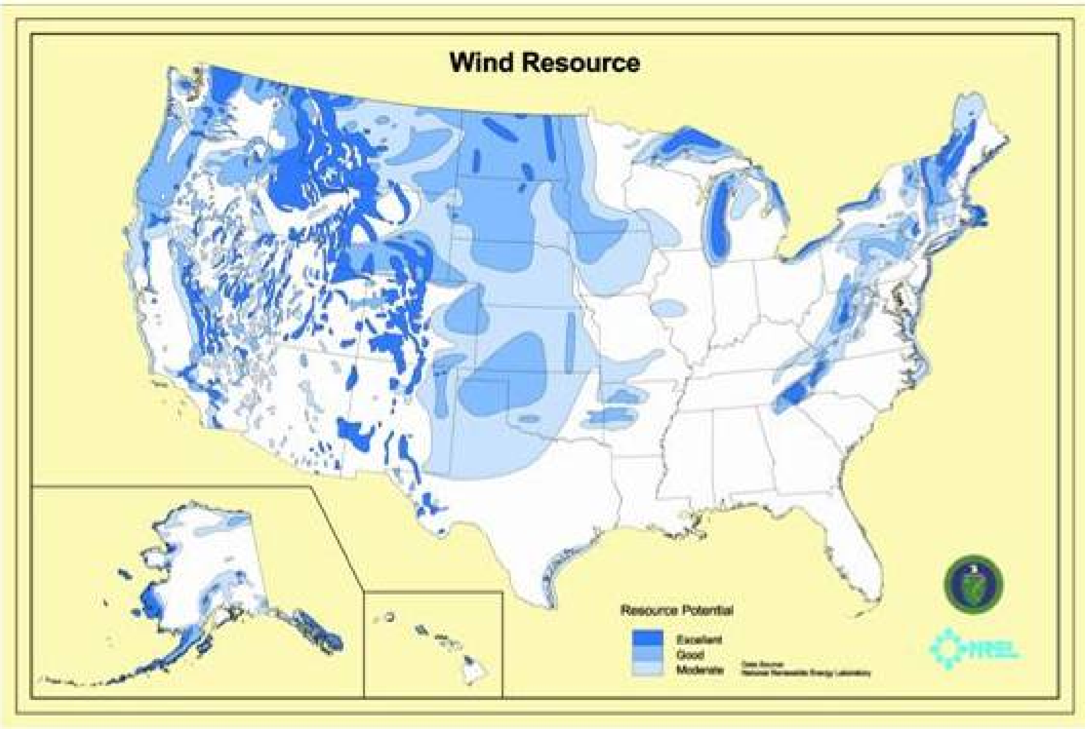


Figure 5-8. U.S. Onshore Wind Resources

(*Source:* DOE Office of Energy Efficiency and Renewable Energy)

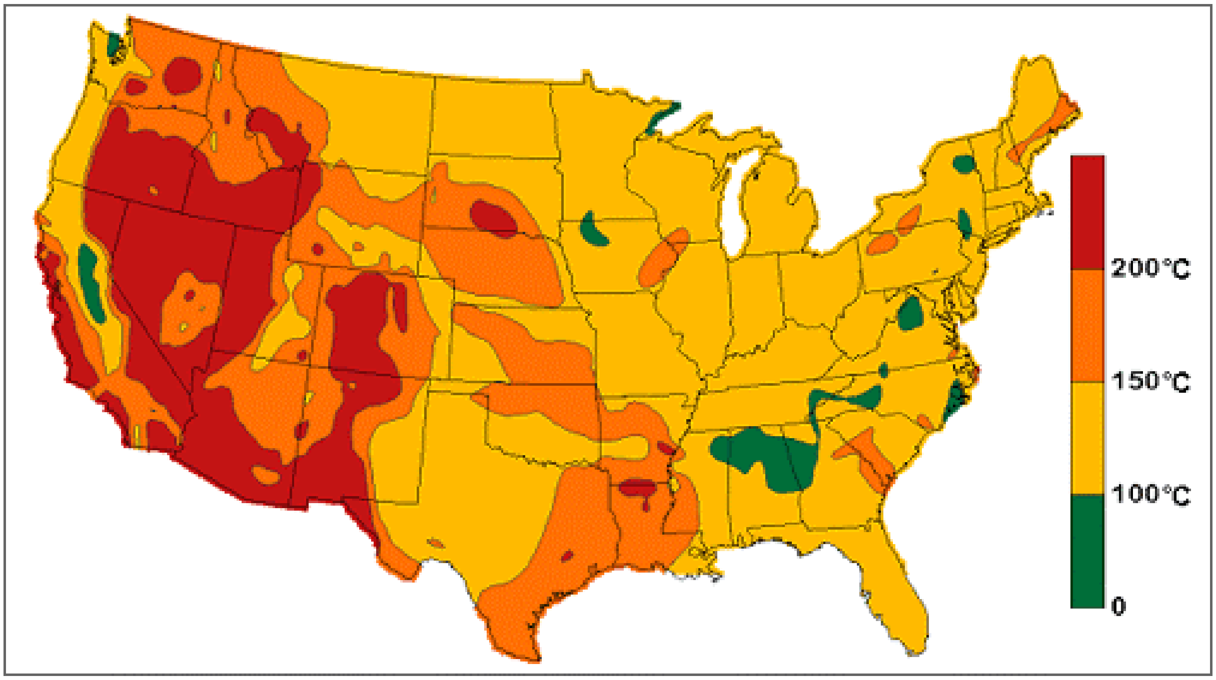


Figure 5-9. U.S. Geothermal Resources

(*Source:* DOE Office of Energy Efficiency and Renewable Energy)

5.3.1 Potential Role of Technology

Renewable energy technologies are generally modular and can be used to help meet the energy needs of a stand-alone application or building, an industrial plant or community, or the larger needs of a national electrical grid or fuel network. Renewable energy technologies can also be used in various combinations—including hybrids with fossil-fuel based energy sources and with advanced storage systems—to improve renewable resource availability. Because of this flexibility, technologies and standards to safely and reliably interconnect individual renewable electric technologies, individual loads or buildings, and the electric grid are very important.

In addition, the diversity of renewable energy sources offers a broad array of technology choices that can reduce CO_2 emissions. The generation of electricity from solar, wind, geothermal, or hydropower sources contributes no CO_2 or other GHGs directly to the atmosphere. Increasing the contribution of renewables to the Nation's energy portfolio will directly lower GHG intensity (GHGs emitted per unit of economic activity) in proportion to the amount of carbon-emitting energy sources displaced.

Analogous to crude oil, biomass can be converted to heat, electrical power, fuels, hydrogen, chemicals, and intermediates. Biomass refers to both biomass residues (agricultural wastes such as corn stover and rice hulls, forest residues, pulp and paper wastes, animal wastes, etc.) and to fast-growing "energy crops," chosen specifically for their efficiency in being converted to electricity, fuels, etc. The CO_2 consumed when the biomass is grown essentially offsets the CO_2 released during combustion or processing. Biomass systems actually represent a net sink for GHG emissions when biomass residues are used, because this avoids methane emissions that result from landfilling unused biomass (see Figures 5-10 and 5-11). Biorefineries of the future could produce value-added chemicals and materials together with fuels and/or power from nonconventional, lower-cost feedstocks (such as agricultural and forest residues and specially grown crops) with no net CO_2 emissions.

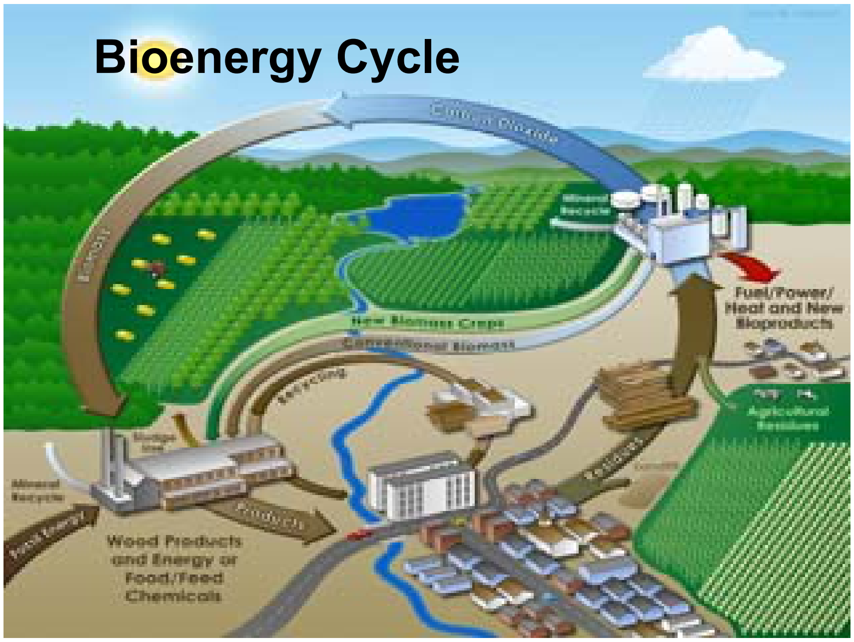


Figure 5-10. Bioenergy Cycle
(*Source:* Oak Ridge National Laboratory internal document)

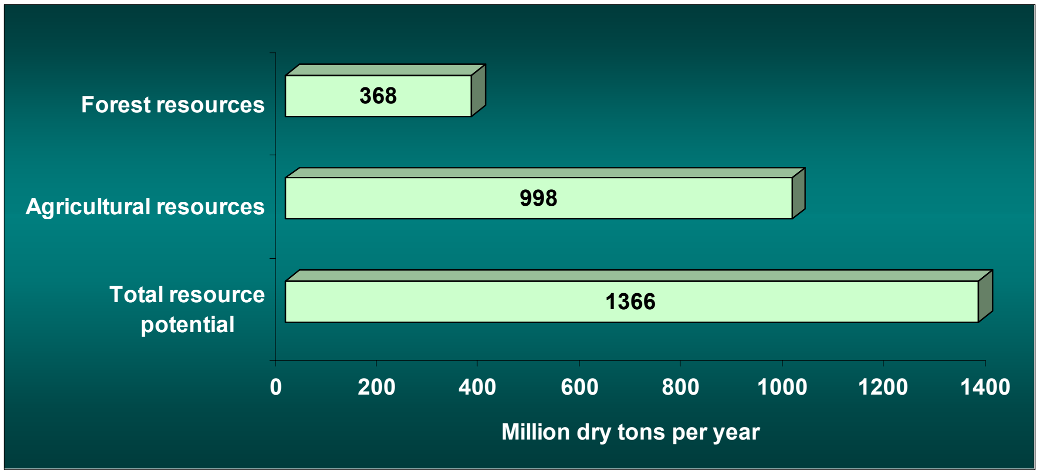


Figure 5-11. Biomass as Feedstock for a Bioenergy and Bioproducts Industry
(*Source:* Oak Ridge National Laboratory http://feedstockreview.ornl.gov/pdf/billion_ton_vision.pdf)

5.3.2 Technology Strategy

Given the diversity of the stages of development of the technologies, impacts on different economic sectors, and geographic dispersion of renewable energy sources, it is likely that a portfolio of renewable energy technologies—not just one—will contribute to lowering CO_2 emissions. The composition of this portfolio will change as R&D continues and markets change. Appropriately balancing investments in developing this portfolio will be important to maximizing the effect of renewable energy technologies on GHG emissions in the future.

Transitioning from today's reliance on fossil fuels to a global energy portfolio that includes significant renewable energy sources will require continued improvements in cost and performance of renewable technologies. This transition would also require shifts in the energy infrastructure to allow a more diverse mix of technologies to be delivered efficiently to consumers in forms they can readily use.

In general, as performance continues to improve and costs continue to decline, improved new generations of technologies will replace today's renewable technologies. Combinations of renewable and conventional technologies and systems—and, therefore, integration and interconnection issues—will grow in importance.

The transition from today's energy mix to a state of GHG stabilization can be projected as an interweaving of individual renewable energy technologies with other energy technologies, as well as market developments through the upcoming decades. Today, grid-connected wind energy, geothermal, solar energy, and biopower systems are well established. Demand for these systems is growing in some parts of the world. Solar hot-water technologies are reasonably established, although improvements continue. Markets are growing for small, high-value or remote applications of solar photovoltaics; wind energy; biomass-based CHP; certain types of hydropower; and integrated systems that usually include natural gas or diesel generators. Other technologies and applications today are in various stages of research, development, and demonstration. Possible near-, mid-, and long-term scenarios for renewable energy are as follows:

In the near term, as system costs continue to decrease, the penetration of off-grid systems could continue to increase rapidly, including integration of renewable systems such as photovoltaics into buildings. As interconnection issues are resolved, the number of grid-connected renewable systems could increase quite rapidly, meeting local energy needs such as uninterruptible power, community power, or peak shaving. Wind energy may expand most rapidly among grid-connected applications, with solar expanding as system costs are reduced, and geothermal expanding as research reduces costs and extends access to resources. Environment-friendly hydropower systems could be developed. The use of utility-scale wind technology is likely to continue to expand onshore and is targeted to become competitive in select offshore locations between 5 and 50 nautical miles from shore and in water depths 30 meters or less. Small wind turbines are on the verge of operating cost-effectively in most of the rural areas of the United States, and more than 15 million homes have the potential to generate electricity with small wind turbines.[3] With a further maturing of the market, costs will be lowered to compete directly with retail rates for homeowners, farmers, small businesses, and community-based projects.

The biomass near-term strategy includes increasing the production of corn-based ethanol (already produced at nearly 4 billion gallons) by making the process more efficient. This will be demonstrated by increasing the quantity of ethanol through residual starch conversion, and conversion of fiber already collected and present at the operating facilities. The inclusion of biochemicals as byproducts will serve to secure the economics, making this a more sustainable industry. Demonstrations of biorefinery concepts could begin in the near term, producing one or more products (bioethanol, bioproducts, electricity, CHP, etc.) from one plant using local waste and residues as the feedstock. Biodiesel use may continue to grow, replacing fossil-fuel-derived diesel fuel.

In the midterm, offshore wind energy could begin to expand significantly. Technology development may focus on turbine-support structures suitable for deeper water depths, and reducing turbine system and balance of plant costs to offset increased distance from shore, decreased accessibility, and more stringent environmental conditions. Onshore use of wind turbines is also likely to expand for large and small turbines as the costs for these systems continue to decrease. Small turbines may be used to harness wind to provide pumping for farm irrigation, help alleviate water-availability problems, and provide a viable source of clean and renewable hydrogen production.[4] Reductions in cost could encourage penetration by solar technologies into large-scale markets, first in distributed markets such as commercial buildings and communities, and later in utility-scale systems. Solar-cooling systems could become cost-effective in new construction. The first geothermal plants using engineered geothermal systems technology could come online, greatly extending access to geothermal resources. Hydropower may benefit from full acceptance of new turbines and operational improvements that enhance environmental performance, lowering barriers to new development. Biorefineries could begin using both waste products and energy crops as primary feedstocks. Bioethanol and biodiesel could make substantial market penetration, beginning to lower U.S. dependence on imported petroleum.

In the long term, hydrogen from solar, wind, and possibly geothermal energy could be the backbone of the economy, powering vehicles and stationary fuel cells. Solar technologies could also be providing electricity and heat for commercial buildings, industrial plants, and entire communities in major sections

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[3] U.S. Small Wind Turbine Industry Roadmap, NREL Report No. BK-500-31958; DOE/GO-102002-1598, 2002 http://www.nrel.gov/docs/gen/fy02/31958.pdf.

[4] National Academy of Science, The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs http://www4.nationalacademies.org/news.nsf/isbn/0309091632?OpenDocument.

of the country, and most residential and commercial buildings could generate their own energy on-site. Wind energy could be the lowest-cost option for electricity generation in favorable wind areas for grid power, and offshore systems could become prevalent in many countries by achieving a commercially viable cost by using floating platforms technologies. Geothermal systems could be a major source of base-load electricity for large regions. Biorefineries could be providing a wide range of cost-effective products as rural areas embrace the economic advantages of widespread demand for energy crops. Vehicle fuels could be powered by a combination of hydrogen fuel cells, with some bioethanol and biodiesel in significant markets.

5.3.3 Current Portfolio

The current Federal portfolio of renewable energy supply technologies encompasses 11areas, described below:

- **Wind Energy**. Generating electricity from wind energy focuses on using aerodynamically designed blades to drive generators that produce electric power in proportion to wind speed. Utility-scale turbines can be several megawatts and produce energy at between 4-6¢/kWh depending on the wind resource. Smaller turbines (under 100 kilowatts) serve a range of distributed, remote, and stand-alone power applications, producing energy between 13-19¢/kWh. Research activities include wind characteristics and forecasting, aerodynamics, structural dynamics and fatigue, control systems, design and testing of new onshore and offshore prototypes, component and system testing, power systems integration, and standards development.

  Research program goals in this area vary by application. For distributed wind turbines under 100 kw, the goal is to achieve a power production cost of 10-15¢/kWh in Class 3 winds by 2007. For larger systems greater than 100 kw, the goal is to achieve a power production cost of 3¢/kWh for onshore at sites with average wind speeds of 13 mph (wind Class 4), and 5¢/kWh at offshore sites with average wind speeds of 13 mph (wind Class 4) by 2012. See Section 2.3.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-231.pdf

- **Solar Photovoltaic Power**. Generating electricity from solar energy focuses on using semiconductor devices to convert sunlight directly to electricity. A variety of semiconductor materials can be used, varying in conversion efficiency and cost. Today's commercial modules are 13 percent to 18 percent efficient, and grid-tied photovoltaic (PV) systems generate electricity for about 17-22¢/kWh. Efficiencies of experimental cells range from 12 percent to 19 percent for low-cost thin-film amorphous and polycrystalline materials, and 25 percent to 37 percent for higher-cost III-V multijunction cells. Research activities, conducted with strong partnerships between the Federal laboratories and the private sector, include the fundamental understanding and optimization of photovoltaic materials, process, and devices; module validation and testing; process research to lower costs and scale up production; and technical issues with inverters and batteries. The photovoltaics industry is growing rapidly, with 1,200 MW produced worldwide in 2004.

  Research program goals in this area focus on scaling up laboratory-sized PV cells to much larger sizes suitable for product markets; validation of new module technologies for outdoors use to achieve 30-year outdoor warrantable lifetimes; and addressing of substantial technical issues associated with high-yield, first-time, and large-scale (greater than 100 MW/yr) manufacturing for advanced technologies. The long-term cost goal for electricity from PV cells for residential PV applications is

$0.06/kWh, compared to costs ranging from $0.18 to $0.23/kWh in 2004. The interim cost goal is to reduce the 30-year user cost for PV electric energy to a range of $0.14 to $0.19/kWh by 2010. See Section 2.3.2 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-232.pdf

- **Solar Heating and Lighting**. Solar heating and lighting technologies being developed for buildings applications include solar water heating and hybrid solar lighting. The near-term solar water heating research goal is to use polymer materials and manufacturing enhancements to reduce the cost of solar water heating systems to 4.5¢/kWh from their current cost of 8¢/kWh. Near-term solar lighting research goals are to demonstrate the second generation of the lighting system, coupled with an enhanced control system, and determine the market potential of the technology. See Section 2.3.3 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-233.pdf

- **Concentrating Solar Power**. Concentrating solar power (CSP) technology involves concentrating solar energy 50 to 5,000 times to produce high-temperature thermal energy, which is then used to produce electricity. Parabolic trough systems (1-100 MWe) that can generate electricity for a power cost of 12 to 14¢/kWh have been demonstrated commercially. Large-scale systems employing power towers (30-200 MWe) have been demonstrated. Prototype dish/Stirling engine systems (2 kWe-10 MWe) are operating in several states.

The program goals in this area are focused on CSP. The long-term goal is to achieve a power cost of between $0.035/kWh and $0.062/kWh, compared to the cost of between $0.12-$0.14/kWh in 2004. The interim goal is to reduce the cost of large-scale CSP power plants in the U.S. Southwest, where solar conditions are most favorable, to $0.09-$0.11/kWh by 2010.. See Section 2.3.4 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-234.pdf

- **Biochemical Conversion of Biomass**. Biochemical technology can be used to convert the cellulose and hemicellulose polymers in biomass (agricultural crops and residues, wood residues, trees and forest residues, grasses, and municipal waste) to their building blocks, such as sugars and glycerides. Using either acid hydrolysis (well-established) or enzymatic hydrolysis (being developed), sugars can then be converted to liquid fuels, such as ethanol, chemical intermediates and other products, such as lactic acid and hydrogen. Glycerides can be converted to a bio-based alternative for diesel fuel and other products. Producing multiple products from biomass feedstocks in a biorefinery could ultimately resemble today's oil refinery.

  Program goals in this area focus on the research and design of biorefinery processes that convert biomass feedstocks into valuable bio-based chemicals and fuels. By 2010, the goal is to finalize a process flow diagram with material and energy balances for an integrated biorefinery with the potential for three bio-based chemicals or materials. By 2012, the goal is to complete a system-level demonstration with corn kernels' fiber and recalcitrant starch aiming at 5 percent to 20 percent increase in ethanol yield from ethanol plants. Also by 2012, the goal is to reduce the estimated cost for producing a mixed, dilute sugar stream suitable for fermentation to ethanol to $0.10/lb, compared to the cost of $0.15/lb in 2003. If successful, this cost goal would correspond to $1.75 per gallon of ethanol, assuming a cost of $45 per dry ton of corn stover. See Section 2.3.5 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-235.pdf

- **Thermochemical Conversion of Biomass.** Thermochemical technology uses heat to convert biomass into a wide variety of products. Pyrolysis or gasification of biomass produces an oil-rich vapor or synthesis gas, which can be used to generate heat, electricity, liquid fuels, and chemicals. Combustion of biomass (or combinations of biomass and coal) generates steam for electricity production and/or space, water, or process heat, occurring today in the wood products industry and biomass power plants. Analogous to an oil refinery, a biorefinery can use one or more of these methods to convert a variety of biomass feedstocks into multiple products. See Section 2.3.6 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-236.pdf

- **Biomass Residues**. Biomass residues include agricultural residues, wood residues, trees and forest residues, animal wastes, pulp, and paper waste. These must be harvested, stored, and transported on a large scale to be used in a biorefinery. Research activities include improving and adapting the existing harvest collection, densification, storage, transportation, and information technologies to bioenergy supply systems—and developing robust machines for multiple applications.

  The long-term research program goal in this area is to develop fully integrated crop and residue harvesting, storage, and transportation systems for food, feed, energy, and industrial applications by 2020. Interim goals toward this end include, by 2006, measurable cost reductions in corn-stover supply systems with modifications of current technology. By 2007, the goal is to develop whole-crop harvest systems for supplying biorefineries of multiple products and, by 2010, enhancements to the whole-crop harvest systems that include fractionation for maximum economic return, including returns to soil for maximum productivity and conservation practices. By 2015, the goal is to develop an integrated system for pretreatment of residues near harvest locations and a means of collecting and transporting partially treated substrates to a central processing operation. See Section 2.3.7 (CCTP 2005):
  http://www.climatetechnology.gov/library/2005/tech-options/tor2005-237.pdf

- **Energy Crops**. Energy crops are fast-growing, often genetically improved trees and grasses grown under sustainable conditions to provide feedstocks that can be converted to heat, electricity, fuels such as ethanol, and chemicals and intermediates. Research activities include genetic improvement, pest and disease management, and harvest equipment development to maximize yields and sustainability.

  The overall research goal of this program is to advance the concept of energy crops contributing strongly to meet biomass power and biofuels production goals by 2020. Interim goals include, by 2006, to develop feedstock crops with experimentally demonstrated yield potential of 6-8 dry ton/acre/year and accompanying cost-effective, energy-efficient, environmentally sound harvest methods. By 2010, the goal is to identify genes that control growth and characteristics important to conversion processes in few model energy crops and achieve low-cost, “no-touch” harvest/ processing/transport of biomass to process facility. By 2020, the goal is to increase yield of useful biomass per acre by a factor of 2 or more compared with year 2000 yields. See Section 2.3.8 (CCTP 2005):
  http://www.climatetechnology.gov/library/2005/tech-options/tor2005-238.pdf

- **Photoconversion**. Photoconversion processes use solar photons to drive a variety of quantum conversion processes other than solid-state photovoltaics. These processes can produce electrical power or fuels, materials, and chemicals directly from simple renewable substrates such as water, carbon dioxide, and nitrogen. Photoconversion processes that mimic nature (termed "bio-inspired") can also convert CO_2 into liquid and gaseous fuels. Most of these technologies are at early stages of research where technical feasibility must be demonstrated, but a few (such as dye-sensitized solar cells) are at the developmental level.

The research program in this area is still in an exploratory stage. In the near term, research will focus on applications related to electrical power and high-value fuels and chemicals, where commercial potential may be expected during the next 5 to 10 years. If successful, larger-scale applications of photoconversion technologies may follow in the period from 2010 to 2015, with materials and fuels production beginning in the period 2015 to 2020, and commodity chemicals production in the period from 2020 to 2030. See Section 2.3.9 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-239.pdf

- **Advanced Hydropower**. The goal of advanced hydropower technology is to maximize the use of water for generation of electricity, while eliminating harmful environmental side effects. Representative technologies include new turbine designs that improve survivability of fish passing through the power plant and increase dissolved oxygen in downstream discharges, new assessment methods to optimize operation of reservoir system, and advanced instrumentation and control systems that modify turbine operation to maximize environmental benefits and energy production.

  The research program goals in this area include, by 2006, the completion of testing of hydroelectric turbine technology capable of reducing the rate of fish mortality to 2 percent, which would equal or better other methods of fish passage (e.g., spillways or fishways). Also in the near term, the goal is to complete the development of the Advanced Hydro Turbine Technology in support of maintaining hydroelectric-generation capacity due for relicensing between 2010 and 2020. See Section 2.3.10 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-2310.pdf

- **Geothermal Energy**. Geothermal sources of energy include hot rock masses, highly pressured hot fluids, hot hydrothermal systems, and shallow warm groundwater. Exploration techniques locate resources to drill; well fields and distribution systems allow the hot fluids to move to the point of use; and utilization systems apply the heat directly or convert it to electricity. Geothermal heat pumps use the shallow earth as a heat source and heat sink for heating and cooling applications. The U.S.-installed capacity for geothermal electrical generation is currently about 2 gigawatts; but, with improved technology, the U.S. geothermal resource could be capable of producing up to 100 gigawatts of electricity at an estimated cost of less than 5¢/kWh.

  The research program goals in this area focus on reducing the cost of geothermal energy. For "flash" power systems, the goal is to reduce the levelized cost of power generated by conventional (hydrothermal) geothermal resources from 6.1 cents per kWh in 2000 to 4.3 cents per kWh by 2010. For "binary" power systems, the goal is to reduce this cost from 8.7 cents per kWh in 2000, to 6.1 cents per kWh by 2010. See Section 2.3.11 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-2311.pdf

5.3.4 Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio. These include:

- **Wind Energy**. Research challenges include developing wind technology that will be economically competitive at low-wind-speed sites without a production tax credit, developing offshore wind technology to take advantage of the immense wind resources in U.S. coastal areas and the Great Lakes, and exploring the role of wind turbines in emerging applications such as electrolytic hydrogen production, water purification, and irrigation.

- **Solar Photovoltaic Power**. Research would be required to lower the cost of solar electricity further. This can occur through developing "third-generation" materials such as quantum dots and nanostructures for ultra-high efficiencies or lower-cost organic or polymer materials; solving complex integrated processing problems to lower the cost of large-scale production of thin-film polycrystalline devices; optimizing cells and optical systems using concentrated sunlight; and improving the reliability and lowering the cost of inverters and batteries.

- **Solar Buildings**. Future research could include reducing cost and improving reliability of components and systems, optimizing energy efficiency and renewable energy combinations, integrating solar technologies into building designs, and incorporating solar technologies into building codes and standards.

- **Concentrating Solar Power**. Future challenges requiring RD&D include reducing cost and improving reliability; demonstrating Stirling engine performance in the field; and developing technology to produce hydrogen from concentrated sunlight and water.

- **Biochemical Conversion of Biomass**. Research is required to gain a better understanding of genomes, proteins, and their functions; the enzymes used for hydrolyzing pretreated biomass into fermentable sugars; the micro-organisms used in fermentation; and new tools of discovery such as bio-informatics, high-throughput screening of biodiversity, directed enzyme development and evolution, and gene shuffling. Research must focus on improving the cost, yield, and equipment reliability for harvesting, collecting, and transporting biomass; pretreating biomass before conversion; lowering the cost of the genetically engineered cellulose enzymes needed to hydrolyze biomass; developing and improving fermentation organisms; and developing integrated processing applicable to a large, continuous-production commercial facility.

- **Thermochemical Conversion of Biomass**. Research is needed to improve the production, preparation, and handling of biomass; improve the operational reliability of thermochemical biorefineries; remove contaminants from synthesis gas and develop cost-competitive catalysts and processes for converting synthesis gases to chemicals, fuels, or electricity. All the processes in the entire conversion system must be integrated to maximize efficiency and reduce costs.

- **Biomass Residues**. Research challenges include developing sustainable agriculture and forest-management systems that provide biomass residues; developing cost-effective drying, densification, and transportation techniques to create more standard feedstock from various residues; developing whole-crop harvest and fractionation systems; and developing methods for pretreatment of residues at harvest locations.

- **Energy Crops**. Future crop research needs include identifying genes that control growth and characteristics important to conversion processes, developing gene maps, understanding functional genomics in model crops, and applying advanced management systems and enhanced cultural practices to optimize sustainable energy crop production.

- **Photoconversion**. Photoconversion research requires developing the fundamental scientific understanding of photolytic processes through multidisciplinary approaches involving theory, mechanisms, kinetics, biological pathways and molecular genetics, natural photosynthesis, materials science, catalysts, and catalytic cycles.

- **Geothermal Energy**. Future research needs include developing improved methodologies for predicting reservoir performance and lifetime; finding and characterizing underground fracture permeability; developing low-cost innovative drilling technologies; reducing the cost and improving the efficiency of conversion systems; and developing engineered geothermal systems that will allow the use of geothermal areas that are deeper, less permeable, or drier than those currently considered as reserves.

The public is invited to comment on the current CCTP portfolio, including future research directions, and identify potential gaps or significant opportunities. No assurance can be provided that any suggested concept would meet the criteria for investment. However, CCTP can be assisted by such comments in its desire to consider a full array of promising technology options.

5.4 Nuclear Fission

Currently, there are 440 nuclear power plants operating in 31 nations that generate 17 percent of the world's electricity (see Figure 5-1) and provide nearly 7 percent of total world energy (see Figure 5-2). Because they emit no GHGs, today's nuclear power plants avoid the CO_2 emissions associated with combustion of coal or other fossil fuels.

During the past 30 years, operators of U.S. nuclear power plants have steadily improved economic performance through reduced costs for maintenance and operations and improved power plant availability, while operating reliably and safely. In addition, science and technology for the safe storage and ultimate disposal of nuclear waste have been advanced. Waste from nuclear energy must be isolated from the environment. High-level nuclear wastes from fission reactors (used fuel assemblies) are stored in contained, reinforced concrete steel-lined pools or in robust dry casks at limited-access reactor sites, until a deep geologic repository is ready to accept and isolate the spent fuel from the environment. Used nuclear fuel contains a substantial quantity of fissionable materials, and advanced technologies may be able to recover energy from this spent fuel and reduce required repository space and the radiotoxicity of the disposed waste.

While the current application of nuclear energy is the production of electricity, other applications are possible, such as cogeneration of process heat, the generation of hydrogen from water or from methane (with carbon capture or integration with other materials production or manufacturing), and desalination.

5.4.1 Potential Role of Technology

The currently operating 103 U.S. nuclear-reactor units are saving as much as 600 million metric tons of carbon dioxide emissions every year. Through the summer of 2005, 33 of these units have received approval to extend their operating licenses for an additional 20 years; 16 others have applications under review. All of the remaining units most likely will follow suit. Such carbon dioxide emission mitigation can be increased if new nuclear capacity were to be brought online.

To the extent the financial risks of new nuclear construction can be addressed and with improvement from new technologies in the longer term, the nuclear option can continue to be an important, growing part of a GHG-emissions-free energy portfolio. Design and demonstration efforts on near-term advanced reactor concepts—in combination with Federal financial risk mitigation tools—will enable power companies to build and operate new reactors that are economical and competitive with other generation technologies, supporting energy security and diversity of supply.

Evolutionary light-water reactors of standardized design (having received U.S. Nuclear Regulatory Commission design certification and having been constructed on schedule in Japan and South Korea) are demonstrated and available now for construction in the United States. Other newer designs should be reviewed and certified over the next several years, making them also available. However, more advanced nuclear energy systems for the longer term have the potential to offer significant advances in the areas of sustainability, proliferation resistance and physical protection, safety, and economics. These advanced nuclear energy systems—described as Generation IV reactors—could replace or add to existing light-water reactor capacity.

5.4.2 Technology Strategy

U.S. leadership is essential to the expansion of nuclear capacity in markets other than Asia and Eastern Europe (see Figure 5-12), through deployment of advanced nuclear power plants in the relatively near term. The untested Federal regulatory and licensing processes for the siting, construction, and operation of new nuclear plants must be demonstrated. In addition, other major obstacles must be addressed, including the initial high capital costs of the first few plants and the business risks resulting from both the costs and the regulatory uncertainty.

In the longer term, advanced nuclear energy systems could serve a vital role in both diversifying the Nation’s energy supply and reducing GHG emissions. By successfully addressing the fundamental research and development issues of system concepts that excel in safety, sustainability, cost-effectiveness, and proliferation resistance, the systems could attract future private-sector sponsorship and ultimate commercialization by the private sector. Advanced nuclear fission-reactor systems aim to extract the full energy potential of the spent nuclear fuel from current fission reactors, while reducing or eliminating the potential for proliferation of nuclear materials and technologies, and reducing both the radiotoxicity and total amount of waste produced.

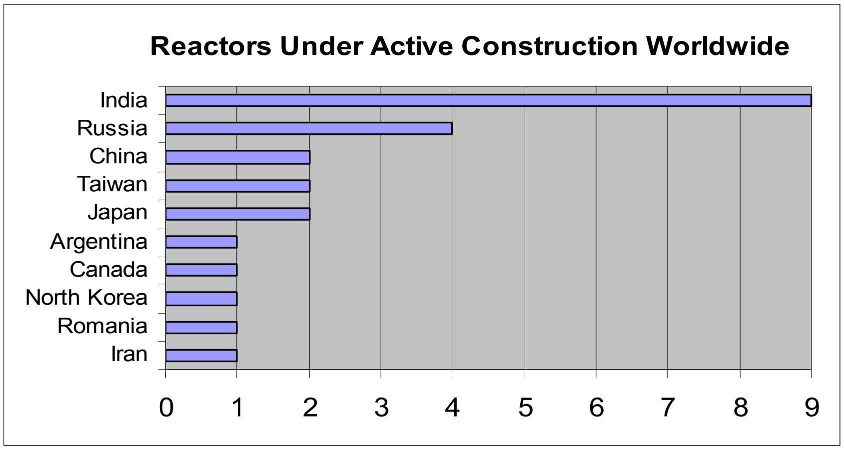

Figure 5-12. Nuclear Reactors Under Construction
(*Source:* World Nuclear Association http://www.world-nuclear.org/info/printable_information_papers/reactorsprint.htm)

A key objective of nuclear energy research and development is to enhance the basic technology; and, through advanced civilian technology research, chart the way toward the next leap in technology. From these efforts, and those of industry and overseas partners, nuclear energy may continue to fulfill its promise as a safe, advanced, inexpensive, and emission-free approach to providing reliable energy throughout the world.

5.4.3 Current Portfolio

The current Federal portfolio focuses on three areas:

- Research on **Nuclear Power Plant Technologies for Near-Term Deployment** is focused on advanced fission reactor designs that are currently available or could be made available with limited additional work to complete design development and deployment in the 2010 time frame.

  A Roadmap to Deploy New Nuclear Power Plants in the United States by 2010, issued in October 2001 (DOE 2001), advises DOE on actions and resource requirements needed to put the country on a path to bringing new nuclear power plants online by 2010. The primary purposes of the roadmap are to identify the generic and design-specific prerequisites to near-term deployment, to identify those designs that best promise to meet the needs of the marketplace, and to propose recommended actions that would support deployment. These include, but are not limited to, actions to achieve economic competitiveness and timely regulatory approvals.

  The Nuclear Power 2010 Program is a joint government/industry cost-shared effort. The program is designed to pave the way for an industry decision to order at least one new nuclear power plant by the end of the decade. Activities under this program support cost-shared demonstration of the Early Site Permit (ESP) and combined Construction and Operating License (COL) processes to reduce licensing uncertainties and minimize the attendant financial risks to the licensee. In addition, the program includes technology research and development to finalize and license a standardized advanced reactor design, which U.S. power-generation companies will find to be more competitive in the deregulated electricity market. The economics and business case for building new nuclear power plants has been evaluated as part of the Nuclear Power 2010 program to identify the necessary financial conditions under which power-generation companies would add new nuclear capacity.

The research program goals in this area are focused on successfully demonstrating the untested regulatory processes for Early Site Permit (ESP) and combined Construction and Operating License (COL) processes, and on the regulatory acceptance (certification) and completion of first-of-a-kind engineering and design. Specific goals include an industry decision to order a new nuclear power plant by 2008 and deployment of one or more new nuclear power plants in the 2010 time frame. See Section 2.4.2 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-242.pdf

- Research under the **Generation IV Nuclear Energy Systems Initiative** will lead to advanced nuclear energy systems that offer significant advances in the areas of sustainability, proliferation-resistance and physical protection, safety, and economics. These newer nuclear energy systems will replace or add to existing light-water reactor capacity and should be available between 2020 and 2030. To develop these advanced reactor systems, DOE manages the Generation IV Nuclear Energy Systems Initiative.

Development of next-generation nuclear energy systems is being pursued by the Generation IV International Forum (GIF), a group of 10 leading nuclear nations (Argentina, Brazil, Canada, France, Japan, the Republic of Korea, the Republic of South Africa, Switzerland, the United Kingdom, and the United States) plus the European Atomic Energy Community (Euratom). The GIF has selected six promising technologies as candidates for advanced nuclear energy systems concepts. The Generation IV (Gen IV) Nuclear Energy Systems Initiative addresses the fundamental research and development issues necessary to establish the viability of next-generation nuclear energy system concepts. By successfully addressing the fundamental research and development issues of system concepts that excel in safety, sustainability, cost-effectiveness, and proliferation resistance, the systems are highly likely to attract future private-sector sponsorship and ultimate commercialization by the private sector.

The primary focus of these Gen IV systems will be to generate electricity in a safe, economic, and secure manner; other possible benefits include the production of hydrogen, desalinated water, and process heat (see Figure 5-13). The GIF and the DOE's Nuclear Energy Research Advisory Committee (NERAC) issued a report on its two-year effort to develop a technology roadmap for future nuclear energy systems (GIF-NERAC 2002). The technology roadmap defines and plans the necessary R&D to support the advanced nuclear energy systems known as Generation IV. The DOE also prepared a report to the U.S. Congress regarding how it intends to carry out the results of the Generation IV Roadmap (DOE-NE 2003a).

Goals for next-generation fission energy systems (Generation IV) research are focused on the design of reactors and fuel cycles that are safer, more economically competitive, more resistant to proliferation, produce less waste, and make better use of the energy content in uranium, in accord with the abovementioned reports and roadmaps. See Section 2.4.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-241.pdf

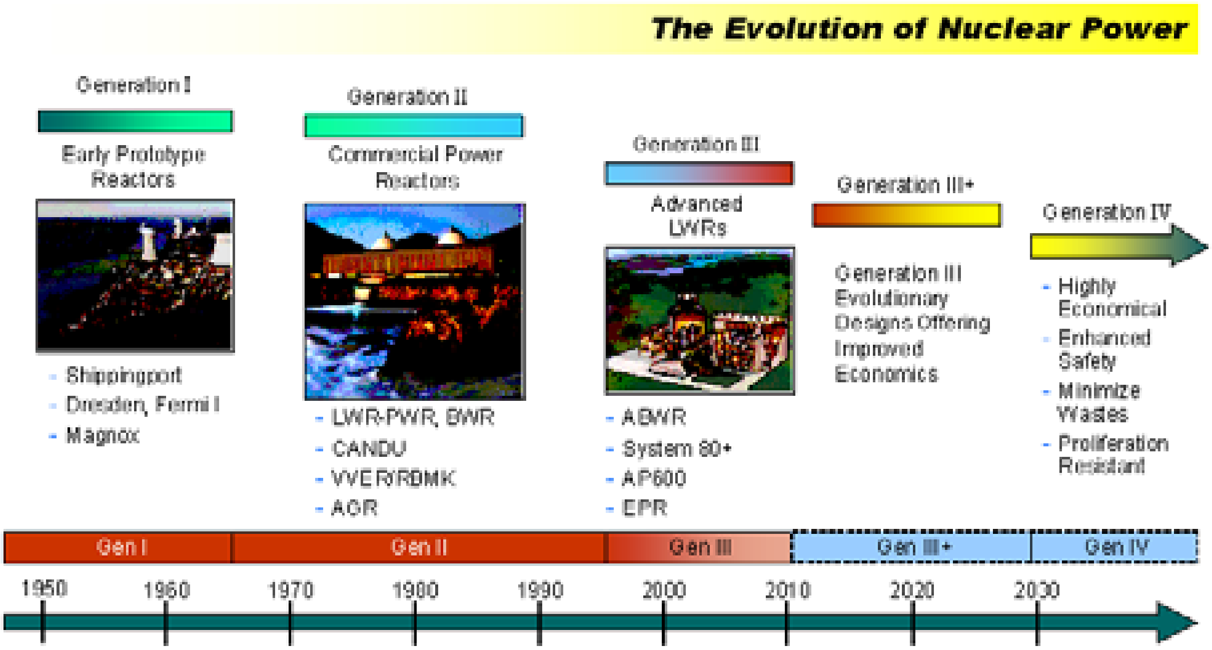

Figure 5-13. Future Nuclear Power Concepts

(*Source:* DOE, Office of Nuclear Energy, Science and Technology internal document)

- **The Advanced Fuel Cycle Initiative (AFCI),** under the leadership of DOE, is focused on developing advanced fuel-cycle technologies, which include spent fuel treatment, advanced fuels, and transmutation technologies, for application to current operating commercial reactors and next-generation reactors; and to inform a recommendation by the Secretary of Energy in the 2007-2010 time frame on the need for a second geologic repository.

The AFCI program will develop technologies to address intermediate and long-term issues associated with spent nuclear fuel. The intermediate-term issues are the reduction of the volume and heat generation of material requiring geologic disposal. The program will develop proliferation-resistant processes and fuels for application to current light-water reactor systems and Generation IV reactor systems to enable the energy value of these materials to be recovered, while destroying significant quantities of plutonium. This work provides the opportunity to optimize use of the Nation's first repository and reduce the technical need for an additional repository. The longer-term issues to be addressed by the AFCI program are the development of fuel-cycle technologies to destroy minor actinides, which would greatly reduce the long-term radiotoxicity and heat load of high-level waste sent to a geologic repository. This will be accomplished through the development of Gen IV fast reactor fuel-cycle technologies and possibly accelerator-driven systems (DOE-NE 2003b).

Goals for advanced nuclear fuel-cycle research focus on proving design principles of spent-fuel treatment and transmutation technologies, demonstrating the fuel and separation technologies for waste transmutation, and deploying Generation IV advanced fast spectrum reactors that can transmute nuclear waste. See Section 2.4.3 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-243.pdf

5.4.4 Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio. These include:

- Provide for development and demonstration of advanced technologies to reduce construction time for new nuclear power plants and to minimize schedule uncertainties and associated costs for construction

- Support operational safety, proliferation-resistant, fuel-cycle concepts; minimization of wastes; and economy of both capital, and operation and maintenance (O&M).

Additional R&D work that could be undertaken for near-term deployment options relate to advanced light-water and gas reactors, including fuel development, characterization, manufacture, testing, and regulatory acceptance; power conversion-system design and testing, including resolution of uncertainties regarding materials, reliability, and maintainability; and fission reactor internal design and verification.

Of the other challenges that must be addressed to enable a future expansion in the use of nuclear energy in the United States and worldwide, none is more important—nor more difficult—than that of dealing effectively with spent nuclear fuel. Compared to other industrial waste, the spent nuclear fuel generated during the production of electricity is relatively small in quantity. However, it is highly radioactive for many thousands of years, and its disposal requires resolution of many political, societal, technical, and regulatory issues. While these issues are being addressed in the license application for the Yucca Mountain repository in Nevada, several countries worldwide have pursued advanced technologies that could treat and transmute spent nuclear fuel from nuclear power plants. These technologies have the potential to dramatically reduce the quantity and toxicity of waste requiring geologic disposal. During the past four years, the United States has joined this international effort and found considerable merit in this area of joint advanced research.

The public is invited to comment on the current CCTP portfolio, including future research directions, and identify potential gaps or significant opportunities. No assurance can be provided that any suggested concept would meet the criteria for investment. However, CCTP can be assisted by such comments in its desire to consider a full array of promising technology options.

5.5 Fusion Energy

Fusion energy holds the possibility of an almost inexhaustible supply of zero-GHG electricity. Fusion is the power source of the sun and the stars. Lighter elements are "fused" together in the core of the sun, producing heavier elements and prodigious amounts of energy. On Earth, fusion energy has been demonstrated in the laboratory at powers of 5 to 15 million watts, with pulse lengths in the range of 1 to 5 seconds. The goal is for fusion power to eventually be produced at much larger scales.

Fusion power generation offers a number of advantageous features. The basic sources of fusion fuel, deuterium and tritium, are actually heavy forms of hydrogen. Deuterium is abundantly available because it occurs naturally in water; and tritium can be derived from lithium, a light metal found in the earth's crust. Tritium is radioactive, but the quantities in use at any given time are quite modest and can be safely handled. There are no chemical pollutants or carbon dioxide emissions from the fusion process. With appropriate advances in materials, the radioactivity of the fusion byproducts would be relatively short-lived, thereby obviating the need for extensive waste management measures.

From a safety perspective, the fusion process poses little radiation risk to anyone outside the facility. Also, since only a small quantity of fuel is in the fusion system at any given time, there is no risk of a critical accident or meltdown, and little after-heat to be managed in the event of an accident. The potential usefulness of fusion systems is great, but many scientific and technical challenges remain.

5.5.1 Potential Role of Technology

Fusion energy is an attractive option to consider for long-term sustainable energy generation. It would be particularly suited for base-load electricity supply, but could also be used for hydrogen production. With the growth of world population expected to occur in cities and megacities, concentrated energy sources that can be located near population centers (such as fusion energy) may be particularly attractive. In addition, the fusion process does not produce GHGs and has well-attested and attractive inherent safety and environmental characteristics that could help gain public acceptance.

Energy scenarios imposing reasonable constraints on nonsustainable energy sources show that fusion energy could contribute significantly to large-scale electricity production during the second half of the 21st century. Also, the cost of fusion electricity could be comparable to other environmentally friendly sources of electricity generation.

Making fusion energy a part of the future energy solution is among the most ambitious scientific and engineering challenges of our era. The following are some of the major scientific questions that need to be answered:

- Can burning plasma that shares the characteristic intensity and power of the sun be successfully produced and sustained?

- To what extent can models be used to simulate and predict the behavior of the burning, self-sustained fuel required for fusion applications?

- How can new materials that can survive the fusion environment (which are needed for fusion power to be commercially viable) be developed?

Answering these questions requires understanding and control of complex and dynamic phenomena occurring across a broad range of temporal and spatial scales. The experiments required for a commercially viable fusion power technology constitute a complex scientific and engineering enterprise that must be sustained over several decades.

5.5.2 Technology Strategy

Given the substantial scientific and technological uncertainties that now exist, the U.S. Government will continue to employ a portfolio strategy that explores a variety of magnetic confinement approaches and leads to the most promising commercial fusion concept. Advanced computational modeling will be central to testing the agreement between theory and experiment, simulating experiments that cannot be readily investigated in the laboratory, and exploring innovative designs for fusion plants. To ensure the highest possible scientific return, the DOE's Fusion Energy Sciences program will extensively engage with and leverage other DOE programs and international programs in areas such as magnetic confinement physics, materials science, ion beam physics, and high energy density physics. Large-scale experimental facilities will likely be necessary, and the rewards, risks, and costs of these major facilities will need to be shared through international collaborations. The target physics aspect of inertial fusion is being conducted now through the National Nuclear Security Administration's (NNSA) stockpile stewardship program. The overall Fusion Energy Sciences effort will be organized around a set of four broad goals.

Fusion Energy Sciences Goal #1: Demonstrate with burning plasmas the scientific and technological feasibility of fusion energy. The goal is to demonstrate a sustained, self-heated fusion plasma, in which the plasma is maintained at fusion temperatures by the reaction products, a critical step to practical fusion power. The strategy includes the following area of emphasis:

- Participate in the international magnetic fusion experiment, ITER (Latin for "the way") project, with the European Union, Japan, Russia, China, South Korea, and perhaps others, as partners.

Fusion Energy Sciences Goal #2: Develop a fundamental understanding of plasma behavior sufficient to provide a reliable predictive capability for fusion energy systems. Basic research is required in turbulence and transport, nonlinear behavior and overall stability of confined plasmas, interactions of waves and particles in plasmas, the physics occurring at the wall-plasma interface, and the physics of intense ion beam plasmas and high energy density plasmas. The strategy includes the following areas of emphasis:

- Conduct fusion science research through individual-investigator and research-team experimental, computational, and theoretical investigations

- Advance the state-of-the-art computational modeling and simulation of plasma behavior in partnership with the Advanced Scientific Computing Research program in DOE's Office of Science

- Support basic plasma science, partly with the National Science Foundation, connecting both experiments and theory with related disciplines such as astrophysics.

Fusion Energy Sciences Goal #3: Determine the most promising approaches and configurations to confining hot plasmas for practical fusion energy systems. The strategy includes experiments and advanced simulation and modeling; innovative magnetic confinement configurations, such as the National Spherical Torus Experiment (NSTX); and a planned compact stellarator experiment, the National Compact Stellarator Experiment (NCSX) at Princeton Plasma Physics Laboratory (PPPL); as well as smaller experiments at multiple sites.

Fusion Energy Sciences Goal #4: Develop the new materials, components, and technologies necessary to make fusion energy a reality. The environment created in a fusion reactor poses great challenges to materials and components. Materials must be able to withstand high fluxes of high-energy neutrons and endure high temperatures and high thermal gradients, with minimal degradation. The strategy includes the following areas of emphasis:

- Design materials at the molecular scale to create new materials that possess the necessary high-performance properties, leveraging investments in fusion energy research with investments in basic materials research

- Explore "liquid first-wall" materials to ameliorate first-wall requirements for advanced fusion energy concepts.

5.5.3 Current Portfolio

The current Fusion Energy Sciences (FES) program, within DOE's Office of Science, is a program of fundamental research into the nature of fusion plasmas and the means for confining plasma to yield energy. This includes: (1) exploring basic issues in plasma science; (2) developing the scientific basis and computational tools to predict the behavior of magnetically confined plasmas; (3) using the advances in tokamak[5] research to enable the initiation of the burning plasma physics phase of the FES program; (4) exploring innovative confinement options that offer the potential of more attractive fusion energy sources in the long term; (5) developing the cutting-edge technologies that enable fusion facilities to achieve their scientific goals; and (6) advancing the science base for innovative materials to establish the economic feasibility and environmental quality of fusion energy.

The overall effort requires operation of a set of unique and diversified experimental facilities, ranging from smaller-scale university programs to several large national facilities that require extensive collaboration. These facilities provide scientists with the means to test and extend theoretical understanding and computer models, leading ultimately to an improved predictive capability for fusion science.

The two major tokamak experiments, DIII-D at General Atomics and the Alcator C-Mod at MIT, are extensively equipped with sophisticated diagnostics that allow for very detailed measurements in time and spatial dimensions as they continuously push the frontiers of tokamak plasma confinement. They each involve an array of national and international collaborators on the scientific programs.

Similarly, the NSTX at PPPL is also a well-diagnosed and highly collaborative experiment on an innovative confinement approach that seems likely to lead to improved understanding of toroidal[6] confinement systems.

An additional innovative concept, the National Compact Stellarator Experiment, is currently being fabricated at PPPL with first operation scheduled for 2009. This machine is a product of new computational capabilities that have optimized the 3-dimensional toroidal magnetic geometry for improved confinement and stability in a compact form.

In addition to these major experiments, there are a larger number of smaller magnetic confinement experiments with more specialized missions. These are generally at universities and provide an opportunity for student training.

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[5] Tokamak (Acronym created from the Russian words, "TOroidalnaya KAmera ee MAgnitnaya Katushka," or "Toroidal Chamber and Magnetic Coil"): The tokamak is the most common research machine for magnetic confinement fusion today.

[6] Toroidal: in the shape of a torus, or doughnut. Toroidal is a general term that refers to toruses as opposed to other geometries (e.g., tokamaks and stellarators are examples of toroidal devices).

A modest-scale high energy density physics program is also underway, with an emphasis on using heavy ion drivers to explore plasma/beam dynamics and warm dense matter with potential applications to future inertial energy systems. This program also explores innovative approaches to improving inertial fusion energy such as the fast-ignition experiments. In addition, the FES program benefits from existing experimental programs conducted elsewhere for NNSA's stockpile stewardship program and the Department of Defense (DoD). Both the "Z" experiment at Sandia National Laboratories and the OMEGA experiment at the University of Rochester, for example, offer opportunities for improving understanding of high energy density physics.

Theory and computing are key parts of the present program, as they provide the intellectual framework for the overall approach to fusion energy, as well as the computer codes, which attempt to systematically rationalize the understanding of fusion plasmas. See Section 2.5.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-251.pdf

5.5.4 Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio. These include:

Burning plasmas represents the next major science and technology frontier for fusion research. In the major international effort mentioned above (ITER), the United States, Europe, Japan, China, Russia, and the Republic of Korea are negotiating an agreement to construct a magnetic fusion burning plasma science and engineering test facility. The ITER international magnetic fusion experiment is a key part of the U.S. strategy to investigate the underlying science for magnetic confinement fusion energy (see Figure 5-14). Additional investments in fusion materials, components, and technologies for MFE are contingent upon favorable results from ITER.

Prior to the anticipated operation of ITER around 2014, experiments on a wide range of plasma-confinement systems worldwide will continue physics research in preparation for ITER operations. These experiments will include detailed simulations of ITER behavior as well as innovative new ways of operating fusion systems to optimize efficiency. Because of the sophisticated measurement techniques employed on modern fusion experiments, detailed data are already available to validate computer models.[7] Work will also continue on

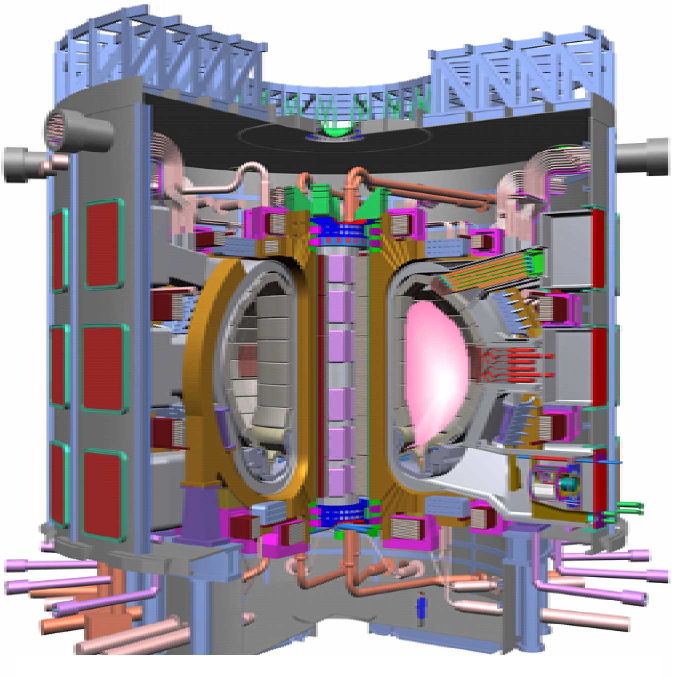

Figure 5-13. ITER Schematic
Source: http://www.iter.org/

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[7] For additional information about ITER, see http://www.iter.org/.

confinement configuration optimization that would allow better understanding or improve the confinement approach for future power systems.

In other efforts, the United States is proceeding with high energy density physics, the science base for inertial fusion, through the development of NNSA's National Ignition Facility (NIF) and other fusion energy work, including driver, target fabrication, and chamber technologies. The drivers include lasers and pulsed power-driven z-pinches in the NNSA program and heavy ion accelerators. Efforts to explore the understanding and predictability of high energy density plasma physics, including the ramifications for energy-producing applications, are also underway.[8] However, any additional investment in the inertial fusion energy approach awaits successful demonstration of ignition and gain in the NIF.

The public is invited to comment on the current CCTP portfolio, including future research directions, and identify potential gaps or significant opportunities. No assurance can be provided that any suggested concept would meet the criteria for investment. However, CCTP can be assisted by such comments in its desire to consider a full array of promising technology options.

5.6 Conclusions

Among the many thrusts for addressing climate change with the aid of technology, improved energy efficiency, CO_2 capture and sequestration, and reduced emissions of non-CO_2 GHGs, soot, and aerosols are all important, if not essential, to goal attainment. Large quantities of energy supplied by low or near-net-zero emissions technology, however, form the core of any long-term technology component of the overall strategy. Just meeting the expected growth in world energy demand over the span of the 21st century will likely be challenging enough. Meeting such demand, while simultaneously reducing emissions and maintaining economic prosperity, will be doubly challenging. Advanced technology as outlined in this chapter on energy supply can facilitate progress in that direction.

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[8] For additional information about U.S. fusion energy research, see http://www.ofes.fusion.doe.gov/.

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