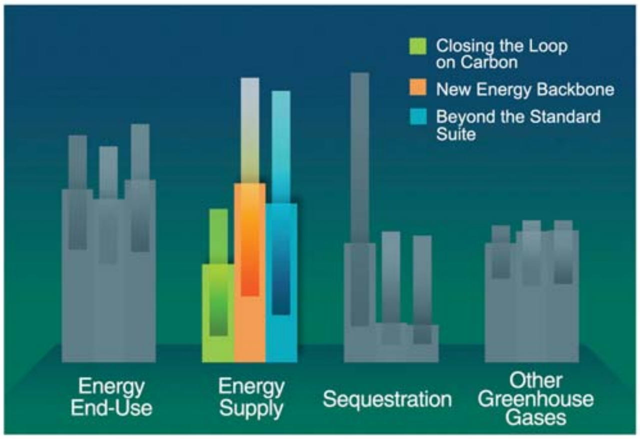
Reducing Emissions from Energy Supply

Reducing greenhouse gas (GHG) emissions from energy supply is an important element of CCTP's technology strategy. In part, this is because global energy demand is projected to grow significantly by the year 2100 and, in part, because the infrastructure that will be built to meet this demand will have long-lasting consequences for future GHG emissions.

Some projections show energy demand over the course of the 21st century growing by a factor of more than 6 (from about 400 exajoules [EJ] in 2000 to more than 2400 EJ in 2100). 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 advance steadily over time. Of this growth, global demand for electricity is projected to increase faster than direct use of fuels in end-use applications. Most infrastructure needed to meet this demand, including the replacement of the facilities to be retired, has yet to be built—a circumstance that poses significant opportunities for new and advanced technology to reduce or eliminate much of these future emissions.

In published scenarios of CO_2 emissions to 2100, increasing demand for energy results in concomitant growth in CO_2 emissions. By contrast, almost all scenarios that explore various future paths toward significant emissions reductions show that various forms of low or near net-zero emissions energy supply play a key role in achieving those reductions. In one set of scenarios, as shown in Figure 3-19 and highlighted above, advanced energy supply technologies contribute an additional 20 to 35 thousand EJ toward global energy demand and result in reductions of global carbon emissions between about 30 and 330 gigatons of carbon (GtC), compared to a reference case used in the study (see Chapter 3). Although bracketed by large uncertainties, these figures suggest both the potential role for advanced technology and a long-term goal for contributions from this sector of the global economy.

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).



Energy Supply
Potential Contributions to Emissions Reduction

Potential contributions of Energy Supply reduction 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.

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. The facility 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).

Advances in novel or visionary energy supply technologies may also make important contributions toward reduced GHG emissions, including fusion energy; advanced fuel cycles based on combinations of nanotechnology and new forms of bio-assisted energy production, using bioengineered molecules for more efficient photosynthesis; and hydrogen production or photon-water splitting. Other possibilities include advanced technologies for capturing solar energy in Earth orbit, on the moon, or in the vast desert areas

World Electricity Generation

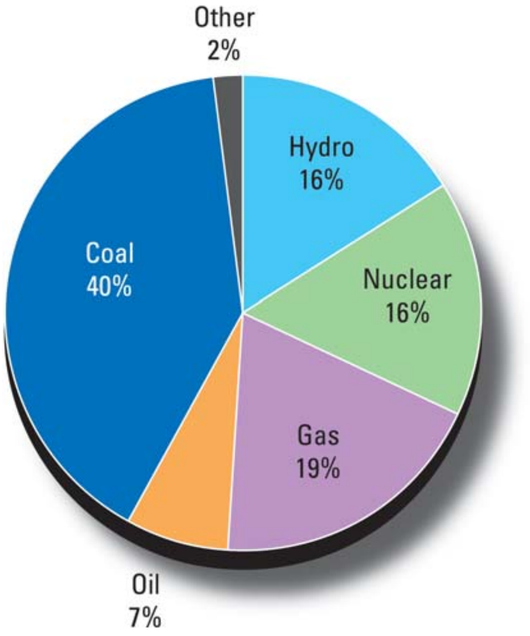


Figure 5-1. World Electricity Generation (Source: IEA 2004)

World Primary Energy Supply

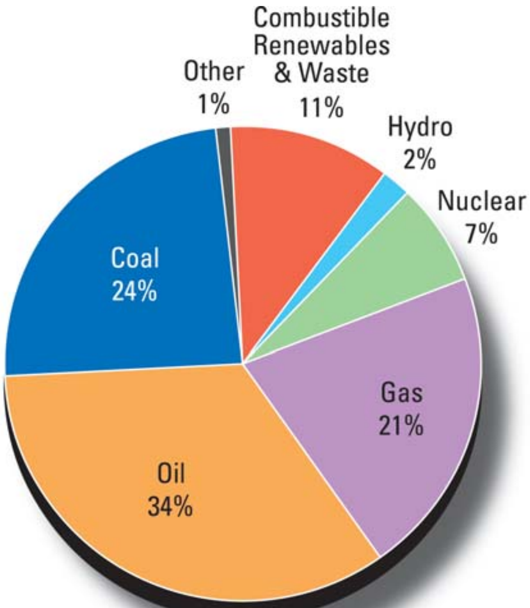


Figure 5-2. World Primary Energy Supply (Source: IEA 2004)

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

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 a 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.

Each of these technology sections contains 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* (CCTP 2005).[2]

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 relatively low cost, coal now accounts for about 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 2030 (EIA 2006). 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.

Potential Role of Technology

Because coal is America’s most plentiful and readily available energy resource, the U.S. Department of Energy has directed a portion of its research and development 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 reduction 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.[3] 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.

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[2] The report is available at http://www.climatetechnology.gov/library/2005/tech-options/index.htm.

[3] 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.

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 near-zero atmospheric emission, coal-based electricity generation plant that has the ability to co-produce low-cost hydrogen. In the mid term, 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 90 percent reduction 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 serve to demonstrate the most advanced technologies, such as hydrogen fuel cells.[4]

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 reductions 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. Current Integrated Gasification Combined Cycle (IGCC) systems average power plant efficiencies are about 40-42 percent; increasing efficiencies to 48-52 percent in the mid term and 60 percent by 2020 (with the integration of fuel cell technology), will nearly halve emissions of CO_2 per unit of electricity, relative to pulverized-coal-based power plants which have efficiencies of 30-35 percent (Figure 5-4). Development and deployment of CO_2 capture and storage technology could reduce atmospheric emissions to near-zero levels through 2100. Recent R&D activities have focused on IGCC plants, with two U.S. IGCC demonstration plants now 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 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. In addition, emissions of criteria pollutants are targeted to be much less than one-tenth of current new source performance standards.[5]

- **Distributed Generation/Stationary Fuel Cells:** The stationary fuel cell (FC) program is focused on reducing the cost of fuel cell technology for distributed generation applications (as opposed to transportation applications) by an order of magnitude.

Coal-Based Energy Complex

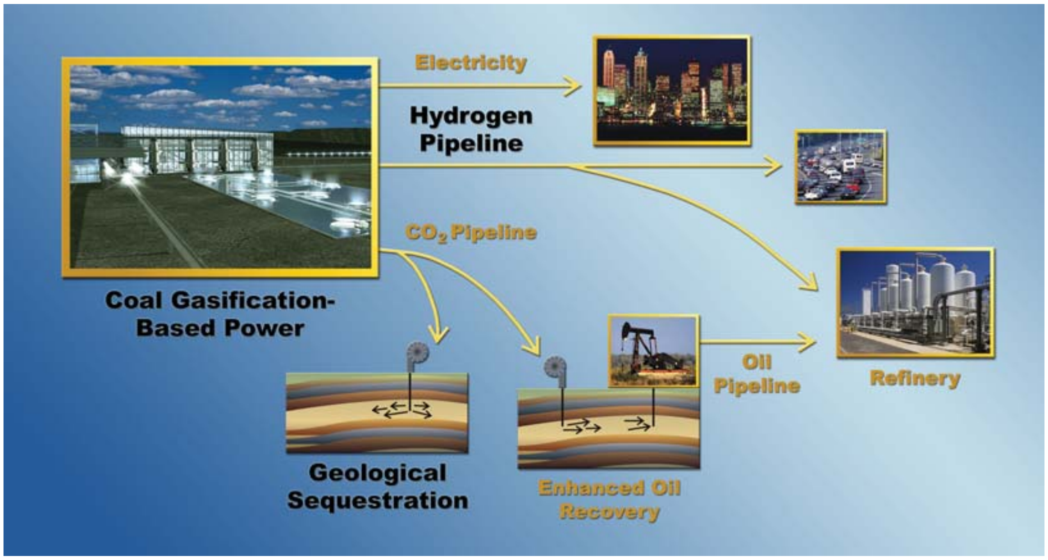

Figure 5-3.
A fully integrated coal-based energy complex will have the ability to co-produce electricity, hydrogen, fuels and chemicals with little or no CO_2 emissions.
(Source: DOE 2004)

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[4] See http://www.fossil.energy.gov/programs/powersystems/futuregen/futuregen_report_march_04.pdf.

[5] See Section 2.1.2 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-212.pdf.

In the near and mid terms, fuel cell cost reductions could enable the widespread deployment of natural-gas-fueled distributed generation in gas-only, CHP, and fuel cell applications. In the mid- 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 fuel cell module larger than 250 kW that can run on coal synthetic gas (syngas), while also reducing the costs of the Solid-State Energy Conversion Alliance fuel cell power system to $400/kW by 2010. In addition, 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; and (2) integrate optimized turbine systems into zero-emission power plants.[6]

- **Co-production/Hydrogen:** This research area focuses on developing technology to co-produce electricity and hydrogen from coal, which could also be relevant to applications using coal and biomass blends, potentially achieving very large reductions in CO_2 emissions when compared to present technologies. This technology will use syngas generated from coal gasification to produce hydrogen.

Near-Zero Atmospheric Emission Power and hydrogen coproduction research goals target a 10-year demonstration project (FutureGen) to create the world's first coal-based, near-zero atmospheric 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.[7]

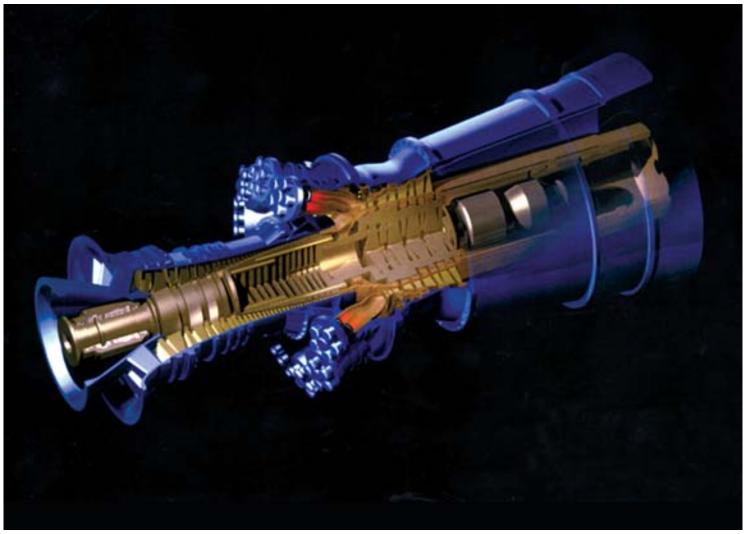

Figure 5-4. Advanced Gas Turbines can increase efficiencies in combined-cycle systems to 60 percent, while also reducing the cost of electricity production.

Courtesy: DOE/NETL

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.

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:

- **Advanced membranes for gas phase separations.** Separations such as oxygen separation from air, which is required for

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[6] See Section 2.1.3 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-213.pdf.

[7] See Section 2.1.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-211.pdf.

oxycombustion technology and hydrogen separation from gasified coal streams, are energy intensive and reduce the overall efficiency of advanced combustion and gasification plants. Near-term technologies are under development for improving these gas separations, but in the longer term it is desirable to develop advanced ion transport membranes for oxygen separation and ceramic membranes for hydrogen recovery.

- **Solid-oxide fuel cells.** Coal gasification plants that produce hydrogen streams as feed to solid-oxide fuel cells for improving electricity production efficiency are being studied. Future research could examine approaches scaling up low-cost solid oxide fuels cells to multi-hundred megawatt sizes for use as power blocks in near-zero atmospheric emissions systems.
- **High-temperature materials and heat transfer technology.** Future generation systems will need to maintain relatively high temperatures between the combustion/gasification stage and the turbine stage to achieve high generation efficiency goals. A primary technology development interest is for high-temperature materials that are stable and resistant to corrosion, erosion, and decrepitation. Advanced materials could improve performance of future heat exchangers, turbine components, particulate filters, and SO_2 removal. Other possible research directions include the use of alternate working fluids and heat-exchange cycles.
- **Unconventional combustion systems.** A promising research direction involves use of chemical cycling for CO_2 enrichment. In this concept, CO_2 is continually looped and enriched within the combustion plant and the enriched CO_2/O_2 gas stream is substituted for air in the main combustion chamber.
- **Hydrogen co-production.** Technology for hydrogen capture and purification in a coal gasification plant for electricity production may enable hydrogen production for a future hydrogen-powered vehicle economy.
- **Advanced hybrid gasification/combustion systems.** These systems appear to offer an alternative path to achieve many of the program goals and may warrant additional study.
- **Reduction of N_2O emissions.** Existing post-combustion emissions technology that reduces the emissions of the controlled pollutant NO_X also tends to increase the emissions of N_2O gas, which is a GHG. Post-combustion processes could simultaneously minimize the emissions of both NO_X and N_2O.

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 adsorbed onto carbon-based nanostructures. If progress can be made on a number of technical fronts, so that costs of producing hydrogen are reduced, hydrogen could play a valuable enabling and synergistic role in heat and power generation, transportation, and energy end use.

Potential Role of Technology

As a major constituent of the world's water, biomass, and fossil hydrocarbons, the element hydrogen 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 hydrogen and fossil fuels, however, is that the production of hydrogen, whether from water, methane or other hydrocarbons, is a net-energy consumer. This makes hydrogen not an energy source, per se, but a carrier of energy, similar to electricity.

Like electricity, the life-cycle GHG emissions associated with hydrogen use would vary depending on the method to produce, store, and distribute it. Hydrogen 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 hydrogen 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," hydrogen 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 hydrogen 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 hydrogen 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 hydrogen demands at petroleum refineries or ammonia (NH_3) synthesis plants can justify investment in dedicated hydrogen pipelines, but smaller or variable demands for hydrogen are usually met more economically by truck transport of compressed gaseous hydrogen or cryogenic and liquefied hydrogen produced by steam methane reforming. These methods have evolved over decades of industrial experience, with hydrogen as a niche chemical commodity, produced in amounts (8 billion kg hydrogen/yr) equivalent to about 1 percent (approximately 1 EJ per year) of current primary energy use in the United States. For hydrogen 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 hydrogen 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).

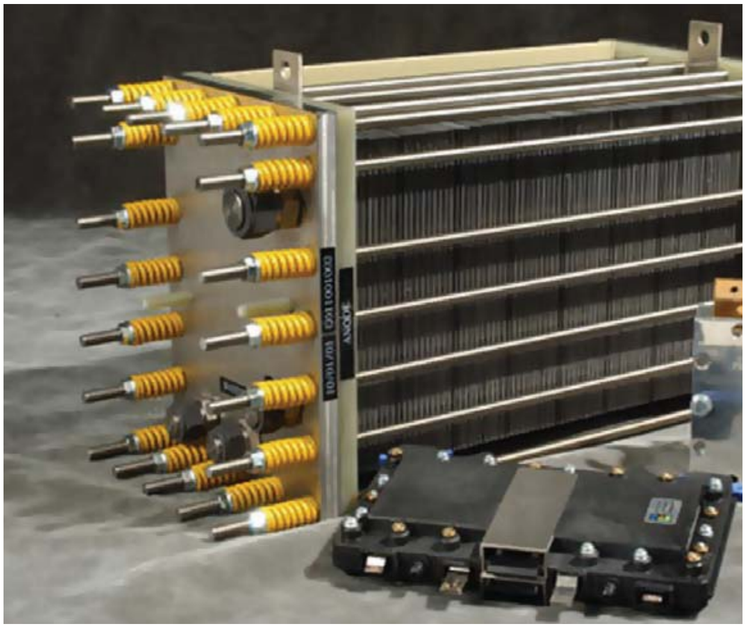

Figure 5-5. Fuel cells use the chemical energy of hydrogen and oxygen from air to produce electricity without combustion.

Courtesy: DOE/NREL, Credit – Matt Stiveson

In the near term, initial deployment of hydrogen fleet vehicles and distributed power systems may provide early adoption opportunities and demonstrate the capabilities of the existing hydrogen 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 hydrogen use may also serve as a commercial proving ground for advanced distributed hydrogen production and conversion technologies using existing storage technology, both stationary and vehicular.

In the mid term, light-duty vehicles likely will be the first large mass market (10-15 EJ per year in the United States) for hydrogen. Fuel cells may be particularly attractive in automobiles, given their efficiency versus load characteristics and typical driving patterns (Figure 5-5). Hydrogen production for this application could occur either in large centralized plants or using distributed production technologies on a more localized level—most probably the latter.

In the long term, production technologies must be able to produce hydrogen at a price competitive with gasoline for bulk commercial fuel use in automobiles, freight trucks, aircraft, rail, and ships. This would 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 hydrogen storage and transportation. Finally, advances in basic science associated with direct water-splitting and solid-state hydrogen storage could possibly permit even lower-cost hydrogen production and safer storage, delivery, and utilization in the context of low or near-net-zero emission futures for transportation and electricity generation.

Technology Strategy

Introducing hydrogen 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 hydrogen 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 national 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 hydrogen light-duty vehicles (Figure 5-6). 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:

- Hydrogen storage systems enabling minimum 300-mile vehicle range while meeting identified packaging, cost, and performance requirements;
- Hydrogen production to safely and efficiently deliver hydrogen to consumers at prices competitive with gasoline and without adverse environmental impacts; and
- Transportation fuel cell power system 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.

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 hydrogen automobiles by 2015, with the longer-term ultimate development of a mature hydrogen economy founded on advanced hydrogen production, storage, and delivery technologies. Elements of the portfolio include:

- **Hydrogen Production from Nuclear Fission.** High-efficiency, high-temperature fission power plants may one day produce hydrogen economically without producing CO_2 as a byproduct. 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 to produce electricity to generate hydrogen from water. 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.[8]

- **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; and (2) development of alternative reactors, including auto-thermal reactors; and, by 2007, 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, at laboratory-bench scale: (1) a photo-electrochemical water-splitting system; and

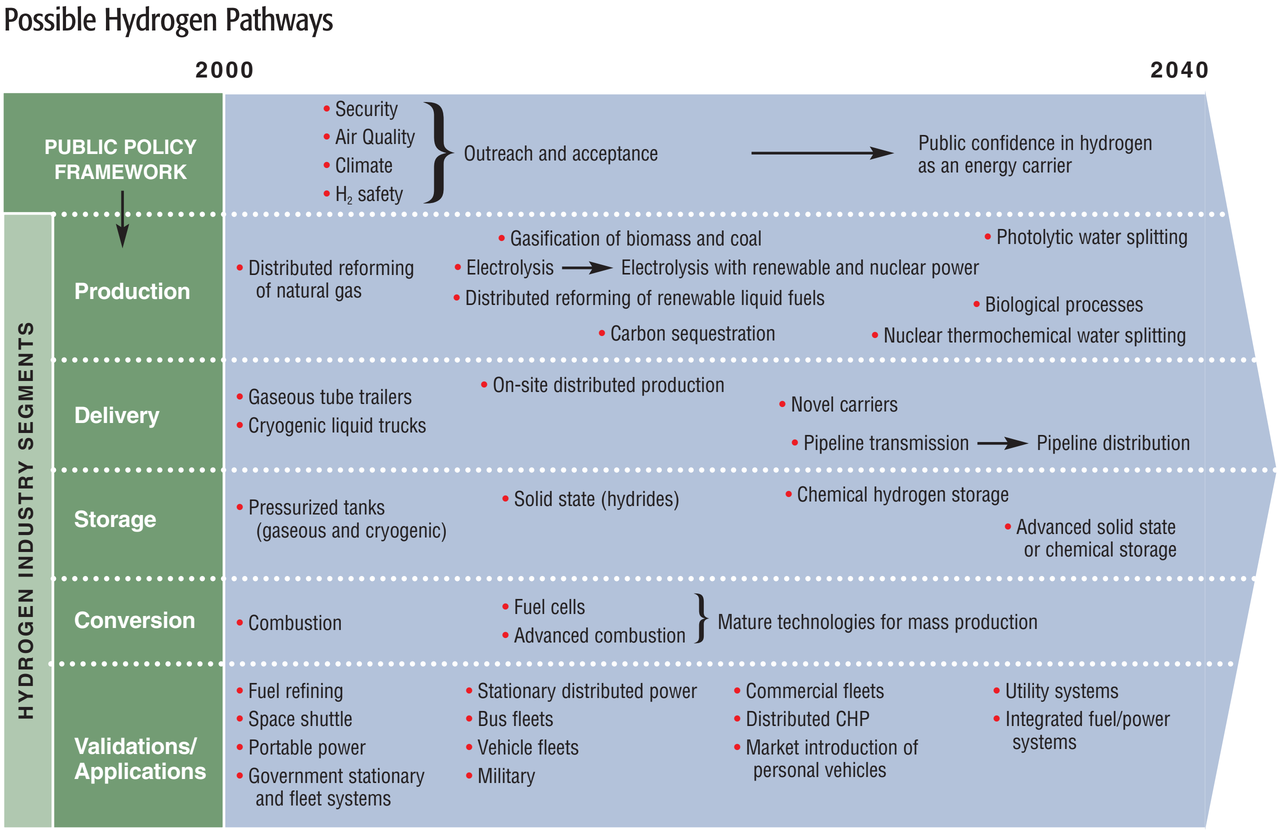

Figure 5-6. Possible Hydrogen Pathways (Source: U.S. Department of Energy Hydrogen Program)

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[8] See Section 2.2.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-221.pdf.

Figure 5-7. A systems approach is needed for integrated hydrogen production, delivery, and storage, as well as for refueling hydrogen vehicles.

Courtesy: DOE/NREL, Credit: Warren Gretz

(2) a biological system for water-splitting (or other substrates) that shows potential to achieve long-term costs that are competitive with conventional fuels.[9]

- **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 adsorption 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—is also planned.

  The research program goals of hydrogen storage are: (1) 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 (2) 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.[10]

- **Hydrogen Use.** DOE aims to demonstrate high-efficiency, solid-oxide fuel cell/turbine hybrid-electric generation systems operating on gasified coal with carbon capture and storage, and to develop efficient and durable polymer electrolyte membrane (PEM) fuel cells appropriate for automotive and stationary applications. Additional research is underway to use hydrogen in auxiliary power units in heavy vehicles to supplant diesel engine power use for refrigeration and housekeeping tasks.

  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.[11]

- **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 (Figure 5-7). 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 the following: (1) by 2006, complete development of a laboratory-scale distributed natural-gas-to-hydrogen production and dispensing system that can produce 5,000 psi hydrogen for $3.00/gge; (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/gge. 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 hydrogen fuel costs between $2.00 and $3.00/gge. The technology-validation effort also provides information in support of technical codes and standards development of infrastructure safety procedures.[12]

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[9] See Section 2.2.3 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-223.pdf.

[10] See Section 2.2.4 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-224.pdf.

[11] See Section 2.2.5 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-225.pdf.

[12] See Section 2.2.2 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-222.pdf.

- **Hydrogen Infrastructure Safety.** Ensuring the safety of hydrogen infrastructure technologies largely depends on the development of sound, internationally agreed upon codes and standards. DOE will study the flammability and explosive, reactive, and dispersion properties of hydrogen and will subject components, subsystems, and systems to environmental conditions that could result in failure in order to verify design practice and to develop failure-mode models and risk-analysis methodologies. DOE is also compiling a hydrogen safety-incident database, and will develop potential accident scenarios, and draft a handbook on Best Management Practices for Safety to be published in 2008. These technical data and models will be provided to the appropriate organizations (i.e., International Code Council, National Fire Protection Association) to write and publish applicable codes and standards for hydrogen production and delivery processes as well as for hydrogen storage and fuel cell systems. The goal is to have all data and testing completed by 2010 to finalize U.S. technical standards for preparation of a Global Technical Regulation. The Department of Transportation (DOT) has regulatory or codes-and-standards responsibilities, including future Federal Motor Vehicle Safety Standards for fuel cell vehicles. The Federal government will facilitate the development of other necessary standards by standards organizations through R&D and support for appropriate technical representation in working groups. In support of on-vehicle safety, DOE will develop hydrogen safety sensor technology that can meet technical targets for response time and accuracy.[13]

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 hydrogen for these modes and explore the infrastructure implications of hydrogen production and/or liquefaction on-site at airports, harbors, rail yards, etc. In the case of hydrogen-powered aircraft, the average length of future flights and whether significant demand for hypersonic passenger aircraft develops over the 21st century will be important factors in determining the relative fuel economy advantages of hydrogen, if any, over conventional jet fuel. Scenarios that include a worldwide shift toward hydrogen-powered aircraft and like substitutes for shorter trips (high-speed rail) could be considered.

- **Integration of Electricity and Hydrogen Transportation Sectors.** Eventual full deployment for optimal use of solar, wind, biomass, and nuclear electricity may require significant hydrogen storage or increased flexibility in electricity demand. Electrolytic coproduction of hydrogen 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 hydrogen vehicles and carbonless electricity generation.

- **Vehicle-to-Grid Options.** Fuel cell vehicles represent a potential new power generation source, supplying electricity to homes and to the grid in emergencies or periods of exceptional demand. In this scenario, fuel-cell vehicles would represent new installed peak or backup power generation capacity. Depending on the source of the fuel used, this could also reduce GHG emissions. Better understanding and modeling of the potential benefits of vehicle-to-grid options could inform integrative strategies regarding the energy sector and climate change.

- **Develop Fundamental Understanding of the Physical Limits to Efficiency of the Hydrogen Economy.** The fundamental electrochemistry and material science of electrolyzers, fuel cells, and reversible devices need to be fully explored. For example, the theoretical limits on electrolyte conductivity bound the power density and efficiency of both fuel cells and electrolyzers.

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[13] See Section 2.2.6 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-226.pdf.

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.

- **Explore advanced concepts in hydrogen production.** Current hydrogen R&D activities have focused much of the available funding for hydrogen production on near-term technologies that can be ready for commercialization to support introduction of hydrogen vehicles soon after a 2015 industry decision-point. As available, funding has also supported advanced renewables-based production approaches such as photoelectrochemical and photobiological pathways. Breakthroughs in these or other advanced production pathways will be necessary to make a true hydrogen economy economically feasible, and the CCTP will be exploring ways to ensure sufficient funding for advanced, post-2015 hydrogen production technologies.

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 and waste. These sources of energy, available in one or more forms across the globe, can be converted and/or delivered to end users as electricity, heat, fuels, hydrogen, and useful chemicals and materials. Box 5-1 lists 12 renewable energy technologies, many of which are 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).

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
- Waste-to-Energy
- Photoconversion
- Advanced Hydropower
- Geothermal Energy

The technologies in the suite of renewable energy technologies are in various states of market penetration or readiness. In many cases, industry has the financial incentive to make incremental improvements to commercialized renewable energy technologies, or other policies exist to promote renewable energy development and deployment (research and experimentation tax credit, State renewable portfolio standards). These and other factors are important to consider as CCTP helps to prioritize Federal investments.

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 59 GW by the end of 2006. Technology improvements will continue to lower the cost of land-based wind energy 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 in early stages of development; but advances in these technologies are expected to make them competitive with conventional sources in the future.

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, and 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. Waste-to-energy accounts for more than 2.5 gigawatts of power production.

The energy-production potential and siting of the various types of renewable energy facilities is dependent on availability of the applicable natural resources. Figures 5-8 through 5-12 show global wind capacity growth and availability of key U.S. renewable resources as estimated by the National Renewable Energy Laboratory (NREL) at the Renewable Resource Data Center (see http://nrel.gov/rredc).

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

Global Wind Capacity Growth

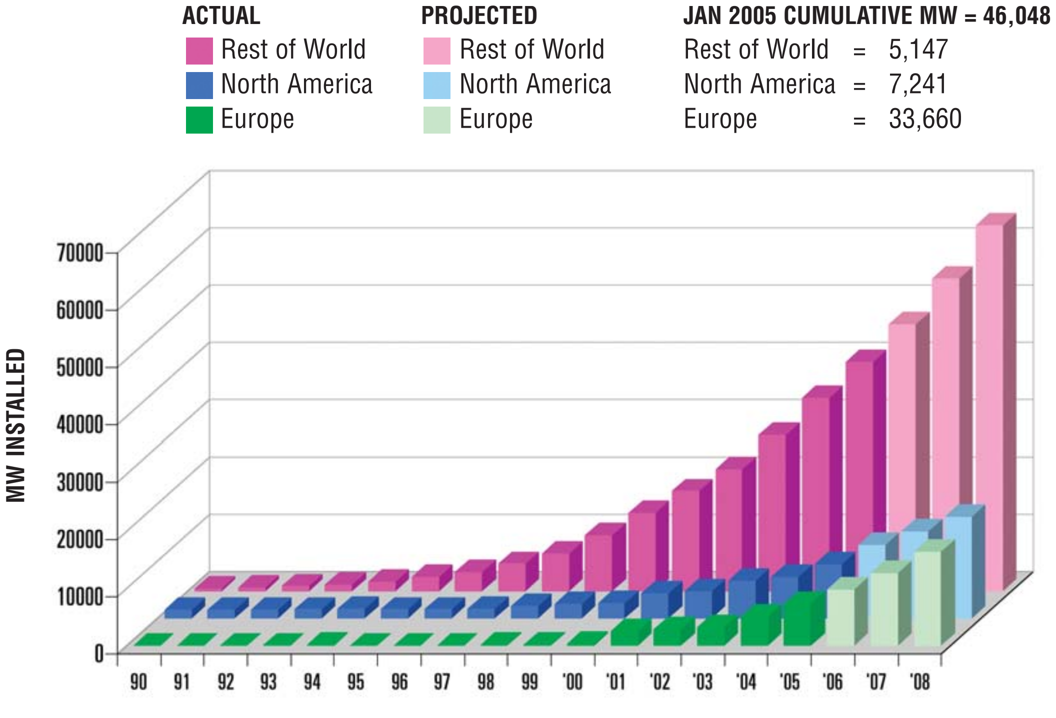
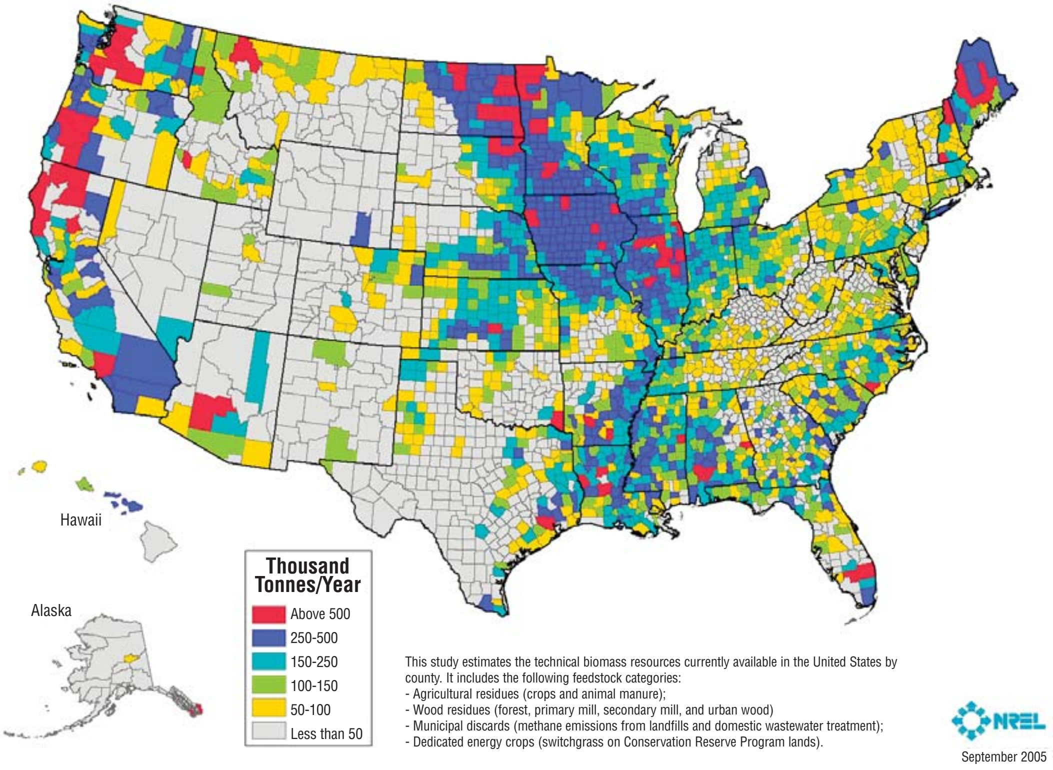


Figure 5-8. Global Wind Capacity Growth (Source: BTM Consult Aps, March 2003; Windpower Monthly, January 2005; NREL estimate for 2005)

U.S. Biomass Resources



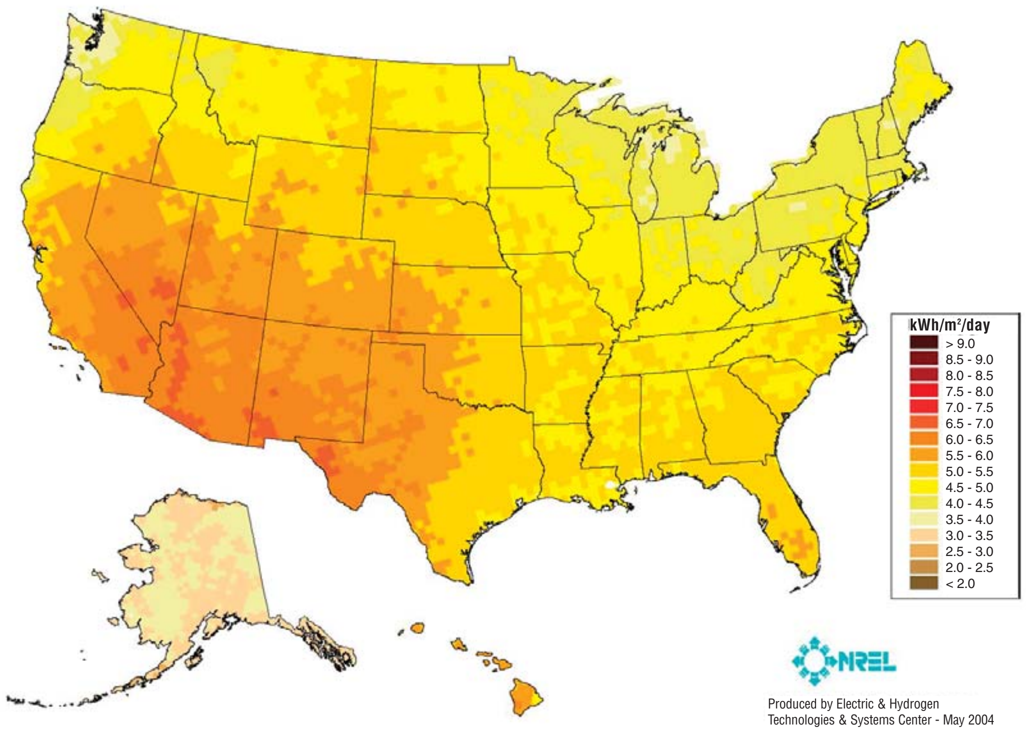
This study estimates the technical biomass resources currently available in the United States by county. It includes the following feedstock categories:
- Agricultural residues (crops and animal manure);
- Wood residues (forest, primary mill, secondary mill, and urban wood)
- Municipal discards (methane emissions from landfills and domestic wastewater treatment);
- Dedicated energy crops (switchgrass on Conservation Reserve Program lands).

September 2005

Figure 5-9. U.S. Biomass Resources (Source: DOE Office of Energy Efficiency and Renewable Energy)

Note: This Biomass Resources map is the "current" resource base (about 500 million dry tons) and does not reflect the potential future resource base as outlined in the "Billion Ton Vision." The map takes into account the resource required for soil conservation. More information can be found at: http://www.nrel.gov/gis/biomass.html.

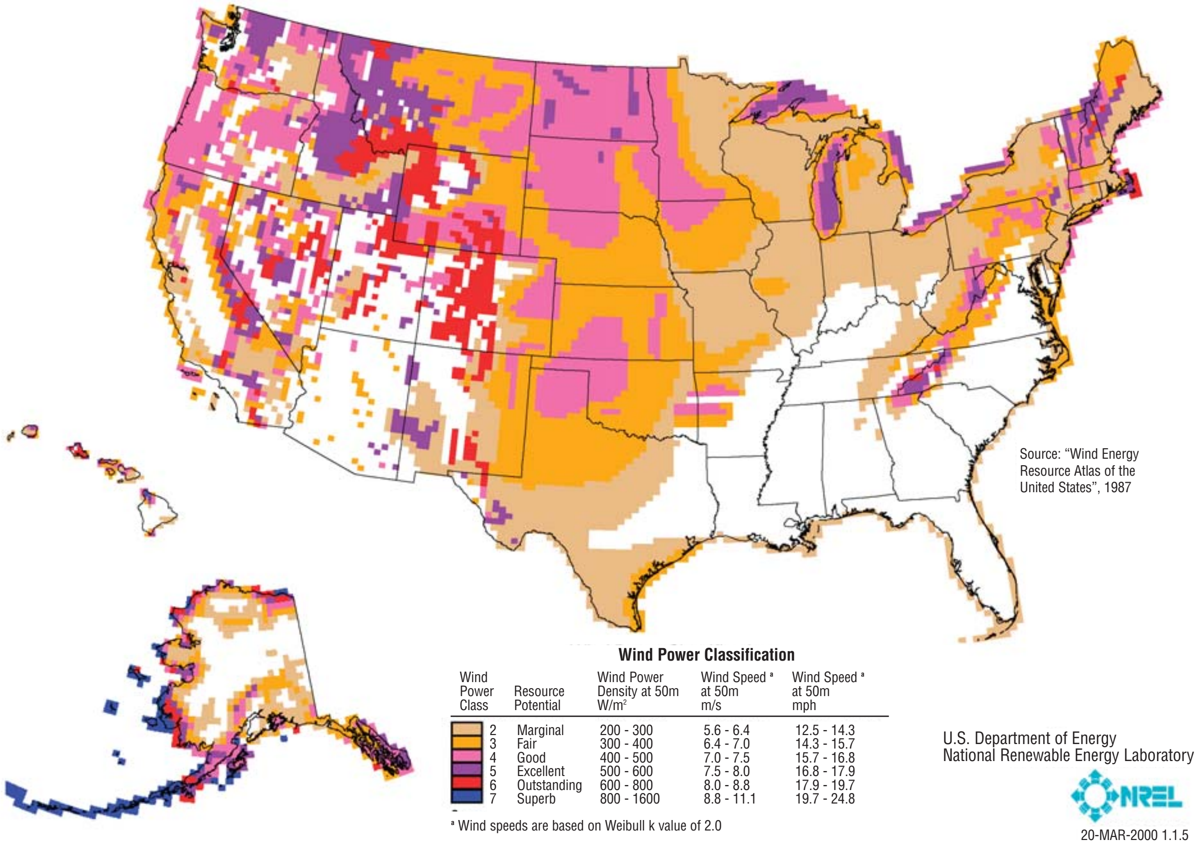
U.S. Solar Resources



Produced by Electric & Hydrogen Technologies & Systems Center - May 2004

Figure 5-10. U.S. Solar Resources (Source: DOE Office of Energy Efficiency and Renewable Energy)

U.S. Wind Resources



Source: "Wind Energy Resource Atlas of the United States", 1987

Wind Power Classification

Wind Power Class	Resource Potential	Wind Power Density at 50m W/m^2	Wind Speed [a] at 50m m/s	Wind Speed [a] at 50m mph
2	Marginal	200 - 300	5.6 - 6.4	12.5 - 14.3
3	Fair	300 - 400	6.4 - 7.0	14.3 - 15.7
4	Good	400 - 500	7.0 - 7.5	15.7 - 16.8
5	Excellent	500 - 600	7.5 - 8.0	16.8 - 17.9
6	Outstanding	600 - 800	8.0 - 8.8	17.9 - 19.7
7	Superb	800 - 1600	8.8 - 11.1	19.7 - 24.8

[a] Wind speeds are based on Weibull k value of 2.0

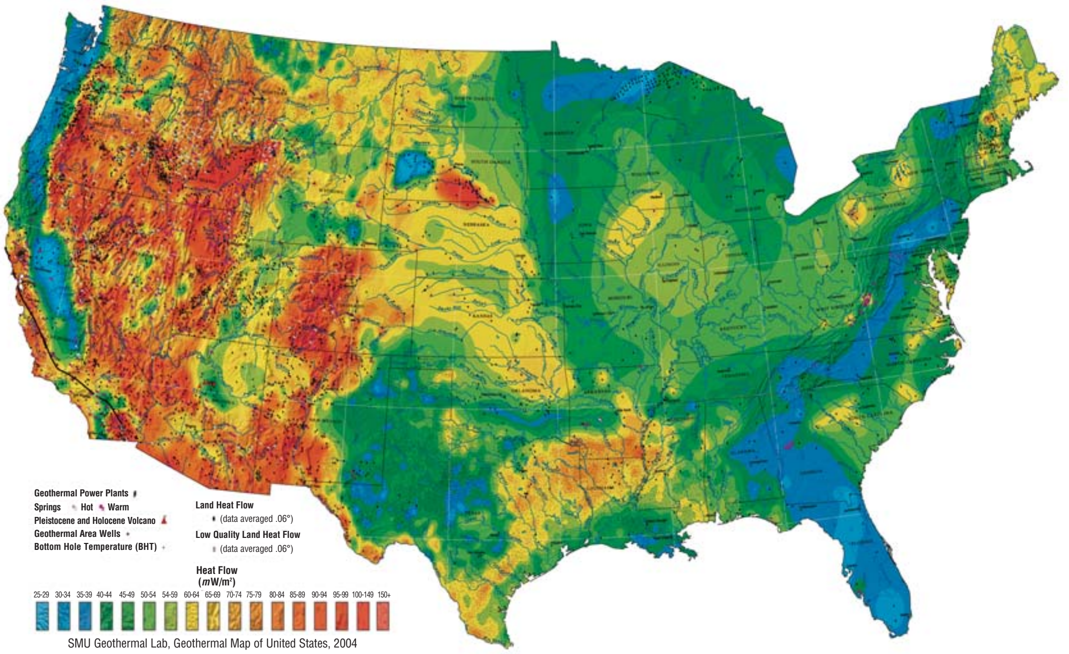
U.S. Department of Energy
National Renewable Energy Laboratory

NREL

20-MAR-2000 1.1.5

Figure 5-11. U.S. Land-Based Wind Resources
(Source: DOE Office of Energy Efficiency and Renewable Energy)

U.S. Geothermal Resources



SMU Geothermal Lab, Geothermal Map of United States, 2004

Figure 5-12. U.S. Geothermal Resources (Source: DOE Office of Energy Efficiency and Renewable Energy)

Bioenergy Cycle

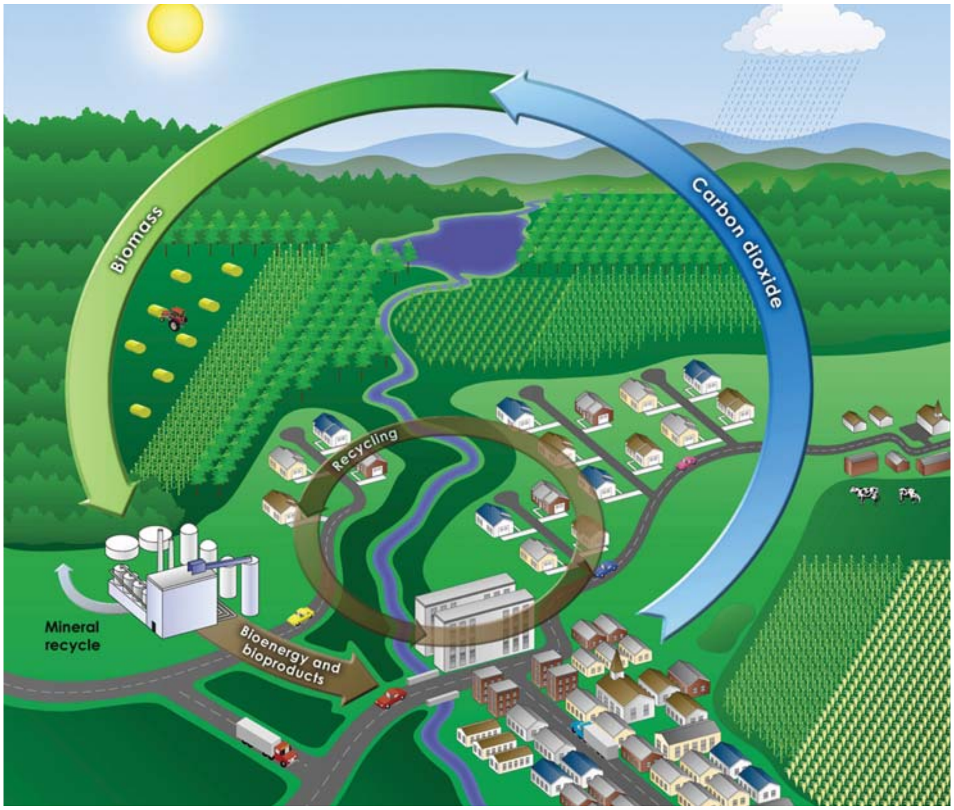


Figure 5-13.
Bioenergy Cycle
Courtesy: DOE/ORNL

used, because this avoids methane emissions that result from landfilling unused biomass (Figures 5-13 and 5-14). 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.

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. For example, changes to the electricity infrastructure are needed to accommodate greatly increased use of renewable electric generation. These changes include additional transmission lines to access those renewable resources that are located far from load centers; grid operating practices and storage to accommodate renewables that are intermittent, such as wind and solar; greater use of renewables in a distributed generation mode; and adapting current fossil generation for biomass co-firing. Fortunately, there already is substantial progress in adapting the electricity infrastructure to enable greater use of renewables generation, and additional changes that would be needed are relatively easy to make in a decade or so. With regard to renewable fuels used for transportation, no significant changes to vehicles and refueling infrastructure are needed until E10 ethanol (90 percent gasoline, 10 percent ethanol) in gasoline blends captures 10 percent of gasoline markets. When 85 percent ethanol/gasoline blends (E85) expand, which is expected if ethanol costs come down further, limited refueling infrastructure modifications will be needed. However, refueling technology needed for E-85 is already well developed, and several

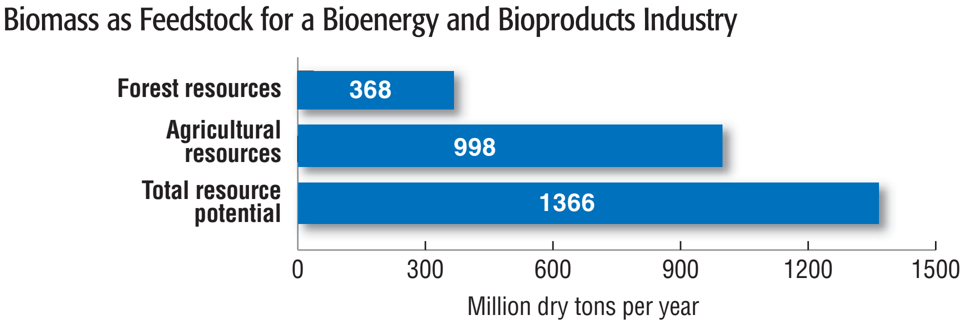


Figure 5-14. Biomass as Feedstock for a Bioenergy and Bioproducts Industry (Source: ORNL 2005)

automobile manufacturers are already selling E-85 vehicles at low or no incremental costs.

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 pathways for renewable energy are discussed in the following paragraphs.

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. Environment-friendly hydropower systems could be further 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 at water depths of 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.[14] 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 outlook includes industry investment to make the production of corn-based ethanol (already produced at nearly 4 billion gallons) more efficient 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 further help to improve the industry's profitability. The Biofuels Initiative launched in FY 2007 will accelerate demonstrations of biorefinery concepts, 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. The technology being developed to convert agricultural residues to ethanol is also partially applicable to the conversion of municipal solid waste to ethanol.

A recent assessment of potential biofuel resources concluded that by mid-21st century it would be technically possible to produce enough biomass to displace about one-third of current petroleum consumption. The study made no conclusions about economic feasibility. This level of biofuel production would require economically-competitive technologies to convert cellulosic biomass (rather than just the sugars and starches) into ethanol, and developing cellulosic ethanol technologies is a central aspect of the Biofuels Initiative and the President's Advanced Energy Initiative.

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[14] 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.

In the mid term, 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. Land-based 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.[15]

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 systems could also become cost-effective in new construction for commercial buildings and homes. 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.

As a result of the Biofuels Initiative, biorefineries could begin using agricultural and forest residues, and eventually energy crops as primary feedstocks. Assuming success in reducing production costs and expanding the fuels distribution infrastructure, bioethanol and, to a lesser extent, biodiesel could achieve substantial market penetration in the 2030-2040 timeframe. This would be an important step in lowering 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 residential and commercial buildings, industrial plants, and entire communities in major sections of the country. A major value for solar is that 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 platform technologies. Geothermal systems could be a major source of baseload 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.

Current Portfolio

The current Federal portfolio of renewable energy supply technologies encompasses the areas 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 $0.04-0.06/kWh depending on the wind resource. Smaller turbines (under 100 kW) serve a range of distributed, remote, and stand-alone power applications, producing energy between $0.12-0.17/kWh. While the focus in the last several years has been on low-wind-speed technology R&D for onshore applications, R&D for reducing the cost of offshore systems, based on recent emergence of U.S. land-based wind power development and the assessment of potential national benefits, is also supported. 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. Federal agencies are also collaborating with interested stakeholders on addressing and minimizing siting concerns (i.e., wildlife and acoustics).

  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 $0.10 to 0.15/kWh in Class 3 winds by 2007. For larger systems greater than 100 kW, the goal is to achieve a power production cost of $0.036/kWh for land-based at sites with average wind speeds of 13 mph (wind Class 4) by 2012, and $0.05/kWh at shallow (depths up to 30 meters) offshore sites with average wind speeds of 15 mph (wind Class 6) by 2014, and $0.05/kWh for transitional (depths up to 60 meters) offshore systems in Class 6 winds by 2016.[16]

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

[16] 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 11 percent to 13 percent efficient, and grid-tied photovoltaic (PV) systems generate electricity for about $0.18 to 0.23/kWh under ideal siting and financing conditions for commercial (low end of range) and residential (high end of range) systems. Actual levelized cost of energy may be significantly greater in parts of the United States where the solar resource potential is less than ideal. Research activities, conducted with 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 (Figure 5-15); and technical issues with inverters and batteries.

  Research program goals in this area focus primarily on a new initiative—the Solar America Initiative (SAI)—which will accelerate R&D efforts designed to achieve market competitiveness for PV solar electricity by 2015 (i.e., 5 to 10 cents/kWh under ideal siting and financing conditions). The accelerated R&D effort will focus on PV technology pathways that have the greatest potential to lower costs and improve performance. New industry-led R&D partnerships, known as "Technology Pathway Partnerships," will be funded to address the issues of cost, performance, and reliability associated with each technology pathway. Potential partners within the Technology Pathway Partnerships include industry, universities, laboratories, States, and other governmental entities. If the research is successful and if other policies remain in place to promote deployment (production tax credits, State renewable portfolio standards), then by 2015, 5-10 GW of new solar power capacity could be deployed, equivalent to the amount of electricity needed to power 1-2 million homes. This deployment level would result in 10 million metric tons of avoided carbon dioxide emissions in the United States. The interim cost goal is to reduce the 30-year user cost for PV electrical energy to a range of $0.11 to 0.18/kWh under ideal conditions by 2010.[17]

- **Solar Heating and Lighting.** Solar heating and lighting technologies are being developed for use in buildings applications that include solar water heating and hybrid solar lighting. Most of the goals for these technologies have been sufficiently developed for use in southern climates and now can be transferred to industry for commercialization.[18]

- **Concentrating Solar Power.** Concentrating solar power (CSP) technology utilizes the heat generated by concentrating and absorbing the sun's energy to produce electric power. The concentrated sunlight produces thermal energy at temperatures ranging from 600 degrees F to over 1500 degrees F to run heat, engines, or steam turbines for generating power or producing clean fuels such as hydrogen. 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.[19]

- **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.

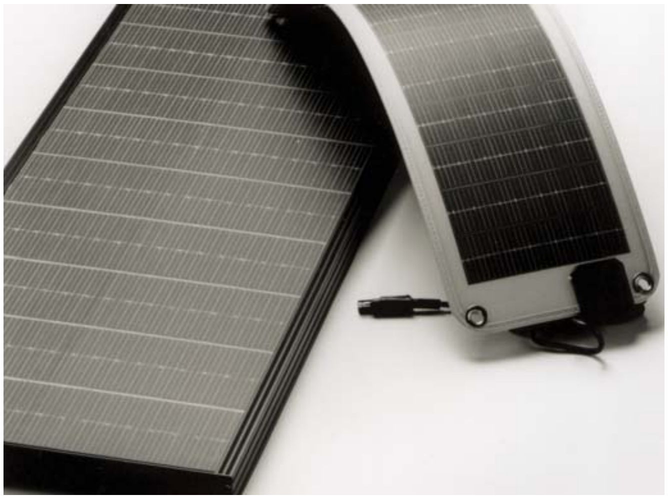

Figure 5-15. Research and development activities on solar photovoltaic power, conducted at Federal laboratories and the private sector, help to improve efficiencies, lower production costs, and resolve technical issues.

Courtesy: DOE/NREL, Credit: United Solar Systems Corp.

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[17] See Section 2.3.2 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-232.pdf.

[18] See Section 2.3.3 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-233.pdf.

[19] See Section 2.3.4 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-234.pdf.

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.

By FY 2007, the goal is to complete a preliminary engineering design package, market analysis, and financial projections for two industrial-scale projects for near-term agricultural pathways (corn wet mill, corn dry mill, oilseed) to produce a minimum of five million gallons of biofuels per year. The intent is to provide proof that the resultant industrial-scale biorefineries could produce and market biofuels at prices competitive with petroleum fuels produced from $50-per-barrel oil. By 2009, develop a conceptual, novel harvesting system and test a wet storage system for agricultural residues. By 2012, the goal is to reduce the estimated cost for producing a mixed, dilute sugar stream suitable for fermentation to ethanol, to $0.096/lb, compared to the cost of $0.15/lb in 2003. If successful, this cost goal would correspond to $1.50 per gallon of ethanol, assuming a cost of $45 per dry ton of corn stover.[20]

◆ **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 syngas, 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.[21]

◆ **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 mid- to long-term research program goal in this area is to reduce biomass harvesting and storage costs so that the delivered cost will be reduced from $53 per dry ton in 2003 to $45 per dry ton by 2012. The Biofuels Initiative of 2007 proposes to establish three regional biomass development partnerships in conjunction with land grant universities to develop research-specific data on feedstock availability, productivity, markets, and economics by 2008, and an additional partnership by 2009. Engineering designs and techno-economic assessments of integrated wet biomass storage and field preprocessing will be completed by 2008. By 2010, engineering design on multi-crop feedstock depot systems that can receive a variety of feedstocks and preprocess will then be completed.[22]

◆ **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: (1) 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; (2) 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 the process facility; and (3) 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.[23]

◆ **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

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[20] See Section 2.3.5 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-235.pdf.

[21] See Section 2.3.6 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-236.pdf.

[22] See Section 2.3.7 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-237.pdf.

[23] See Section 2.3.8 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-238.pdf.

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.[24]

- **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. Government geothermal research and development activities are being transferred to the private sector for commercialization.[25]

- **The Green Power Partnership** facilitates purchases of environmentally friendly electricity products generated from renewable energy sources by addressing the market barriers that may be stifling demand. It publishes information about low-cost purchasing strategies, educates partners about features of different green power products, and reduces the transaction costs for organizations interested in making green power purchases.

- **The Combined Heat and Power Partnership** provides technical assistance designed to meet CHP project needs along each step of the project development cycle in order to make investments in CHP more attractive. EPA educates industry about the benefits of CHP and project development strategies and provides networking opportunities. EPA also works with State governments to design air emissions standards and interconnection requirements that recognize the benefits of clean CHP.

- **The Renewable Energy Systems and Energy Efficiency Improvements Program** supports biomass/renewable energy related ventures.

- **The Renewable Energy and Energy Efficiency Partnership** seeks to accelerate and expand the global market for renewable energy and energy efficient technologies.

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

Figure 5-16. The Department of Energy is working closely with industry to research and develop new, advanced wind turbine technology.

Courtesy: GE Energy, ©2005, General Electric International, Inc.

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[24] See Section 2.3.9 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-239.pdf.

[25] See Section 2.3.11 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-2311.pdf.

the Great Lakes (Figure 5-16); 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 and 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.
- **Solar Fuels**. Research could focus on artificial photosynthetic systems that operate at higher rates and efficiencies than natural photosynthetic processes in plants. Such systems might either be photo-biologically-based or electro-photo-chemistry-based and would consume CO_2 and water from the atmosphere and produce H_2, O_2, and (very) small photosynthetic electric currents. Research would include solar-powered photo-catalyzed production of liquid transportation fuels from H_2 and CO_2
- **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 syngas; and develop cost-competitive catalysts and processes for converting synthetic gases to chemicals, fuels, or electricity. All 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.
- **Waste-to-Energy.** Waste-to-energy technologies can produce valued energy, with low "net-emissions" of GHGs when the full fuel cycle is considered, by processing and combusting municipal solid waste and doing so in an environmentally acceptable manner with specially designed and equipped modern equipment and pollution controls. Research challenges remain in the areas of better understanding contaminants, pre-cleaning of waste streams, separations and recycling, and overall environmental and safety performance.
- **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.
- **Bio-X**. Combines advanced biological processing with emerging advances in other fields such as nanotechnology, computer science, and physics to develop new approaches for renewable technologies.

- **Geothermal Energy.** Future research areas that industry may pursue 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.
- **Advanced Solid State Thermoelectric Devices.** If additional technical progress can be achieved, thermoelectric devices could allow conversion of mid-grade and low-grade heat to electricity at economically attractive efficiencies. To the extent that waste heat might otherwise be discarded, the conversion could add significantly to net energy supply. There could be multiple applications for adding a cogeneration "bottoming cycle" and improving the overall efficiency of any process involving significant amounts of heat, including conversion of solar heat.

5.4 Nuclear Fission

Currently, 443 nuclear power plants, operating in 31 nations, generate 17 percent of the world's electricity (Figure 5-1) and provide nearly 7 percent of total world energy (Figure 5-2). Twenty-three new plants are under construction in ten countries. Because they emit no GHGs, today's nuclear power plants avoid the CO_2 emissions associated with combustion of coal or other fossil fuels (Figure 5-17).

Figure 5-17. More than 400 successfully operating civilian nuclear power plants around the world avoid billions of tons of CO_2 emissions for the atmosphere.

Credit: ©Royalty-Free/CREATAS

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.

Potential Role of Technology

The 103 currently operating 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, 39 of these units have received approval to extend their operating licenses for an additional 20 years; 12 others have applications under review. All of the remaining units most likely will follow suit. Such CO_2 emission mitigation could be increased if new nuclear capacity were to be brought online.

To the extent that 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.

Nuclear Reactors Under Active Construction Worldwide

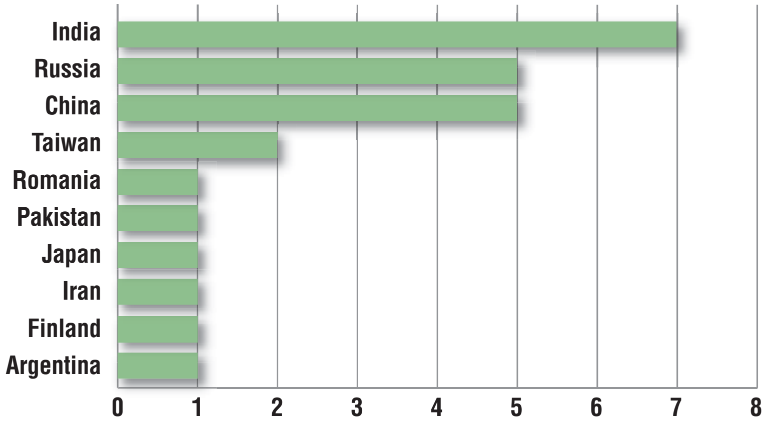

Figure 5-18. Nuclear Reactors Under Active Construction Worldwide (Source: World Nuclear Association[26])

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.

Technology Strategy

U.S. leadership is essential to the expansion of nuclear capacity in markets other than Asia and Eastern Europe (Figure 5-18), through deployment of advanced nuclear power plants in the relatively near term. The new Federal regulatory 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.

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.

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 on-line in the next decade. The primary purposes

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[26] See http://www.world-nuclear.org/info/printable_information_papers/reactorsprint.htm.

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 ESP and combined COL, and on the regulatory acceptance (certification) and completion of first-of-a-kind engineering and design. Specific goals include industry decisions to build new nuclear power plants by 2009 with commercial operation in the next decade.[27]

- **Research under the Generation IV Nuclear Energy Systems Initiative (Gen IV)** will enhance the viability of 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 Gen IV.

  Development of next-generation nuclear energy systems is being pursued by the Generation IV International Forum (GIF) [www.gen-4.org], 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 Gen IV addresses the fundamental research and development issues necessary to establish the viability of next-generation nuclear energy system concepts. After successfully addressing the viability issues, 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, economical, and secure manner; other possible benefits include the production of hydrogen, desalinated water, and process heat (Figure 5-19). In particular, making nuclear power sustainable over the long term requires developing and deploying proliferation-resistant fuel recycling technology and fast reactors for breeding new fuel and transmuting higher actinides. The GIF and 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 Gen IV. DOE also prepared a report to the U.S. Congress regarding how it intends to carry out the results of the Gen IV Roadmap (DOE-NE 2003a).

  Goals for next-generation fission energy systems (Gen 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 above-mentioned reports and roadmaps.[28]

- **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.

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[27] See Section 2.4.2 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-242.pdf.

[28] See Section 2.4.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-241.pdf.

Future Nuclear Power Concepts

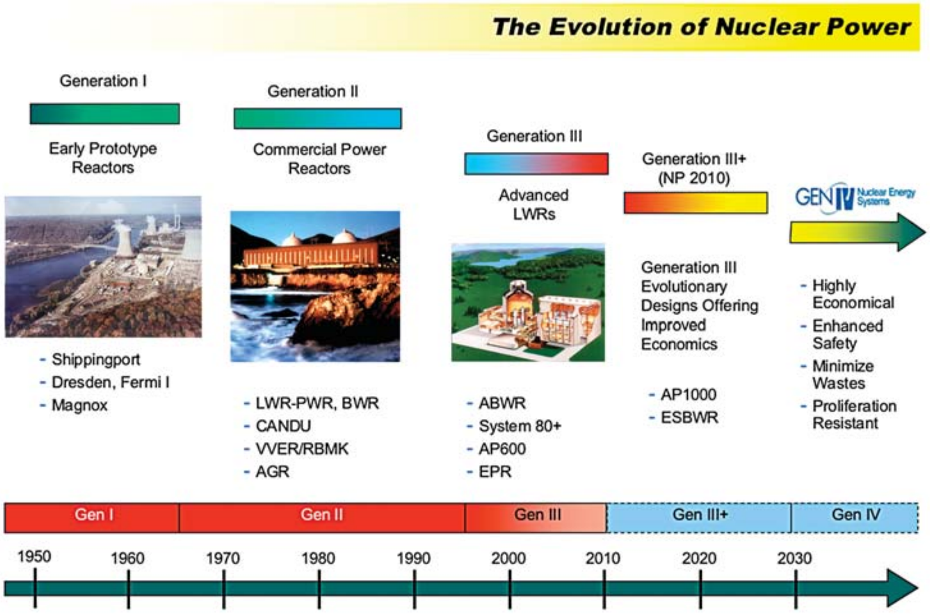

Figure 5-19. Future Nuclear Power Concepts (Source: DOE, Office of Nuclear Energy Internal Document).

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 Gen 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 of 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 Gen IV advanced fast spectrum reactors that can transmute nuclear waste.[29]

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:

- **Reducing the financial risks and costs of advanced nuclear power plants.** 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.
- **Next Generation nuclear plants and advanced fuel cycles.** Develop reactor designs that excel in operational safety, sustainability, and proliferation-resistance, and achieve economy of both capital and operation and maintenance (O&M), including advanced fuels that are more resistant to melting and are operated to minimize wastes. Included in these designs are small, exportable reactors, which can be used by reactor user nations under the Global Nuclear Energy Partnership that will not develop indigenous fuel cycle capabilities. Primary research needs are for development and characterization of fuel fabrication processes; testing of in-reactor fuel performance; power

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[29] See Section 2.4.3 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-243.pdf.

conversion-system design and testing, including resolution of uncertainties regarding materials, reliability, and maintainability; and fission-reactor internal design and verification.

- **High-temperature materials and heat transfer technology.** Develop and test high-temperature materials (central to future nuclear reactor systems). Low-activation materials that resist corrosion and embrittlement at high temperatures are needed for structural materials within the core and fuel assemblies and for reactor pressure vessel systems. Advanced materials are needed for future heat exchangers, turbine components, radiochemical particulate filters, and transport of heat to hydrogen production plants. Other research needs include the use of alternate working fluids and heat-exchange cycles.
- **Closing the fuel cycle.** Investigate proliferation-resistant, closed fuel-cycle concepts that reduce the quantity and heat load of wastes requiring geological emplacement. 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, such as advanced burner reactors. 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.
- **Nuclear computations.** Use the emerging DOE supercomputer system capabilities to combine more rigorous computational models of 3-dimensional radiation transport, thermal transport, fluid flow and more detailed accounting of energy resonances in nuclear cross-section data into powerful new tools for exploring novel reactor concepts. Although the current generation of nuclear computational techniques is adequate for design and evaluation of current nuclear reactors, the computer models use many approximate techniques that ultimately limit the ability to design innovative nuclear fuels and core geometries.

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 and in longer pulse lengths.

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 CO_2 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 significant scientific and technical challenges remain.

Potential Role of Technology

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

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 technical 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.

Technology Strategy

Given the substantial scientific and technological uncertainties that now exist, the U.S. Federal 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, DOE's Fusion Energy Sciences (FES) 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 may 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 FES 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 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, India, 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.

Current Portfolio

The current 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[30] 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.

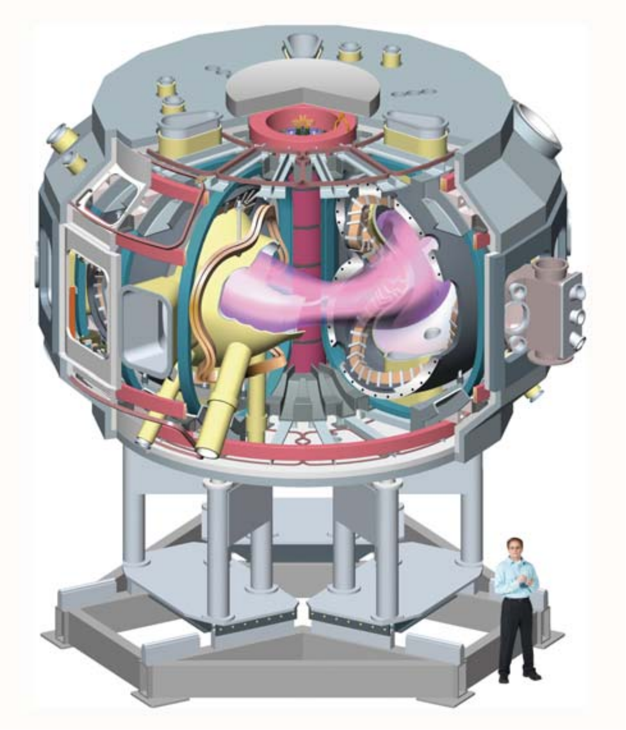

Figure 5-20. Fusion energy affords the possibility of long-term, sustainable energy supply, with little or no emissions of GHGs.

Credit: National Compact Stellarator Experiment, DOE/PPPL

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[31] confinement systems.

An additional innovative concept, the National Compact Stellarator Experiment, is currently being fabricated at PPPL with first operation scheduled for 2009 (Figure 5-20). 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 located at universities and provide an opportunity for student training.

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 fusion systems. This program also explores innovative approaches to improving inertial fusion such as the fast-ignition experiments. In addition, the FES program benefits from existing experimental programs conducted elsewhere for NNSA's stockpile

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[30] 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.

[31] 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).

ITER International Magnetic Fusion Experiment

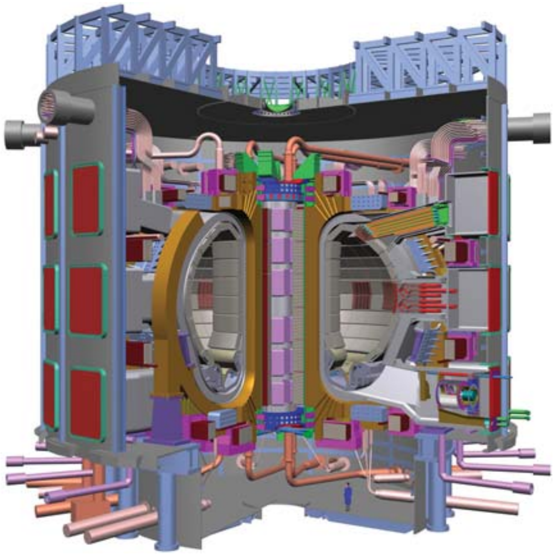

Figure 5-21. The United States is participating with other countries in the building of ITER, a large-scale fusion process machine, which will provide experimental data to inform future technology directions. Credit: ITER

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.[32]

Future Research Directions

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:

- **ITER.** Burning plasmas represent 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, the Republic of Korea, and India plan 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 (MFE), (Figure 5-21). Additional investments in fusion materials, components, and technologies for MFE are contingent upon favorable results from ITER.
- **Plasma Confinement Systems.** Prior to the anticipated operation of ITER around 2015, physics research experiments on a wide range of plasma-confinement systems worldwide will continue 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.[33] Work will also continue on confinement configuration optimization that would allow better understanding or improve the confinement approach for future power systems.
- **High-Energy-Density Physics and Related Technology.** In other efforts, the United States is proceeding with high-energy-density physics, the science base for inertial fusion[34], through the development of NNSA's National Ignition Facility (NIF) and other 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.[35] However, any additional investment in the inertial fusion energy approach awaits successful demonstration of ignition and gain in the NIF.

5.6 Summary

This chapter reviews various forms of advanced technology, their potential for reducing emissions from energy supply, and the R&D strategies intended to accelerate their development. Although

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[32] See Section 2.5.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-251.pdf.

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

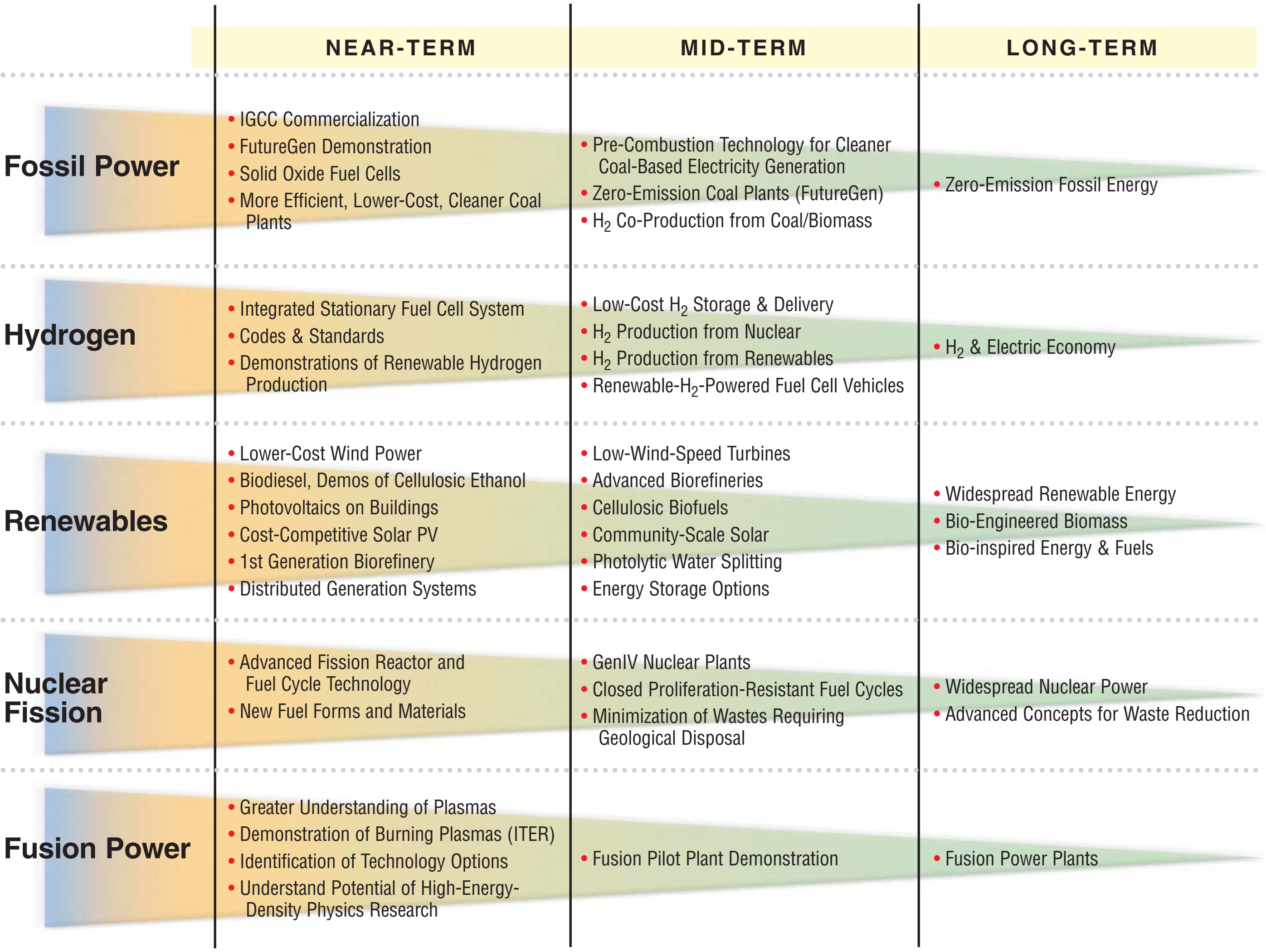
[34] Inertial fusion is an alternative approach to creating the physical conditions necessary for light elements to fuse and release binding energy, in which an array of intense x-rays, lasers, or heavy ion beams are used to contain, compress, and heat the fusible materials to fusion enabling conditions.

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

uncertainties exist about both the level at which GHG concentrations might need to be stabilized and the nature of the technologies that may come to the fore, the long-term potential of advanced energy supply technologies is estimated to be significant, both in reducing emissions (as shown in Figure 3-19 and highlighted in the figure at the beginning of this chapter) and in reducing the costs for achieving those reductions, as suggested by Figure 3-14. Further, the advances in technology development needed to realize this potential, as modeled in the associated analyses, animate the research and development goals for each energy supply technology area.

As one illustration among the many hypothesized cases analyzed,[36] when GHG emissions were constrained to a high level over the course of the 21st century the lowest-cost arrays of advanced technology in energy supply, when compared to a reference case, resulted in reduced or avoided emissions of roughly between 110 and 210 GtC. This amounted to, roughly, between 20 and 35 percent of all GHG emissions reduced, avoided, captured and stored, or otherwise withdrawn and sequestered, needed to constrain emissions at this level. Similarly, the costs for achieving such emissions reductions, when compared to the reference case, were reduced by

Technologies for Goal #2: Reducing Emissions from Energy Supply



	NEAR-TERM	MID-TERM	LONG-TERM
Fossil Power	• IGCC Commercialization • FutureGen Demonstration • Solid Oxide Fuel Cells • More Efficient, Lower-Cost, Cleaner Coal Plants	• Pre-Combustion Technology for Cleaner Coal-Based Electricity Generation • Zero-Emission Coal Plants (FutureGen) • H_2 Co-Production from Coal/Biomass	• Zero-Emission Fossil Energy
Hydrogen	• Integrated Stationary Fuel Cell System • Codes & Standards • Demonstrations of Renewable Hydrogen Production	• Low-Cost H_2 Storage & Delivery • H_2 Production from Nuclear • H_2 Production from Renewables • Renewable-H_2-Powered Fuel Cell Vehicles	• H_2 & Electric Economy
Renewables	• Lower-Cost Wind Power • Biodiesel, Demos of Cellulosic Ethanol • Photovoltaics on Buildings • Cost-Competitive Solar PV • 1st Generation Biorefinery • Distributed Generation Systems	• Low-Wind-Speed Turbines • Advanced Biorefineries • Cellulosic Biofuels • Community-Scale Solar • Photolytic Water Splitting • Energy Storage Options	• Widespread Renewable Energy • Bio-Engineered Biomass • Bio-inspired Energy & Fuels
Nuclear Fission	• Advanced Fission Reactor and Fuel Cycle Technology • New Fuel Forms and Materials	• GenIV Nuclear Plants • Closed Proliferation-Resistant Fuel Cycles • Minimization of Wastes Requiring Geological Disposal	• Widespread Nuclear Power • Advanced Concepts for Waste Reduction
Fusion Power	• Greater Understanding of Plasmas • Demonstration of Burning Plasmas (ITER) • Identification of Technology Options • Understand Potential of High-Energy-Density Physics Research	• Fusion Pilot Plant Demonstration	• Fusion Power Plants

Figure 5-22. Technologies for Goal #2: Reducing Emissions from Energy Supply (Note: Technologies shown are representations of larger suites. With some overlap, "near-term" envisions significant technology adoption by 10 to 20 years from present, "mid-term" in a following period of 20-40 years, and "long-term" in a following period of 40-60 years. See also List of Acronyms and Abbreviations.)

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[36] In Chapter 3, various advanced technology scenarios were analyzed for cases where global emissions of GHGs were hypothetically constrained. Over the course of the 21st century, growth in emissions was assumed to slow, then stop, and eventually reverse in order to ultimately stabilize GHG concentrations in the Earth's atmosphere at levels ranging from 450 to 750 ppm. In each case, technologies competed within the emissions-constrained market, and the results were compared in terms of energy (or other metric), emissions, and costs.

roughly a factor of 3. See Chapter 3 for other cases and other scenarios.

As described in this chapter, CCTP's technology development strategy supports achievements in this range. The overall strategy is summarized schematically in Figure 5-22. Advanced technologies are seen entering the marketplace in the near, mid, and long terms, where the long term is sustained indefinitely. Such a progression, if successfully realized worldwide, would be consistent with attaining the energy supply potential portrayed at the beginning of this chapter.

The timing and pace of technology adoption are uncertain and must be guided by science. In the case of the illustration above, the first GtC per year (1GtC/year) of reduced or avoided emissions, as compared to an unconstrained reference case, would need to be in place and operating between 2040 and 2060. For this to happen, a number of new or advanced energy supply technologies would need to penetrate the market at significant scale before this date. Other cases would suggest faster or slower rates of deployment, depending on assumptions. See Chapter 3 for other cases and other scenarios.

5.7 References

Energy Information Administration (EIA). 2006. *Annual Energy Outlook 2006*, DOE/EIA-0383(2006). Washington, DC: U.S. Department of Energy.

Generation IV International Forum (GIF) and the U.S. Department of Energy's Nuclear Energy Research Advisory Committee (NERAC). 2002. *A Technology Roadmap for Generation IV Nuclear Energy Systems.* GIF-002-01, December. www.gen-4.org/Technology/roadmap.htm

International Energy Agency (IEA). 2004. *Key World Energy Statistics 2004.* http://library.iea.org/dbtw-wpd/Textbase/nppdf/free/2004/keyworld2004.pdf

National Research Council (NRC), National Academy of Engineering (NAE). 2004. *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs.* Washington, DC: The National Academies Press. http://www.nap.edu/books/0309091632/html/

Oak Ridge National Laboratory (ORNL). 2005. *Biomass as Feedstock for a Biorefinery and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Supply.* http://feedstockreview.ornl.gov/pdf/billion_ton_vision.pdf

U.S. Climate Change Technology Program (CCTP). 2003. *Technology Options for the Near and Long Term.* DOE/PI-0002. Washington, DC: U.S. Department of Energy. http://www.climatetechnology.gov/library/2003/tech-options/index.htm Update is at http://www.climatetechnology.gov/library/2005/tech-options/index.htm

U.S. Department of Energy (DOE). 2005. *Hydrogen Fuel Cells and infrastructure Technologies Multi-Year Research, Development and Demonstration Plan, 2003-2010.* Washington, DC: U.S. Department of Energy. http://www.eere.energy.gov/hydrogenandfuelcells/mypp/

U.S. Department of Energy (DOE). 2004. *Hydrogen Posture Plan, an Integrated Research, Development, and Demonstration Plan.* Washington, DC: U.S. Department of Energy. http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/hydrogen_posture_plan.pdf

U.S. Department of Energy (DOE), Office of Nuclear Energy Science and Technology (NE). 2001. *A Roadmap to Deploy New Nuclear Power Plants in the United States by 2010.* Washington, DC: U.S. Department of Energy. http://nuclear.gov/nerac/ntdroadmapvolume1.pdf and http://nuclear.gov/nerac/NTDRoadmapVolII.PDF

U.S. Department of Energy, (DOE), Office of Nuclear Energy Science and Technology (NE). 2003a. *The U.S. Generation IV Implementation Strategy.* Washington, DC: U.S. Department of Energy. http://nuclear.gov/reports/Gen-IV_Implementation_Plan_9-9-03.pdf

U.S. Department of Energy, (DOE), Office of Nuclear Energy Science and Technology (NE). 2003b. Report to Congress on Advanced Fuel Cycle Initiative: the Future Path for Advanced Spent Fuel Treatment and Transmutation Research. Washington, DC: U.S. Department of Energy. http://nuclear.gov/reports/AFCI_CongRpt2003.pdf