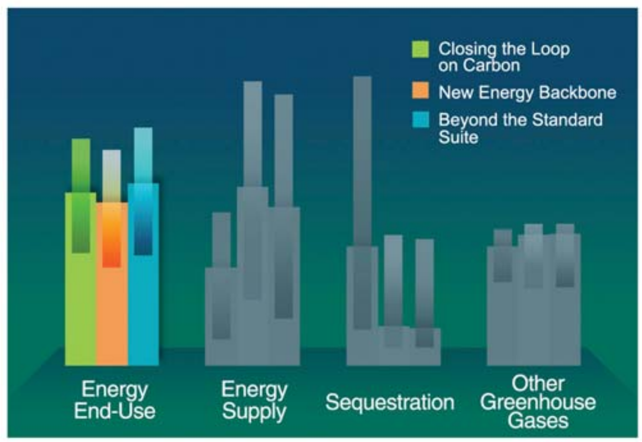
4 Reducing Emissions from Energy End Use and Infrastructure

The potential for advanced technology to enable and facilitate accelerated reductions in greenhouse gas (GHG) emissions, mainly carbon dioxide (CO_2), from energy end use and infrastructure is believed to be significant—on a par with, or greater than, that of each of the other main elements of CCTP's technology strategy. Emissions reductions can be achieved from all end-use sectors of the global economy, including industry, residential and commercial buildings, and transportation, through conservation practices,[1] technological and other economic productivity improvements that lead to increased energy efficiency, and shifts in the composition of economic activity toward lower energy- and GHG-intensive outputs.

Historically, global energy productivity—loosely measured in terms of economic output per unit of energy input—has shown steady increases, averaging gains of about 0.9 percent per year over the period 1971 to 2002 (IEA 2004). Use of more energy-efficient processes and replacement of older, less-efficient capital stock are important contributors to these gains. Another factor in increasing individual country measures of energy productivity, especially in industrialized countries, has been a shift over the past several decades in the composition of economic output toward less energy-intensive goods and services.



Energy End-Use
Potential Contributions to Emissions Reduction

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

In published scenarios of CO_2 emissions over the 21st century, increasing demand for energy services, driven by population and economic growth, results in growth of CO_2 emissions. By contrast, almost all scenarios that explore various future paths toward significant emissions reductions show that energy end-use reduction[2] plays a key role in achieving those reductions. In one set of scenarios, as shown in Figure 3-19 and highlighted above, energy end-use reductions led to a cumulative decrease (over 100 years) of between 7 and 22 thousand exajoules (EJ) in global energy use, and between 110 and 270 gigatons of reduced or avoided global emissions of carbon (GtC), compared to a reference case used in the study (see Chapter 3). Although bracketed by uncertainties, this figure suggests both the potential role for advanced technology and a long-term goal for contributions from this sector of the global economy.

In the United States, the largest end-use sources of CO_2 emissions (Table 4-1) are the following:

- Electricity and fuel use in buildings;

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1 In this context, "conservation" refers to practices that conserve resources or reduce waste, such as in the case of energy, turning off lights, equipment, etc., when not in use.

2 End use reduction includes improvements in energy efficiency in the end-use sectors, as well as improvements in efficiency of energy conversion, e.g., increased efficiency in electricity generation.

- Transportation fuels;
- Electricity and fuel use in industry; and
- A few industrial processes not related to combustion.

This chapter explores energy end-use and carbon emission-reduction strategies and opportunities within each of these end-use categories. Sections 4.1 through 4.3 address transportation, buildings, and industry, respectively. Section 4.4 deals with technology strategies for the electric grid and infrastructure that can enable and facilitate CO_2 emissions reductions in all sectors. Each section provides information on its respective sector, explores the potential role for advanced technology in reducing emissions, outlines a strategy for technology development, describes the current portfolio, and identifies potential directions for future research. This chapter focuses primarily on reducing and avoiding CO_2 emissions. Many industrial processes and energy end uses produce significant quantities of other non-CO_2 GHGs. These other GHGs are addressed in Chapter 7, "Reducing Emissions of Other Greenhouse Gases." The descriptions of the technologies and deployment programs in this section include active Internet links to an updated version of the CCTP report *Technology Options in the Near and Long Term* (CCTP 2005).[3]

4.1 Transportation

The transport of people, goods, and services accounts for a significant share of global energy demand, mostly in the form of petroleum, and is among the fastest growing sources worldwide of emissions of GHGs, mainly CO_2. In the developing parts of Asia and the Americas, emissions from transportation-related use of energy are expected to increase dramatically during the next 25 years. In the United States, from 1991 to 2000, vehicle miles traveled, a measure of highway transportation demand, increased at an average rate of 2.5 percent per year (DOT 2002a), outpacing population growth. In 2003, the U.S. transportation sector accounted for 39 percent of total CO_2 emissions, with the highway modes accounting for more than 82 percent of these (Table 4-2). Through 2025, future growth in U.S. transportation energy use and emissions is projected to be strongly influenced by the growth in light-duty trucks (pickup trucks, vans, and sport utility vehicles, under 8,500 lb gross vehicle weight rating) (Figure 4-1). According to the Federal Highway Administration's Freight Analysis Framework, freight tonnage will grow by 70 percent during the first two decades of the 21st century (DOT 2002b).

CO_2 Emissions in the United States by End-Use Sector, 2003 (GtC)

END-USE SECTOR	EMISSIONS FROM ELECTRICITY	EMISSIONS FROM COMBUSTION OF FUELS	EMISSIONS, TOTAL	% OF TOTAL
Transportation	0.009	0.485	0.493	31.1%
Residential and Commercial Buildings	0.410	0.169	0.579	36.5%
Industrial Energy Use	0.211	0.258	0.468	29.5%
Industrial Processes			0.040	2.5%
Waste Disposal Activities		0.005	0.005	0.3%
Total	**0.630**	**0.957**	**1.586**	**100.0%**

Source: EPA 2005, Tables 2-16, 3-44, and 4-1.
Note: Values may not sum to total due to independent rounding of values.

Table 4-1. CO_2 Emissions in the United States by End-Use Sector, 2003 (GtC)

3 See http://www.climatetechnology.gov/library/2005/tech-options/index.htm.

Potential Role of Technology

Advanced technologies can make significant contributions to reducing CO_2 emissions from transportation activity. In the near term, advanced highway vehicle technologies, such as electric-fuel-engine hybrids ("hybrid-electric" vehicles) and clean diesel engines, could improve vehicle efficiency and, hence, lower CO_2 emissions. Other reductions might result from modal shifts (e.g., from cars to light rail) higher load factors, improved overall system-level efficiency, or reduced transportation demand. Improved intermodal connections could allow for better mode-shifting and improved efficiency in freight transportation. Application of developing technology will reduce idling and the concomitant emissions from heavy-duty vehicles, including vessels, trains, and long-haul trucks. Intelligent transportation systems can reduce congestion, resulting in decreases in fuel use. In the long term, technologies such as cars and trucks powered by hydrogen, bio-based fuels, and electricity show promise for transportation with either no highway CO_2 emissions or no net-CO_2 emissions.

CO_2 Emissions in the United States from Transportation, by Mode, in 2003 (GtC)

	EMISSIONS	% OF TOTAL
Passenger Cars	0.173	35.6%
Light-Duty Trucks	0.131	26.9%
Other Trucks	0.093	19.2%
Aircraft [a]	0.047	9.6%
Other [b]	0.013	2.6%
Boats & Vessels	0.016	3.2%
Locomotives	0.012	2.4%
Buses	0.002	0.5%
Total [c]	**0.477**	**100.0%**

(a) Aircraft emissions consist of emissions from all jet fuel (less bunker fuels) and aviation gas consumption.

(b) "Other" CO_2 emissions include motorcycles, pipelines, and lubricants.

(c) Percentages may not sum to 100 percent due to independent rounding of values.

Source: EPA 2005.

Table 4-2. CO_2 Emissions in the United States from Transportation, by Mode, in 2003 (GtC)

Transportation Sector Energy Use by Mode and Type

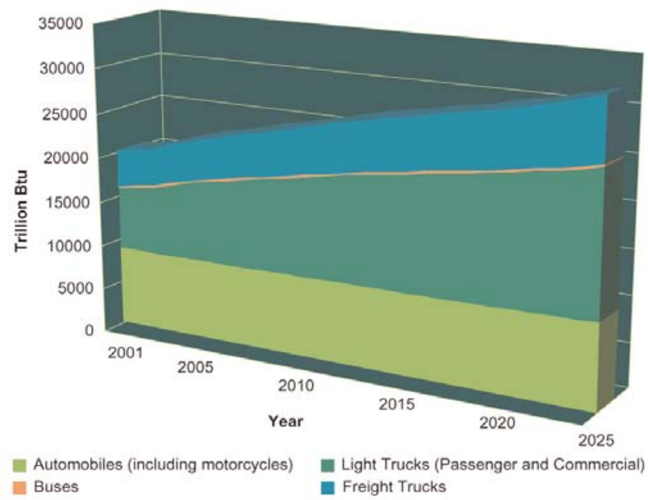

Figure 4-1. Projected Energy Consumption in U.S. Highway Vehicles.

Source: EIA 2004

The focus of CCTP is on technology developments that may reduce or capture GHG emissions, but it should be noted that, in the transportation sector particularly, there are non-technological options for policymakers to consider as well. They will not be discussed in the rest of this chapter, but they are worth mentioning here. For instance, local investments in bicycle lanes and paths and in pedestrian-friendly development planning can help reduce total vehicle-miles traveled. Urban and suburban planning that is well integrated with public transportation can similarly reduce fuel use per person-mile of travel. In addition, new communications technologies may alter the concepts about individual mobility. Work locations may be centered near or in residential locations, and work processes and products may be more commonly communicated or delivered via digital media. With global trends toward increasing urbanization in both population concentrations and opportunities for employment, people may rely in the future on improved modes of local, light-rail or intra-city passenger transport, coupled with other advances in electrified intercity transport that would curb the growth of fuel use and emissions from transportation.

Technology Strategy

Realizing these opportunities requires a research portfolio that embraces a combination of advanced vehicle, fuel, and transportation system technologies. Within constraints of available resources, a balanced portfolio needs to address major sources of CO_2 emissions in this sector, including passenger cars, light trucks, and other trucks; key modes of transport, including highway, aviation, and urban transit; system-wide planning and enhancements; and both near- and long-term opportunities.

In the near term, CO_2 emissions and transportation energy use can be reduced through improved vehicle efficiency, clean diesel engines, hybrid propulsion, and the use of hydrogenated low-sulfur gasoline. Other fuels, such as ethanol, natural gas, electricity with storage, and biodiesel, can also provide attractive means for reducing emissions of CO_2. These efficiency gains and fuel alternatives also provide other benefits, such as improving urban and regional air quality and enhancing energy security.

In aviation, emissions could be lowered through new technologies to improve air traffic management. An example is Reduced Vertical Separation Minimums (RVSM). RVSM has been used for transatlantic flights since 1997, and it became standard in U.S. airspace in January 2005. Full implementation of RVSM may reduce fuel use by approximately 500 million gallons each year.

In the long term, hydrogen may prove to be a low- or no-net-carbon energy carrier, if it can be cost-effectively produced with few or no GHG emissions, such as with renewable or nuclear energy, or with fossil fuels in conjunction with carbon capture and storage. Hydrogen and biofuels as substitutes for petroleum-based fuels in the transportation and other sectors also offer significant national security benefits. Hydrogen and alternative fuels are discussed in more depth in Chapter 5, "Reducing Emissions from Energy Supply." Hydrogen can be used in internal combustion engines, but its use in highly efficient fuel-cell-powered vehicles is considered a very important future option (Figure 4-2). In aviation, new engines and aircraft will feature enhanced engine cycles, more efficient aircraft aerodynamics, and reduced weight— thereby improving fuel efficiency. Research sponsored by the Federal Government through NASA, in collaboration with the Next Generation Air Transportation System (NGATS) plan, could enable these enhancements. NGATS is a multi-agency-integrated effort to ensure that the future air transportation system meets air transportation security, mobility, and capacity needs, while reducing environmental impacts.

Current Portfolio

Across the current Federal portfolio of transportation-related R&D, activities are focused on a number of major programs.

- Research on **light vehicles**, organized primarily in support of the FreedomCAR and Fuel Partnership, focuses on materials; power electronics; hybrid vehicles operating on gasoline, diesel, or alternative fuels; high-efficiency, low-emission advanced combustion engines, enabled by improved fuels; and high-volume, cost-effective production of lightweight materials. Beginning in Fiscal Year 2007, the Department of Energy is increasing the funding for advanced batteries, power electronics, and systems analyses specifically needed to accelerate the introduction of "plug-in" hybrid vehicles, which provide their owners with the option of operating as a normal hybrid vehicle or in all-electric mode, consuming no petroleum at all. With appropriate power-aggregation infrastructure, these vehicles can potentially also act as grid-attached storage when they are parked, contributing to electric grid stability.

  The vehicle technologies research programs have a number of specific goals: (a) electric propulsion systems with a 15-year life capable of delivering at least 55 kW for 18 seconds and 30 kW continuous at a system cost of $12/kW peak; (b) internal combustion engine powertrain systems costing $30/kW, having peak brake engine efficiency of 45 percent, and that meet or exceed emissions standards; (c) electric drivetrain energy storage with a 15-year life at 300 Wh with discharge power of 25kW for 18 seconds and $20/kW; (d) material and manufacturing technologies for high-volume production vehicles, which enable/support the simultaneous attainment of 50 percent reduction in the weight of vehicle structure and subsystems, affordability, and increased used of recyclable/renewable materials; and (e) internal combustion engine powertrain systems, operating on hydrogen with a cost target of $45/kW by 2010 and $30/kW in 2015, having a peak brake engine efficiency of 45 percent, and that meet or exceed emissions standards.[4]

- Research areas for **heavy vehicles**, organized primarily under the 21st Century Truck Partnership, include lightweight materials, aerodynamic drag, tire rolling resistance,

4 For more information, see Section 1.1.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-111.pdf. See also: http://www.eere.energy.gov/hydrogenandfuelcells/fuelcells/transportation.html, and http://www.epa.gov/otaq/technology.

electrification of ancillary equipment, advanced high-efficiency combustion propulsion systems (including energy-efficient emissions reduction), fuel options (both petroleum- and non-petroleum-based), hybrid technologies for urban driving applications, and onboard power units for auxiliary power needs. The research objectives are to: (1) reduce energy consumption in long-haul operations, (2) increase efficiency and reduce emissions during stop-and-go operations, and (3) develop more efficient and less-polluting energy sources to meet truck stationary power requirements (i.e., anti-idling). By 2010, the goals include a laboratory demonstration of an emissions-compliant engine system that is commercially viable for Class 7-8 highway trucks, and an engine that improves the system efficiency to 53 percent by 2010 and to 55 percent by 2013, from the 2002 baseline of 40 percent. By 2012, the goals include advanced technology concepts that reduce the aerodynamic drag of a Class 8 tractor-trailer combination by 20 percent.[5]

- **Fuels research** encompasses the development of new fuel blend formulations that will enable more efficient and cleaner combustion and the development of renewable and non-petroleum-based fuels that could displace 5 percent of petroleum used by commercial vehicles.[6]

- Research on **intelligent transportation systems** infrastructure includes sensors, information technology, and communications to improve efficiency and ease congestion. Intelligent transportation systems (ITS) goals include improved analysis capabilities that properly assess the impact of ITS strategies and strategies that will improve travel efficiency resulting in lower delays, thereby reducing emissions.[7]

- Research on **aviation fuel efficiency** includes engine and airframe design improvements. Aviation fuel efficiency goals include improved aviation fuel efficiency per revenue plane-mile by 1 percent per year through 2008, and new technologies with the potential to reduce CO_2 emissions from future aircraft by 25 percent within 10 years and by 50 percent within 25 years.[8]

- **Best Workplaces for Commuters** program is a voluntary employer-adopted program that increases commuter flexibility by expanding transportation mode options, using flexible scheduling, and increasing work location choices.

Figure 4-2. In the longer term, hydrogen fuel cell vehicles may provide for a transportation future that has much lower CO_2 emissions.

Courtesy: DOE/NREL, Credit: SunLine Transit Agency

- The **Clean Cities** program supports efforts to deploy alternative fuel vehicles (AFVs) and develop the necessary supporting infrastructure. Clean Cities works through a network of more than 80 volunteer, community-based coalitions, which develop public/private partnerships to promote the use of alternative fuels and vehicles, expand the use of fuel blends, encourage the use of fuel economy practices, increase the acquisition of hybrid vehicles by fleets and consumers, and advance the use of idle reduction technologies in heavy-duty vehicles.

- **Congestion Mitigation and Air Quality Improvement Program**, administered by the U.S. Department of Transportation, in consultation with the EPA, provides states with funds to reduce congestion and to improve air quality through transportation control measures and other strategies.

- **Mobile Air Conditioning Climate Protection Partnership** strives to reduce GHG emissions from vehicle air conditioning systems through voluntary approaches. The program promotes cost-effective designs and improved service procedures that minimize emissions from mobile air conditioning systems.

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5 See Section 1.1.2 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-112.pdf. See also: http://www.epa.gov/otaq/technology.

6 See Section 1.1.3 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-113.pdf.

7 See Section 1.1.4 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-114.pdf.

8 See Section 1.1.5 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-115.pdf.

- **SmartWay Transport Partnership** program is designed to reduce emissions from the freight sector through the implementation of innovative technology and advanced management practices. To date, 133 companies have joined the Partnership and have committed to reduce the CO_2 emissions associated with their respective freight operations. Additionally, there are now over 50 diesel truck and locomotive engine idling reduction projects around the country.

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:

- **Freight Transport.** Strategies and technologies to address congestion in urban areas and freight gateways by increasing freight transfer and movement efficiency among ships, trucks and rail in anticipation of large growth in freight volumes.
- **Advanced Urban Concepts.** Studies of advanced urban-engineering concepts for cities to evaluate alternatives to urban sprawl. Such engineering analysis would consider the co-location of activities with complementary needs for energy, water, and other resources; and would enable evaluation of alternative configurations that could significantly reduce vehicle-miles traveled and GHG emissions.
- **Integrated Urban Planning**. Concept and engineering studies for large-scale institutional and infrastructure changes required to manage CO_2, electricity, and hydrogen systems reliably and securely. Analysis of the infrastructure requirements for plug-in hybrid electric vehicles is needed. By being plugged into the power grid at night, when electricity is cheapest and most available, and by operating solely on battery power for the first 10-60 miles, this technology could significantly reduce oil consumption.
- **Large-Scale Hydrogen Storage.** Technologies for large-scale hydrogen storage and transportation and low-cost, lightweight electricity storage including advanced batteries and ultracapacitors.

In addition, supporting or crosscutting areas for future research include the following:

- **Advanced Thermoelectric Concepts.** Advanced thermoelectric concepts to convert temperature differentials into electricity, made more affordable through nanoscale manufacturing.
- **Battery and Fuel Cell Systems.** Basic electrochemistry to produce safe, reliable battery and fuel cell systems with acceptable energy and power density, cycle life, and performance under temperature extremes.
- **New Combustion Regimes.** Advanced combustion research on new combustion regimes in conventional vehicle propulsion technologies, using conventional fuels as well as alternatives such as cellulosic ethanol and biodiesel where near-zero regulated emissions and lowered carbon emissions can be achieved.

4.2 Buildings

The built environment—consisting of residential, commercial, and institutional buildings—accounts for about one-third of primary global energy demand (IPCC 2000) and represents a major source of energy-related GHG emissions, mainly CO_2. Growth in global energy demand in buildings has averaged 3.5 percent per year since 1970 (IPCC 2001).

Over the long term, buildings are expected to continue to be a significant component of increasing global energy demand and a large source of CO_2 emissions. Energy demand in this sector will be driven by growth in population, by the economic expansion that is expected to increase the demand for building services (especially electric appliances, electronic equipment, and the amount of conditioned space per person), and by the continuing trends toward world urbanization. As urbanization occurs, energy consumption increases, because urban buildings usually have electricity access and have a higher level of energy consumption per unit area than buildings in more primitive rural areas. According to a recent projection by the United Nations, the percentage of the world's population living in urban areas will increase from 49 percent in 2005 to 61 percent by 2030 (UN 2005).

In the United States, energy consumption in residential buildings has been increasing proportionately with increases in population, while energy consumption in commercial buildings has tended to follow the level of economic activity, or real Gross Domestic Product (GDP).[9] This trend masks significant increases in efficiency in some building components that are being offset by new or increased energy uses in others. In the United States in 2003, CO_2 emissions from this sector, including those from both fuel combustion and use of electricity derived from CO_2-emitting sources, accounted for nearly 37 percent of total CO_2 emissions (Table 4-1). These emissions have been increasing at 1.9 percent per year since 1990 (EIA 2005). Table 4-3 shows a breakdown of emissions from the buildings sector, by fuel type, in the United States.

Residential and Commercial CO_2 Emissions in the United States, by Source, in 2003 (GtC)

	EMISSIONS	% OF TOTAL
RESIDENTIAL		
Electricity	0.2121	66.9%
Natural Gas	0.0756	23.8%
Petroleum	0.0291	9.2%
Coal	0.0003	0.1%
Total Residential	**0.3171**	**100.0%**
COMMERCIAL		
Electricity	0.2005	76.2%
Natural Gas	0.0466	17.5%
Petroleum	0.0147	5.4%
Coal	0.0025	0.9%
Total Commercial	**0.2643**	**100.0%**

Note: Percentages may not sum to 100 percent, due to independent rounding of values.
Source: EPA 2005, Tables 2-16 and 3.3.

Table 4-3. Residential and Commercial CO_2 Emissions in the United States, by Source, in 2003 (GtC)

Potential Role of Technology

Many opportunities exist for advanced technologies to make significant reductions to energy-related CO_2 emissions in the buildings sector. In the near term, widespread adoption of advanced commercially available technologies, such as ENERGY STAR® compliant equipment, can improve efficiency of energy-using equipment in the primary functional areas of energy use. In residential buildings, these functional areas include space heating, appliances, lighting, water heating, and air conditioning. In commercial buildings, functional areas are lighting, space heating, cooling and ventilation, water heating, office equipment, and refrigeration. Through concerted research, major technical advances have occurred during the past 20 years, with many application areas seeing efficiency gains of 15 percent to 75 percent. Figure 4-3 gives an example of technological improvements that have occurred in refrigerators as an illustration of the kind of gains that have been achieved. Over the longer term, more advances can be expected in these areas, and significant opportunities also lie ahead in the areas of new buildings design, retrofits of existing buildings, and the integration of whole building systems and multi-building complexes through use of sensors, software, and automated maintenance and controls.

By 2025—with advances in building envelopes, equipment, and systems integration—it may be possible to achieve up to a 70 percent reduction in a building's energy use, compared to the average energy use in an equivalent building today (DOE 2005). If augmented by on-site energy technologies (such as photovoltaics or distributed sources of combined heat and power), buildings could become net-zero GHG emitters and net energy producers.

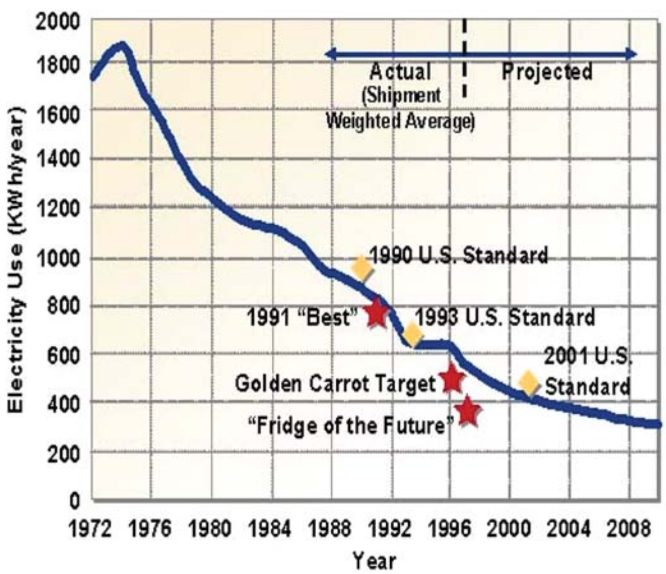
Technology Strategy

While the built environment is a complex mix of heterogeneous building types (commercial, service, detached dwelling, apartment buildings) and functional uses, all have common features, each of which may benefit from technological research, both as individual components and as integrated systems. Within constraints of available resources, a balanced portfolio needs to address three important aspects of buildings that affect their CO_2 emissions: (1) integrated building design, construction, and operation, including the optimal integration of components; (2) advanced building envelope components, including windows and walls; and (3) advanced, building equipment, appliances, and lights. The portfolio should look at both near- and long-term opportunities.

9 According to the Annual Energy Review 2004, residential primary energy use increased 53 percent from 1970 to 2004, while the nation's population increased 44 percent over the same period. Commercial energy use increased 111 percent over this period, driven (in part) by the nearly 200 percent increase in real Gross Domestic Production (GDP).

In the near term, building energy use and CO_2 emissions could be lowered in several ways. Especially in new construction, design strategies that incorporate energy- and material-saving strategies from the very start of the building process can result in significant avoided carbon. Intelligent building systems (such as load balancing and automated sensors and controls) can also be included to help ensure the comfort, health, and safety of residents, as well as aid in the reduction of CO_2. In the building envelope, application of advanced materials such as high R-value insulation, foams, vacuum panels, and spectrally selective windows can reduce space conditioning loads significantly. Choosing highly recyclable materials such as aluminum can reduce the end-of-life impact of building design and contribute to sustainable building practices. Technologies to improve the efficiency of lighting, appliances, heating, cooling, and ventilation are other options.

Refrigerator Energy Efficiency



Note: The curve applies to 18-20 cu. ft. top-mount refrigerator/freezers, which capture the largest market share in the United States. The term,"1991 Best" stands for the 1991 top-mount model with lowest energy use. "Golden Carrot Target" was an EPA/electric utility program in the early 1990s to develop a model that was 25 percent more efficient than the then current technology. "Fridge of the Future" is a refrigerator that had a target energy use of 365 kWh/yr or 1 kWh/day for 18-20 cu. ft. top-mount models based on an cooperative research agreement between Oak Ridge National Laboratory (ORNL) and the Association of Home Appliance Manufacturers; this target was exceeded in a test unit (0.93 kWh/day) in FY 1996.

Figure 4-3. Refrigerator Energy Efficiency (Source: Brown 2003)

In the long term, more advanced research on the building envelope—including dynamic switchable window glazings and dynamic walls, panelized housing construction, façade and roof integration of photovoltaics, and new storage technologies—can drive CO_2 emissions even lower. Distributed power systems, advanced refrigeration and cooling technologies, integrated heat pumps that serve space conditioning and water heating, and solid-state lighting technology are among some of the more promising options for equipment. Among the alternatives, building integration should focus on including sensors and controls, community-scale integration tools, and urban engineering.

Current Portfolio

The current Federal portfolio focuses on four major thrusts. In combination, these activities aim to achieve net-zero-energy residential buildings by 2020 and commercial buildings by 2025.

- Research on the **building envelope** (the interface between the interior of a building and the outdoor environment) focuses on systems that determine or provide control over the flow of heat, air, moisture, and light in and out of a building; and on materials that can affect energy use, including insulation, foams, vacuum panels, optical control coatings for windows and roofs, thermal storage, and related controls (such as electrochromic glazings). Research program goals in the building envelope area include the following: (1) by 2008, demonstrate dynamic solar control windows (electrochromics) in commercial buildings, and by 2010 demonstrate market-viable windows with R6 insulation performance for homes; (2) by 2025, develop marketable and advanced energy systems capable of achieving "net-zero" energy use in new residential and commercial buildings; (3) for the long term, and consistent with achieving net zero energy performance, achieve a 30 percent decrease in the average envelope thermal load of existing residential buildings and a 66 percent decrease in the average thermal load of new buildings.[10]
- Research on **building equipment** focuses on means to significantly improve efficiency of heating, cooling, ventilating, thermal distribution, lighting (Figure 4-4), home appliances, and on-site energy and power devices. This area also includes a number of crosscutting elements, including advanced refrigerants and cycles, solid-state

[10] See Section 1.2.2 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-122.pdf.

lighting, smart sensors and controls, small power supplies, microturbines, heat recovery, and other areas.

Specific goals include: (1) for distributed electricity generation technologies (including microturbines), by 2008, enable a portfolio of equipment that shows an average 25 percent increase in efficiency; (2) for solid-state lighting in general illumination applications, by 2008, develop equipment with luminous efficacy of 79 lumens per watt (LPW); and, for laboratory devices by 2025, a luminous efficacy of 200 LPW. The long-term goals are: (1) by 2025, develop and demonstrate marketable and advanced energy systems that can achieve "net-zero" energy use in new residential and commercial buildings through a 70 percent reduction in building energy use; and (2) by 2030, enable the integration of all aspects of the building envelope, equipment, and appliances with on-site micro-cogeneration and zero-emission technologies.[11]

- Research on **residential systems integration**, focuses on progressively higher levels of energy performance over time, and follows a three-phase approach. Phase 1, systems evaluation, involves the design, construction and testing of subsystems for whole house designs (by climate zone) in research houses to evaluate how components perform. In Phase 2, prototype houses (Figure 4-5), the successful Phase 1 subsystems are designed and constructed by production builders to evaluate the ability to implement the systems on a production basis. Phase 3, community evaluations, provides technical support to builder partners to advance from the production prototypes to evaluation of production houses in a subdivision.

- Research on **commercial buildings integration** includes development of advanced design "packages" of system-integrated design strategies and operational methodologies for high-performance buildings, which can be used by architects and others to design, build, and operate commercial buildings in an integrated manner. This approach is targeted at new construction, because the opportunities for aggressive performance are much greater than in existing buildings. In addition, R&D includes load balancing and automated sensors and controls, sometimes referred to as intelligent building systems. Such systems continuously monitor building performance, detect anomalies or degradations, optimize operations across all building systems, guide maintenance, and document and report results. They can also be extended to coordinate on-site energy generation and internal loads, with external power (grid) demands and circumstances, allowing responsiveness to time-variant cost savings, system efficiencies, and grid contingencies. They also ensure occupant comfort, health, and safety, met at the lowest possible cost.

Figure 4-4. Many opportunities exist for advanced technologies, such as the sub-compact fluorescent coil light bulb, to make significant reductions of CO_2 emissions in the building sector.

Courtesy: DOE/NREL

- Whole building integration goals include fully and seamlessly integrated building design tools, such as **EnergyPlus**, that support all aspects of design and provide rapid analysis of different pathways to improved energy performance. Also included are the development of automatic operation of buildings systems that require little operator attention; and highly efficient combined cooling, heating, and power systems that use waste heat from small-scale, on-site electricity generation to provide heating and cooling for the buildings, as well as export excess electricity to the grid.[12]

- The **ENERGY STAR®** is a joint program of EPA and DOE that enables businesses, organizations, and consumers to realize the cost savings and environmental benefits of energy efficiency investments. Introduced in 1992, the ENERGY

[11] See Section 1.2.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-121.pdf.

[12] See Section 1.2.3 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-123.pdf.

Figure 4-5. Design strategies that incorporate energy- and material-saving strategies can result in significant reduction of CO_2 emissions.

Courtesy: DOE

STAR® program focuses on four areas of energy efficiency that include products, home improvement, new homes, and business improvement. By providing resources, working with local partners, and labeling ENERGY STAR® qualified-products, the program makes it easy for consumers and businesses to make smart energy-efficient choices that can save about a third on energy bills with similar savings of GHG emissions, without sacrificing features, style or comfort.

- **Federal Energy Management Program** aims to reduce energy use in Federal buildings, facilities, and operations by advancing energy efficiency and water conservation, promoting the use of renewable energy, and managing utility choices of Federal agencies. The program accomplishes its mission by leveraging both Federal and private resources to provide Federal agencies the technical and financial assistance they need to achieve their goals.
- **Rebuild America** works with a network of hundreds of community-based partnerships across the nation that are saving energy, improving building performance, easing air pollution through reduced energy demand, and enhancing the quality of life through energy efficiency and renewable energy technologies.
- **Residential Building Integration: Building America** is intended to design, build, and evaluate energy-efficient homes that use from 30 to 40 percent less total energy than comparable traditional homes with little or no increase in construction costs; and to encourage industry to adopt these practices for new home construction. In addition, ongoing research focuses on integrating onsite power systems, including renewable energy technologies. Through the Building America program, DOE and its more than 470 industry partners are conducting research to develop advanced building energy systems to make homes and communities much more energy efficient.
- **State Energy Program** extends grants from DOE to states for a variety of energy-efficiency and renewable-energy activities. Most states have a state energy office designated to help reduce energy waste and increase the use of renewables in the state.
- **Weatherization Assistance Program** provides cost-effective energy-efficiency improvements to low-income households through the weatherization of homes. Priority is given to the elderly, persons with disabilities, families with children, and households that spend a disproportionate amount of their income on energy bills (utility bills make up 15 to 20 percent of household expenses for low income families, compared to five percent or less for all other Americans).

Future Research Directions

The current portfolio supports many of the 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:

- **Building Envelope.** Improved panelized housing construction; methods for integrating photovoltaic systems in building components such as roofs, walls, skylights, and windows, and with building loads and utilities; and exploration of fundamental properties and behaviors of novel materials to maximize moisture resistance and the storage and release of energy. Through nanotechnology advances, research will develop smart roofs and walls that reflect infrared solar radiation in summer and absorb it in winter, with substantial energy savings.

- **Building Equipment.** Advances in on-site power production (including fuel cells, microturbines, and reciprocating engines); ultra-efficient Heating, Ventilating, and Air-Conditioning-Residential (HVACR) (including magnetic or solid state cooling systems, advanced desiccants and absorption chilling systems, integrated heat pump systems for space conditioning and water heating, and highly efficient geothermal heat pumps); improved hot water circulation systems; and solid state lighting technology and improved lighting distribution systems. Low-power ubiquitous sensors with wireless communications can optimize building operations through anticipatory and selective heating, cooling, and lighting that manage loads in response to occupant requirements and real-time energy prices.

- **Whole Building Integration.** Further development and widespread implementation of building design tools for application in new and retrofit construction; tools and technologies for systems integration in buildings, with a particular focus on sensors and controls for supply and end-use system integration; development of pre-engineered, optimized net-zero energy buildings; community-scale design and system integration tools; and urban engineering to reduce transport energy use and congestion.

4.3 Industry

Industrial activities were estimated to account for about 41 percent of primary global energy consumption in 1995 (IPCC 2000) and a commensurate share of global CO_2 emissions. Certain activities are particularly energy-intensive, including metals industries, such as iron, steel, and aluminum; petroleum refining; basic chemicals and intermediate products; fertilizers; glass; pulp, paper, and other wood products; and mineral products, including cement, lime, limestone, and soda ash. Others are less energy-intensive, including the manufacture or assembly of automobiles, appliances, electronics, textiles, food and beverages, and others. Each regional or national economy varies in the structure, composition, and growth rates of these industries, shaped in part by its state of economic development and in part by regional advantages in international trade. The industrial sector worldwide is expected to expand in the future and will likely continue to account for a substantial portion of future CO_2 emissions. As competitive environments grow and energy demand increases, industrial firms increasingly will have a financial incentive to invest in improving their energy efficiency.

In the United States in 2003, industry accounted for about one-third of total U.S. CO_2 emissions (Table 4-1). These are attributed to combustion of fuels (51 percent), use of electricity derived from CO_2-emitting sources (41 percent), and industrial processes, including non-combustion processes, that emit CO_2 (8 percent) (Table 4-4).[13]

Potential Role of Technology

The industrial sector presents numerous opportunities for advanced technologies to make significant contributions to the reductions of CO_2 emissions to the Earth's atmosphere. In the near term, advanced technologies can increase the efficiency with which process heat is generated, contained, transferred, and recovered. Process and design enhancements can improve quality, reduce waste, minimize reprocessing, reduce the intensity of material use (with no adverse impact on product or performance), and increase in-process material recycling. Cutting-edge technologies can significantly reduce the intensity with which energy and materials (containing embedded energy) are used. Industrial facilities can implement direct manufacturing processes, which can eliminate some energy-intensive steps, thus both avoiding emissions and enhancing productivity. On the supply side, industry can self-generate clean, high-efficiency power and steam; and create products and byproducts that can serve as clean-burning fuels. The sector can also make greater use of coordinated systems that more efficiently use distributed energy generation, combined heat and power, and cascaded heat.

In the long term, fundamental changes in energy infrastructure could effect significant CO_2 emissions reductions. Revolutionary changes may include novel heat and power sources and systems, including renewable energy resources, hydrogen, and fuel cells. Innovative concepts for new products and high-efficiency processes may be introduced that can take full advantage of recent and promising developments in nanotechnology, micro-manufacturing, sustainable

13 Emissions of GHGs other than CO_2 from industry and agriculture are discussed in Chapter 7, "Reducing Emissions of Other Greenhouse Gases."

biomass production, biofeedstocks, and bioprocessing. As global industry's existing, capital-intensive equipment stock nears the end of its useful service life and as industry expands in rapidly emerging economies in Asia and the Americas, this sector will have an opportunity to adopt novel technologies that could revolutionize basic manufacturing. Advanced technologies will likely involve a mix of pathways, such as on-site energy generation, conversion, and utilization; process efficiency improvements; innovative or enabling concepts, such as advanced sensors and controls, materials, and catalysts; and recovery and reuse of materials and byproducts (Figure 4-6). In the United States, the development and adoption of advanced industrial technologies can not only provide GHG benefits, but also help to maintain U.S. competitiveness.

CO_2 Emissions in the United States from Industrial Sources in 2003 (GtC)

	EMISSIONS 10^9 TONNES C	SHARE OF INDUSTRY TOTAL (%)	SHARE OF INDUSTRIAL PROCESSES (%)
Industrial Fuel Combustion	**0.258**	**50.7%**	
Coal	0.034	6.6%	
Petroleum	0.087	17.1%	
Natural Gas	0.111	21.9%	
Industrial Electricity	**0.211**	**41.4%**	
Industrial Processes (excluding fuel combustion emissions above)	**0.040**	**7.9%**	(See Breakout Below)
Total Industrial CO_2	**0.509**	**100.0%**	
Breakout of Emissions from Industrial Processes:			
Iron and Steel Production	0.0147		36.5%
Cement Manufacture	0.0117		29.2%
Ammonia Manufacture & Urea Application	0.0043		10.6%
Lime Manufacture	0.0035		8.8%
Limestone and Dolomite Use	0.0013		3.2%
Aluminum Production	0.0011		2.9%
Soda Ash Manufacture and Consumption	0.0011		2.8%
Petrochemical Production	0.0008		1.9%
Titanium Dioxide Production	0.0005		1.4%
Phosphoric Acid Production	0.0004		1.0%
Ferroalloy Production	0.0004		1.0%
Carbon Dioxide Consumption	0.0004		0.9%
Total Industrial Process CO_2	**0.0402**		**100.0%**

Source: EPA 2005, Tables 2-14, 2-16, 3-44, and 4-1.

Note: Percentages may not sum to 100 percent due to independent rounding of values.

Table 4-4. CO_2 Emissions in the United States from Industrial Sources in 2003 (GtC) (Excludes Indirect Emissions from Industrial Use of Centrally-Generated Electric Power)

Technology Strategy

A research portfolio should address the more important current and anticipated sources of CO_2 emissions in this sector, with careful attention to whether there is an appropriate role for Federal investment. Some of the largest sources of CO_2 emissions today, and expected in the future, arise from energy conversion to power industrial processes, inefficiencies in the processes themselves, and ineffective reuse of materials or feedstocks; and, in some cases, the intensive use of fossil fuels, especially natural gas.

In the near term, industrial energy use and CO_2 emissions could be lowered through improvements in the industrial use of electricity and fuels to produce process heat and steam, including steam boilers, direct-fired process heaters, and motor-driven systems, such as pumping and compressed air systems. Opportunities for reducing emissions in these areas lie with the adoption of best energy-management practices; adoption of more modern and efficient power and steam generating systems; integrated approaches that combine cooling, heating, and power needs; and capture and use of waste heat. Other areas of opportunity include improvements in specific energy-intensive industrial processes, including hybrid distillation systems; process intensification by combining or removing steps, or designing new processes altogether while producing the same or a better product; the recovery and utilization of waste and feedstocks, which can reduce energy and material requirements; and crosscutting opportunities, such as improved operational capabilities and performance.

In the long term, highly efficient coal gasifiers coupled with CO_2 sequestration technology could provide an alternative to natural gas, and even enable the export of electricity and hydrogen to the utility grid and supply pipelines. Bioproducts could replace fossil feedstocks for manufacturing fuels, chemicals, and materials; while biorefineries could utilize fuels from nonconventional feedstocks to jointly produce materials and value-added chemicals. For non-combustion sources of CO_2, gas capture, separation and sequestration could be applied, or alternative processes or materials could be developed as substitutes. Further, integrated modeling of fundamental physical and chemical properties, along with advanced methods to simulate processes, will stem from advances in computational technology.

Four Possible Pathways to Increased Industrial Efficiency

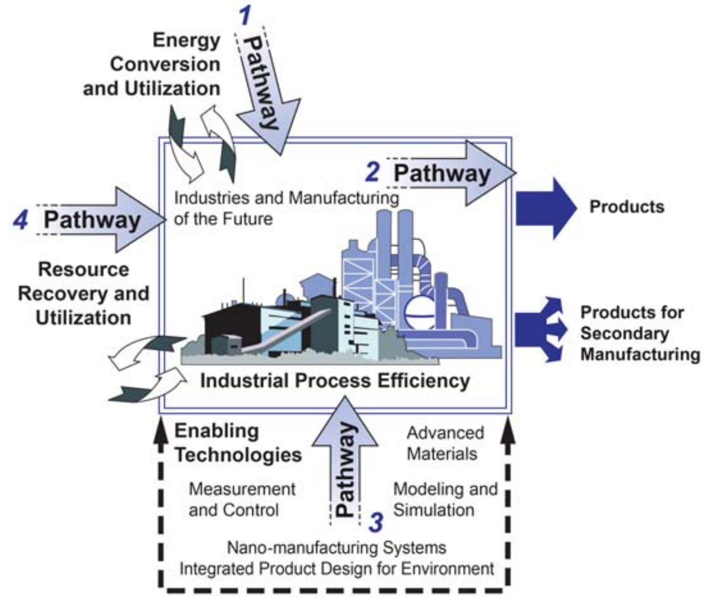


Figure 4-6. Four Possible Pathways to Increased Industrial Efficiency (Source: DOE 1997)

Current Portfolio

The current Federal portfolio focuses on four major thrusts.

- Research on **energy conversion and utilization** focuses on a diverse range of advanced and integrated systems. These include advanced combustion technologies, gasification technologies, high-efficiency burners and boilers, thermoelectric technologies (Figure 4-7) to produce electricity using industrial waste heat streams, co-firing with low-GHG fuels, advanced waste heat recovery heat exchangers, and heat-integrated furnace designs. Integrated approaches include combined-cycle power generation, and cogeneration of power and process heat or cooling.

  The overall research program goal in this area is to contribute to a 20 percent reduction in the energy intensity (energy per unit of industrial output, as compared to 2002) of energy-intensive industries by 2020. Several specific goals include: (1) by 2006, demonstrate a greater than 94 percent efficient packaged boiler, and, by 2010, have commercially available packaged boilers with thermal efficiencies of 10-12 percent higher than conventional technology; (2) by 2008, demonstrate high-efficiency pulping technology in the pulp and

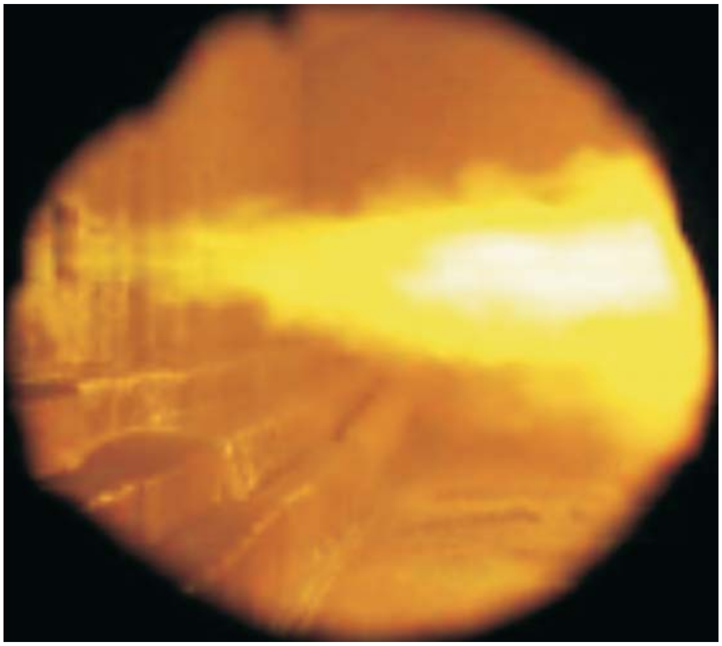


Figure 4-7. Industrial energy use and CO_2 emissions could be lowered through the use of high-efficiency combustion processes, such as oxy-fuel firing for glass manufacturing.

Courtesy of DOE/EERE

paper industry that redirects green liquor to pretreat pulp and reduce lime kiln load and digester energy intensity; and (3) by 2011, demonstrate isothermal melting technology, which could improve efficiency significantly in the aluminum, steel, glass, and metal-casting industries.[14]

- Research on **specific, energy-intensive and high-CO_2-emitting industrial processes** focuses on identifying (compared to theoretical minimum energy requirements) and removing process inefficiencies, lowering overall energy requirements for heat and power, and reducing CO_2 emissions. One process under development is a means to produce high-quality iron without the use of metallurgical coke, which—under current methods of steelmaking—is a significant source of CO_2 emissions. Other areas of research focus on processes that may also improve product yield, including oxidation catalysis, advanced processes, and alternative processes that take a completely different route to the same end product, such as use of noncarbon inert anodes in aluminium production.

  Industrial process efficiency goals are focused on industry partnerships. The overall research program goal in this area is to realize, before 2020, a 20 percent improvement in energy intensity by the energy-intensive industries through the development and implementation of new and improved processes, materials, and manufacturing practices.[15]

- Research on **enabling technologies** includes an array of advanced materials that resist corrosion, degradation, and deformation at high temperatures and pressures; inferential sensors, controls, and automation, with real-time nondestructive sensing and monitoring; and new computational techniques for modeling and simulating chemical pathways and advanced processes.

  Research program goals for this area target new enabling technologies that meet a range of cost goals depending on the technologies and on the applications where they are to be used. Specific goals include: (1) by 2010, demonstrate production and application of nano-structured diamond coatings and composites and other ultra-hard materials for use in wear-intensive industrial applications, and develop materials for use in a wide array of severe industrial environments (corrosive, high temperature, and pressure); (2) by 2012, demonstrate the generation of efficient power from high-temperature waste heat using systems with thermoelectric materials; and (3) by 2017, develop and demonstrate integration of sensing technologies with information processing to control plant production.[16]

- Research on **resource recovery and utilization** focuses on separating, capturing, and reprocessing materials for feedstocks. Recovery technologies include materials designed for recyclability, advanced separations, new and improved process chemistries, and sensors and controls. Reuse technologies include recycling, closed-loop process and plant designs, catalysts for conversion to suitable feedstocks, and post-consumer processing.

  Research program goals in this area target a range of improved recycling/recovery efficiencies. For example, in the chemicals industry the goal is to improve recyclability of materials by as much as 30 percent. Additional goals target new and improved processes to use wastes or byproducts;

14 See Section 1.4.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-141.pdf.

15 See Section 1.4.3 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-143.pdf.

16 See Section 1.4.4 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-144.pdf.

improve separations to capture and recycle materials, byproducts, solvents, and process water; and identify new markets for recovered materials, including ash and other residuals such as scrubber sludges.[17]

- **Climate Leaders** is an EPA partnership encouraging individual companies to develop long-term, comprehensive climate change strategies. Under this program, partners set corporate-wide GHG reduction goals and inventory their emissions to measure progress. The partnership now includes about 70 partners, 38 of whom have already set GHG emissions reduction goals. The US GHG emissions of these partners are equal to more than 7 percent of the U.S. total.
- **Climate VISION** assists industry efforts to accelerate the transition to practices, improved processes, and energy technologies that are cost-effective, cleaner, more efficient, and more capable of reducing, capturing, or sequestering GHGs. Already, business associations representing 14 industry sectors and the Business Roundtable have become program partners with the Federal Government and have issued letters of intent to meet specific targets for reducing GHG emissions intensity. These partners represent a broad range of industry sectors: oil and gas production, transportation, and refining; electricity generation; coal and mineral production and mining; manufacturing; railroads; and forestry products. Partnering sectors account for about 90 percent of industrial emissions and 40 to 45 percent of total U.S. emissions.
- **Industries of the Future** works in partnership with the nation's most energy-intensive industries, enhancing their long-term competitiveness and accelerating research, development, and deployment of technologies that increase energy and resource efficiency. This program has contributed to the development of hundreds of commercialized industrial technologies, resulting in a cumulative tracked energy savings of over 3,500 trillion Btu.
- **Voluntary GHG Emissions Reporting** under 1605(b) provides a means for organizations and individuals that have reduced their emissions to record their accomplishments and share their ideas for action. The enhanced registry will boost measurement accuracy, reliability, and verifiability, working with and taking into account emerging domestic and international approaches. Currently about 230 U.S. companies and other organizations file GHG reports.

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 considered for the future R&D portfolio. These include:

- **Industrial Alternatives to Natural Gas.** Research could be conducted to develop coal gasification systems for large industrial plants (e.g., 100 megawatts). The coal gasifiers would be highly integrated into complex manufacturing plants (e.g., chemical or glass plants). The industrial plant's feedstock, process heat, and power requirements could be accommodated from the coal gasifier, which could also export electricity, hydrogen, or other fuels to the utility grid and gas supply pipelines.
- **Industrial Waste Heat Reduction.** Energy conversion and utilization in industry creates large amounts of waste heat. This waste heat could be minimized through beneficial electrification (including infrared drying and induction heating); novel materials that do not require drying or curing; micro-CHP (combined heat and power) systems to convert waste heat to drive other thermal processes; and new ways of boosting low-grade temperatures to more useful high-grade heat.
- **Advanced Industrial Materials.** Research on advanced materials can reduce energy requirements and emissions in most industries. Characterization of materials at the nanoscale can lead to engineered materials with improved functionality, including improved properties such as strength, corrosion resistance, and power conversion (e.g., thermoelectrics).
- **Cement and Related Products.** Research could focus on various means to reduce or eliminate CO_2 emissions from non-combustion, high-emitting industrial processes, including the

[17] For more information, see Section 1.4.2 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-142.pdf.

cement, lime, limestone, and soda ash industries. Worldwide infrastructure building over the 21st century can be expected to create a high demand for these mineral products, the production of which releases CO_2 as a consequence of the calcining process. In the United States in 2003, CO_2 emissions from these sources accounted for 44 percent of the non-energy-related industrial emissions and about 1 percent of total U.S. emissions. Research could be focused on carbon capture and sequestration and on the exploration of substitutes for the end product. Carbon matrixes for construction, for example, might be lighter and stronger than concrete and would provide a means for carbon sequestration.

- **Advanced Applications of Biotechnology.** Bioproducts soon could replace fossil feedstocks, such as oil, in current industrial processes for manufacturing fuels, chemicals, and materials. Advances in biosciences and engineering include a better understanding of genomes, proteins, and their functions, including carbon dioxide capture, fixation, and storage; the effects of pre-treatment on biomass feedstock properties; enzymes for hydrolyzing pre-treated biomass into fermentable sugars; 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. Biorefineries of the future could produce transportation fuels, value-added chemicals, materials, and/or power from non-conventional feedstocks such as agricultural and forest residues, energy crops, and other biomass materials.

- **Water and Energy System Optimization.** Energy used by water infrastructure and water used in power and fuel supply systems provide numerous opportunities for improvement with GHG reduction benefits. Opportunities include better matching of water temperatures and purity to end-use requirements; revolutionizing the design of municipal water systems to reduce use, minimize conveyance, and maximize re-use; and integrating water storage and treatment with the intermittency of renewable power supplies.

- **Computational Technology.** Process simulation enables more effective design and operation, leading to increased efficiency and improved productivity and product quality. Integrated modeling of fundamental physical and chemical properties can enhance understanding of industrial material properties and chemical processes. For example, modeling of counterflows through structured packings within distillation columns can improve hydrodynamic efficiencies and save a significant portion of the 3 quads of energy used annually in distillation processes, about half in petroleum refineries.

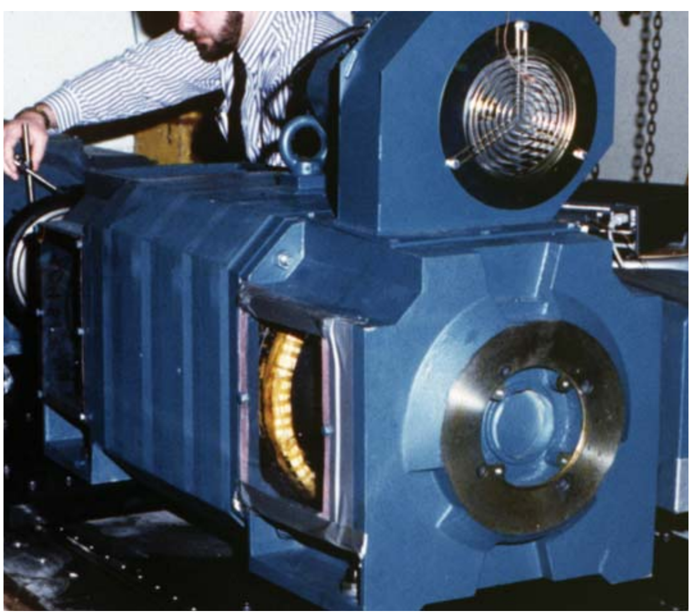


Figure 4-8. Advanced industrial materials, such as those used in high-temperature superconductive wires, can reduce energy losses and improve performance in electric motors.

Courtesy: DOE/NREL, Credit: Reliance Electric Co.

4.4 Electric Grid and Infrastructure

Large reductions in future CO_2 emissions may require that a significant amount of electricity be generated from carbon-free or carbon-neutral sources, including nuclear power and renewable electricity producers such as wind energy, geothermal energy, and solar-based power generating systems. Some renewable energy resources are concentrated in regions of the country that are distant from large urban markets. To accommodate such sources, the future electricity transmission infrastructure (the "grid") would need to extend its capacity and evolve into an intelligent and flexible system that enables the use of a wide and varied set of baseload, peaking, and intermittent generation technologies. The cost of expanding the grid to provide transmission from remote areas to load centers, or to make very long international links between Alaska and Russia, as sometimes proposed, is potentially very expensive, and proper allocation of the investment costs would need to be considered, as well as the overall cost-effectiveness of such projects.

In recent years, the demand for electricity in the United States has increased at a rate such that it could eventually exceed current transmission capacity. Demand is projected to increase by 19 percent from 2003-2012 (EIA 2005); only a 6 percent increase in transmission is planned for 2002-2012 (DOE 2002). There have been few major new investments in transmission during the past 15 years. Outages experienced in parts of the country—including the August 2003 blackout in the Midwest and Northeast—highlight the need to enhance grid reliability.

Enhancements for grid reliability will likely go hand in hand with improved efficiency of electricity transmission. Energy losses in the U.S. transmission and distribution (T&D) system were 5.5 percent in 2003, accounting for 201 billion kilowatt hours of electricity generation and 133 million metric tons of CO_2 emissions (EIA 2005, Table A8; EPA 2005 Table 2-14). About 10 percent of GHG emissions resulting from transmission and distribution are SF_6 emissions from certain high-voltage transmission equipment. The remainder of GHG emissions is from increased operations needed to compensate for energy losses.

Notwithstanding these improvements, the extent to which transmission and distribution losses could be reduced is uncertain, and energy losses on the transmission system could even increase as more long-distance transmission lines are brought into service to transmit power from remote generation sources.

The current portfolio supports the main components of the technology development strategy. Within constrained Federal resources, this portfolio addresses the highest priority current investment opportunities. 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 and others are currently being explored. These include:

- **High-Temperature Superconducting Cables and Equipment.** The manufacture of promising HTS materials in long lengths at low cost remains a key program challenge. New, continuously scanning analytical systems are necessary to ensure uniformly high superconductor characteristics over kilometer lengths of wire. Research and development could help develop highly reliable, high-efficiency cryogenic systems to economically cool the superconducting components, including materials for cryogenic insulation and standardized high-efficiency refrigerators and motors (Figure 4-8). Scale-up of national laboratory discoveries for "coated conductors" could be another promising area for the laboratories and their industry partners.
- **Materials Science for Energy Conversion.** The digital economy is demanding more low-voltage DC power, which underscores the need for more efficient AC-DC conversion. In addition, on-site sources of photovoltaic (PV) and wind energy would be more efficiently utilized by supplying electricity to DC appliances, which will necessitate a new generation of smart wiring in homes and offices to allow both AC and DC power and end uses.
- **Energy Storage.** Energy storage that responds over timescales from milliseconds to hours and outputs that range from watts to megawatts is a critical enabling technology for enhancing customer reliability and power quality, more effective use of renewable resources, integration of distributed resources, and more reliable transmission system operation.
- **Real-Time Monitoring and Control.** Introduction of low-cost sensors throughout the power system is needed for real-time monitoring of system conditions. New analytical tools and software must be developed to enhance system observability and power flow control over wide areas.

Potential Role of Technology

There are many T&D technologies that can improve efficiency and reduce GHG emissions. In the near term, these include high-voltage DC (HVDC) transmission, high-strength composite overhead conductors, solid-state transmission controls such as Flexible AC Transmission System (FACTS) devices that include fault current limiters, switches and converters, and information technologies coupled with automated controls (i.e., a "Smart Grid"). High-efficiency conventional transformers—commercially available although not widely used—also could have impacts on distribution system losses.

Advanced conductors integrate new materials with existing materials and other components and

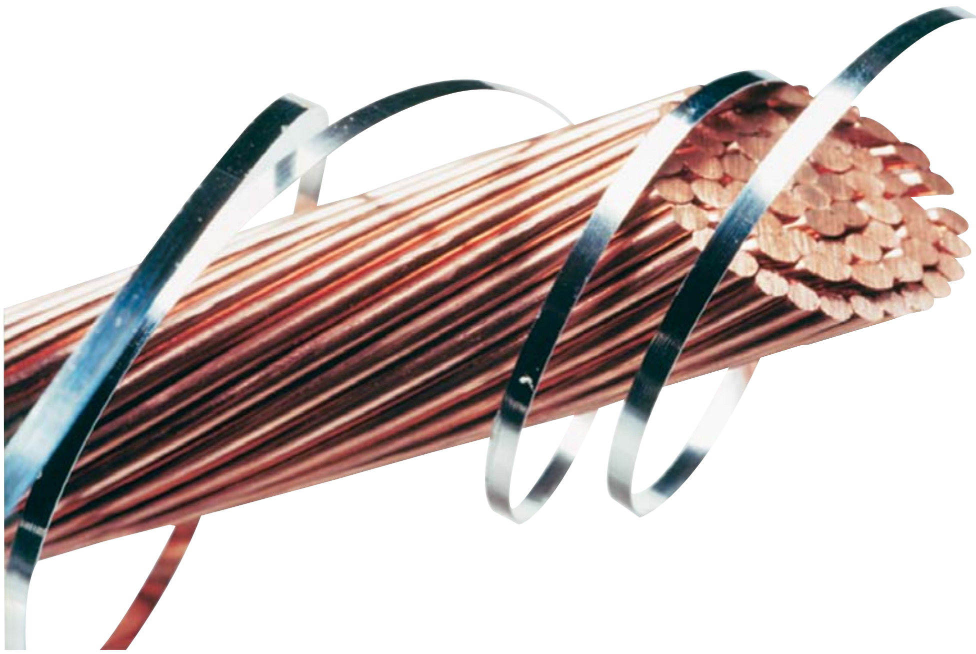


Figure 4-9. Superconductor wires have the ability to conduct more than 150 times the electrical current of copper wire of the same dimension.

Courtesy: American Superconductor.

subsystems to achieve better technical, environmental, and financial performance—e.g., higher current carrying capacity, more lightweight, greater durability, lower line losses, and lower installation and operations and maintenance costs. Improved sensors and controls, as part of the next-generation electricity T&D system, could significantly increase the efficiency of electricity generation and delivery, thereby reducing the GHG emissions intensity associated with the electric grid. Outfitting the system with digital sensors, information technologies, and controls could further increase system efficiency, and allow greater use of more efficient and low-GHG end-use and other distributed technologies. High-temperature superconductors may be able to be utilized in key parts of the T&D system to reduce or eliminate line losses and increase efficiency. Energy storage allows intermittent renewable resources, such as photovoltaics and wind, to be dispatchable.

Advanced storage concepts and particularly high-temperature superconducting wires and equipment represent longer-term solutions with great promise. Digital sensors, information technologies, and controls may eventually enable real-time responses to system loads. HTS electrical wires might be able to carry 150 times the amount of electricity compared to the same-size conventional copper wires (Figure 4-9). Such possibilities may create totally new ways to operate and configure the grid. Power electronics will be able to provide significant advantages in processing power from distributed energy sources using fast response and autonomous control.

Technology Strategy

Realizing these opportunities requires a research portfolio that focuses on a balance between advanced transmission grid and distributed-generation technologies. Within the constraints of available resources, a balanced portfolio needs to address conductor technology, systems and controls, energy storage, and power electronics to help reduce CO_2 emissions in this sector.

Early research is likely to focus on ensuring reliability, e.g., establishing "self-healing" capabilities for the grid, including intelligent, autonomous device interactions, and advanced communication capabilities. Additional technologies would be needed for wide-area sensing and control, including sensors, secure communication and data management; and for improved grid-state estimation and simulation. Simulation linked to intelligent controllers can lead to improved protection and discrete-event control. Digitally enabled load-management technologies, wireless communications architecture and algorithms for system automation, and advanced power storage technologies will allow intermittent and distributed energy resources to be efficiently integrated.

Longer-term research is likely to focus on the development of fully operational, pre-commercial prototypes of energy-intensive power equipment that, by incorporating HTS wires, will have greater capacity with lower energy losses and half the size of conventional units. Over the long term, the T&D system would also be enhanced by integrating storage and power electronics.

Current Portfolio

Across the current Federal portfolio of electric infrastructure-related R&D, multi-agency activities are focused on a number of major thrusts in high-temperature superconductivity, T&D technologies, distributed generation and combined heat and power, energy storage, sensors, controls and communications, and power electronics. For example:

- Research on **high-temperature superconductivity** (HTS) is focused on improving the current carrying capability of long-distance cables; its manufacturability; and cost-effective ways to use the cable in equipment such as motors, transformers, and compensators. More reliable and robust HTS transmission cables that have three to five times the capacity of conventional copper cables and higher efficiency—which is especially useful in congested urban areas—are being developed and built as pre-commercial prototypes. Through years of Federal research in partnership with companies throughout the nation, technology has developed to bond these HTS materials to various metals, providing the flexibility to fashion these ceramics into wires for use in transmission cables; bearings for flywheels; and coils for power transformers, motors, generators, and the like.

  Research program goals in this area include HTS wires with 100 times the capacity of conventional copper/aluminum wires. More broadly, the program aims to develop and demonstrate a diverse portfolio of electric equipment based on HTS, such that the equipment can achieve a 50 percent reduction in energy losses, compared to conventional equipment, and a 50 percent size reduction, compared to conventional equipment with the same rating. Low-cost, high-performance, second-generation coated conductors are expected to become available in 2008 in kilometer-scale lengths. Cost goals include: (1) in 1,000 meter lengths, a wire-cost goal of $50 or less per ampere of current carried by superconducting wire used in power lines cooled to liquid nitrogen temperatures; (2) by 2015, the cost performance ratio for superconducting wires improved by at least a factor of 2.[18]

- Research on **transmission and distribution technologies** is focused on real-time information and control technologies; and systems that increase transmission capability, allow economic

A Distributed Energy Future

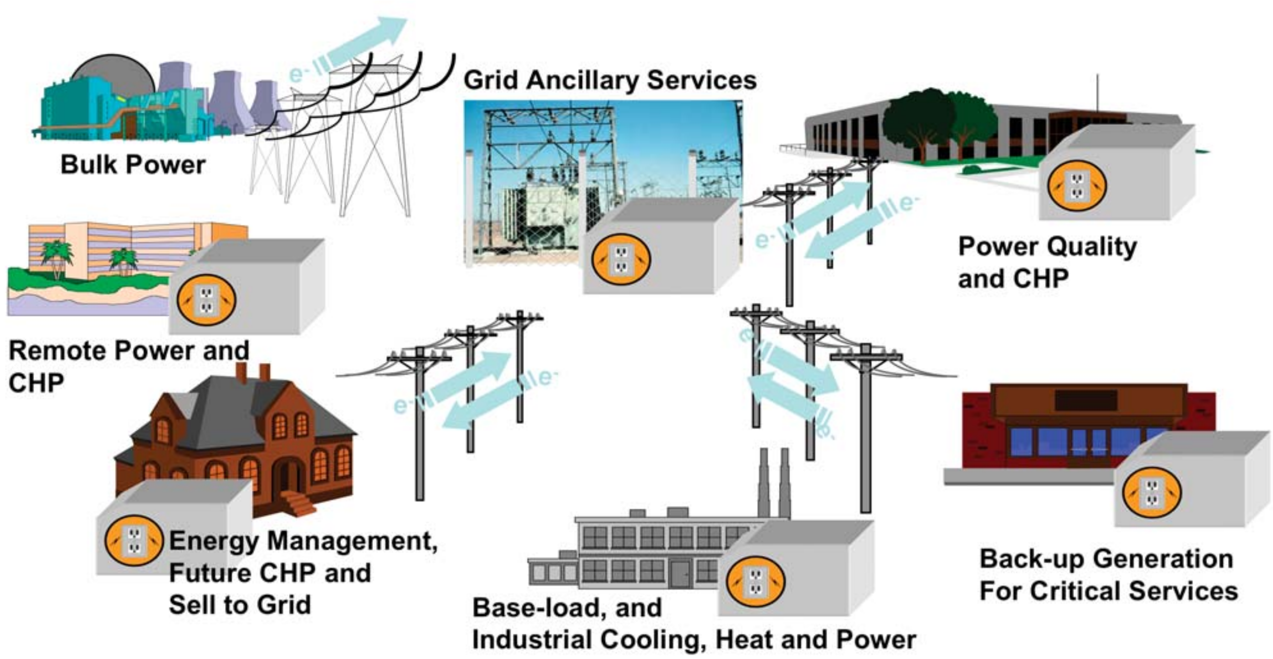


Figure 4-10. A Distributed Energy Future (Source: ORNL, Oak Ridge, Tennessee)

18 See Section 1.3.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-131.pdf.

and efficient electricity markets, and improve grid reliability. Examples include high-strength composite overhead conductors, grid-status measurement systems that improve reliability by giving early warning of unstable conditions over major geographic regions, and technologies and regulations that enable the customer to participate more in electric markets through a demand response.[19]

Research program goals in this area include, by 2010, demonstrated reliability of energy-storage systems; reduced cost of advanced conductors systems by 30 percent; and operation of a prototype smart, switchable grid in a region within the U.S. transmission grid.

- Research on **distributed generation** (DG) includes renewable resources (e.g., photovoltaics), natural gas engines and turbines, energy-storage devices, and price-responsive loads. These technologies can meet a variety of consumer energy needs, including continuous power, backup power, remote power, and peak shaving. They can be installed directly on the consumer's premises or located nearby in district energy systems, power parks, and mini-grids (Figure 4-10).

  Current research focuses on technologies that are powered by natural gas combustion and are located near the building or facility where the electricity is being used. These systems include microturbines, reciprocating engines and larger industrial gas turbines that generate from 25 kW to 10 MW of electricity that is appropriate for hotels, apartment buildings, schools, office buildings, hospitals, etc. Combined cooling, heating, and power (CHP) systems recover and use waste heat from distributed generators to efficiently cool, heat, or dehumidify buildings or make more power.

  Research is needed to increase the efficiency and reduce the emissions from microturbines, reciprocating engines, and industrial gas turbines to allow them to be sited anywhere, even in nonattainment areas. These technologies can meet a variety of consumer energy needs, including continuous power, backup power, remote power, and peak shaving. Microturbines and reciprocating engines can also be utilized to burn opportunity fuels such as landfill gases or biogases from wastewater-treatment facilities or other volatile species from industrial processes that would otherwise be an environmental hazard.[20]

  CHP technologies have the potential to take the DG technologies one step further in GHG reduction by utilizing the waste heat from the generation of electricity for making steam, heating water, or producing cooling energy. The average power plant in the United States converts approximately one-third of the input energy into output electricity and then discards the remaining two-thirds of the energy as waste heat. Integrated DG systems with CHP similarly produce electricity at 30 percent to 45 percent efficiency, but then capture much of the waste heat to make steam or heat, to cool water, or to meet other thermal needs and increase the overall efficiency of the system to greater than 70 percent. Research is needed to increase the efficiency of waste-heat-driven absorption chillers and desiccant systems to overall efficiencies well above 80 percent.

  The overall research goal of the Distributed Energy Program is to develop and make available, by 2015, a diverse array of high-efficiency, integrated distributed generation and thermal energy technologies, at market-competitive prices, so to enable and facilitate widespread adoption and use by homes, businesses, industry, communities, and electricity companies that may elect to use them. If successful, these technologies will enable the achievement of a 20 percent increase in a building's energy utilization, when compared to a building built to ASHRAE 90.1 standards, using load management, CHP, and energy-storage technologies that are replicable to other localities.

- Research on **energy storage** is focused in two general areas. First, research is striving to develop storage technologies that reduce power-quality disturbances and peak electricity demand, and improve system flexibility to reduce adverse effects to industrial and other users. Second, research is seeking to improve electrical energy storage for stationary (utility, customer-side, and renewable) applications. This work is being done in collaboration with a number of universities and industrial partners. This work is set within an international context, where others are investing in high-temperature, sodium-sulfur batteries for utility load-leveling applications and pursuing large-scale vanadium reduction-oxidation battery chemistries.

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19 See Section 1.3.2 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-132.pdf.

20 See Section 1.3.3 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-133.pdf.

The research program goals in this area focus on energy-storage technologies with high reliability and affordable costs. For capital cost, this is interpreted to mean less than or equal to those of some of lower-cost new power generation options ($400-$600/kW). Battery storage systems range from $300-$2,000/kW. For operating cost, this figure would range from compressed gas energy storage (which can cost as little as $1 to $5/kWh) to pumped hydro storage (which can range between $10 and $45/kWh).[21]

- Research on **sensors, controls, and communications** focuses on developing distributed intelligent systems to diagnose local faults and coordinate with power electronics and other existing, conventional protection schemes that will provide autonomous control and protection at the local level. This hierarchy will enable isolation and mitigation of faults before they cascade through the system. The work will also help users and electric-power-system operators achieve optimized control of a large, complex network of systems; and will provide remote detection, protection, control, and contingency measures for the electric system.

  The initial research program goals for sensors, controls, and communications are to develop, validate, and test computer simulation models of the distribution system to assess the alternative situations. Once the models have been validated on a sufficiently large scale, the functional requirements and architecture specifications can be completed. Then more specific technology solutions can be explored that would conform to the established architecture.[22]

- Research on **power electronics** is focused on megawatt-level inverters, fast semiconductor switches, sensors, and devices for Flexible Automated Control Transmission Systems (FACTS). The Office of Naval Research and DOE have a joint program to develop power electronic building blocks. The military is developing more electricity-intensive aircraft, ships, and land vehicles, which are providing power electronic spinoff technology for infrastructure applications.

  The research program goal in this area is to build a power electronic system on a base of modules. Each module or block would be a subsystem containing several components, and each one has common power terminals and communication connections.[23]

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:

- **High-Temperature Superconducting Cables and Equipment.** The manufacture of promising HTS materials in long lengths at low cost remains a key program challenge. New, continuously-scanning analytical systems are necessary to ensure uniformly high superconductor characteristics over kilometer lengths of wire. Research and development could help develop highly reliable, high-efficiency cryogenic systems to economically cool the superconducting components including materials for cryogenic insulation and standardized high-efficiency refrigerators. Scale-up of national laboratory discoveries for "coated conductors" could be another promising area for the laboratories and their industry partners.
- **Energy Storage.** Energy storage that responds over timescales from milliseconds to hours—and outputs that range from watts to megawatts—is a critical enabling technology for enhancing customer reliability and power quality, more effective use of renewable resources, integration of distributed resources, and more reliable transmission system operation.
- **Real-Time Monitoring and Control.** Introduction of low-cost sensors throughout the power system is needed for real-time monitoring of system conditions. New analytical tools and software must be developed to enhance system observability and power flow control over wide areas.

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21 See Section 1.3.4 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-134.pdf.

22 See Section 1.3.5 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-135.pdf.

23 See Section 1.3.6 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-136.pdf.

4.5 Summary

This chapter reviews various forms of advanced technology, their potential for reducing emissions from end use and infrastructure, and the R&D strategies intended to accelerate their development. Although uncertainties exist about both the level at which GHG concentrations might need to be stabilized in the future and the nature of the technologies that may come to the fore, the long-term potential of advanced end-use and infrastructure technologies is estimated to be significant, both in reducing emissions (as shown 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 R&D goals for each end-use and infrastructure technology area. It will remain important to continue to coordinate research closely with industrial firms, since in many cases they will have the financial incentive and expertise to make technology advancements without Federal support.

As one illustration among the many hypothetical cases analyzed,[24] when a high-emissions constraint was placed on GHG emissions over the course of the 21st century, the lowest-cost arrays of advanced technology in end use and infrastructure, when compared to a reference case, resulted in 100-year cumulative reductions of emissions of roughly between 190 and 210 GtC. This amounted, roughly, to between 30 and 35 percent of all GHG emissions reduced, avoided, captured and stored, or otherwise withdrawn and sequestered, as needed to attain this level of constrained emission. Similarly, the costs for achieving such emissions reductions, when compared to the reference case, were reduced by 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 potential achievements in this range. The overall strategy is summarized schematically below in Figure 4-11. 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 end use and infrastructure potential portrayed in Figure 3-19.

The timing and the 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 a reference case, would need to be in place and operating, roughly, between 2030 and 2050. For this to happen, a number of new or advanced end-use and infrastructure technologies would need to penetrate the market at significant scale before these dates. Other cases would suggest faster or slower rates of deployment, depending on assumptions. See Chapter 3 for other cases and other scenarios.

Throughout Chapter 4, the discussions of the current activities in each area support the main components of this approach to technology development. The activities outlined in the current portfolio sections address the highest-priority investment opportunities for this point in time. Beyond these activities, the chapter identifies promising directions for future research, identified in part by the end-use and infrastructure technical working group and assessments and inputs from non-Federal experts. CCTP remains open to a full array of promising technology options as current work is completed and changes in the overall portfolio are considered.

24 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.

Technologies for Goal #1: Reduce Emissions from End Use and Infrastructure

	NEAR-TERM	MID-TERM	LONG-TERM
Transportation	• Hybrid & Plug-In Hybrid Electric Vehicles • Clean Diesel Vehicles • Alternative and Fuel-Flexible Vehicles • Improved Batteries, Energy Storage • Power Electronics • Engineered Urban Designs • Reduction of Vehicle Miles Traveled • Improved Air Space Operations	• Fuel Cell Vehicles and H_2 Fuels • Efficient, Clean Heavy Trucks • Cellulosic Ethanol Vehicles • Intelligent Transport Systems • Integrated Regional Planning • Low-Emission Aircraft • Intercity Transport Systems	• Zero-Emission Vehicle Systems • Optimized Multi-Modal Intercity & Freight Transport • Widespread Use of Engineered Urban Designs & Regional Planning • Very Low Aviation Emissions (all GHGs)
Buildings	• High-Performance, Integrated Homes • Energy-Efficient Building Materials • High-Efficiency Appliances • Solar Control Windows	• "Smart" Buildings • Solid-State Lighting • Ultra-Efficient HVACR • Intelligent Building Systems • Neural Net Building Controls	• Energy Managed Communities • Low-Power Sensors with Wireless Communications
Industry	• Improved Processes in Energy-Intensive Industries • High-Efficiency Boilers and Combustion Systems • Greater Waste Heat Utilization • Improved Recyclability and Greater Use of Byproducts • Bio-Based Feedstocks	• Transformational Technologies for Energy-Intensive Industries • C&CO_2 Managed Industries • Superconducting Electric Motors • Efficient Thermoelectric Systems • Advanced Separation Technologies • Low-Emission Cement Alternatives • Water and Energy System Optimization	• Integration of Industrial Heat, Power, Processes and Techniques • High-Efficiency, All-Electric Manufacturing • Widespread Use of Bio-Feedstocks • Closed-Cycle Products & Materials
Electric Grid & Infrastructure	• Distributed Generation • Smart Metering & Controls for Peak Shaving • Long-Distance DC Transmission • High-Temperature Superconductivity Demonstrations • Power Electronics • Composite Conductor Cables	• Energy Storage for Load Leveling • Neural Net Grid Systems • Advanced Controls and Power Electronics	• Superconducting Transmission and Equipment • Standardized Power Electronics • Wireless Transmission

Figure 4-11. Technologies for Goal #1: Reduce Emissions from End Use and Infrastructure (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.)

4.6 References

Brown, M.A. 2003. *What are the administration priorities for climate change technology?* November 6, 2003. http://www.house.gov/science/hearings/energy03/nov06/brown.pdf

Energy Information Administration (EIA). 2004. *Annual energy outlook 2004: with projections to 2025*, DOE/EIA-0383(2004). Washington, DC: U.S. Department of Energy.

Energy Information Administration (EIA). 2005. *Annual energy outlook 2005: with projections to 2025*, DOE/EIA-0383(2005). Washington, DC: U.S. Department of Energy.

Intergovernmental Panel on Climate Change (IPCC). 2000. *Special report on emissions scenarios.* Cambridge, UK: Cambridge University Press. http://www.grida.no/climate/ipcc/emission/

Intergovernmental Panel on Climate Change (IPCC). 2001. *Climate change 2001: mitigation.* Working Group III to the Third Assessment Report. Cambridge, UK: Cambridge University Press. http://www.grida.no/climate/ipcc_tar/wg3/index.htm

International Energy Agency (IEA). 2004. *World energy outlook.* Paris: International Energy Agency.

United Nations (UN) Population Division. 2005. *World population prospects: the 2004 revision population database.* http://esa.un.org/unpp/

U.S. Climate Change Technology Program (CCTP). 2005. *Technology options for the near and long term.* Washington, DC: U.S. Department of Energy. http://www.climatetechnology.gov/library/2005/tech-options/index.htm

U.S. Department of Energy (DOE). 1997. *Technology opportunities to reduce U.S. greenhouse gas emissions.* Washington, DC: U.S. Department of Energy. http://www.ornl.gov/~webworks//cppr/y2003/rpt/110512.pdf

U.S. Department of Energy (DOE). 2002. *National transmission grid study.* Washington, DC: U.S. Department of Energy. http://www.pi.energy.gov/pdf/library/TransmissionGrid.pdf

U.S. Department of Energy (DOE). 2005. *Hydrogen fuel cells and infrastructure technologies multi- year research, development and demonstration plan: 2003-2010* (Draft). Washington, DC: U.S. Department of Energy. http://www.eere.energy.gov/hydrogenandfuelcells/mypp/

U.S. Department of Energy (DOE), Energy Efficiency and Renewable Energy (EERE). 2005. *FY 2006: budget-in-brief.* http://www.eere.energy.gov/office_eere/pdfs/fy05_budget_brief.pdf

U.S. Department of Transportation (DOT). 2002a. *Highway statistics 2001.* Washington, DC: Federal Highway Administration.

U.S. Department of Transportation (DOT). 2002b. *Freight analysis framework.* Washington, DC: Federal Highway Administration.

U.S. Environmental Protection Agency (EPA). 2005. *Inventory of U.S. greenhouse gas emissions and sinks: 1990-2003.* EPA 430-R-05-003. http://yosemite.epa.gov/oar/globalwarming.nsf/UniqueKeyLookup/RAMR69V4ZS/$File/05_complete_report.pdf