2. TECHNOLOGY PATHWAYS

Many technological opportunities exist to reduce U.S. GHG emissions. Some involve incremental improvements to existing equipment and processes; others can be realized only through breakthroughs in the fundamental sciences and subsequent technological developments. Some technologies can be translated into market-ready products during the next decade; others may be available as one-of-a-kind prototypes by 2025. Some can be inserted into our current energy economy with relative ease; others require major transformations of infrastructure.

This section contains an inventory of climate change technologies. The authors concluded that about 50 technological pathways warrant serious consideration (see Table 2.1 and Appendix B). The pathways are divided into nine technological areas that can be addressed by three major approaches: improving energy efficiency, using more clean energy, and sequestering carbon (Fig. 2.1). Coverage of electric utility technologies is included in the fossil power generation, nuclear energy, and renewable energy areas.

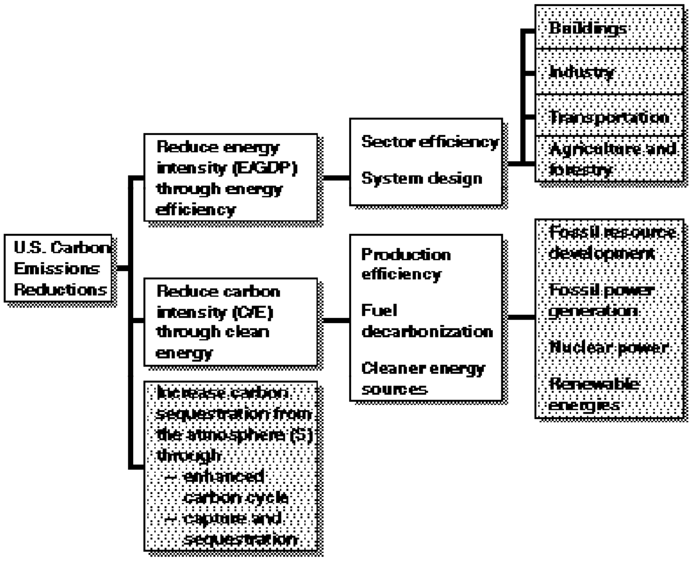

Fig. 2.1. Alternative technological opportunities for reducing greenhouse gas emissions. Electric utility technologies are covered in the fossil power generation, nuclear energy, and renewable energy areas.

Table 2.1. Technology pathways[a]

1. Buildings
    1.1 Equipment and Appliances
    1.2 Building Envelope
    1.3 Intelligent Building Systems
2. Industry
    2.1 Energy Conversion and Utilization
    2.2 Resource Recovery and Utilization
    2.3 Industrial Process Efficiency
    2.4 Enabling Technologies
3. Transportation
    3.1 Advanced Conventional Vehicle
    3.2 Freight Vehicles
    3.3 Hybrid, Electric, and Fuel Cell Vehicles
    3.4 Alternative Fuel Vehicles
    3.5 Air and High-speed Ground Transport
4. Agriculture and Forestry
    4.1 Conversion of Biomass to Bioproducts
    4.2 Advanced Agricultural Systems
    4.3 Plant/Crop Engineering
5. Fossil Resource Development
    5.1 Energy Efficiency for Crude Oil Refining
    5.2 Natural Gas to Liquids
    5.3 Increased Natural Gas Production
    5.4 Co-production with Integrated Gasification Combined Cycle
    5.5 CO_2 for Improved Oil and Gas Recovery
6. Fossil Power Generation
    6.1 Accelerated Development of High-Efficiency Coal-Based Power Generation Technologies
    6.2 Low-Carbon Fuels and High-Efficiency Power Generation
    6.3 Ultra-High Efficiency, Zero-Carbon Emission Energyplexes
7. Nuclear
    7.1 Lifetime Extension and Generation Optimization
    7.2 Next-Generation Fission Reactors
    7.3 Fusion Power
8. Renewable Energy
    8.1 Biomass Electric
    8.2 Wind Energy
    8.3 Advanced Hydropower
    8.4 Solar Photovoltaics
    8.5 Geothermal Energy
    8.6 Solar Thermal Electric and Buildings
    8.7 Biomass Transportation Fuels
    8.8 Solar Advanced Photoconversion
9. Carbon Sequestration and Management
    9.1 Augmented Ocean Fertilization to Promote Additional CO_2 Sequestration
    9.2 Advanced Chemical and Biological Conversion and Sequestration
    9.3 Terrestrial Storage of CO_2
    9.4 Carbon Sequestration in Soils
    9.5 Elemental Carbon Sequestration
    9.6 Ocean Storage

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[a] This table does not include basic research needs (i.e., global carbon cycle modeling and measurement, materials science, chemical sciences, biotechnology, geosciences, environmental and ecological sciences, and nuclear sciences) and enabling technologies (hydrogen and fuel cells, electrical transmission, distribution, and components, sensors and controls, and energy storage) needed to support the technology pathways (see Chap. 3).

2.1 CARBON LEVELS: PRESENT AND FUTURE

The sources of carbon emissions in the United States must be understood before characterizing the potential benefits of technologies to reduce GHG emissions. For example, in 1995, most anthropogenic (human activity–related) CO_2 emissions in the United States were caused by the combustion of coal, natural gas, and petroleum. A fraction (less than 2%) came from other sources, including the manufacture of cement and lime. Figure 2.2 shows how these primary fuels are transformed to provide energy and products that are ultimately consumed in homes, office buildings, factories, cars, trucks, and farms.

Energy Efficiency. In 1995, the three major end-use sectors (buildings, industry, and transportation) emitted approximately equivalent levels of carbon. However, the sources of this carbon vary widely. For instance, 80% of the carbon emissions attributable to the energy used in buildings comes from electricity, whereas 99% of the energy used for transportation comes directly from consumption of petroleum products. Energy consumption in each of the end-use sectors has grown during the past decade at about the same rate as the nation’s GDP, causing significant increases in carbon emissions. The increases illustrate the importance of reducing the amount of energy consumed per unit of economic output, or “energy intensity,” of our economy (see Chap. 1). Technology that increases energy efficiency is the key to achieving this goal. It can reduce the energy used per square foot of home or office space, the energy required per unit of industrial output, and the energy consumed per vehicle-mile traveled. Through advances in technology, these energy intensities can be decreased without sacrificing any of the services that energy provides.

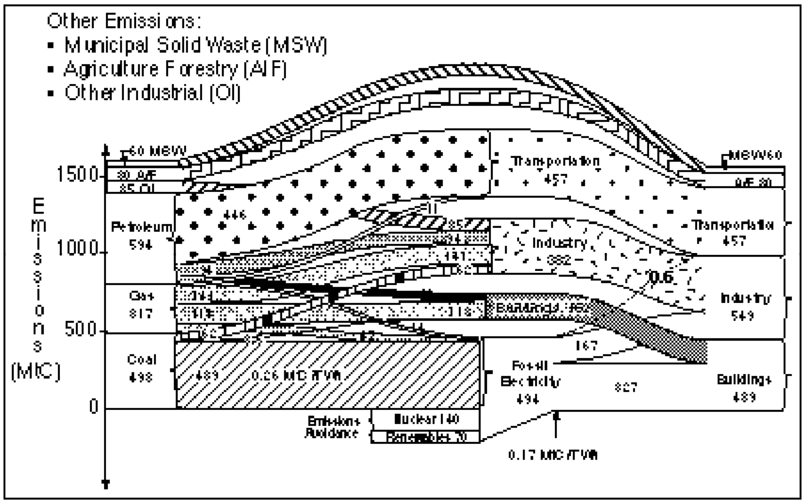

Fig. 2.2. Sources of greenhouse gas emissions in the United States in 1995 (in million metric tons equivalent). Note that if nuclear and renewables had not been used to generate electricity in 1995, carbon emissions would have been 210 MtC higher on each side of the chart. *Source:* Based on EIA 1996b.

Clean Energy. “Clean energy” technologies can decrease the amount of carbon produced per unit of energy, or “carbon intensity,” of the nation’s energy economy. In 1995, coal, natural gas, and a small amount of petroleum were responsible for 494 MtC of emissions in the electricity industry (Fig. 2.2). Nuclear power and renewable sources can be credited with displacing what would have been an additional 140 and 70 MtC of carbon emissions, respectively, if fossil fuels had been used. As a result, the electricity sector produced only 0.17 MtC per terawatt hour (TWh), instead of 0.26 MtC/TWh. Switching to low-carbon fuels for transportation is an important means of reducing carbon emissions; for instance, biofuels can replace petroleum-based liquid fuels. Another option for reducing carbon intensity involves fuel decarbonization, in which carbon is removed from fuel and sequestered before the fuel is used. Improving the efficiency of producing energy from fossil fuels is also important.

Carbon Sequestration. Carbon sequestration is another technological route to reducing the magnitude and impacts of U.S. carbon emissions. One approach is to sequester CO_2 emissions captured during fossil fuel conversion processes, thus preventing their release into the atmosphere. A second approach is to increase the absorption of CO_2 by either the oceans or the terrestrial biosphere.

Synergies and Integrations. While these three approaches of energy efficiency, clean energy, and carbon sequestration are convenient for discussion, the synergies and interdependencies among them and among sectors must be considered as well in further development of a technology strategy. For example, the carbon reductions that result from energy efficient technologies depend on the carbon content of the energy that is being displaced, and reductions from the use of electric vehicles depend on the carbon content of the electricity generated. If electricity continues to be generated largely by inefficient coal plants, end-use efficiency improvements will produce sizeable carbon reductions. Greater reliance on electricity from renewables or nuclear reactors will reduce the carbon benefits resulting from energy efficiency.

Some interactions are potentially positive. Fuel cells using methane require that carbon and hydrogen be separated anyway, so there would be no separation cost in sequestering the carbon. Some interactions are potentially negative, such as the possibility that the heavy use of natural gas for low-carbon electricity production and cogeneration could increase prices for natural gas, if not paired with more efficient natural gas consumption in buildings and industry. Also, increases in energy efficiency can cause lower prices, which can increase demand and potential carbon emissions. Some interactions make it possible for certain technologies to be more effectively adopted, such as integrating intermittent renewables such as solar thermal electric with IGCC using natural gas.

A potentially dramatic synergy is expected between non-carbon electricity generation (e.g., solar, wind, biomass, and nuclear) and vehicles using electricity or hydrogen produced from electricity. The large but flexible electricity demand these technologies could represent (25–50% of the electricity market) would enable large reductions in energy storage needed for intermittent renewables to become widely adopted.

This report does not examine these types of synergies in depth, but some examples include the pathways for energyplexes (Fossil Power Generation), resource recovery and utilization (Industry), and hydrogen (Crosscutting). Other integrated systems are mentioned in Chap. 5, Synthesis and Moving Forward.

2.2 STUDY METHODOLOGY AND ASSUMPTIONS

Participants. Compiling detailed information on the potential of a wide range of energy-related technologies to reduce CO_2 emissions required the expertise and judgment of a large number of individuals. The laboratory directors first identified representatives from each of the 11 labs involved in this study. These representatives defined the 11 technology areas that formed the structure of the study (9 categories of technology pathways plus cross-cutting enabling technologies and related areas of basic research). Each representative then assumed responsibility for a working group corresponding to one of the 11 areas. Each working group, consisting of relevant experts from the various laboratories, identified the individual technology pathways appropriate to its technology area as listed in Table 2.1 and prepared the pathway drafts.

Overall direction for the study was provided by the laboratory directors through a coordinating committee and the group of lab representatives. The coordinating committee and lab representatives provided guidance and assumptions to the working groups for developing the desired information and took on the task of summarizing the information into the main report. Participants in these groups are listed in Appendix A.

In addition, a small focus group served an important role in the overall study methodology by carefully reviewing all of the technology pathways for consistency and credibility and then interviewing their authors to ensure that the material presented had a firm technical basis and had been developed in a reasonable way. This process included ensuring that the guidelines for developing the carbon emission reduction estimates and the risk factor scores had been followed.

The assumptions for the study are given in detail in the introduction to Appendix B and summarized here. In general, the working groups relied upon Delphi method principles to reach their conclusions about the technology pathways. Conditions and assumptions not defined herein were based on a consensus of the working group members.

Information Considered. The technology pathways provide detailed information describing the technology: its developmental status and outlook for technological progress through RD&D, recent successes, commercialization and deployment prospects, potential benefits and costs, various types and levels of risks the technology faces, and recommendations for federal actions. The potential benefits and costs were quantified, under common assumptions, in terms of the estimated carbon emissions reductions in each of the next three decades and a general estimate of what levels of federal RD&D support might be needed to fully develop the individual technology pathways over the next three decades.

It is important to note that the descriptive text and the numerical estimates presented in these pathways are based on the judgment of teams from the 11 participating national laboratories (in some cases in collaboration with experts from other organizations across the country). Some of the numerical estimates were supported by analysis; others were simply the best estimates of experts based on available information. The estimates for each technology area were developed independent of the other technology areas; competition and interactions among the technology areas were not considered. Therefore, summing carbon reduction estimates from different technology areas would lead to "double counting."

The time frame of this study did not allow analysis of all of the various factors that could affect the performance and market penetration of a new technology. However, the study has compiled a considerable amount of information on a wide range of factors and has taken this information into account in estimating carbon reductions and in drawing conclusions. The working groups and other teams considered the following factors:

- Size of domestic and international markets for the technology
- Turnover rate of capital stock
- Technical risks associated with the RD&D
- Size of the federal RD&D resources required
- Magnitude of the technology's capital and operating costs
- Extent of changes in infrastructure required for commercialization
- Size of the resource base available to support the technology
- Technical, commercial, ecological, human health, economic and regulatory risks associated with the development and use of the technology
- Characteristics of competing technologies

The timeframe of the study also did not allow for the important process of prioritizing the technology areas and pathways; thus the study recommends that some type of prioritization be included in the development of a detailed and comprehensive technology strategy for reducing greenhouse gas emissions.

Reference Case. All carbon emission reductions are relative to the "business as usual" scenario outlined by the DOE EIA (Fig. 2.3 and Table 2.2). This scenario assumes that some efficiency and process improvements will offset what would otherwise be a larger rate of CO_2 increases. The rise in emissions is driven by a forecasted GDP growth rate of 1.9%. (Underlying this growth rate is the assumption of sustained economic growth and an increasing population.) Without a major intervention, CO_2 emissions will increase by almost 50% from the current annual level of approximately 1.4 billion MtC to about 2.1 billion MtC in 2030.

The data shown in Fig. 2.3 and Table 2.2 for the period 2015 to 2030 are based on extrapolations of the EIA reference case for 2015. Thus they do not take into account the significant reduction in nuclear power that could occur after 2015 if nuclear power plants are retired according to their current license expiration dates.

Federal Policies. One of the key features of these carbon emission reduction estimates is that they assume no significant changes in existing market policies that would

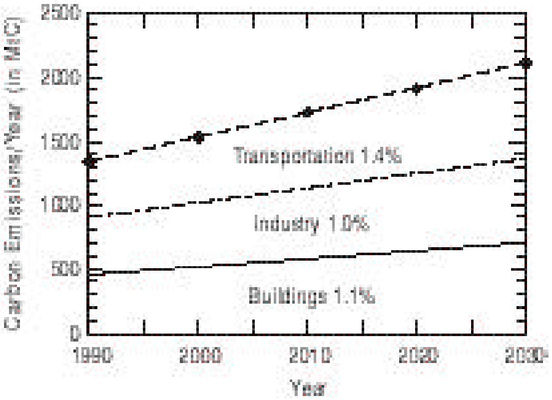

Fig. 2.3. Projected U.S. carbon dioxide emissions (in MtC per year). *Source:* Based on EIA 1996b.

Table 2.2. U.S. carbon dioxide emissions by end-use sector
(in MtC per year)

	Emissions				Change from 1990		
	1995	2010	2020	2030	2010	2020	2030
Buildings							
Fossil	159	170	178	185	22	30	37
Electricity	335	406	463	515	94	151	203
Subtotal	494	576	641	700	116	181	240
Industry							
Fossil	293	335	357	380	49	71	94
Electricity	171	213	241	269	47	75	103
Subtotal	464	548	598	649	96	146	197
Transportation							
Fossil	464	591	655	727	160	224	296
Electricity	1	7	10	14	6	9	13
Subtotal	465	598	665	741	166	233	309
Total							
Fossil	918	1096	1189	1291	231	324	426
Electricity[a]	506	626	714	798	147	235	319
Total	1424	1722	1904	2089	378	560	745

[a] The extrapolation beyond 2015 does not take into account the significant reduction in nuclear power that could occur as nuclear power plants are retired according to their current license expirations. Recent results of a new forecast by the Energy Information Administration suggest that carbon emissions will grow at a slightly faster pace through the year 2015. This new forecast is not yet published and is therefore not used in this report. In any event, using the new forecast would not substantially change the results of this report.

Sources: The carbon estimates for 1995 and the forecast for 2010 are taken directly from the Reference Case of EIA 1996a. Carbon emissions for 2020 and 2030 are forecasted using the same growth rates as for 2010. Electric utility emissions are distributed across sectors. GHGs other than CO_2 are not included.

affect adoption of advanced technologies. For example, policies such as tax incentives or rebate measures that encourage energy efficiency or clean energy technologies, or carbon charges or carbon emissions trading programs, could provide both additional and earlier reductions in carbon emissions.

Restructuring. The data in Fig. 2.3 and Table 2.2 also do not take into account any long-term impacts that might be precipitated by restructuring of the electric utility industry. If restructuring produces lower electricity rates, energy use will increase and investments in conservation technologies might decrease, with a concomitant rise in GHG emissions.

On the other hand, future utility restructuring legislation calling for renewable portfolio standards and public benefits programs could significantly promote clean power, thereby reducing GHG production. The deregulation issue underscores the uncertainties faced by developers and consumers of advanced energy technologies. Such uncertainties tend to dampen private-sector investments in research on advanced technologies, making the role of government-funded RD&D that much more critical. In general, the competitive market forces that accompany utility restructuring are significantly reducing utility sector investment in R&D, and the focus of that R&D is shifting to near-term results and becoming less strategic.

The introduction to Appendix B further discusses the methodology and assumptions relevant to the study. The remaining sections of this chapter describe the nine technological areas that constitute the menu of technological opportunities identified in this report (Fig. 2.1). We note the following for each area:

- the magnitude of carbon-emission reductions that could be realized as a result of successful development and subsequent market adoption of the technologies, without any significant policy changes
- the specific pathways and related scientific and technological challenges that must be met
- the technical, market, and other risks associated with pursuing the technological area
- anticipated collateral benefits
- recommended strategies for moving forward

2.3 ENERGY EFFICIENCY

Improving the efficiency of energy use in the United States by developing advanced technologies can offer immediate, significant carbon reductions. Incremental and breakthrough technologies hold the promise of buildings that consume half the energy of current new construction, industries (such as forest products) that can meet all of their energy needs internally, cars that offer three times the fuel economy of current vehicles, and farms that are more productive and enable greater carbon fixation while using less energy.

Many technological opportunities exist for improving the efficiency of the U.S. economy. These are described in the following sections, by end-use sector:

- buildings
- industry
- transportation
- agriculture and forestry

2.3.1 Buildings

The Potential for Reduced Emissions

The buildings sector in the United States accounts for 36% of the nation’s use of primary energy. Buildings are responsible for 66% of electricity use and 37% of natural gas use. In 1995, the energy consumed in the buildings sector accounted for emissions of 489 MtC, and this is forecasted to increase to 576 MtC in 2010 and to 700 MtC in 2030. Thus the buildings sector is key to constraining or reducing the nation’s use of energy—whether the concern is GHG emissions and global climate change, urban and regional air quality, energy security, sustainable development, or any number of other concerns associated with energy use. Also, the “human dimensions” must be kept in mind—buildings exist to house the myriad needs and activities of our civilization: shelter, community involvement, relaxation, office work, industrial processes, and the like. Energy only serves to help meet these needs. Within this broad context, the following are technological approaches for reducing GHG emissions associated with buildings:

- reducing electricity use through energy efficiency measures and thereby reducing GHG emissions from fossil fuel power plants
- reducing natural gas and oil use for space and water heating and other

domestic uses through energy efficiency measures and thereby reducing on-site GHG emissions
- generating electricity on site and/or providing space and water heating using measures that are inherently more efficient than conventional ones (e.g., advanced cogeneration concepts) or that do not emit GHGs (e.g., building-integrated photovoltaic systems and solar hot water systems).

The status of various building energy technologies and their potential to reduce GHG emissions by the year 2010 are covered in the report *Scenarios of U.S. Carbon Reductions: Potential Impacts of Energy-Efficiency and Low-Carbon Technologies*, by a group representing five national laboratories (Interlaboratory Working Group 1997). Most of the technological opportunities presented in the following table would have an actual impact on emissions by the year 2020, although in some cases the impacts would not occur until 2030.

Estimated carbon emissions reductions (MtC/year)

	2010	2020	2030
Total buildings	25–50	50–100	75–150

Assumes successful technology development and subsequent marketplace adoption without significant policy changes.

Technology Pathways and Opportunities

Equipment and Appliances. By definition, all primary energy used in buildings is consumed by equipment that transforms fuel or electricity into end-uses, such as delivered heat or cooling, light, fresh air, vertical transport, cleaning of clothes or dishes, information management, or entertainment. The overall efficiency of this transformation depends largely on the efficiency of the equipment itself.

Numerous opportunities exist to develop equipment that is much more efficient than that currently available. Just a few examples of exciting new prospects include gas heat pumps with twice the efficiency of today's residential furnaces, distribution systems that deliver 50% more conditioned air, highly efficient lamps with long lifetimes, full-size refrigerator-freezers that use as little power as a 40-W light bulb, fuel cells in the garage, photovoltaics systems integrated into the building envelope, and flat panel displays to replace cathode ray tubes.

Efficient components, by themselves, are not enough, however. It is equally important to ensure that the equipment is properly sized to meet the load, that its operation conforms to varying demands (i.e., controls that vary output as load varies and that minimize standby losses), and that individual pieces of equipment are intelligently integrated into a multifunction unit or into a total building system (to exchange and reuse heat, balance electrical demand, or combine functions to share the use of burners or compressors).

The Building Envelope. The building envelope provides fundamental thermal load control for a building. Walls, roofs, and floors block or delay the flow of heat between a building's interior and exterior. Windows can also block heat flow, provide daylight, transmit solar energy, and provide a view of the outside. High-capacitance internal walls, ceilings, and floors can provide thermal storage that reduces energy use by storing solar energy and reduces peak loads by balancing energy use over a 24-hour period. Improvements in the energy performance of these building elements reduce energy use in buildings and thereby reduce GHG emissions.

Decreasing the building thermal load reduces the need for heating and cooling energy. These emerging building envelope technologies will significantly reduce building energy use:

- super insulation, based on vacuum principles
- new-formula high-efficiency foam insulation that uses no CFCs or hydrochlorofluorocarbons
- advanced gas-filled, multiple-glazing, low-emittance windows and electrochromic glazing
- self-drying roofs
- passive solar components
- durable high-reflectance coatings
- advanced thermal storage materials

Intelligent Building Systems. The process of designing, constructing, starting up, controlling, and maintaining building systems is very complex. If it is done properly, the final product delivers comfort, safety, and a healthy environment and operates efficiently at reasonable cost. If any part of this process breaks down, the product fails to deliver these benefits. The lost health and productivity in office environments alone costs U.S. businesses over $400 billion per year (Cramer-Krasselt Research 1996). In addition, operating these “broken” systems is estimated to cost at least 30% of commercial building energy use (more than $45 billion). The key to designing and operating buildings efficiently is the ability to manage information, deliver it in a timely manner to the proper audience, and use it effectively for building design and operation. More intelligently designed and operated buildings use energy more efficiently and thus reduce GHG emissions.

In the intelligent building systems concept, data from the design of the building, together with sensed data, will be used to automatically configure controls and commission (i.e., start up and check out) and operate buildings. Control systems will use advanced, robust techniques based on smaller, cheaper, and more abundant sensors than are in use today. Intelligent devices will use this wealth of data to ensure optimal building performance by continuously controlling and recommissioning building systems using automated tools that detect and diagnose performance anomalies and degradation. Such systems will optimize operation across building systems, inform and implement energy purchasing, guide maintenance activities, and report building performance while ensuring that occupant needs for comfort, health, and safety are met at the lowest possible cost.

Such human factors as productivity, health, comfort, safety, and aesthetic acceptance can serve as barriers to advanced technologies that adversely affect (or are perceived to adversely affect) these factors. Conversely, technology options that take these factors into account in a positive way (e.g., cause productivity to increase in an office) will be accepted quickly in the market. Most buildings are in an urban or suburban environment; they affect their local community and are affected by it. Thus research on human factors and community systems is a necessary complement to application of energy-efficient technologies if their full potential for reducing GHG emissions is to be realized. The research on intelligent building systems will also require considerable investment in whole-building demonstrations.

Collateral Benefits

DOE has a remarkable record of "success stories"—cases of federally supported R&D leading to products in the marketplace that have resulted in substantial energy and cost savings. Electronic ballasts for fluorescent lighting, low-emissivity windows, design tools, and advanced HVAC equipment are examples of products resulting from R&D for which the reduction in life-cycle costs from reduced energy use more than compensates for the increase (if any) in first costs. These products have reduced energy costs to consumers by an estimated $28 billion through 1996, many times the cost of all federal R&D on buildings. Additional benefits typically result from energy-efficiency improvements in buildings, including improved indoor air quality, public health and safety, and worker productivity.

Technical Risks and Other Issues

The risks associated with a broadly based research program (technical, economic, commercial, ecological, human health, and regulatory) tend to be low, or can be kept low if proper regard is given to these topics in the research program. A building consists of many components and systems that affect energy use. Therefore, a research line that leads to a technical or economic success is likely to more than compensate for a line that is not successful. The historical experience of federal building energy R&D indicates substantial successes leading to important commercial products that have enabled large reductions in energy use and GHG emissions. There is every indication that continued R&D will lead to continued commercial success.

The ecological impact of buildings energy use is associated with (1) direct emissions of air pollutants from combustion devices and (2) resource extraction, conversion, transport, and the waste streams of conventional energy sources. Energy efficiency and renewable energy measures that reduce GHG emissions will also reduce the ecological impacts. Regulations can either impede or accelerate the introduction of advanced energy technologies in buildings. For example, energy-efficient appliance and building standards are credited with substantial energy savings.

Basic research is very important to buildings technology advances. Areas include "smart" materials for controlling energy flows; optical, thin film, and semiconductor materials for advanced windows, lighting, and flat-panel displays; and advanced techniques for heat transfer.

Strategy and Recommendations

The report *Scenarios of U.S. Carbon Reductions: Potential Impacts of Energy-Efficiency and Low-Carbon Technologies* indicates that by the year 2010 a high-energy-efficiency case in the building sector could reduce energy consumption in buildings from 33.7 quads in 1997 to 32 quads in 2010 (relative to the business-as-usual forecast of 36 quads), at a net economic benefit to consumers, if very vigorous efforts are made to bring energy-efficient technologies into widespread market acceptance. A vigorous R&D program is essential to achieve some of the efficiency gains by 2010 and to develop advanced technological options that are cost-effective in the longer term.

2.3.2 Industry

The Potential for Reduced Emissions

Industry's efficient use of energy is critical to the U.S. economy. Through efficient use of energy, the industrial sector also can be a direct contributor to reducing GHG emissions. Industry consumed 34.5 quads of primary energy in 1995—about 38% of all energy used in the United States. It was responsible for emitting the equivalent of 549 MtC during that same year (297 MtC from fossil energy consumption, 167 MtC from electricity consumption, and 85 MtC from other industrial emissions). About 83% of industrial energy is used in the manufacturing sector. Nonmanufacturing industries—including mining, oil and gas extraction, construction, and agriculture—account for about 17%. Within manufacturing, about 80% of the energy used is consumed by a total of just seven highly energy-intensive materials and process industries; the other 20% is consumed by industries primarily engaged in fabrication and assembly. EIA projects that industrial sector end-use energy consumption will remain roughly constant (between 29.1 and 34.4 quads) in the year 2015 even with economic growth. In the longer term, technological advances will play a key role in reducing industrial energy use and GHG emissions. Experts believe that it is possible for some industries (e.g., forest products) to meet all of their energy needs internally by 2010 without purchasing from outside sources.

EIA forecasts that industrial energy efficiency will improve in the future, contributing to the expected decline in energy intensity. The major factors are gradual restructuring of industry toward knowledge-intensive rather than materials-intensive products, higher-capacity use because of improved computer controls, gains in process efficiency, and just-in-time manufacturing methods. Increased on-site power generation using materials currently sent for disposal and noncombustion technologies, such as fuel cells and gasification, will also play a crucial role in reaching energy reduction targets in the industrial sector. Within manufacturing, materials and process industries account for about 80% of the hazardous and toxic wastes and about 95% of nonhazardous wastes. These wastes often impose high cleanup and disposal costs but offer the potential for recovering the "embedded" energy and materials value.

Energy remains an important driver of investment and operating decisions for materials and process industries because of their intensive energy use. Industry spent approximately $104 billion on energy in 1993 and approximately $29 billion for pollution abatement and control. Although this cost represents less than 5% of total costs of operation for all industry, the percentage of costs attributable to energy and waste ranges from about 7% to more than 30% for materials and process industries. It is clear that industry will deploy an energy-reducing technology or process only if it can see the economic benefits. Where such a combination of favorable economics, energy savings, and waste reductions is recognized, the chance of seeing the technology implemented and achieving GHG reductions increases markedly because of accelerated penetration of technologies into the market.

DOE has targeted for its collaborative R&D program the seven materials and process industries (forest products, chemicals, steel, aluminum, metal casting, glass, and petroleum refining).

To plan and direct its research effectively, DOE has initiated the Industries of the Future (IOF) program, which encourages industries to identify their collective high-risk, high-payoff technology needs. This analysis allows DOE and other federal R&D organizations (in particular the Department of Commerce–National Institute of Standards and Technology Advanced Technology Program) to align their resources to best meet those needs. Using this same process, technologies for reducing GHG emissions will be developed in collaboration and cost-shared by industry, thus ensuring accelerated implementation and deployment in industrial processes.

An analysis of the current programs indicates that when implemented, the technologies currently being researched with industrial participation could lead to the following annual reductions.

Estimated carbon emissions reductions (MtC/year)

	2010	2020	2030
Total industry	25–50	65–95	100–140

Assumes successful technology development and subsequent marketplace adoption without significant policy changes.

Technologies developed through the IOF process and crosscutting technologies under development are likely to be adopted by the seven energy-intensive industries, other nonmanufacturing industries, and, in some cases, all sectors of the U.S. economy. For example, advanced turbine systems (ATSs) are high-efficiency, next-generation gas turbines that produce less carbon per kilowatt hour than technologies used in conventional power markets. ATS deployment will reach an electric-generating capacity of an estimated 24 to 27 GW (4 to 6 MtC) by 2010. Through the National Industrial Competitiveness for Energy, Environment, and Economics program, which DOE is conducting with a more than 55% industry cost share, innovative technologies are introduced in industrial processes, leading to wider use of these technologies. Full deployment of these technologies (currently in their demonstration stage) is expected to result in energy savings of more than 1 quad by 2010.

Technology Pathways and Opportunities

The industrial sector is extraordinarily complex and heterogeneous. The needs are diverse: hundreds of different processes are used to produce millions of different products at many locations throughout the United States. In the U.S. chemicals industry alone, more than 70,000 products are produced at more than 12,000 plants. The primary opportunities to reduce GHG emissions exist in the technologies identified in the IOF program. In addition, redesign of whole facilities with a view toward environmental and energy performance can accelerate the objective of reducing GHGs by completely eliminating some of the production steps now deemed necessary. This new way of thinking may also involve designing for the environment in all steps along the way, from extraction of raw materials through the production stages to the consumption stage.

More than 90% of the carbon emissions from the industrial sector are associated with the conversion and use of energy. Reviewing the industrial needs and opportunities that lie ahead, four major technological pathways have been identified. Figures 2.4 and 2.5 illustrate the relationship among them for the industrial sector.

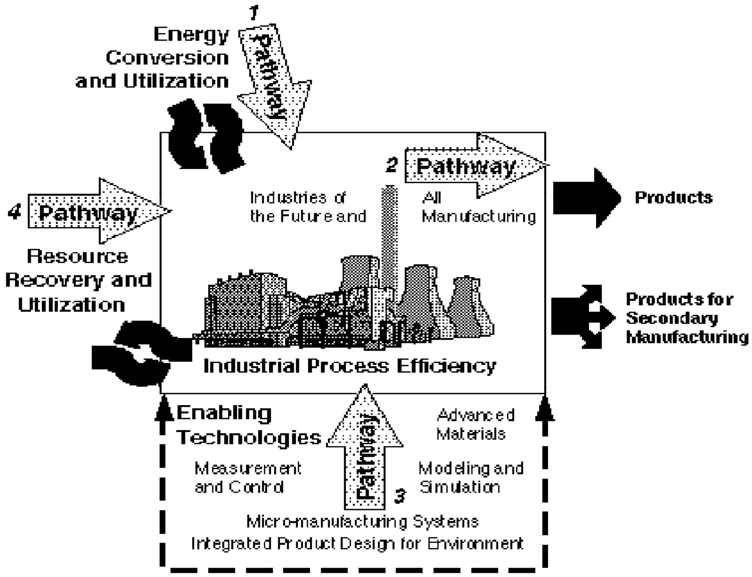

Fig. 2.4. Four technology pathways to increased industrial efficiency.

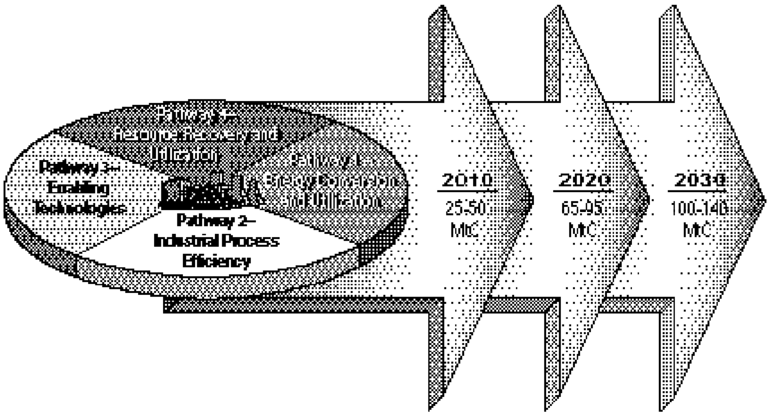

Fig. 2.5. Technology pathways for industry with associated benefits in carbon emission reductions.

Energy Conversion and Utilization. Energy efficiency could be improved through incorporating the best technologies in a systems approach. Technologies include ATSs, fuel cells, higher combustion efficiencies, and using thermal energy in a systems approach to mill/plant design. In the longer term, noncombustion technologies are likely to have a significant impact, such as fuel cells and gasification of biomass and in-plant residues (e.g., black liquor in the forest products industry).

Biobased materials are also discussed under Agriculture and Forestry (Conversion of Biomass to Bioproducts) and Renewable Energy (Solar Advanced Photoconversion). Carbon reduction estimates are included only under Conversion of Biomass to Bioproducts.

Industrial Process Efficiency. Emissions from energy use in industrial processes can be substantially reduced by developing new, more efficient processes as well as by the energy conversion processes mentioned earlier. These more efficient processes can encourage new, higher-quality products, while generating less waste and fewer undesirable by-products; they also offer the potential for increased economic growth. DOE is pursuing many opportunities for improving process efficiency via more selective catalysts, advanced separations, improved measurement and control systems, improved materials, and improved electric motor systems, such as large motors with superconductivity wires. A particularly attractive longer-term opportunity is the use of biotechnology and bioderived materials. DOE is already developing technologies to employ crop and forest materials in the production of chemicals and materials. Other agencies such as the U.S. Department of Agriculture are leaders in evaluating new uses for agricultural goods and conducting research on products from biomass. Large chemical companies, such as Eastman Chemicals, Monsanto Chemicals, and DuPont, have announced that they will pursue bioprocessing and plant-based processing as avenues to the production of chemicals and materials in the future.

Enabling Technologies. Increased fundamental understanding in chemistry, metallurgy, and biotechnology will allow the development of novel manufacturing processes. This knowledge, along with advanced modeling and simulation, improved industrial materials, and measurements (sensors) and intelligent control systems, will result in major incremental improvements and lead to fundamental breakthroughs. Likewise, developing and demonstrating micromanufacturing systems (i.e., mini-mills, micro-chemical reactors) for flexible process configuration and on-site/just-in-place (similar to just-in time) manufacturing can reduce GHG emissions in the long term. Decentralized manufacturing using locally distributed resources offers the advantage of reduced transport of raw materials and finished goods.

Resource Recovery and Utilization. This technology pathway is built upon the idea of an industrial ecology, wherein a community of producers and consumers perform in a closed system. Fossil energy is conserved and/or energy is obtained from non-GHG sources; materials are reused or recycled. Through technological advances, the raw materials and resources needed for manufacturing can be obtained by designing products for ease of disassembly and reuse, using more recycled materials in finished goods, and selecting raw materials to eliminate waste discharge or undesirable by-products. Some examples are developing new advanced polymers, composites, fibers, and ceramics engineering through advances in surface techniques and molecular structures. Another approach is to substitute materials such as biomass feedstocks for petroleum feedstocks in producing chemicals. Some longer-term technological approaches will seek to use CO_2 as a feedstock and non-GHG reductants as substitutes for carbon. Such fundamental changes in the way raw materials are obtained, the properties they exhibit, and the way they are used in the design process are likely to yield energy and GHG savings. Economic success will depend upon industry's using new design approaches and involving the entire supply chain in thinking about energy reduction in the materials life cycle.

Collateral Benefits

Numerous environmental benefits would result from improved industrial process efficiency and waste minimization. In addition to reduced carbon emissions, these collateral benefits include reduced ground-level ozone, less demand for landfill space, and decreased emissions from incinerators and hazardous waste sites. U.S. industries would also be better prepared to compete in the $400 billion international market for environmental technologies.

Technical Risks and Other Issues

Industry faces a number of risks (technical, regulatory, financial) in addition to the risk posed by international competitiveness. U.S. industry has met the challenges of higher productivity and increased profitability, as evidenced by the increase in market value of U.S. industries. Consolidation and integration in industry is an ongoing process that keeps the industrial sector focused on its costs. The technical risks in general are low, while the regulatory and financial risks are relatively high. International competition is moderate to high, leading U.S. industry to increase production capacity in other countries and increase market share. Environmental and economic pressures will continue to encourage industry in other countries to employ new technologies also, as the technical and economic risks are reduced through R&D.

Strategy and Recommendations

The IOF program provides an excellent foundation of strategic public–private R&D alliances for achieving GHG reduction goals in the energy-intensive industries. These alliances need to be extended to embrace climate change mitigation goals. Different types of public–private R&D partnerships are needed to reduce GHG emissions in the light manufacturing sector. Finally, utility restructuring may challenge industrial self-generation and power sales using advanced industrial turbines integrated with combined-cycle generation or with noncombustion generation techniques such as fuel cells.

2.3.3 Transportation

The Potential for Reduced Emissions

Accounting for 32% of U.S. CO_2 emissions and 26% of energy use, and almost totally dependent on petroleum fuels, the transportation sector presents significant opportunities and challenges for advanced technology. Opportunities lie in the continuous improvement of conventional vehicle technologies; in the promise of new, revolutionary propulsion systems and alternative fuels; and in the application of information technologies to manage and integrate intermodal transport systems in innovative and more efficient ways. Advances in information technology create new opportunities to increase system-wide efficiency and substitute communication for transportation to enhance economic well-being and the overall quality of life.

Improvements and new technologies in transportation can make substantial reductions in GHG emissions, as shown in this table.

Estimated carbon emissions reductions (MtC/year)

	2010	2020	2030
Total transportation	40–70	100–180	200–300

Assumes successful technology development and subsequent marketplace adoption without significant policy changes.

Technology Pathways and Opportunities

Advanced Conventional Vehicles. The modern internal combustion engine vehicle has made significant technological advances during the past three decades, yet the potential for technology to further reduce the environmental impacts of conventional vehicles is far from exhausted. The direct-injection stratified-charge gasoline engine and the turbocharged direct-injection diesel engine offer efficiency improvements of 15% to 30% over conventional gasoline engines; these technologies are already in commercial production outside the United States. Relatively high NO_x and particulate emissions and additional cost hinder their penetration into U.S. markets; improved NO_x catalysts must be developed and particulate emissions reduced. Replacing gasoline engines in light trucks, vans, and sport utility vehicles with more efficient diesel engines represents a significant opportunity to reduce carbon emissions from the transportation sector.

Lightweight materials, from aluminum to carbon fiber composites, have the potential to reduce vehicle weight but pose significant problems with respect to low-cost fabrication and recycling. Improved aerodynamic design, lightweight materials, and improved tires could help to double the efficiency of new passenger cars and light trucks during the next 10 to 15 years, cutting the transport sector's carbon emission by one-fourth. Many of these technologies are currently under development by the Partnership for a New Generation of Vehicles (PNGV) program and by foreign competitors, but considering that the expected life of a passenger car is nearly 14 years, implementing such changes would require more than a decade.

Hybrid, Electric, and Fuel Cell Vehicles. Developing commercially viable, mass-market electric-drive vehicles (EVs) would free the automobile from dependence on carbon-based liquid fuels while simultaneously reducing vehicular emissions. Hybrid vehicles (HEVs), the PNGV design of choice to achieve triple the miles per gallon of the conventional passenger car, combine electric drive with an auxiliary power unit and energy storage device (e.g., battery). A heat engine could be used as the auxiliary power source, but if fuel cell technology could be sufficiently advanced and the infrastructure for supplying hydrogen fuel developed, a potentially pollution-free propulsion system would be available.

HEVs, EVs, and fuel cell vehicles all face formidable technical hurdles, many of which they share. Developing low-cost, rapidly rechargeable batteries is a critical factor in the success of HEVs and EVs. Fuel cells will also require cost reductions (on the order of 95%) as well as improvements in energy density and reliability. Recent, dramatic progress in batteries and fuel cells (much of it attributable to the PNGV effort) suggests that commercially competitive EVs can eventually be developed. A U.S. manufacturer has introduced an improved battery-electric vehicle that has been leased to 215 customers; a Japanese manufacturer has introduced a first-generation HEV. Although still prohibitively expensive at U.S. fuel prices, the Japanese HEV showcases the hybrid's potential for very low emissions and high efficiency. Proton-exchange-membrane fuel cells are currently being demonstrated in buses and have shown dramatic improvements during the past few years.

Carbon savings from battery-electric vehicles depend directly on the primary energy sources used to generate electricity. Potential advances in electricity generation technology could make EVs very-low-carbon vehicles. The power plants for HEVs may be fossil-fuel-burning internal combustion engines that could run on alternative fuels or could someday be replaced by fuel cells. In any case, an HEV that is three times more efficient would cut carbon emissions by at least two-thirds. Fuel cells may initially run on gasoline or alcohol fuels (reformed to produce hydrogen) and ultimately would use hydrogen stored on board the vehicle.

Which fuels are used and how they are produced will determine whether carbon emissions are reduced by 50 or 100% over those of conventional vehicles.

Freight Vehicles. Freight vehicles—heavy trucks, railroad locomotives, and ships—are the second largest energy consumers in the transport sector after light-duty vehicles. Heavy trucks and locomotives are universally powered by highly efficient (40–45%) diesel power plants. The efficiency of diesel engines could be further improved to 55% by use of such technologies as advanced thermal barrier coatings, high-pressure fuel injection, turbocharging, and reduced-friction and lightweight, high-strength materials. Fuel cells are an especially promising technology for locomotives, where problems of size and fuel storage and reforming are greatly reduced. Emissions of NO_x and particulates remain the greatest barriers to ultrahigh-efficiency diesels, while for fuel cells, cost and the state of development of mobile fuel cell systems present the biggest challenges.

Improvements to heavy truck fuel economy could reduce carbon emissions by 20 to 33%, or by up to 100% for hydrogen-powered fuel cells, depending on how the hydrogen is produced. Because freight vehicles and their power plants have useful lives measured in decades, the transition to low-carbon technologies would require decades.

Alternative Fuel Vehicles. Alternative transportation fuels are those that require substantial changes in conventional infrastructure, whether in fuel production, distribution, and retailing or in vehicles. Most alternative fuels currently under consideration are being explored for their ability to reduce pollutant emissions or displace petroleum and would have modest GHG reduction potential. Fuels such as compressed natural gas and propane can reduce carbon emissions by 10 to 20%, on a full fuel-cycle basis, over conventional gasoline or diesel fuel.

Far more promising from a GHG reduction perspective are biofuels, such as biodiesel produced from soy or rapeseed oils or ethanol or methanol produced from cellulosic feedstocks. Ethanol from cellulosic feedstocks using conversion processes under development by DOE has been independently estimated to produce essentially zero carbon emissions over the full fuel cycle. Vehicle technology for using ethanol and biodiesel is at a relatively advanced stage of development. The chief barriers to widespread use of these fuels are cost and limitations on feedstock production. Recent estimates by DOE indicate that by 2010, 5 to 10 billion gal of cellulosic ethanol could be produced in the United States per year at prices that would make it economical for refiners to use it as an octane-enhancing, oxygenating blend stock, although ethanol still would not be competitive with gasoline as a neat fuel. This 5 to 10 billion gal would produce zero net carbon emissions and displace imported petroleum. (Biomass fuels are also discussed in Renewables Sect. 2.4.4.)

Air And High-speed Ground Transport. Commercial air travel is the second largest and fastest growing energy-using mode of transport. It is also the mode that has achieved the greatest improvements in energy efficiency during the past three decades. Yet commercial air transport is also the most petroleum-dependent mode. Opportunities to replace kerosene jet fuel appear to be many decades away. In the meantime, petroleum displacement in high-speed intercity transport may be achievable by integrating high-speed rail systems with the commercial air network. Operating at 180 to 300 mph, magnetically levitated or steel wheel rail cars could substitute electricity for kerosene in short-distance intercity travel, at the same time relieving both air traffic and highway congestion.

Although air transport has already more than doubled its energy efficiency over the past quarter century, opportunities remain for at least another 50% improvement during the next 25 years. Propfan technology, improved thermodynamic efficiency of turbine engines, hybrid laminar flow control and other aerodynamic improvements, and greater use of lightweight materials could accomplish this 50% improvement, and they are currently under development by NASA and aircraft and engine manufacturers. A potentially important issue for civil aviation will be the advent of a new generation of far more energy-intensive supersonic high-speed civil transports. The unique requirements of supersonic and hypersonic aircraft could eventually drive the development of alternative fuels for commercial transport.

Having the best and most efficient commercial aircraft technology not only would reduce carbon emissions and petroleum use, but also will be critical to keeping the U.S. aircraft industry competitive. The principal impediment to continued efficiency improvement and lower carbon emissions is likely to be the relatively low cost of jet fuel, providing an inadequate incentive to adopt new, more complex, and possibly more costly aircraft technology.

Technical Risks and Other Issues

There are technical challenges to be met in certain areas, including reducing pollutants and improving performance, but there are clear ways to address these challenges. Also, while smaller and lighter vehicles may result from advanced vehicle development, R&D program goals generally specify equal or improved performance, comfort, and safety. Therefore, ecological and human health risks are expected to be low for these advanced technologies. Commercial risks are moderate, led by the success of existing transportation systems and determined global competitors that are investing heavily in the race to develop sustainable transportation technology for the expanding global economy. The ability of U.S. industry to develop clean, efficient, environmentally sustainable technologies for global transport markets will be critical to the competitiveness of the U.S. transportation industry, an industry that accounts for more than one-tenth of U.S. GDP and directly or indirectly employs one U.S. worker in ten. Social risks are moderate in some areas—such as high-speed ground transportation, which may require public subsidy to be economical—and demand reduction—which to date has achieved only modest success.

The revolution in information technology is creating expanding opportunities for efficient transportation alternatives to improve the efficiency of transportation systems and reduce the vehicle miles traveled. Already, railroads, trucking firms, and shipping and air freight companies are using advanced information technology to more efficiently plan and manage their operations. Development of more comprehensive frameworks for intermodal integration could produce still greater efficiency benefits, leading to improved service with less energy use. Telecommuting and electronic marketing are well known examples of virtual travel.

Advances in information technology create new opportunities to increase system-wide efficiency and substitute communication for transportation to enhance economic well-being and the overall quality of life. R&D activities in these areas include continued development of the concept of transportation as an integrated network of physical and electronic services that can be coordinated by systems engineering approaches, by development of such analysis tools as the National Transportation System initiative, and by research that encourages the infusion of information and network technology into transportation operations.

Collateral Benefits

In addition to reducing emissions, the development of these transportation options would reduce pollutant emissions, improve human health, and reduce the nation's dependence on imported petroleum.

Strategy and Recommendations

Advanced technologies offer enormous potential to reduce U.S. and world carbon emissions from transport. Efficiency improvements of 50 to 200% across all modes appear to be possible for new equipment over the next two to three decades. Beyond that point, use of electricity and hydrogen that are not derived from fossil fuels could virtually eliminate carbon emissions from the transport system during the next century, if the necessary technological advances could be made in other sectors. Significant cost and technical barriers remain; however, a technological pathway from the present fossil fuel-dependent transport system to a future globally sustainable system is in sight.

The comprehensive R&D programs described in the transportation pathways would produce substantial economic benefits in the form of avoided costs of GHG mitigation. The concept of efficient transportation alternatives may also have the potential to develop as a significant technology pathway. There would also be important benefits in the form of cleaner air and reduced national dependence on petroleum. To achieve these goals, a significantly greater investment in federal transportation energy R&D budgets would be necessary. Because of the importance of the endeavor and the magnitude of its cost, estimates should be made not in haste, but after carefully and thoroughly planning the full range of R&D efforts required.

2.3.4 Agriculture and Forestry

The Potential for Reduced Emissions

Sustained economic growth depends on having a secure supply of raw materials. Agriculture and forestry can supply additional and renewable resources for industrial production and energy needs. Currently, managed forest and agricultural lands in the United States fix 3.6 billion tonnes of carbon annually from the atmosphere. Most of this carbon is rereleased in short-lived products, and little is used to substitute for fossil-based products.

The primary opportunities to reduce GHG emissions in the agriculture and forestry sector lie in technologies that remove GHG from the atmosphere (carbon sequestration in durable biobased products, soils, and standing crops) and substitution of biomass-based products for fossil-based products. The carbon sequestration and renewable energy sections of this report cover carbon sequestration and biomass-based energy. The focus of this section is on development of biomass to bioproducts technologies (other than fuel) that can further reduce GHG emissions through both biomass substitution and reduced energy and fertilizer consumption.

Technology pathways that offer the best opportunities to realize these GHG emission reductions are conversion of biomass to bioproducts, advanced agricultural systems, and plant/crop engineering, as shown below.

Estimated carbon emissions reductions (MtC/year)

	2010	2020	2030
Total agriculture and forestry	3–7	15–25	30–45

Assumes successful technology development and subsequent marketplace adoption without significant policy changes.

Technology Pathways and Opportunities

Conversion of Biomass to Bioproducts. Annual crops, perennials, and short-rotation woody species represent plant/crop-based resources that are renewable source materials in the food, feed, and fiber industries (National Corn Growers Association 1997). The use of such biomass-based processes to produce materials and products provides a modest but significant reduction in GHGs because biomass-based feedstocks are synthesized from the CO_2 in the atmosphere and petroleum-based feedstocks are not.

Historically, plant/crop resources have seen limited use as industrial feedstocks in fossil material processing systems. However, in the future, biomass-based products are likely to become functional replacements for fossil-derived products with the same level of performance. The technology needs involve the following challenges:

- to use plant/crop-based inputs in modified processing systems
- to develop modified plant/crop production systems to provide desirable feedstocks
- to integrate these approaches to create optimized systems that generate a new economic platform based on the use of plant/crop-derived inputs

The use of plant/crop-based resources requires the development of concepts around “alternative processing” rather than just “alternative sources” for existing processes. New advances in biotechnology and plant genetics, new discoveries in organic synthesis using carbohydrates, and novel materials and micromanufacturing technologies should drive development of these new “alternative processing” options.

Substitution of biomass-based products for fossil-based products has significant potential to reduce U.S. GHG emissions. Additional emissions reductions could come from new markets, chemical production, process improvements, and energy savings. The forest products industry is 63% energy self-sufficient, and the cogeneration techniques it uses could be adapted to other bioindustries.

The barriers to use of biomass-based processes arise from the history of our country’s use of its indigenous resources. While biomass-based feedstocks are employed at competitive costs by the paper- and grain-processing industries, chemical manufacturing systems are optimized for petroleum and natural gas and are not designed to process alternative feedstocks. A successful scenario for using biomass-based processes involves the development of viable manufacturing platforms based on renewable forestry/crop feedstocks. These industries would produce materials and chemicals, such as cosmetics, textiles, and pharmaceuticals, that either would fill their own particular niche or would be integrated into the mainstream fossil-based chemical-processing industry.

Conversion of biomass to bioproducts is also discussed under Industry (Resource Recovery and Utilization) and Renewable Energy (Solar Advanced Photoconversion). Carbon reduction estimates are included only in Resource Recovery and Utilization.

Advanced Agricultural Systems. Agriculture and forest management practices have achieved significant increases in productivity and carbon fixation with decreased energy use. However, intensive agriculture and forestry production continue to add to the emissions of GHG and significantly affect nitrogen, soil carbon, and water biogeochemical cycles. Research should focus both on technologies that continue to increase productivity without increasing GHG emissions and on those which offer the possibility of significantly reducing GHG emissions. Advanced agricultural systems involve ways to deliver adequate quantities of nutrients that are efficiently assimilated by plants and water to maintain photosynthesis and support plant growth. Advanced agricultural systems include sensors, controls and monitoring, improved fertilizers and pesticides, improved delivery systems, genetic design of pest-resistant crops, and control of microbial processes. These technologies will result in increased biomass production for a given area of land with reduced nutrient, water, and energy inputs.

Advanced agricultural systems will lead to small but significant reductions in GHG emissions along with reduced energy consumption and fertilizer use. Currently, 3% of U.S. fossil fuel emissions result from agricultural crop production and only 27% of U.S. agriculture uses low- or no-till systems. Advanced agricultural systems technologies have the potential to significantly increase the use of no- or low-till systems. In addition, technologies that lead to improved fertilizer efficiency could result in significant carbon savings.

Some components of advanced agricultural systems, such as the use of global positioning systems to map yields, are in or close to commercial use. Others, such as real-time monitoring of water and nutrient status, are not. Although fertilizer delivery and chemistry have significantly improved during the last 10 years, advancements in biologically released fertilizers and control of microbial processes still require significant efforts. Detailed real-time and small-area geographic matching of fertilizers and other agricultural chemicals to plant requirements are in the early stages of development. Technologies involving biocontrol of pests are evolving; some are to the point of commercial development.

Plant/Crop Engineering. Plant/crop engineering is expected to contribute to reductions in GHG emissions through improvements in biomass production, carbon sequestration, and biomass conversion to bioproducts. Technologies include

- engineering plants with improved carbon-use efficiency, and therefore increased yield and carbon fixation
- control of physiological processes that determine a plant’s ability to grow on low nitrogen and to recycle nitrogen
- manipulation of cell wall structure and assembly to create crops and to produce high-strength structural wood and composites for use in construction
- genetic transformation of desirable genes into target biomass plant species for specific biomass-to-bioproduct conversions

To successfully develop these technologies, basic research is necessary for better understanding of the metabolic pathways that control how plant productivity responds to changes in nutrients, water, and CO_2 concentrations. Research on gene insertion efficiency is also needed across the wide range of species relevant to bioproducts. In addition, gene identification to improve biomass quality is needed and will result from functional genomics research (sequencing and characterization of gene function).

Successful deployment of these technologies will occur only through integration with the development of bioproducts technologies and advanced agricultural technologies. Transgenic varieties and common crops are being introduced that are resistant to specific diseases and pests and that require smaller amounts of nutrients and water. They constitute a significant advancement in this field. Ecosystem assessments are needed as these new varieties are introduced. Because of the strong interdependency among advanced agricultural systems, the production of bioproducts, and plant/crop engineering, the carbon savings that can be realized with plant engineering are incorporated into the carbon savings reported in this section.

Strategy and Recommendations

Integrated research, both basic and applied, needs to be pursued in cooperation with commercial agricultural and forest sectors as well as with manufacturing industries. Key objectives should include integrated systems management and improvement of agriculture and forestry sustainability and cost-competitiveness.

Technical Risks and Other Issues

The rate of fundamental plant engineering research is limiting; it is inherently slow because of the life cycles of plants (especially trees). Ecological, commercial, and economic risks include the availability of and competition for land among agriculture, forestry, cities, and recreational areas. Trade-offs between food-feed-fiber and chemicals production have not been fully evaluated, and the environmental impacts of increased land cultivation will have to be carefully considered.

2.4 CLEAN ENERGY

The development and use of advanced energy production technologies has a large potential for reducing GHG emissions without increasing energy costs. Technological approaches include using fuels with lower or zero carbon content; increasing the useful energy output per unit of carbon emitted; and capturing carbon emissions to prevent their entry into the atmosphere. With successful development, these advanced technologies generally have the potential to reduce carbon emissions by 25 to 50% or more in the time frame beyond 2020. Their potential for carbon emission reductions by 2010 is considerably more limited because of stock turnover rates in energy production.

These advanced energy production technologies are described in four technology areas:

- fossil resource development
- fossil power generation
- nuclear energy
- renewables

2.4.1 Fossil Resource Development

The Potential for Reduced Emissions

Fossil energy dominates the nation's and the world's energy supplies and is likely to do so for the foreseeable future. It provides more than 87% of the nation's energy (40% oil, 25% natural gas, and 22% coal; Fig. 2.6) and about 90% of the world's energy (40% oil, 23% natural gas, and 27% coal). Because the nation's economy is so heavily reliant on each of these three fuels, altering this fuel mix will require at least two decades of dedicated technical and infrastructure development.

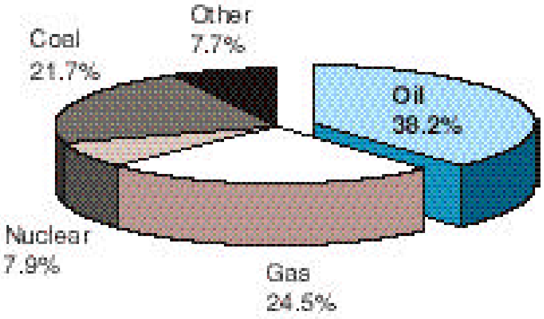

Fig. 2.6. Fossil fuels account for most of the energy used in the United States.

Because of the desire to reduce CO_2 emissions per unit of energy expended, fossil fuels containing a lower carbon:hydrogen ratio need to be developed. Therefore, any major clean fossil-fuel-based alternative energy plan must center on enhanced production of natural gas and the efficient conversion of abundant fossil feedstocks into electricity, clean liquid transportation fuels, and chemical feedstocks whose impact would be to reduce net CO_2 emissions compared with current sources for these commodities. Coal reserves are expected to last for many hundreds of years, and increasing amounts of natural gas are being discovered. Estimates of the impact of new technologies on carbon emissions are shown in this table.

Estimated carbon emissions reductions (MtC/year)

	2010	2020	2030
Total fossil resource development	15–30	80–115	115–225

Assumes successful technology development and subsequent marketplace adoption without significant policy changes.

Technology Pathways and Opportunities

Energy Efficiency for Crude Oil Refining. Developing technology to increase the efficiency of converting crude oil to transportation fuels, and separating and using valuable components of refinery off-gases (light hydrocarbons) would have a significant impact on increasing liquid hydrocarbon utilization efficiency. Because the United States produces significant quantities of heavy oil, an improved refining process could add $1 to $2 per barrel to the value of this oil. Capturing off-gases produced during refining adds value to the process and eliminates GHGs that are more damaging per molecular weight than CO_2.

Natural Gas to Liquids. The cost-effective conversion of natural gas to clean liquid transportation fuels and commodity chemicals offers a significant potential for GHG emissions reduction while allowing greater use of domestic natural gas supplies. Breakthrough technologies under development include deriving diesel fuel from natural gas (far exceeds conventional diesel fuels in emission reductions), converting natural gas or synthesis gas to methanol or gasoline, and converting gas to liquefied natural gas in remote areas at commercial efficiencies using thermoacoustic refrigeration technology.

Increased Natural Gas Production. The nation (and North America) has abundant natural gas resources that help to fuel the industrial and electric power sectors. It needs only the development of new technology to make natural gas available as a substitute for some oil consumption in transportation fuel markets and for coal use in electricity generation. Current U.S. natural gas supplies can be augmented in the near term through secondary gas recovery (230 tcf); in the mid-term through low-permeability formation development (500 tcf), offshore supplies (100 tcf), and coalbed methane (400 tcf); and in the long term by exploiting currently untapped methane hydrates (2700 tcf) and deep-source gas (3000 tcf). Only a moderate success rate would be needed to effectively meet the expected demand of 28 tcf in 2010.

Co-Production with Integrated Gasification Combined Cycle. To make full use of abundant supplies of low-cost solid fuels, the integrated gasification combined cycle (IGCC) process represents a unique combination of technologies that offers industry low-cost, highly efficient options for meeting a variety of market requirements. Compared with today's commercial and advanced technologies, IGCC is one of the most efficient and environmentally friendly technologies for the production of low-cost electricity and is capable of processing a number of feedstocks including coal, petroleum coke, biomass, and municipal wastes. The IGCC system, operated in conjunction with steam reforming, is capable of producing a stream rich in H_2 with only a CO_2 byproduct (which is ready for sequestration). In combination with synthesis gas conversion technologies, it is the only advanced power generation technology that is capable of coproducing a wide variety of commodity and premium products in addition to power to meet future market requirements.

Through coproduction, other products can be obtained either by processing the feedstock before gasification to extract valuable components or by converting the synthesis gas to products. With feedstocks such as coal, valuable precursors can be extracted for the production of high-strength, lightweight carbon fibers and of anode coke for manufacturing industries. Clean synthesis gas can be catalytically converted into environmentally superior transportation fuels, high-value chemicals, or hydrogen.

Numerous IGCC gasification demonstration projects using coal, petroleum coke, or other petroleum refinery wastes are currently in operation or under construction both in the United States and worldwide. Many of these facilities have been designed for operation in the coproduction mode, whereby improved thermal efficiencies can be gained.

The conversion of coal-based synthesis gas to transportation fuels has been the subject of investigation for several decades; however, significant recent advances in catalysis and reactor design are generating considerable interest from industry. The environmental superiority of the resulting transportation fuels—which have substantially reduced emissions of hydrocarbons, carbon monoxide, and particulates—has been demonstrated; and they are recognized as a key ingredient for meeting future environmental regulations in the transportation sector.

CO_2 for Improved Oil and Gas Recovery. From a carbon management perspective, improvements in reducing GHG emissions could be attributed to flooding petroleum reservoirs with recycled CO_2 and minimizing fugitive gas emissions from pipelines and other remote sites. CO_2 is pumped into oil reservoirs to enhance the recovery of petroleum. Instead of present practice, CO_2 that would otherwise be emitted to the atmosphere (from fossil fuel combustors) could be captured and used to enhance energy recovery. In the future, CO_2 contained within power plant stack gases could also be pumped into coal seams to recover methane economically or to replace base gas in storage wells. Estimates have placed the sequestration potential of this approach at 50 MtC/year.

Tracers can be developed to identify fugitive emissions of methane from refineries and pipelines. Backscatter absorption gas imaging and light detection and ranging (LIDAR) technologies have recently proved effective in imaging methane plumes at remote distances and concentrations in the part-per-million range. Recent improvements in LIDAR systems for national security missions should be applicable to fugitive gases as well. The GHG reduction potential of eliminating leaks has been estimated at 12 MtC/year in the United States.

Crosscutting Technologies. Technologies that affect the conversion of abundant fossil fuels to liquids are very important for reducing GHG emissions. Some of the most significant challenges are the identification of new catalyst compositions to promote the efficient synthesis of diesel fuel and the production of chemical feedstocks from natural gas or coal. Additionally, the use of predictive simulation and concurrent process development of various schemes to determine the most economical configuration merit further attention.

The following areas should also be investigated:

- optimizing an integrated process using ion-transport membranes for conversion of natural gas to synthesis gas, followed by the conversion of synthesis gas to transportation fuels
- addressing the broad range of technical issues related to commercial scale-up in remote locations
- demonstrating high daily production of liquefied natural gas from sources previously vented to the atmosphere, using improved thermoacoustic refrigeration

Increased natural gas production in the short term will result from incremental improvements in drilling, completion, and stimulation technology; improved seismic imaging of natural fracture systems; fracture access to low-permeability formations; and enhanced methane drainage from coalbeds (perhaps stimulated by CO_2 or flue gas injection). In the intermediate time frame, conversion of natural gas from the North Slope of Alaska or other remote sites into a high-quality liquid fuel that is moved by pipeline to a distribution infrastructure would have the greatest impact on increasing natural gas production. (This technique will be keyed to the success of the gas-to-liquids effort.)

In the long term, entirely new technology will be required to map and produce undersea methane hydrates and perhaps even deep-source gas. Gas hydrates are physical combinations of hydrocarbon gas (predominantly methane) and water that are classified as clathrates. They represent a potential energy source greater in volume than all known oil, gas, and coal deposits combined. No technology exists to extract methane from these undersea deposits, but there recently has been some resurgence of interest in this resource in the United States and internationally.

Efficiency improvements in crude oil refining and processing will be keyed to new catalysts with improved efficiencies and selectivities, advanced membrane separation methods with high throughputs and high separation factors, and the development of pretreatment conversion technologies that would allow more heavy oil to be converted to higher-value, efficient transportation fuels. Advanced inorganic membranes that could be used to separate and utilize refinery off-gases would be particularly valuable.

An extension of this work would be improved gas-gas separations, particularly the separation of air into oxygen and nitrogen and the separation of CO_2 from nitrogen in very large-scale flows. Development of these high-throughput gas separation technologies would allow recycled CO_2 from fossil fuel combustors to replace CO_2 that is produced from dedicated production wells.

Collateral Benefits

Improved crude oil refining processes would eliminate GHGs that are considerably more damaging than CO_2. Converting coal-based synthesis gas to transportation fuels would reduce several pollutants compared with conventional fuels, as would using CO_2 for improved oil and gas recovery. Increased natural gas production would enhance energy security, as would IGCC systems. IGCC would also coproduce a variety of products in addition to power, creating new jobs.

Technical Risks and Other Issues

Technical and commercial risk ranges from low to challenging, depending on the pathway. For example, natural gas-to-liquids conversion and crude oil efficiency improvements face scale-up problems; increased natural gas production may require demonstrations; and IGCC requires advanced materials and technologies for membranes and filters. Ecological risk is generally low to moderate, and human health risks would be lower than for current technology.

Strategy and Recommendations

While natural gas is expected to capture an increasing share of the new market for fossil fuels during the next decade, the 2010–2020 time frame should usher in a significantly larger potential for natural gas and for more highly efficient coal-based IGCC technologies. If research efforts were well funded and successful, breakthrough developments in catalysts, simulations, membrane separations, and overall gas-to-liquids conversion (including IGCC-based) technology would be pilot-scale tested by 2010. Allowing for further improvements and scale-up to commercial size plants, a major impact could be expected by 2020.

Increased natural gas production to satisfy these needs can be seen as taking place over three time periods. Near term improvements would be seen through incremental improvement of extractive technologies, such as drilling, completion, and reservoir stimulation technology; seismic imaging of fracture systems; access to low-permeability formations; and enhanced methane drainage from coalbeds (via CO_2 injection).

Intermediate term improvements in production would occur through increased use of Alaskan natural gas, or natural gas from other remote resources, via the transport of a liquefied product. Finally, long-term contributions can be expected from the use of vast undersea methane hydrates. Currently, no known technology exists to extract methane from these undersea deposits.

Liquid fuels from Alaskan natural gas may even be ahead of this schedule. The commercial success of the gas-to-liquids industry would spur even greater increases in natural gas production beyond 2020, including the first contributions from undersea methane hydrates.

Development of a large-scale, oil-competitive, commercial gas-to-liquids industry (natural gas and coal-based) offers the highest technical risk. Research on this topic has been ongoing for decades, and although some commercial plants are in operation, much remains to be accomplished. In addition, long-term R&D in major oil companies continues to decrease (Fig. 2.7), which does not bode well for the implementation of new high-technology programs.

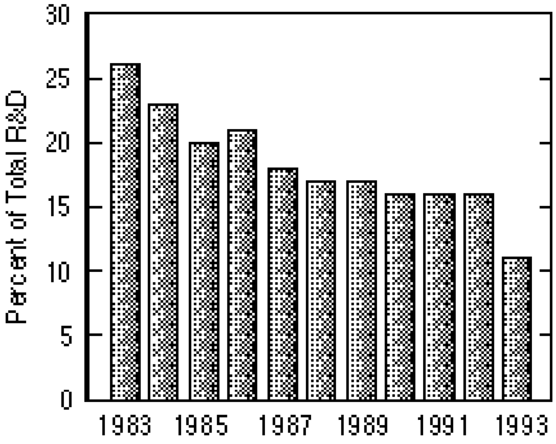

Fig. 2.7. Long-term R&D in major oil companies continues to decline.

Efficiency improvements in crude oil refining and processing pose a high level of commercial risk. As shown in Fig. 2.8, 46% of domestic refineries have closed since 1981, many because of perceived environmental problems. Reconfiguring a new domestic refinery industry will entail very significant commercial risks.

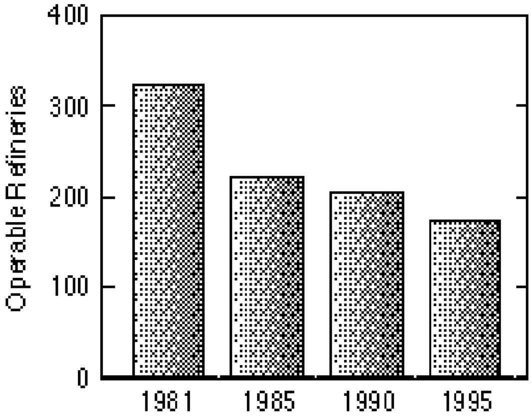

Fig. 2.8. Operable refineries in the United States.

2.4.2 Fossil Power Generation

Today, coal supplies 55% of electricity, while natural gas makes a small contribution to U.S. electricity needs. By 2015, EIA predicts that coal will still account for 50% of electricity, but that the contribution of natural gas will rise to 20%. EIA also predicts that, barring significant technology developments or policy changes, carbon emissions from coal will rise from 460 to 550 MtC between 1995 and 2015, while carbon emissions from natural gas for power generation will rise from 50 to 125 MtC during that period.

The Potential for Reduced Emissions

To reduce this projected increase in carbon emissions, several approaches are being studied. Low-cost approaches to reduce emissions from existing plants include cofiring with natural gas or biomass; reburning to reduce NO_x; and land-based capture of CO_2 to be used in aquaculture, pharmaceuticals, or waste encapsulation. However, for a major impact on emissions, more advanced technologies are being developed that have excellent potential to reduce carbon via more efficient power generation in the near, mid, and long terms, based on the success of on-going research and development efforts. Estimates are shown in the table below.

Estimated carbon emissions reductions (MtC/year)

	2010	2020	2030
Total fossil power	0–20	40–90	110–185

Assumes successful technology development and subsequent marketplace adoption without significant policy changes.

Technology Pathways and Opportunities

The three fossil power generation pathways that are outlined in Appendix B represent a broad technology portfolio that could reduce GHG emissions in the near term and accelerate these reductions as new technologies are phased in at normal or near-normal replacement rates in the mid and long terms. All technologies within this portfolio are targeted for availability within the first third of the next century, but the success of these pathways depends on the success of ongoing R&D efforts.

High-Efficiency Coal-Based Technologies. It is unlikely that high-efficiency coal-based technologies would achieve significant market penetration before 2010. But by 2020, introduction of high-efficiency coal-based technologies could significantly reduce carbon emissions. By 2050, total carbon emissions could be below those produced from the electricity sector in 1990 (a reduction of about 210 MtC/year).

The high-efficiency coal-based pathway increases power generation cycle efficiency by combining two or more advanced energy conversion cycles. Ideas being developed include low-emission boiler systems, pressurized fluidized bed combustion, IGCC, and high-efficiency power systems. Goals are to increase conversion efficiencies from around 33% to 42% in 2000 to more than 55% in 2010, at a cost considerably lower ($0.03/kWh) than today's pulverized coal costs and with pollutant emissions at one-third to one-tenth of current new-source performance standards. These technologies may have additional potential for performance improvement of up to 60%, depending on the success of ongoing basic research. An area where primary technology development is needed is high-temperature materials that are stable and that resist corrosion, erosion, and decrepitation so that they can be used for heat exchangers, turbine components, particulate filters, and SO_x removal. Other challenges include the use of alternate working fluids for turbine and heat-exchange cycles, cycle optimization environmental control technologies with low energy penalties, and solids handling.

Low-Carbon Fuels. Low- or no-carbon fuels—such as natural gas, synthesis gas, or hydrogen—used in the technologies being proposed for accelerated development in this initiative could lead to a significant reduction of carbon emissions after 2020.

Fuel cells and gas turbines are currently in use, taking advantage of plentiful supplies of natural gas.

However, neither technology has reached its potential. For gas turbines, the R&D goals are to lower bus-bar energy costs to 10% less than costs for current state-of-the-art technology and to develop ATSs and gasification adaptation technology by 2010. Improvements in blade cooling and materials will be required to move these technologies beyond the current practice, and considerable development is required before they will be capable of high performance when firing hydrogen. Also, further improvements are needed to avoid increasing NO_x emissions as operating temperatures rise. For industrial applications, small and medium-sized turbines are being developed to achieve a 15% improvement in efficiency over vintage equipment. These may supply distributed generation of power to serve customers unable to obtain needed power from the transmission grid, or they may be employed in industry to contribute both power and heat. Advanced turbines and industrial cogeneration are important technologies for both industrial efficiency and fossil power and are counted for the purpose of emissions projections in industrial efficiency.

Fuel cells represent another gas-fueled technology. Recent successes have shown the potential to build larger stacks of fuel cells, leading to larger generating capacity, but costs need to be reduced to make them competitive. Performance targets include developing market-ready fuel cell systems with efficiencies higher than 50%; adapting them to operate on synthesis gases from coal and other solids; and validating the hybrid fuel cell/advanced gas turbine system that could have efficiencies approaching 70% by 2010. Demonstration of advanced turbines on hydrogen alone or in some hybrid cycle is expected to occur between 2020 and 2030. Additional effort would be required to address all the system integration issues identified in these two validation steps.

Energyplexes. These two pathways, high-efficiency coal and low-carbon fuels, converge in a third group of technologies that integrates production of power, fuels, and /or chemicals, maximizing use of available energy. It would create “energyplexes,” a type of industrial ecosystem. An energyplex is a series of modular plants capable of coproducing power and chemicals or fuels that can be integrated to use local sources of carbon (coal, biomass, municipal solid waste) as fuel and feedstocks. Eventually, modules would be included for capture and sequestration of CO_2.

These energyplexes would feature high efficiencies of carbon use, essentially zero carbon emissions, and cost-competitive power. Unlike the first two pathways, which focus on electricity generation, this pathway strives to optimize the entire cycle of carbon utilization by incorporating coprocessing concepts and the tenets of industrial ecology. Energyplexes would have essentially zero carbon emissions and could result in 100% reduction of carbon after 2030.

Substantial benefits are possible when carbon sequestration strategies are coupled with advanced energy production systems. Fossil fuel production and conversion facilities that either integrate cost-effective sequestration into the facility design or incorporate an equivalent offset can achieve zero net CO_2 emissions. If this zero emission strategy were applied to all new fossil fuel energy production facilities after 2010, the cumulative reductions (carbon emissions avoided), in addition to those realized from advanced efficiency systems, would be about 4 GtC by 2030 in the United States alone. This estimate was derived by extrapolating the EIA *Annual Energy Outlook 1997* projection to 2050 as the baseline, or business-as-usual, scenario (EIA 1996a). Commensurate benefits could be realized if sequestration were implemented worldwide for fuels production as well.

This pathway challenges the R&D community to make significant technology breakthroughs—or "grand challenges"—such as novel industrial process configurations, novel power cycles, and coproduction of heat and power, with suitable energy-efficient reuse or disposal options for carbon and CO_2. A series of activities are envisioned that would develop a portfolio of breakthrough technologies by 2015, including coal liquefaction, development and validation of combinations of fuel cells and advanced gas turbines, and validation of fuel cell systems incorporating carbon capturing and/or reuse methods. Between 2015 and 2030, system integration issues and larger-scale testing would be needed to bring this approach to the point of commercialization.

Along with developing cost-effective CO_2 capture methods for this pathway, including similar methods in the technologies from the first two pathways could lead to additional reductions. Typically, CO_2 may be captured by chemical, biological, or physical means. CO_2 capture is a common practice in some process industries, where the process usually occurs in some type of chemical absorber. In addition, biological systems capture CO_2 by conventional means and use it as a nutrient for growth of algae or other simple organisms. Finally, cryogenic processes, membrane processes, and adsorption using molecular sieves are physical means to capture CO_2, but these are only cost effective if the CO_2 exists at a high concentration in the effluent stream.

Research needs that have been identified in CO_2 capture include (1) means to concentrate the CO_2 which will facilitate existing capture processes and (2) improvements in chemical absorption, including identification of improved solvents and advances in contacting methods to reduce the size and cost of process vessels. Means to concentrate CO_2 could include use of a blend of pure oxygen and recycled CO_2 as a replacement for air in the combustion processes under development. Furthermore, IGCC system concepts could be carried to the point where they produce a product stream of only CO_2 and hydrogen. Improved separation techniques for the hydrogen would then leave a concentrated CO_2 stream, which would be available for further processing.

Currently, CO_2 capture technologies would impose an energy penalty of approximately 30% on a coal-fired plant if one sought 90% capture. Improvements in existing approaches could reduce this penalty to 9%. This pathway would encompass research to blend high-efficiency power production with fuel and chemical production. This synergistic approach is based on analyses that indicate that a closed carbon system could be developed having a competitive levelized cost of electricity for the period after 2025.

Technical Risks and Other Issues

The highest risks associated with the high-efficiency coal-based pathway are commercial and economic because of formidable competition with domestic natural gas and international coal technologies. There is a near-term critical window of time to achieve long-term carbon reduction and capture international market share arising from the 50-year service life of power plants. The low-carbon fuels pathway faces moderate risks both technologically and commercially, although ATSs for stand-alone systems are probably low risk. The energyplex pathway faces low to moderate technical risk related to the challenges for system integration, and moderate to high risk related to the breakthroughs in capture, including those related to novel combustion configurations. The health and ecological risks are considered low to moderate.

Supporting science and crosscutting technologies needed to achieve these pathways include combustion; materials for high-temperature and corrosion-resistant performance; industrial ecology; hydrogen separation or production, transportation, and storage; improved processes for low-cost separation of oxygen; advances in fuel cells; and identification of alternative working fluids and determination of their thermodynamic properties.

Collateral Benefits

These pathways not only will reduce GHG emissions but also will provide a clean, secure energy future and help the nation respond to its international commitments. An accelerated RD&D program will enable the United States to capture a larger share of the $1.4 trillion export market for coal technologies between now and 2010 and help the U.S. economy grow by creating an energy technology export business. An accelerated R&D program would also allow U.S. industry to take advantage of the domestic markets for ATSs and fuel cells, which are estimated to be worth tens of billions of dollars between now and 2010.

Strategy and Recommendations

For the high-efficiency coal-based pathway, about $70 million per year is currently being spent on DOE programs. For the low-carbon fuel pathway (fuel cells and advanced turbines), about $90 million per year is currently being spent on DOE programs. As part of this initiative, accelerating and completing the development of these technologies is recommended. For the energyplexes pathway, relevant technical ideas (such as fuel cells and coal liquefaction) are currently being funded at various levels. Pursuing the grand challenges envisioned both for this pathway and for additional options is recommended for the next two decades.

In summary, the technology pathways described provide a range of options for using coal, natural gas, and other solid fuels—such as biomass, synthesis gas, and hydrogen—to generate power at competitive power costs, to reduce emissions of criteria pollutants and CO_2 to the atmosphere, and to develop strong positions in crucial technologies important to economic growth in the next century. Not all of these will necessarily enjoy widespread commercialization; however, they represent a family of options that spread technology risks, address fuel flexibility, and hedge against upsets in fuel prices. They include both improvements on familiar technologies, which should pose reduced commercialization risks, and bold new concepts that may pose as yet unrecognized commercialization risks.

2.4.3 Nuclear Energy

Nuclear power is deployed worldwide to produce 20% of world electrical generating capacity (in some countries, as much as 80%). Electricity generation using nuclear power results in very small emissions of GHGs, so nuclear power is an important tool in reducing global CO_2. In the period when France converted 70% of its electricity generation to nuclear, all related emissions were reduced dramatically. CO_2 was reduced by 80%, SO_2 by 90%, NO_x by 60%, and particulates by 97% (Fig. 2.9). Today, in the United States, 109 nuclear power plants generate nearly 22% of U.S. electrical capacity (100 GWe). This nuclear generating capacity avoids the emission of about 140 MtC/year compared with generating this electrical capacity by burning fossil fuels.

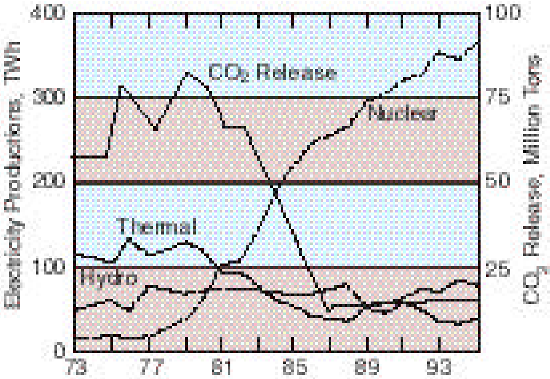

Fig. 2.9. Relationship between CO_2 release and electricity production in France, 1973–1996.

The Potential for Reduced Emissions

In the near term, the development and use of technologies for lifetime extension and for generation optimization (LEGO) of existing nuclear power plants could reduce carbon emissions by increasing nuclear electricity contributions from existing plants over the next several decades. A modest carbon reduction is also assumed for new nuclear plants in 2020 and 2030. Total potential reductions are shown in the following table.

Estimated carbon emissions reductions (MtC/year)

	2010	2020	2030
Total nuclear	0–15	30–70	70–150

Assumes successful technology development and subsequent marketplace adoption without significant policy changes.

If the current 100 GWe of nuclear electrical generating capacity were eventually replaced by next-generation nuclear plants, the United States would continue to avoid emissions of more than 100 MtC/year. If, in addition, electrical demand in the United States continued to grow at 1.5% per year and the installed nuclear generating capacity grew along with it to maintain its current share of the U.S. market (22%), then this new nuclear capacity could result in the avoidance of about 160 MtC/year by 2030. If the market for nuclear generated electricity expanded to 30%, then the result would be an avoidance of about 250 MtC/year by 2030 (see Fig. 2.10).

In the long term, by 2030, the development and use of evolutionary and advanced fission reactors are projected to reduce carbon emissions by about an additional 100 MtC/year. In the longer term, the second half of

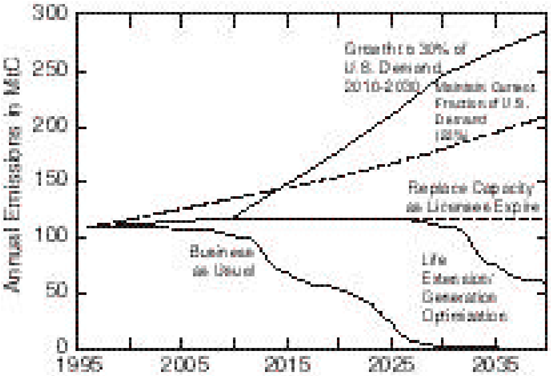

Fig. 2.10. Carbon emissions avoided under various scenarios of nuclear electricity generation.

the twenty-first century, fusion energy systems may become a significant economic power generation source, free of GHG emissions. The actual amount of nuclear-generated electricity will depend on the future financial viability of the nuclear option.

Technology Pathways and Opportunities

Lifetime Extension and Generation Optimization. The near-term approach to the use of nuclear energy should be to provide technologies to increase electricity generation and extend lifetimes of the existing set of 108 nuclear power plants. The initial 40-year license period for these reactors will expire roughly from 2005 to 2030. If the United States is faced with replacing this capacity with fossil-fueled generating plants, CO_2 emissions will ***increase*** more than 100 MtC/year. Both the renewal of plant licenses and increases in plant capacity factors can be enabled by new nuclear and nonnuclear technologies. With targeted R&D investments in monitoring, diagnostic, and materials technologies, these nuclear plant lifetimes could be extended for an additional 20 years, and the efficiency and output of the plants could be incrementally increased, thus avoiding the GHG emissions that would result from replacing this nuclear capacity with other power generation systems.

Examples of generation optimization technologies include advanced technologies for on-line monitoring of cables and conventional equipment (pumps, valves, etc.) to minimize losses of production because of unplanned outages. In addition, improved materials measurement and diagnostic technologies could reduce scheduled downtime for diagnostics and repairs. Plants could be operated at higher net power output to the grid by using sensors and controls that more accurately measure operational parameters, thereby reducing in-plant power demands, improving the thermal-to-electric conversion efficiency, and increasing the core power.

Nuclear power plant life extension hinges on the resolution of issues related to the aging of key components, including reactor pressure vessel embrittlement, stress corrosion cracking of reactor internals, degradation of instrumentation and power cables, and steam generator tube cracking. The effort to resolve these issues could also benefit from improved instrumentation and materials characterization technologies. In addition, R&D on in situ component annealing and on materials cladding processes could provide effective and economical repair technologies. Specific examples of approaches that offer the promise of resolving these issues include gas-fired thermal annealing, water chemistry control to avoid stress corrosion cracking, and various approaches to the deposition of lining materials.

Next-Generation Fission Reactors. The mid-term approach to the use of nuclear energy is to develop and install next-generation fission reactors. Even if LEGO technologies were fully utilized, a major increase in carbon emissions could only be avoided through new nuclear capacity after 2015, which would replace existing reactors that reach the end of their lives.

Evolutionary designs for next-generation fission reactors have received Nuclear Regulatory Commission licensing certification and are available for construction today without significant research;

several have been built in Japan. These designs are simple and rugged, and they incorporate passive safety features intended to provide safer, more trouble-free operation over 60-year design lifetimes. Advanced fission reactors, which use fuel cycles that are proliferation resistant, are also designed for higher efficiencies coupled with improved safety compared with currently operating plants.

The long-term (beyond 2030) approach to the use of nuclear energy would likely use nuclear reactor concepts, such as the liquid-metal cooled fast-spectrum reactor, that extract far more of the energy available in the uranium fuel than the 1% currently used and that produce less waste per GWe, thus extending the resource. In addition, efforts are under way to develop accelerator-driven systems using high-energy protons to produce nuclear energy from subcritical targets.

Finally, one can conceive of a new set of technologies that could be implemented in the next century. The concept of a hybrid nuclear-hydrogen cycle in which nuclear heat is used for production of hydrogen, with subsequent use of hydrogen as an energy source, has considerable potential. R&D on fission heat-to-hydrogen conversion technologies and on hydrogen distribution technologies has the longer-term potential to produce fundamental changes in the world’s energy supply approach and make it consistent with our ecological goals.

Fusion Power. Fusion power, when developed and deployed, would be a carbon-free energy source. The U.S. domestic fusion energy sciences program is concentrating on science and innovation supporting the development of attractive fusion systems based on toroidal magnetic configurations. It also supports a small R&D effort on driver systems for inertial fusion energy. Most of the research effort for the inertial approach to fusion energy is supported for its defense applications. The development of technologies required for fusion, and the pursuit of ignited or burning plasmas, are being pursued through international collaboration.

Collateral Benefits

One collateral benefit of the continued pursuit of nuclear power would be the economic benefit of serving as a domestic and international supplier for this major electric power technology. The increased use of nuclear energy is foreseen around the developing world, especially in the Pacific Rim countries. As of today, the United States has invested $200 billion in nuclear power plants and has 400,000 nuclear-related jobs. In addition, a benefit of pursuing LEGO technologies would be enhanced safety and reduced worker radiation dose at existing plants.

Furthermore, if the United States did not pursue research into next-generation reactors, there would be several negative impacts. The first would be the loss of the technical infrastructure to support the nuclear enterprise, which also supports nuclear medicine, isotope production, and neutron science. This loss could also lead to increasing safety concerns for existing reactors. The second would be the decreased ability to design and construct fission, and eventually fusion, plants to export or to replace the existing ones in the United States at the end of their lives. Finally, with the loss of U.S. infrastructure, the ability to influence the nuclear policy of other countries would disappear.

Technical Risks and Other Issues

Nuclear power faces environmental risks and issues, including the disposal of nuclear wastes. But most of all, the risk is economic. Nuclear power shares the same economic attributes of many renewable technologies—a high fixed cost and a low variable cost—that make market penetration difficult today in the United States. Technology R&D along the technology pathways outlined here could have a major impact on alleviating all of these risks.

Strategy and Recommendations

Nuclear technology is currently offsetting approximately 140 MtC emissions per year. Pursuit of technologies for both LEGO and next-generation nuclear power would allow this offset to continue, as well as provide additional GHG emission reductions in the future. Successful development and use of improved nuclear power technologies could also have a major impact on global GHG emissions.

This study recommends pursuit of nuclear energy R&D to provide the United States and the world with an improved nuclear technology option to help address the very challenging climate change issue. Continued support of a broad base of concepts in fusion R&D is required, and, as these concepts mature, investment will be necessary and appropriate.

2.4.4 Renewable Energy

The Potential for Reduced Emissions

Renewable energy pathways—using energy from sunlight, wind, rivers and oceans, the hot interior of the earth (geothermal energy), and biomass (agricultural and industrial wastes, municipal solid waste, energy crops) to produce electricity, fuels, and heat—hold significant potential for reducing GHG emissions in the next century by displacing fossil-fuel-generated electricity or petroleum transportation fuels. This potential is shown in the table below and is compared with the business-as-usual carbon projections in Fig. 2.11.

Estimated carbon emissions reductions (MtC/year)

	2010	2020	2030
Total renewable energy	30–60	75–130	135–260

Assumes successful technology development and subsequent marketplace adoption without significant policy changes.

All regions of the United States have renewable resources of one type or another. Renewable resources currently account for about 8 to 10% of the energy consumed in the United States; most of this is from hydropower and traditional biomass sources. Solar, wind, and geothermal technologies are cost-effective today in small and niche markets, which are important steps to full commercialization.

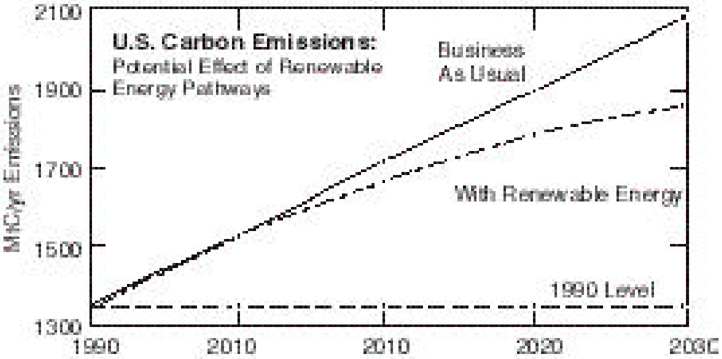

Fig. 2.11. Renewables have the potential for significant reductions of U.S. carbon emissions.

- In the electricity sector, renewable power avoids emission of about

70 MtC per year at the present emissions rate of 0.17 MtC/TWh for electricity.

- Renewable energy technologies are well along a path of decreasing cost (Fig. 2.12), making their expanded commercialization prospects very realistic for early in the next century.
- A level of 20% use in 2025 and 50% use in 2050 is foreseen for the world in a number of projected energy scenarios from, for example, Shell Petroleum Limited (1996), the World Energy Council, and the International Panel on Climate Change (1995). A group of U.S. environmental organizations has also projected the future uses of renewables in the United States in a just-released report, *Energy Innovations* (1997).

Each of the renewable energy technologies is in a different stage of research, development, and commercialization; and all have differences in current and future expected costs, current industrial base, resource availability, and potential impact on GHG emissions. Appendix B describes each of these aspects of the various technologies.

While today's renewables are usually more expensive than the conventional competition on a first-cost basis, they are cost-effective in certain niche markets, especially on a life-cycle-cost basis. Several technologies produce electricity from renewable sources; those nearing commercialization face common problems such as difficulty in obtaining capital, uncertainties related to future electric utility restructuring, and current competition from natural gas. Those technologies further from commercialization need more emphasis on R&D, from fundamental research to resolution of process scale-up issues.

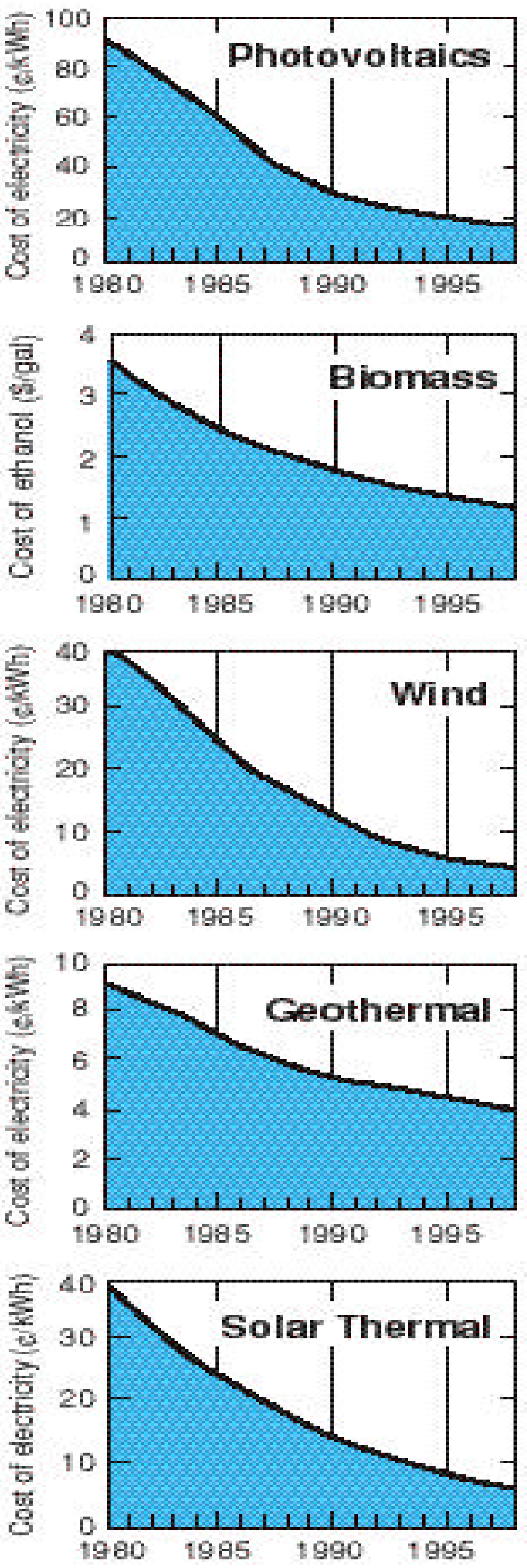

Fig. 2.12. Renewable energy technologies are well along a path of decreasing costs.

Technology Pathways and Opportunities

Biomass Electric refers to technologies that generate electric power from such biomass resources as cofiring biomass with coal, using biomass as the sole fuel in new power plants, or gasifying biomass to replace natural gas. From now through 2010, new biomass electric technologies (including landfill gas) are likely to be commercialized and should have a strong impact on CO_2 emissions. Biomass cofired with coal could also replace a significant portion of coal in electricity production in the near term. Biomass gasification could have a major impact in the forest products industry during the next 10 to 15 years, when many existing boilers will be replaced. RD&D challenges include resolving issues around ash chemistry and NO_x reduction, demonstrating long-term operation of gas turbines on synthesis gas, improving materials, developing sufficient energy crops for feedstocks, and demonstrating advanced technologies.

Wind Energy systems today are very close to being cost-competitive, on a levelized cost basis, with projects at $0.04 to $0.07 per kWh; nearly 1800 MW are installed in the United States, and another 6000 MW in other nations. High-quality wind resources are available in 34 of the 50 states and could provide major carbon offsets before 2010. Technology challenges to achieve lower cost and increased reliability include further advances in the understanding of wind flow, aerodynamics, structural dynamics, advanced power conversion devices, and development of durable and lightweight structural components. In the near term, up to 10 to 20% of a region's electrical capacity could be from wind power without any adverse operating or economic effects. Larger market penetrations in the mid to long term would require addressing the impact of the variation of wind through modification of systems operation, hybrids with other technologies, energy storage, transmission and infrastructure, and improved wind forecasting.

Studies on the effects of avian–wind turbine interactions have shown that when wind turbines are properly sited in areas of low avian usage (away from high resident local populations and migratory flyways), then bird fatalities are negligible.

Hydropower currently generates 10% of the nation's electricity, but generation is declining. Current technology often has adverse effects on fish and downstream water quality and quantity; the goal is to generate electricity without these adverse effects. R&D challenges include quantifying the biological response of fish affected by hydropower projects, modeling the forces inside turbines to predict stress levels on fish, and demonstrating the cost-effectiveness of retrofits.

Solar Photovoltaic (PV) technology uses semiconductor-based cells and modules to directly convert the energy of sunlight to electricity. PV can be used to produce electricity on almost any scale, depending only on how many PV modules are connected together. About 100 MW of PV modules were sold in 1997; annual growth has been 15 to 20%. Hundreds of U.S. applications are currently cost-effective for off-grid electric power needs, such as powering remote telecommunications installations and utility sectionalizing switches. International interest is also very high. PV costs are currently too high for bulk power generation, but costs are decreasing rapidly. Goals are to compete for peak power shaving by 2010, then daytime utility electricity by 2020. RD&D challenges including improving the fundamental understanding of materials and processes to provide a technology base for advanced PV options, optimizing cell and module materials and design, scaling up cells to product size, validating performance in outdoor and accelerated conditions, and improving manufacturing processes.

Geothermal Energy technologies use energy from within the earth to produce electricity or provide heat for industrial processes. Geothermal heat pumps use the thermal mass of the earth as a heat sink for air-conditioning and heating. Hydrothermal reservoirs produce about 2100 MWe in the United States and about 6000 MWe worldwide. In the United States, direct-use applications produce about 400 MWt; heat pumps produce 4000 MWt and are increasing by 25% per year. Only a small fraction of the huge geothermal resource can be used economically today. With research and policy support, electricity production could be doubled, and thermal production (including heat pumps) could be tripled or more. Geothermal RD&D challenges include improved methods for predicting reservoir performance and lifetime, innovative low-cost drilling technologies, new concepts to expand the use of the resource, improved energy conversion through thermal and fluids science and modeling, and lowering costs through thermal science and process chemistry.

Solar Thermal Electric and Buildings includes technologies that concentrate the heat of the sun to generate electricity or use the heat directly. Solar thermal electric technologies have been successfully demonstrated in nine commercial plants (354 MW) operating in California. Using existing, relatively conventional technology, including unique cost-effective storage, hundreds of additional megawatts of peaking power could be on-line by 2005; and evolutionary R&D improvements will allow bulk power market penetration by 2020. Solar hot water systems are commercially available, and ventilation preheat systems using unglazed transpired collectors have made significant progress in commercial/industrial markets. RD&D challenges include improving performance and lifetime and reducing manufacturing costs with improved designs and manufacturing technologies, and addressing commercialization challenges similar to those facing wind energy.

Biomass Transportation Fuels include methanol, ethanol, and hydrogen, which can displace petroleum in internal combustion engines. Biomass sources, including agricultural and other wastes, energy crops, and microalgae, are converted to fuels through biotechnology methods (using microbes) or through thermochemical processes. R&D goals are to demonstrate a biomass waste-to-fuels process with an industrial partner by 2000 and larger-scale production and conversion technologies by 2005. By 2010, energy crops should begin to be available, allowing biofuels to compete with petroleum for direct fuel replacement. R&D challenges include low-cost production of enzymes, development of microorganisms for consolidated processes, improved performance of thermochemical processing, and advances in energy crop productivity, cultivation, and harvesting. Biomass transportation fuels are also discussed in Transportation Sect. 2.3.3.

Solar Advanced Photoconversion technologies use the energy of sunlight to directly produce fuels, materials, chemicals, and electricity from renewable sources such as water, CO_2, and nitrogen. Most of these technologies—involving photobiological, photochemical, and photoelectrochemical approaches—are in the fundamental research stage where technical feasibility must be demonstrated. Examples of these natural and artificial photosynthesis processes include producing hydrogen from water or biomass and producing biodiesel, methane, and methanol from water, waste, and CO_2.

Collateral Benefits

A significant increase in the use of renewable energy pathways would provide benefits beyond reducing GHGs, such as lessening the reliance on foreign oil (especially biomass for transportation fuels), contributing little to waste storage or safety problems, and reducing pollutants. Renewable resources are widespread around the world, are highly attractive to developing countries, and represent a huge potential market for U.S. companies.

Technical Risks and Other Issues

The technical risks vary among the pathways, but there are clear R&D paths to address these risks. Overall, ecological and human health risks are low. Commercial, regulatory, and economic risks are generally moderate to high. In many cases, first costs are higher than for conventional energy choices, while the benefits of renewables do not currently motivate and reward private investment. Mechanisms are required that acknowledge the public value of renewables and help to attract private capital to develop these technologies. Small renewable energy companies in the United States face very strong international competition. Finally, decisions made under utility restructuring will have a major impact on market penetration for renewable electricity technologies.

Supporting R&D is needing in a variety of basic science and crosscutting areas, such as photosensitive materials, innovative semiconductors, corrosion-resistant and higher-temperature materials, biotechnology, catalysts and separations systems, sustainable agriculture, sensors and controls, electrical components, and computational modeling. A wide range of energy storage and transmission systems—along with the production of hydrogen as transportation fuel—would broaden the opportunities for the deployment of intermittent renewable energies, such as wind, solar photovoltaic, and solar thermal electric.

Strategy and Recommendations

Eventually, the private sector is likely to complete the development and commercialization of renewable energy technologies. But well-considered and sustained government investments, both in the underlying R&D and in actions that will remove deployment barriers, are critical. This is the most important step in realizing the full potential that renewable energy pathways can contribute to reducing carbon emissions early in the next century.

Significant investment would be required from both the private and the public sectors. Currently, the annual federal investment is about $250 million for these pathways. Increased federal investments to reduce carbon emissions would also return additional environmental benefits and the opportunity for U.S. companies involved in the area to be key players in the $1 trillion global energy market and the $400 billion market for environmental technologies.

2.5 CARBON SEQUESTRATION AND MANAGEMENT

This section discusses the reduction of net carbon emissions by capturing and sequestering CO_2 after combustion, decarbonizing fuel before combustion, or increasing the absorption of CO_2 from the atmosphere. These approaches are required for the continued use of fossil fuels as energy sources with reduced impacts on concentrations of atmospheric CO_2. For both approaches, there are a number of technological options, ranging from storage of CO_2 in the ocean or in geologic formations to chemical or biological stimulation of the absorption of CO_2 from the atmosphere.

The eventual path to stabilization of atmospheric CO_2 concentrations would require portfolios of GHG reduction technologies, portfolios that would vary from nation to nation and require systems-level analysis. Risks associated with any one pathway suggest that developing an effective approach to large-scale carbon sequestration would require evaluation of a number of alternatives as described in this report. These ideas and technologies should have a sound basis in science, both for understanding each technology and for evaluating the effectiveness of the technologies in actually ameliorating the atmospheric carbon loading. Thus it is imperative that we have a science-based model of the carbon cycle (atmospheric, oceanic, and terrestrial ecosystems) and that we verify the actual effectiveness of our model through measurements. One set of essential elements are models of each part of the carbon cycle, anchored with georeferenced measurements and verified by checking performance predictions against data gathered using remote sensing technologies on local, regional, and global scales. The resulting science-based program would permit us to direct our investments with greater confidence and with improved cost-effectiveness.

The Potential for Reduced Emissions

The developmental status of the carbon sequestration technologies discussed in this report varies widely. For example, the injection of CO_2 into oil wells or coal seams to enhance oil or methane production is a commercial practice today, whereas the understanding of soil biochemistry is not yet adequate to identify the most promising means for increasing soil uptake of atmospheric CO_2. Therefore, estimating the potential impacts of these carbon sequestration technologies on net carbon emissions is difficult. It is generally believed that net carbon emission reduction from carbon sequestration could be very high in the time frame of the late 2030s and beyond. In the nearer term, carbon sequestration potentials are uncertain, but they may range from low to medium. All of these estimates should be considered possible targets and should only be considered within an order of magnitude indication of what might be likely to result from R&D on these technologies.

Technology Pathways and Opportunities

CO_2 and Carbon Storage Technologies. Promising concepts for reducing CO_2 emissions are the storage of CO_2 in the ocean or in geologic formations. The technical feasibility of both of these storage concepts has been established, and it is believed that the CO_2 escape rates in both cases could be low enough to consider the carbon as permanently sequestered. However, the ecological impacts of various specific approaches—which are likely to depend on the location and type of storage media—are not known, nor are the economics of different oceanic or terrestrial CO_2 injection technologies.

For ocean storage, the most critical R&D questions include the stability of CO_2 clathrates and hydrates at various temperatures and ocean depths, as well as the diffusivity of CO_2 in the ocean, again as a function of temperature, depth, and concentration. In addition, the biological impacts of oceanic injection need to be studied.

Terrestrial storage of CO_2 in depleted oil or gas wells, coal seams, or underground aquifers deserves analysis. For the injection of CO_2 into oil or gas wells or coal seams, which has enhanced oil and gas production (as well as, perhaps, mine safety), to be commercially motivated, the critical research questions center on understanding the total potential storage capacity and the economics of different specific candidate sites. Answers to these questions will depend on proximity to CO_2 sources, as well as on the size and other characteristics of the site.

For storage in underground aquifers, the critical research questions include fluid, thermal, geological, and chemical properties of aquifers and the implications of that environment for injected CO_2. For example, would the formation of complex carbonates result from CO_2 injection, and at what rate? The economics of such CO_2 storage also needs to be analyzed.

A third approach to reducing net emissions through storage is the terrestrial storage of elemental carbon. This concept basically entails removing some or all of the carbon from a fossil fuel and then storing the carbon as a solid. For this approach, the challenge is primarily economic, because the carbon component of the starting fossil resource represents a major part of the energy value of that resource. Not using the carbon fraction in effect increases the energy cost of the remaining hydrogen-rich energy fraction. The advantage of this approach is that it should be less expensive to store carbon than to store CO_2. It may also be possible to market the carbon as a materials commodity to offset the increased energy cost. If carbon is placed in retrievable storage, the carbon energy may be used at a later date under less severe CO_2 emission control conditions.

Currently, storage is believed to be relatively less expensive than capture technologies, but neither is being employed on a large scale. This, however, will change with time as combustion processes are reengineered to facilitate capture. As the cost of capture comes down, storage becomes a greater part of the cost equation. Managing this cost suggests that storage near the point of combustion is advantageous because it reduces the transportation cost of the waste carbon.

Which of the storage pathways is best matched to any single combustion or conversion location will vary, so parallel development is required. As discussion of the individual technology pathways highlights, it is important to emphasize that very clear technological and environmental risks are associated with these technologies. The R&D agenda must therefore be very aggressive if cost-effective technologies are to be in place in time.

Advanced Chemical and Biological Sequestration. There are also several advanced chemical and biological concepts for CO_2 sequestration, including

- chemical sequestration as a mineral carbonate
- direct solar conversion of CO_2 to methanol or other benign products
- reducing the carbon/hydrogen ratio of fossil fuels and capturing the excess carbon
- microalgae sequestration

Advanced chemical and biological sequestration is aimed at permanent stable sequestration and at recycle of carbon to new fuels and chemical feedstocks. Reduction of emissions is accomplished through converting CO_2 into an environmentally benign product, reducing atmospheric CO_2 while generating liquid fuels, generating hydrogen as a fuel from coal without CO_2 emissions, and converting CO_2 into organic compounds. The major advantage of these technologies is that they eliminate the hazards to humans and to the environment that are intrinsic in the disposal of gaseous CO_2. Carbonate disposal accomplishes this by forming environmentally benign and thermodynamically stable waste forms; the other approaches instead generate viable products. All of these are at a research stage, with conceptual engineering design currently being completed. A better understanding of the basic processes is needed before practical achievable technology performance or cost levels can be estimated. However, because of the inherent attractiveness of these sustainable solutions, further work is merited.

Technologies for Removing CO_2 from the Atmosphere. The annual exchange of CO_2 between the atmosphere and the combination of the ocean and terrestrial biosphere is very large (IPCC 1995):

- gross annual atmosphere–ocean exchange—approximately 92 GtC
- gross annual atmosphere–terrestrial exchange—approximately 63 GtC (IPCC 1995)
- oceans currently hold 44,000 GtC

By comparison, the total annual anthropogenic emissions of CO_2 are only around 7 GtC. This suggests that small increases in the absorption of CO_2 as a manipulation of the global carbon cycle could have a very significant effect on net GHG emissions.

Dissolved CO_2 in the oceans is removed by the growth of phytoplankton. When carbon is thus removed, it is ultimately replaced by CO_2 drawn from the atmosphere. Two concepts have been proposed for enhancing oceanic uptake of atmospheric CO_2. These are iron enrichment or nitrogen enrichment, both targeted at stimulating the growth of phytoplankton. The general understanding of these approaches is in its infancy. While some experiments on iron fertilization have been conducted, no such studies of nitrogen fertilization exist. Key questions include what rates of CO_2 uptake can be achieved, what the biological impacts are, and to what extent the gains would be offset by carbon or methane emissions resulting from increasing harvests or decay of higher levels of the food chain. The economics of these approaches, which depend directly on the costs and efficacy of different fertilization approaches and rates, also need to be studied. An important risk factor is that of anoxia, or oxygen depletion, which needs to be understood as a function of site characteristics and fertilization rates.

An important component of terrestrial uptake of CO_2 is plant growth, which is treated in the Agriculture and Forestry technology pathway. However, carbon sequestration in soils is also a key of the carbon cycle. The fundamental concept here is the level of "soil organic matter" (SOM). Many agricultural practices, such as breaking of grasslands for crop farming or draining of wetlands, tend to decrease SOM. Technologies that can increase SOM include minimum tillage agriculture, increased return of crop residues to the soil, use of irrigation and fertilizers at levels that maximize crop and root biomass, and return of lands to forests or perennial plants. The most critical R&D needs include research on soil productivity (including the interactions of fertilization levels), tillage practices, water management practices, different plant species, regional soil biochemistry and climate, and the implications of these for affecting SOM. A better understanding of these factors and their interactions can then enable the analysis of the economics of specific technological approaches to increasing SOM.

Collateral Benefits

The most important benefit of successes with these carbon sequestration technologies would be that they could help to enable the continued extensive use of fossil fuels without harm to the climate. Thus they could indirectly have a major impact on global economics, given that economic growth is highly dependent on energy use, about 75% of which is derived from fossil fuels.

Technical Risks and Other Issues

The most important risks for these carbon sequestration technologies are environmental and economic. Each has the potential for environmental damage, and developing means to prevent that is a primary research need in each case. The economics for all of these technologies should be analyzed to determine their actual carbon sequestration potential and their associated costs.

The risks that are difficult to quantify today, however, are those associated with scaling up limited but promising field experiments to full-scale practice. The global infrastructure requirements for realizing large net carbon sequestration rates from carbon sequestration technologies would require a system of technologies that match or exceed the infrastructure requirements of the fossil fuel combustion enterprise of the next century. It will only be through an aggressive R&D program that we can develop a fundamental understanding of these risks.

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